

LITHOPROBE

Slave-*NOR*thern Cordillera Lithospheric Evolution (*SNORCLE*)

and

CORDILLERAN TECTONICS WORKSHOP

Report of the 2000 Combined Meeting
February 25-27, 2000
University of Calgary

LITHOPROBE Report No. 72

Recommended Citation:

Cook, F. and P. Erdmer (compilers), 2000, Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) Transect and Cordilleran Tectonics Workshop Meeting (February 25-27), University of Calgary, Lithoprobe Report No. 72, 257 pp.

**LITHOPROBE SLAVE/NORTHERN CORDILLERA
LITHOSPHERIC EVOLUTION WORKSHOP
and
CORDILLERAN TECTONICS WORKSHOP**

University of Calgary, February 25-27, 2000

FRIDAY, February 25, 2000

**SESSION 1 - INTRODUCTION AND RESULTS FROM THE WESTERN
SLAVE PROVINCE TO CORDILLERA**

		Page
08:30-08:45	Introduction and Welcome <i>F.A. Cook and P. Erdmer</i>	
08:45-09:00	LITHOPROBE update <i>R.M. Clowes (Project Director)</i>	
09:00-09:15	1) Constraints on the geological evolution at Point and Beniah Lakes, Northwest Territories: Results from preliminary U-Pb zircon age determinations <i>W.U. Mueller, J.K. Mortensen, P.L. Corcoran and R.L. Simard.....</i>	8
09:15-09:30	2) Lithofacies characteristics and petrology of stable Archean shelf sequences: Slave province, NWT <i>C. Pickett and W.U. Mueller.....</i>	11
09:30-09:45	3) Crustal architecture of the Slave craton <i>W. Bleeker, J. Ketchum, R. Stern, K. Sircombe and B. Davis.....</i>	25
09:45-10:00	4) New field and U-Pb data from the central Slave cover group near Yellowknife and the central Slave basement complex at Point Lake <i>J. Ketchum and W. Bleeker.....</i>	27
10:00-10:30	<u>DISCUSSION</u> (discussion to be distributed among previous talks)	
10:30-11:00	<u>COFFEE AND POSTERS</u>	
11:00-11:15	5) Archean collisional tectonics imaged on Lithoprobe SNORCLE line1 <i>A.J. van der Velden and F.A. Cook.....</i>	32
11:15-11:30	6) The electric Slave craton <i>A.G. Jones, I. Ferguson, R. Evans and A. Chave.....</i>	36

11:30-11:45	7) Magnetotelluric response and geoelectric structure of southwestern Northwest Territories, Canada <i>X. Wu, I.J. Ferguson and A.G. Jones</i>	43
11:45-12:00	8) Mantle strain beneath the Great Slave Lake shear zone, NWT from measurements of seismic and electrical anisotropy <i>D.E. Eaton, I. Asudeh and A.G. Jones</i>	56
12:00-12:30	<u>DISCUSSION</u> (discussion to be distributed among previous talks)	
12:30-13:30	<u>LUNCH</u>	
13:30-13:45	9) Origin of chemical stratification of the Slave peridotitic mantle <i>M.G. Kopylova and J.K. Russell</i>	64
13:45-14:00	10) Interpretation of mantle structure and lithology using kimberlite-borne garnets from the Slave province and other locations in North America <i>D. Canil, D.J. Schulze, G.B. Carbone and K. Scully</i>	73
14:00-14:15	11) Wedge geometries in arc-continent convergence tectonics of the Wopmay, Svecofennian orogens and beyond <i>D.B. Snyder</i>	74
14:15-14:30	12) Lithology and U-Pb geochronology of shallow basement along the SNORCLE line, southwest Northwest Territories: A preliminary report <i>G.M. Ross, H.C. Ansell and M.A. Hamilton</i>	76
14:30-15:00	<u>DISCUSSION</u> (discussion to be distributed among previous talks)	
15:00-15:30	<u>COFFEE AND POSTERS</u>	

SESSION 2 - NORTHERN CORDILLERA

15:30-15:45	13) The thermal regime of the SNORCLE Lithoprobe transect and tectonic consequences <i>R.D. Hyndman, T.J. Lewis and P. Flueck</i>	81
15:45-16:00	14) Lithospheric structure across the Canadian Cordillera of northeastern British Columbia: Results from the SNoRE '97 experiment, line 21 <i>J.K. Welford and R.M. Clowes</i>	85
16:00-16:15	15) Mesoproterozoic evolution of northeastern British Columbia <i>D.G.F. Long and B.R. Pratt</i>	91

16:15-16:30	16) Isotopic provenance of the lower Muskwa assemblage, (Mesoproterozoic, Rocky Mountains, British Columbia): New clues to correlation and source areas <i>G.M. Ross, M.E. Villeneuve and R.J. Theriault</i> 93
16:30-17:00	<u>DISCUSSION</u> (discussion to be distributed among previous talks)
17:00-????	<u>POSTERS</u>

SATURDAY, February 26, 2000

08:30-08:45	17) Geology of lower Cambrian strata at Muncho Lake, northern British Columbia <i>R.T. Post and D.G.F. Long</i> 97
08:45-09:00	18) Joint subfabrics and their tectonic significance in sedimentary rocks of the Cordilleran shelf-miogeocline, southwest Inualuit, Canada <i>D.K. Norris, B.R. Pelletier and L.D. Dyke</i> 100
09:00-09:15	19) Evolution of the Laurentian margin during the late Cambrian to early Silurian: Stratigraphy and conodont biostratigraphy of a platform to basin transect, northeastern British Columbia <i>L.J. Pyle and C.R. Barnes</i> 101
09:15-09:30	20) Progress report on middle and late Triassic ichthyolith biostratigraphy and regional thermal maturation studies in the Trutch map area of northeastern British Columbia <i>M.J. Johns, C.R. Barnes and M.J. Orchard</i> 104
09:30-10:00	<u>DISCUSSION</u> (discussion to be distributed among previous talks)
10:00-10:45	<u>COFFEE AND POSTERS</u>
10:45-11:00	21) Crustal seismic velocity structure of the northern Cordillera, southern Yukon Territory, Lithoprobe SnoRE line 31 <i>B. Creaser and G. Spence</i> 110
11:00-11:15	22) Reflections on Lithoprobe-SNORCLE line 31 in light of the structure of the Teslin zone in the Last Peak area (NTS map 105E/9), southern Yukon Territory <i>M. de Keijzer, P.F. Williams and S.D. Carr</i> 114

	Page
11:15-11:30	23)SNORCLE reflection survey 1999-2000: Corridors 2 and 3 <i>F.A. Cook, R.M. Clowes, D.B. Snyder, A.J. van der Velden, K.W. Hall and K. Vasudevan</i> 122
11:30-11:45	24)New SNORCLE magnetotelluric data: preliminary implications <i>J. Ledo, A.G. Jones and I.J. Ferguson</i> 124
11:45-12:30	<u>DISCUSSION</u> (discussion to be distributed among previous talks)
12:30-13:30	<u>LUNCH</u>
13:30-13:45	25)New digital compilation of Yukon geology <i>S.P. Gordey and A.J. Makepeace</i> 128
13:45-14:00	26)Arc-rifting and ensialic back-arc basin magmatism in the northern Canadian Cordillera: Evidence from the Yukon-Tanana terrane, Finlayson Lake region, Yukon <i>S.J. Piercey, D.C. Murphy, J.K. Mortensen and S. Paradis</i> 129
14:00-14:15	27)Mid-paleozoic tectonism in Yukon-Tanana terrane, northern Canadian Cordillera: Record of intra-arc deformation <i>M. Colpron, D. Murphy and J. Mortensen</i> 139
14:15-14:30	28)Geochemical and isotopic constraints on the source terranes of mid-Cretaceous granites in the Teslin area <i>G.A. Morris and R.A. Creaser</i> 140
14:30-15:00	<u>DISCUSSION</u> (discussion to be distributed among previous talks)
15:00-15:30	<u>COFFEE AND POSTERS</u>
15:30-15:45	29)Eocene magmatism along the Sloko volcanic arc <i>J. Resnick and D. Francis</i> 143
15:45-16:00	30)Minimal geotectonic motion of the Yukon-Tanana terrane relative to North America: Preliminary paleomagnetic results from the Dawson Range batholith <i>P.J.A. McCausland, D.T.A. Symons, C.J.R. Hart and W.H. Blackburn</i> 146
16:00-16:15	31)Paleomagnetic evidence for the tectonic motions of the terranes underlying the northern Intermontane belt, Canadian Cordillera: A summary <i>M.J. Harris, D.T.A. Symons, C.J.R. Hart, W.H. Blackburn and P.J.A. McCausland</i> 155

16:15-16:45 **DISCUSSION** (discussion to be distributed among previous talks)

16:45-???? **POSTERS**

SUNDAY, February 27, 2000

SESSION 3 - SOUTHERN CORDILLERA

- 08:30-08:45 32) Multiple deformations, multiple intrusions, multiple tectonic levels and the dating of fabrics: A cautionary tale from Valhalla
P.S. Simony and S.D. Carr.....165
- 08:45-09:00 33) Age constraints on penetrative structures at Joss Mountain, in the Selkirk allochthon, southern Canadian Cordillera
Y.D. Kuiper, S.D. Carr and P.F. Williams.....168
- 09:00-09:15 34) Volcanic stratigraphy: Enderby Cliffs and Trinity Hills outliers of the Eocene Kamloops group, southern British Columbia
K. Breitsprecher, D.J. Thorkelson and R.I. Thompson.....169
- 09:15-09:30 35) Structural, metamorphic, and plutonic history of rocks adjacent to Shuswap Lake, British Columbia: Evidence of early to middle Paleozoic deformation
N. Slemko.....172
- 09:30-10:00 **DISCUSSION** (discussion to be distributed among previous talks)
- 10:00-10:30 **COFFEE AND POSTERS**
- 10:30-10:45 36) Nicola horst: Toward a geochronological and cooling history
J.M. Moore, J.E. Gabites and R.M. Friedman.....177
- 10:45-11:00 37) Geological setting of the Rea and Samatsum sulphide deposits, Eagle Bay assemblage south central British Columbia
S.L. Bailey, S. Paradis, S.T. Johnston and T. Höy.....186
- 11:00-11:15 38) Lateral asthenospheric flow through slab windows
D.J. Thorkelson, S.T. Johnston, R.M. Russo and R.E. Murdie.....187
- 11:15-12:30 **DISCUSSION** (discussion to be distributed among previous talks)
- 12:30-13:30 **LUNCH**

Posters

(listed alphabetically)

- 1) Coherent stratigraphic succession from Little Salmon range
(Yukon-Tanana terrane), central Yukon
M. Colpron.....189
- 2) The role of provenance, chemical weathering, and sorting in the
evolution of late-stage orogenic basins in the Slave craton: A
combined geochemical, petrographic and facies analysis approach
P.L. Corcoran, W.U. Mueller and J. Dostal.....192
- 3) Physical modelling documents mechanical coupling between the
thrust-sheet and footwall panels near lateral ramps and tear-faults
J.M. Dixon, B. Dietrich and D. Deline.....202
- 4) Coherent blueschist terrane, French range, British Columbia
P. Erdmer, E.D. Ghent, M. Mihalynuk and F. Cordey.....203
- 5) Geology along the southern 250 km of SNORCLE line2 -
Iskut to Stewart
C.A. Evenchick.....204
- 6) Sedimentology and tectonic setting of the late Archean Burwash
formation, southern Slave province, Northwest Territories
M. Ferguson, J. Waldron and W. Bleeker.....210
- 7) U-Pb geochronologic constraints on metamorphism and deformation
within the northern Selkirk Mountains, southeastern Canadian Cordillera
H.D. Gibson, S.D. Carr and R.L. Brown.....213
- 8) A new look at eastern Nass River map-area (103P), British Columbia
*J.W. Haggart, J.B. Mahoney, A.J. Justason, C. Rowe
and M. Schimdt*.....215
- 9) Lithospheric structure across the Coast orogen of NW British Columbia
and SE Alaska from seismic wide-angle studies: Lithoprobe SNORE
line 22 and ACCRETE profiles
P.T.C. Hammer and R.M. Clowes.....218
- 10) A summary of Jurassic paleomagnetic data describing the tectonic
motions of the terranes underlying the Intermontane belt,
Canadian Cordillera
M.J. Harris, D.T.A. Symons, W.H. Blackburn and C.J.R. Hart.....224

	Page
11)Regional electrical conductivity of the southern Canadian Cordillera <i>J. Ledo and A.G. Jones</i>	225
12)Ancient crystalline basement in western Canada: Its influence on the platformal sedimentary cover, and basement remnants across the Cordillera <i>H. Lyatsky</i>	232
13)SNORCLE Digital Data Archive Website <i>C.E.Lynn</i>	244
14)Magma storage depths beneath northern British Columbia: Inferences from thermodynamic modeling <i>J. Nicholls and M.Z. Stout</i>	245
15)Modeling the evolution of the lower lithosphere during continental collision <i>R. Pysklywec, C. Beaumont and P. Fullsack</i>	246
16)Clastic dykes as paleoslope indicators in the Nanaimo group, Hornby Island, British Columbia <i>C.E. Rowe, D.C. Katnick, P.S. Mustard and J.B. Mahoney</i>	247
17)Comparative geochemistry of the Spences Bridge group and coeval volcanic rocks: Potential constraints on large scale translation <i>M.J. Schmidt, M.L. Haskin, J.B. Mahoney and P.S. Mustard</i>	249
18)Magnetotelluric response and geoelectric structure of Great Slave Lake shear zone along SNORCLE transect corridor 1a <i>X. Wu, I.J. Ferguson and A.G. Jones</i>	251

Preface

This volume includes the abstracts and short articles submitted for the 2000 LITHOPROBE Slave - Northern Cordillera Lithospheric Evolution (SNORCLE) transect meeting and Cordilleran Tectonics Workshop. These meetings were held concurrently at the University of Calgary. Accordingly, this volume includes several contributions related to both the southern and northern Cordillera. We sincerely thank Elissa Lynn for her assistance in organizing the meeting and compiling this volume.

Frederick A. Cook and Philippe Erdmer

*ABSTRACTS of
ORAL
PRESENTATIONS*

Constraints on the Geological Evolution at Point and Beniah Lakes, Northwest Territories: results from preliminary U-Pb zircon age determinations

Mueller, W.U., Sciences de la terre, Université du Québec à Chicoutimi, Chicoutimi, Québec, G7H 2B1;
Mortensen, J.K., Earth & Ocean Sciences, University of British Columbia, Vancouver, B.C., V6T 1Z4;
Corcoran, P.L., Dept. of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5;
Simard, R.L., Sciences de la terre, Université du Québec à Chicoutimi, Chicoutimi,

The Archean Slave Craton has been the focus of an extensive mapping program in recent years. Emphasis has been placed on large-scale tectonic features, as well as U-Pb zircon age constraints (e.g. Bleeker et al., 1999), structure, Sm-Nd isotope geochemistry and geochronology (Northrup et al., 1999), physical volcanology (Corcoran, 2000), sedimentology (Mueller et al., submitted), and regional lithological aspects of specific greenstone belt segments (Jackson, 1996; Henderson, 1998). The complexity of Slave Province evolution can be demonstrated along the crustal-scale Beniah Lake fault, which transects the craton from south to north. The importance of this fault is shown by (1) the presence of an extensive 2.8-3.3 Ga basement high, (2) well-preserved 2.8-2.9 Ga protocontinental quartz-arenite sequences, (3) the formation of late-stage, tectonically-controlled molasse basins, and (4) the development of 2.6-2.7 Ga greenstone belts. One of the striking features of the Slave Province is the abundance of unconformable-disconformable contacts between (1) basement-greenstone belt, (2) basement-molasse sequences, (3) basement-flysch successions, (4) flysch and molasse deposits, (5) platformal and molasse sequences, and (6) greenstone belt-molasse basins that enable pan-Slave correlations (Mueller et al., 1998). The combination of well-defined field relationships associated with precise U-Pb dating of zircons helps constrain the evolution of specific segments in the Slave Craton.

Point Lake Results

Preliminary data from selected samples at Point and Beniah Lakes is employed to infer possible evolutionary trends of volcano-sedimentary assemblages that developed along the Beniah Lake fault. Samples YK-PL-2 from the felsic Beuparlant Formation and YK-PL-4 from a feldspar-phyric porphyry at Point Lake, combined with previous structural and geochronological studies (Relf, 1992; Northrup et al., 1999; Daigneault, unpublished data) give important new insights. A small amount of fine-grained zircons were recovered from sample YK-PL-2, a possible lateral equivalent of the Itchen-Contwoyto Formation turbidites. Four strongly abraded single and multi-grain analyzed fractions, ranging from 12.1-25.7% discordant, define a linear array with upper and lower concordia intercepts, yielding ages of 2683.3 $\pm$ 8.6/-8.2 Ma and 397 Ma, respectively. The upper intercept is considered the crystallization age of the sample. The Point Lake porphyry stock, YK-PL-4, intrudes the Contwoyto Formation, and is aligned parallel to a fault possibly splaying off the principal N-trending Beniah Lake fault: Four zircon grains recovered from the sample are strongly abraded single grains. Two analyses range from 3.2-5.2% discordant and have overlapping $^{207}\text{Pb}/^{206}\text{Pb}$ ages, with a weighted average of 2650.0 $\pm$ 3.2 Ma. This is tentatively interpreted as the crystallization age of the rock, whereas the two other single grains which give much older ages of 2906 Ma and 3251 Ma are interpreted as xenocrystic in origin.

Importance of data

The samples were chosen to constrain the age of formation of the Point Lake greenstone belt and to possibly define the age of deformation. The volcanoclastic deposits and brecciated felsic flows of the Beuparlant Formation are interstratified with the Samandre and Contwoyto formations. Paleogeographic reconstruction and evolution of the Point Lake greenstone belt based on physical volcanology, geochemistry and sedimentology is presently being conducted by P.L. Corcoran (PhD-thesis, Dalhousie, Nova Scotia). The age of $2683.3 \pm 8.6/-8.2$ Ma for the Beuparlant Formation shows that it is contemporaneous with intermediate volcanoclastic deposits of the Peltier Formation (2673 ± 4 Ma) and related mafic dykes intruding the Augustus granite (2690 ± 3 Ma; Northrup et al., 1999). The feldspar-phyrlic porphyry, which is part of a BSc-thesis concerning porphyry intrusions along the Beniah Lake fault (R.L. Simard, UQAC), with an age of 2650.0 ± 3.2 Ma, may possibly represent the change in deformation from early E-W shortening (Northrup et al., 1999) or thrusting (Kusky, 1991; Relf, 1992) to N-S transcurrent movement or sinistral strike-slip faulting (Northrup et al., 1999). Similar changes from thrusting to strike-slip movement have been documented in several greenstone belts (Mueller et al., 1996; Kusky and Polat, 1999), but the inferred change in crustal dynamics would be ca. 50 m.y. older than initially perceived (Northrup et al., 1999). Alternatively, the porphyry indicates emplacement during the latter stages of E-W shortening and therefore indicates the age of early deformation in the Point Lake greenstone belt. In addition, the date provides a minimum age for the deposition of the Contwoyto Formation, demonstrating that the turbidites are not deep-water equivalents of the 2.6 Ga Keskarrah Formation, as supported by the unconformity between the molasse and flysch deposits (Corcoran et al., 1998; Mueller et al., 1998). Multi-element geochemical analysis will further help interpret the genesis of the porphyry stock.

Beniah Lake Results

The quartz-feldspar porphyry (QFP-98-1) at Beniah Lake, aligned along a NNW-SSE trending lineament, is part of a plutonic suite of rocks that both locally act as basement to the Beniah quartz arenite-BIF-volcanoclastic-volcanic sequence (Isachsen and Bowring, 1997) and intrude the Beniah clastic-dominated sedimentary sequence. Sample QFP-98-1 with seven strongly abraded single zircon grains are 5.4-21.8% discordant. Four of the analyses define a linear array with upper and lower concordia intercept ages of $2708.8 \pm 5.5/-5.1$ Ma and 442 Ma, respectively. This excludes the most discordant analysis. Two other analyses fall slightly to the right of the regression line and are interpreted to have contained minor inherited zircon cores. If the remaining analyses are free of an inherited component, then the upper intercept age suggests a crystallization age.

Importance of data:

The QFP sample shows that there is no simple temporal trend concerning the evolution of porphyry stocks emplaced along or close to the Beniah Lake fault. The stock, based on the map pattern (Roach, 1989) and field evidence, intrudes highly strained mafic volcanic rocks and quartzo-feldspathic hornblende gneiss (Roach, 1989) both with a prominent foliation of approximately 150/80. The age of $2708.8 \pm 5.5/-5.1$, if borne out by further analyses, will support that the strongly foliated gneiss probably represents basement, whereas the mafic rocks are an integral part of the older 2.8-2.9 Ga Beniah platformal sequence, as are the fine-grained, finely-laminated volcanoclastic rocks. In addition, this would support the contention that the

Beniah Formation is a complex volcano-sedimentary succession and not simply a clastic quartz arenite-BIF unit.

Studies are presently being conducted on the felsic volcanoclastic (tuffaceous) units in order to constrain the age of the Beniah Formation. Alternatively, these deposits could be part of the 2.7 Ga Yellowknife arc-backarc forming event. Several samples from the Beaulieu River volcanic belt are also being processed and the results will demonstrate whether the volcanic sequence is the temporal equivalent of the Point Lake greenstone belt.

References

- Bleeker, W., Ketchum, J.W.F., Jackson, V.A., and Villeneuve, M.E., 1999. The central Slave basement complex, Part I: its structural topology and autochthonous cover. *Can. J. Earth Sci.* 36, 1083-1109.
- Corcoran, P.L., Mueller, W.U., Chown, E.H., 1998. Climatic and tectonic influences on fan deltas and wave- to tide-controlled shoreface deposits: evidence from the Archean Keskarrh Formation, Slave Province, Canada. *Sed. Geol.*, 120: 125-152.
- Corcoran, P.L., 2000. Recognizing distinct portions of seamounts using volcanic facies analysis: examples from the Archean Slave Province, Northwest Territories, Canada. *Precamb. Res.*, in press.
- Jackson, V.A., 1996. Preliminary geology of part of the lower supracrustal succession in the Bell Lake area (85J/16). NWT Geology Division, Indian and Northern Affairs Canada, Report with marginal notes, EGS 1996-17.
- Henderson, J.B., 1998. Geology of the Keskarrh Bay Area, District of Mackenzie, Northwest Territories. *Geol. Surv. Can. Bull.* 527, 122 pp.
- Isachsen, C.E. and Bowring, S.A., 1997. The Bell Lake group and Anton Complex: a basement – cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation. *Can. J. earth Sci.* 34, 169-189.
- Kusky, T.M., 1991. Structural development of an Archean orogen, western Point Lake, Northwest Territories. *Tectonics*, 10: 820-841.
- Kusky, T.M. and Polat, A., 1999. Growth of granite-greenstone terranes at convergent margins and stabilization of Archean cratons. *Tectonophysics* 305, 43-73.
- Mueller, W.U., Corcoran, P.L., and Donaldson, J.A., submitted. Sedimentology of a tide-influenced high energy Archean coastline: the Jackson Lake Formation, Slave Province, Canada. Submitted to *IAS on Precambrian Sedimentation*.
- Mueller, W.U., Bowring, S.A., Corcoran, P. L., and Pickett, C., 1998. Unconformities, major faults and the evolution of volcano-sedimentary basins on the Slave craton. In Cook, F. and Erdmer, P. (compilers). *Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) Transect and Cordilleran Tectonics Workshop meeting (March 6-8)*, Simon Fraser University, Lithoprobe report No. 64, p.15-16.
- Mueller, W.U., Daigneault, R., Mortensen, J.K., and Chown, E.H., 1996. Archean terrane docking: Upper crust collision tectonics, Abitibi greenstone belt, Quebec, Canada. *Tectonophysics*, 265, 127-150.
- Northrup, C.J., Isachsen, C. and Bowring, S.A., 1999. Field relations, U-Pb geochronology and Sm-Nd isotope geochemistry of the Point Lake greenstone belt and adjacent gneisses, central Slave craton, N.W.T., Canada. *Can. J. Earth Sci.* 36, 1043-1059.
- Relf, C., 1992. Two distinct shortening events during late Archean orogeny in the west-central Slave Province, Northwest Territories, Canada. *Can. J. Earth Sci.* 29, 2104-2117.
- Roach, D., 1989. Preliminary geology of the Beniah Lake area (NTS 85 P/8). NWT Geology division, Indian and Northern Affairs, Canada, EGS-1989-9 (map with marginal notes).

Lithofacies characteristics and petrography of stable Archean shelf sequences: Slave Province, NWT.

Pickett, C. and Mueller, W.U., Sciences de la terre, Université du Québec à Chicoutimi,
Québec, Canada, G7H 2B1; rechgeo@uqac.quebec.ca

Introduction

Mineralogically mature sedimentary successions that rest above Archean basement and underlie the Yellowknife Supergroup and pan-Slave equivalents are found in several locations throughout the Slave Structural Province (Bleeker et al. 1999). Two such successions, mapped in detail, include the Beniah and Bell Lake formations (Figure 1), both having formed at ca. 2.8-2.9Ga (Isachsen and Bowring 1997). The Beniah Formation is a 200- to 1000m-thick volcano-sedimentary succession located at Beniah Lake, 145km NE of Yellowknife (63°19'N, 112°12'E). The Bell Lake Formation, 30- to 70m-thick, is situated at Bell Lake, ~45km north of Yellowknife (65°50'N, 114°20'E). The sedimentary sequences, composed of quartz-arenite, heterolithic sandstone-siltstone, banded iron-formation, minor volcanoclastic rocks, and local quartz-pebble conglomerate, overlie a tonalite to granodiorite gneissic basement. Both the Beniah and Bell Lake formations are capped by thick sequences of subaqueous tholeiitic mafic volcanic flows and cut by several metre-thick gabbroic dykes/sills. Metamorphic grade ranges from upper greenschist to lower amphibolite, but primary sedimentary structures are preserved.

Sedimentology of the Beniah Formation

Detailed sedimentology of the Beniah Formation reveals the presence of four distinct lithofacies including, 1) conglomerate, 2) quartz-arenite, 3) sandstone-siltstone, and 4) siltstone-sandstone defined by grain-size and corresponding sedimentary structures. Figure 2 is a stratigraphic section with three corresponding detailed stratigraphic columns representing the distinct lithofacies of the Beniah Formation.

The conglomerate lithofacies comprises 5% of the Beniah Formation and is subdivided into quartz-pebble conglomerate (QPSL) and sedimentary breccia (SBSL) sublithofacies. The QPSL is characterized by 1 to 8m-thick massive and graded beds, with local trough crossbeds and clay drapes, and is predominantly composed of well-sorted, well-rounded, pebble- to cobble-size quartz clasts, ranging from 2-10cm. These characteristics suggest deposition in a high-energy environment whereby traction currents are the predominant means of bedload transport with considerable clast interaction, abrasion and an overall high net movement of grains. Clay drapes intercalated with the quartz-pebble conglomerate are suggestive of a fluctuating wave-energy environment with alternating fairweather and storm conditions (Reading and Collinson 1996). This sublithofacies may represent coastal gravel bars in an upper shoreface to foreshore setting. The sedimentary breccia, containing angular fragments of siltstone and quartz-arenite supported in a quartz/mica-rich matrix, is consistent with a mass flow deposit.

The 10 to 120m-thick quartz-arenite lithofacies (QAL), comprising 58% of the Beniah Formation, contains local mm- to cm-thick mudstone laminae and 0.25 to 2m-thick tabular bedsets containing complex composite planar and low-angle cross-stratification,

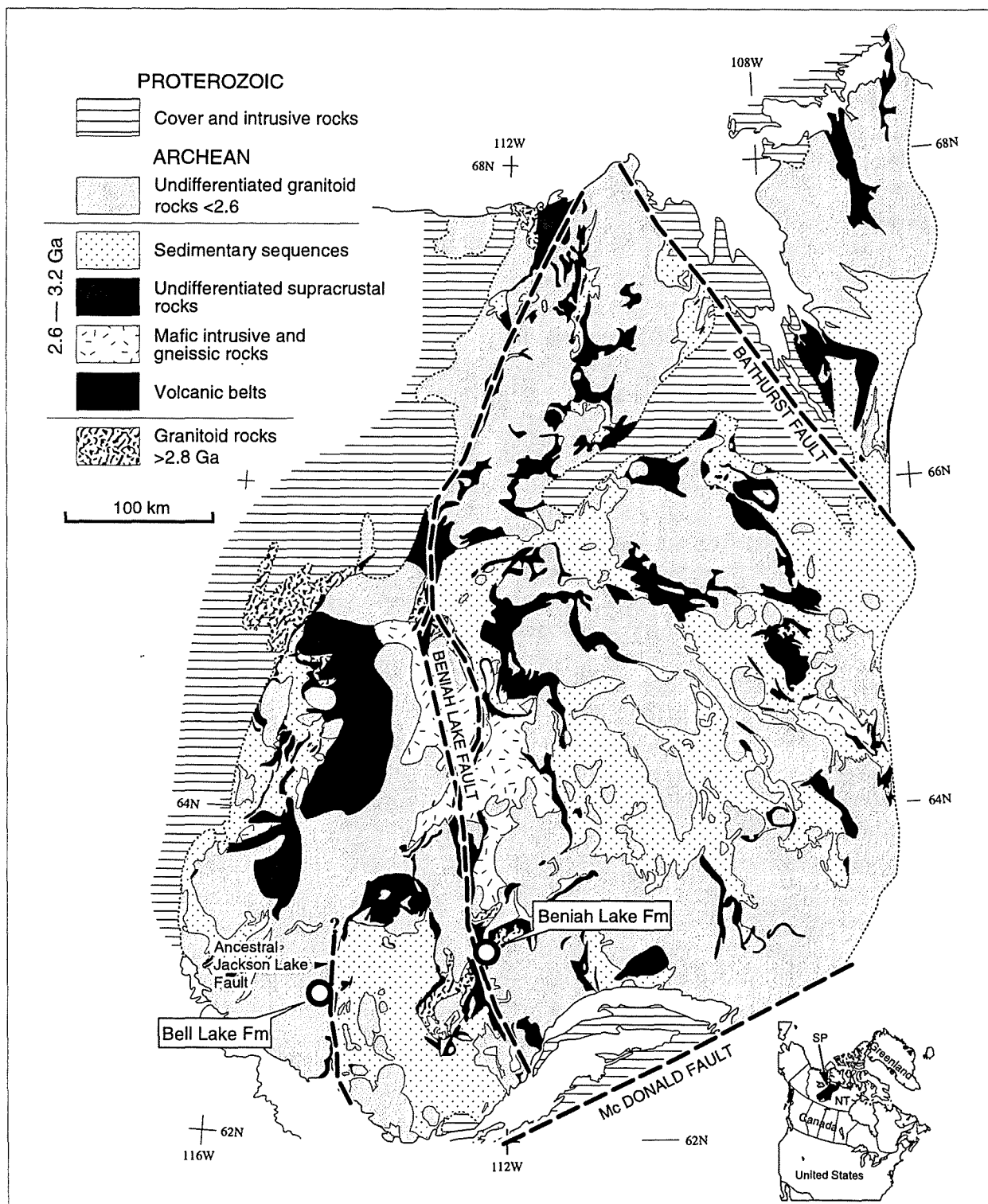


Figure 1. Geological map of the Slave structural province indicating the location of the two main study areas.

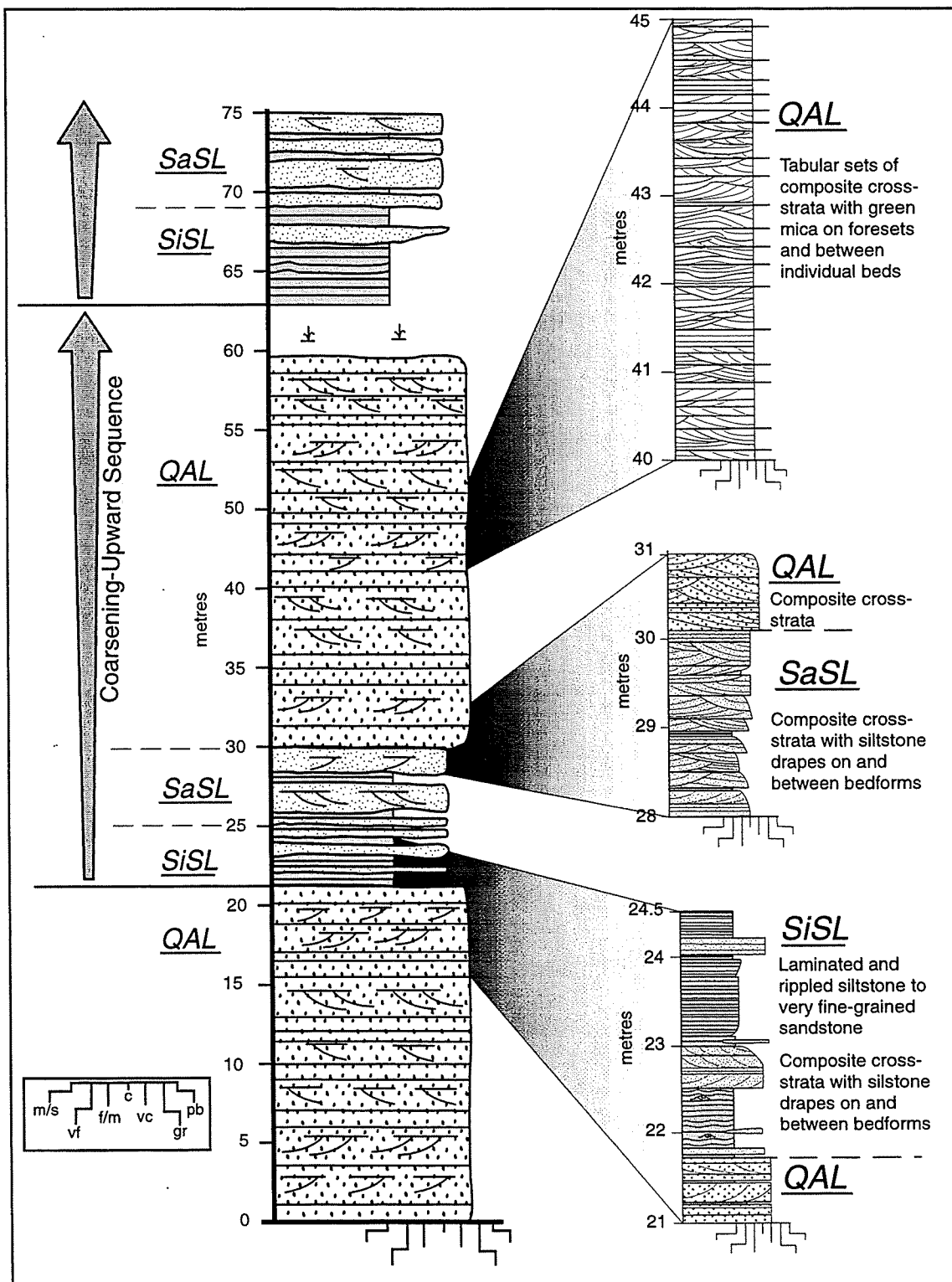


Figure 2. Stratigraphic section from south-central Beniah Lake revealing two coarsening-upward sequences and corresponding detailed stratigraphic columns illustrating the general characteristics for each of the lithofacies. QAL=quartz-arenite lithofacies, SiSL=siltstone-sandstone lithofacies, SaSL=sandstone-siltstone lithofacies.

including medium- to large-scale tangential crossbeds, local tabular crossbeds, and possible herringbone crossbeds. The bedforms within the QAL are associated with tides and the mica-rich laminae were deposited from suspension during pauses in tidal action (Visser 1980). The local absence of mudstone laminae may reflect increased wave influence (Dalrymple 1992). The large-scale sedimentary structures found in the coarse-to very coarse-grained sandstones and the intercalating siltstone laminae of the QAL represent laterally migrating dunes (Mueller and Dimroth 1987) at the nearshore-offshore boundary, with tide-, wave-and possible storm-influence.

The sandstone-siltstone lithofacies (SaSL), constituting 20% of the Beniah Formation, is defined by >50% sand-size grains with minor interstratified beds of silt-sized material 10-16m thick. Medium to very-coarse grained sandstone beds (5 to 30cm thick) contain abundant low-angle tangential to planar crossbeds, small-scale ripples superposed on larger trough-cross beds, reactivation surfaces, local channel scours, and siltstone laminae on and between bedsets. Subordinate siltstone beds are 2-16cm thick and are parallel laminated. Ripple marks, large-scale cross-stratification with clay drapes and reactivation surfaces suggest flow variability and may be related to changes in tidal flood-ebb cycles (de Mowbray and Visser 1984). Oscillatory ripples capping crossbeds reflect fairweather wave reworking of the upper surface of tidal sand waves during quiet periods within tidal cycles (Soegaard and Eriksson 1985). Cross-stratification revealing opposing paleocurrent directions is consistent with tidal influence. The SaSL represents tidal channels in a shoreface setting.

The siltstone-sandstone lithofacies (SiSL) comprises 17% of the Beniah Formation and is subdivided into wavy- to planar-bedded siltstone (WPSL) and banded iron-formation sublithofacies (BIFSL). The WPSL, defined by >50% silt-sized material with subordinate (<50%) sand-sized grains, attains a thickness varying from 5-13m and is characterized by 0.1- to 3m-thick siltstone beds with planar to wavy laminations and rippled horizons, as well as local graded bedding and pebble lags. Subordinate medium to coarse-grained sandstones, 5-20cm thick, contain both planar and low angle cross-laminae that are often continuous along strike, although many pinch out laterally. The BIFSL contains alternating (mm- to cm-thick) bands of fine quartz-rich (cherty?) material and magnetite-rich, sulfide-poor layers. The SiSL, with abundant fine-grained material, planar to wavy bedforms and local pebble lag, is indicative of a transitional offshore to lower shoreface setting. In addition, the down-cutting trend of the SaSL over the PWSL suggests lateral migration of a tidal channel into the lateral tidal shoal counterpart (i.e. topographic highs in relation to the channel). Graded beds were deposited below mean wave base and pebble lags were deposited immediately following intense storms or flash floods. Interbedded sandstones in the WPSL reflect alternating fairweather and storm deposits in a proximal offshore to lower shoreface environment (Okazaki and Masuda 1995).

Mineralogical maturity of the Beniah Formation is evaluated through point-counting. Based on the results of 16 samples from the quartz-arenite lithofacies (at 400 points per sample), two thin-sections contained 99 and 99.5% quartz with all other samples consisting of 100% quartz. These results, along with four samples from the Bell Lake Formation, have been plotted in Figure 3.

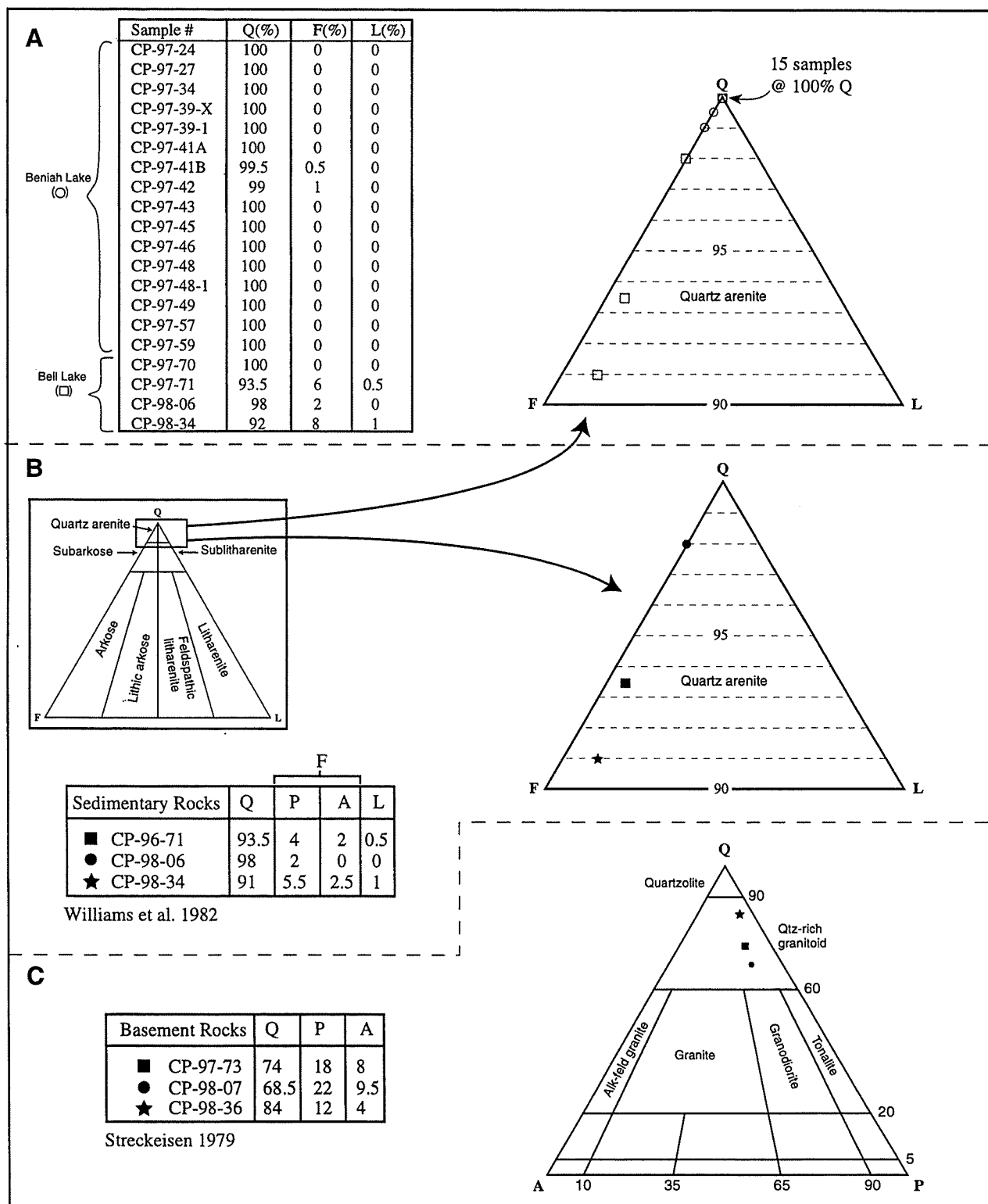


Figure 3. A) QFL diagram comparing point-counting results of the quartz-arenite lithofacies from the Beniah and Bell Lake formations. B) QFL diagram of samples from the quartz-arenite lithofacies, Bell Lake Formation. C) Basement samples plotted on a QAP ternary diagram, Bell Lake Formation. Q=quartz, A=alkali feldspars, P=plagioclase, F=total feldspars (A+P), L=lithic rock fragments. Complete references for cited authors are located in main reference list.

Facies Analysis

A detailed facies analysis of the Beniah Formation indicates a shallow marine shelf-type setting with tide-, wave- and possible storm-influence. More specifically, the formation is composed of a series of tidal channels composed of tangential to planar crossbedded sandstones and interbedded siltstone (SaSL) with corresponding shoaling deposits of abundant siltstone and finer sandstone (SiSL). The middle- to upper-shoreface predominantly contains tabular sets of tangential to planar crossbedded, coarse-grained quartz-arenite (QAL), and local interbedded quartz-pebble conglomerate (CL), indicative of close proximity to the shoreline. Bidirectional and bipolar paleocurrents (Figure 4), reactivation surfaces, and the presence of clay drapes, suggest highly fluctuating current- and wave-energy conditions, commonly associated with tide-influence.

Vertical stacking of the lithofacies reveals a number of coarsening-upward parasequences, 10m-85m thick (see Fig. 2). Well-defined parasequences contain the SiSL at the base, followed by a middle SaSL and the QAL, with local CL at the top. Contacts between lithofacies are gradual over 1-2m and each parasequence is separated by a marine flooding surface showing a sharp and abrupt change from the coarser-grained lithofacies (either QAL or CL) to the finer-grained rocks of the SiSL. The development of these coarsening-upward parasequences could have occurred through a combination of eustatic sea-level change and basin subsidence, as described by Duke et al (1996). However, another theory pertaining to the influence of tectonic activity on sedimentation is equally conceivable.

Sedimentology of the Bell Lake Formation

The sedimentary rocks of the Bell Lake Formation are separated into three distinct lithofacies including, 1) quartz-arenite, 2) sandstone-siltstone, and 3) banded iron formation. Figure 5 illustrates a 50m stratigraphic section from Bell Lake representing the various lithofacies and revealing the contact with the basement.

The quartz-arenite lithofacies (QAL), up to 7m thick, constitutes 21% of the Bell Lake Formation and is characterized by parallel and cross-laminated (revealed by green mica-rich laminae on forsets), locally graded and tabular-shaped beds. Composite beds are generally less than one metre thick and are moderately- to well-sorted, with some differences in both grain-size and mineralogical maturity. The QAL also contains mm-size, subrounded detrital chromite grains that are often enveloped by seams of green mica (fuchsite?). Although sedimentary structures are obscured by regional deformation, the composite bedforms, low-angle cross-stratification and mica-rich drapes within the QAL suggest wave- and/or tidal-influence, similar to the QAL of the Beniah Formation, but with thinner bedsets and smaller-scale structures.

The sandstone-siltstone lithofacies (SaSL), 1-12m thick, comprises 29% of the Bell Lake Formation and is characterized by intercalated medium-grained sandstone and siltstone with semipelitic textures and local garnet-rich layers. The cm- to dm-thick alternation of sandstone and siltstone beds gives the lithofacies a "striped" appearance. Locally found within the SaSL are minor felsic to intermediate volcanoclastic units, generally less than 2m thick, characterized by fine- to medium-grained volcanoclastic sandstones with flattened and elongated pumiceous(?) material. The predominant

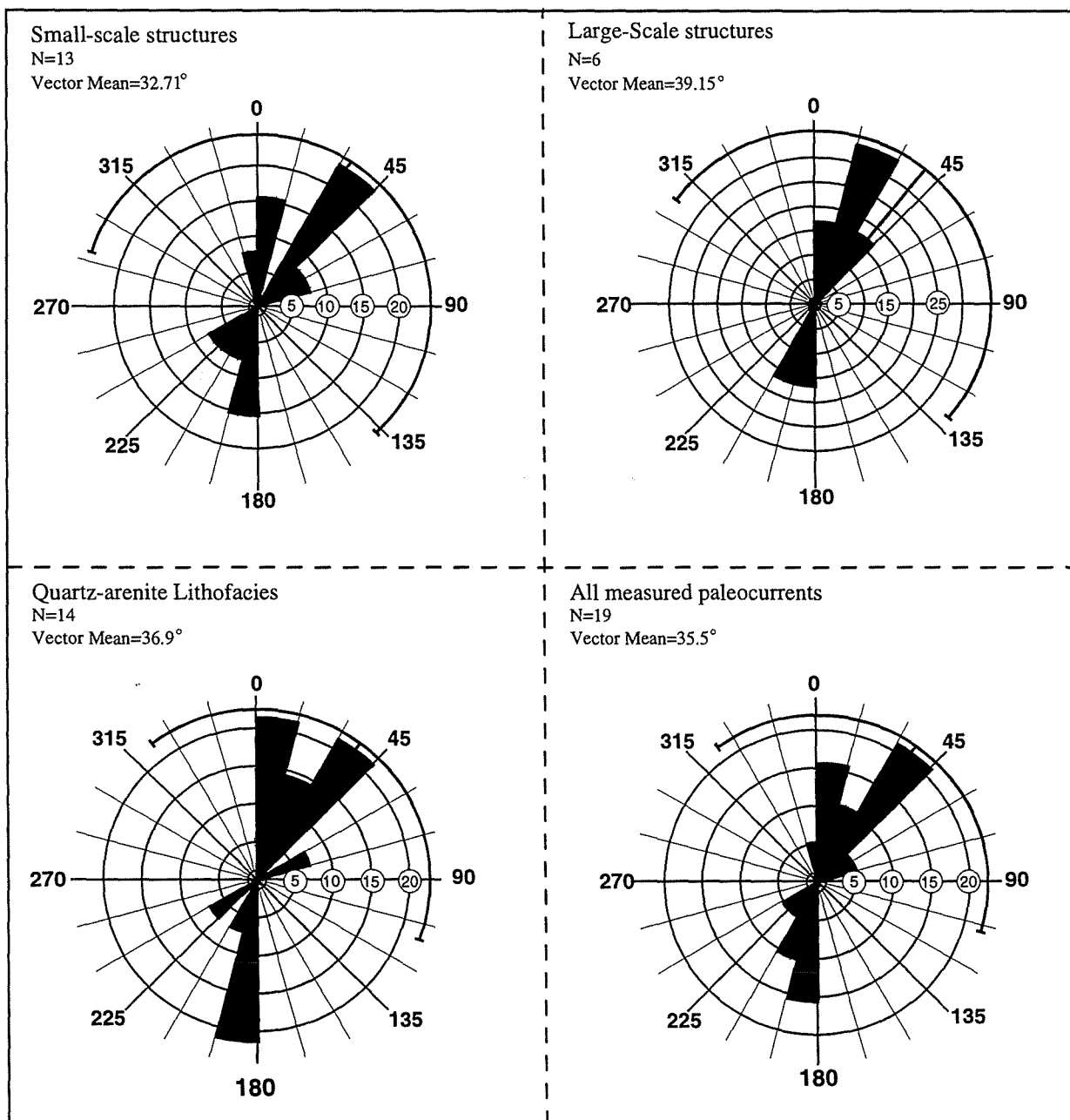


Figure 4. Rose diagrams plotted using paleocurrent measurements from the Beniah Lake Formation revealing both a bimodal and bipolar distribution. N=sample population, ②0= percentage.

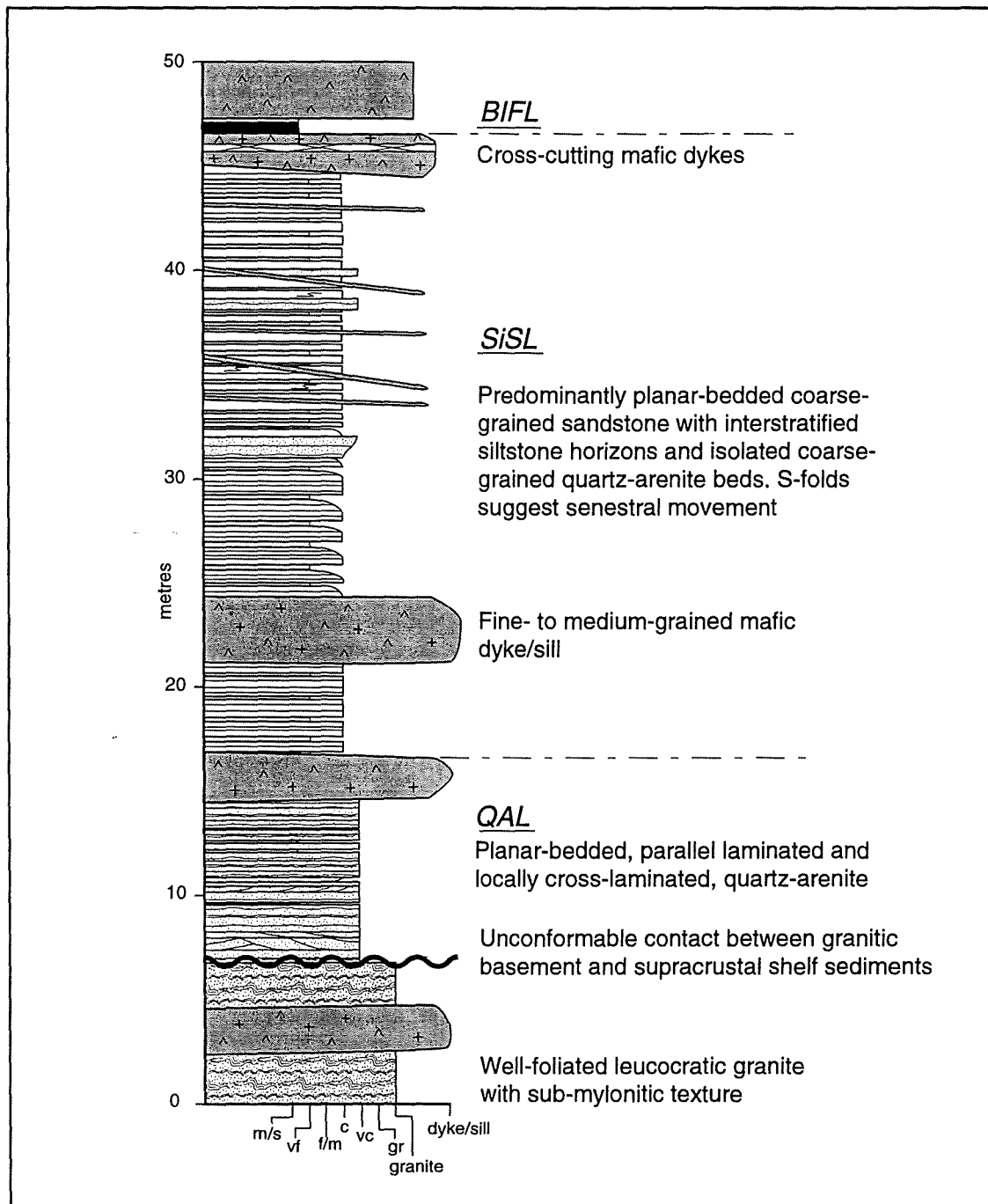


Figure 5. Fifty-metre stratigraphic column representing the lithofacies of the Bell Lake Formation. QAL=quartz-arenite lithofacies, SaSL=sandstone-siltstone lithofacies, BIFL=banded iron formation lithofacies.

sedimentary structures in the SaSL are parallel laminae with local graded bedding, although many beds appear massive and structureless. The interbedded sandstone and siltstone likely resulted from rhythmic deposition, with silty layers deposited from suspension under calm conditions and regular influxes of sand giving rise to the coarser grained layers (Strachan 1986). The graded bedding likely reflects suspension deposition in a milieu of low-energy, under low flow-strength conditions immediately following a storm (Johnson and Baldwin 1996). Together, these structures suggest alternating current-energy conditions either by tide or storm influence. The SaSL of the Bell Lake Formation differs significantly from that of the Beniah Formation in that beds are thinner and cross-laminae, reactivation surfaces and channel scours are generally lacking.

The Banded Iron-Formation lithofacies (BIFL), 0.5 to 30m thick, occupies 40% of the Bell Lake Formation and is characterized by alternating bands of cm-thick, fine-grained siliceous material and darker bands of iron-rich material with varying degrees of magnetism. Two main occurrences of the BIFL are located in the Bell Lake Formation and in the thick sequence of mafic volcanic flows to the east. Rare isolated beds, less than one metre thick, are found between the SaSL and QAL, although contact relationships are obscured by abundant mafic dyke intrusions. Beds are parallel laminated, suggesting suspension deposition in a calm setting, on a relatively flat surface with little topographic influence, i.e. lower shoreface or offshore. The cm-thick bedding of the BIFL is strikingly similar to the tidal rhythmites described by Nio and Yang (1991).

Facies Analysis

The stratigraphy of the Bell Lake Formation reveals a basal medium- to coarse-grained QAL that directly overlies the basement. Up section, the QAL abruptly changes to predominantly SaSL with thin, minor quartz-arenite intercalations. The BIFL constitutes uppermost part of the formation with subordinate beds interstratified with the SaSL. Overlying the Bell Lake Formation is a thick sequence of tholeiitic mafic flows. The relationship between the mafic volcanic and sedimentary rocks remains enigmatic as outcrops revealing any contacts are lacking.

The thin, laterally continuous bedding in the Bell Lake Formation represents deposition in an open shelf-type environment suitable for the formation of extensive thinly-bedded sheet sands (Walker and Plint 1992). The depositional setting is proximal offshore to lower shoreface with wave and possible tide influence. The overall stratigraphy of the Bell Lake Formation differs from the Beniah Formation in many aspects, including thinner beds and corresponding lithofacies, smaller-scale sedimentary structures, a lack of large-scale crossbeds, an absence of conglomerate, and an abundance of finer-grained material.

Basement/Cover Relationship at Bell Lake

Contacts between the basement and overlying sedimentary rocks are more prevalent at Bell Lake, including two main outcrops located along the eastern shore (Figure 6). Field evidence, such as onlapping of sedimentary structures over the basement and the overall lack of irregular surfaces characteristic of intrusions, suggests an unconformable contact between the two rocks. In addition, petrographic evidence reveals plagioclase and microcline present in both the basement and sedimentary rocks. This suggests that the

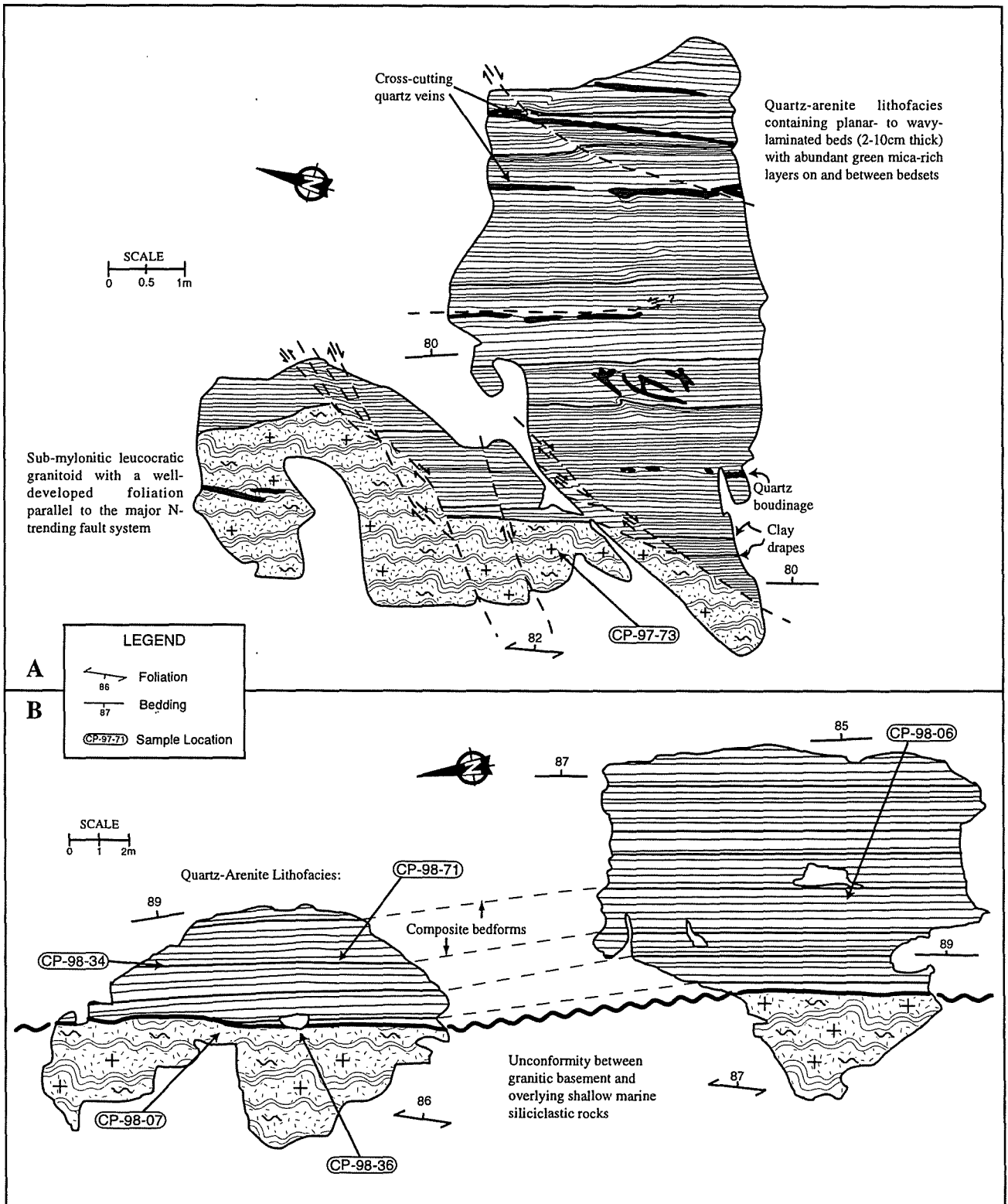


Figure 6. Unconfomable contacts between quartz-rich granitoid basement and overlying quartz-arenite. The contact in (A) is off-set by a series of small-scale faults. The predominant sedimentary structures of the quartz-arenite are planar, parallel laminations with low-angle cross-laminations (not visible at this scale). The location of the samples used for point-counting are indicated for both sketches.

feldspars are detritus shed from erosion of the older granitoid basement. The results of point-counting analyses (@ 400 points per sample) for both the basement and overlying quartz-arenites reveal similarities in the proportions of plagioclase, microcline and quartz, considering the effects of chemical and physical weathering (see Fig. 3).

Tectonic Implications

The presence of upward-coarsening sedimentary cycles suggests that the Beniah Formation was influenced by rift-related tectonism. Crustal attenuation of the shelf, caused by episodes of extension, resulted in rapid sedimentation, producing the sedimentary cycles, markedly similar to those described by Reading and Collinson (1996), Johnson and Baldwin (1996) and Duke and Prave (1991). Although age constraints have not been established, the abundance of cross-cutting mafic dykes also implies extension. A depositional contact between volcanoclastic rocks and overlying pillowed flows provides evidence that mafic volcanism is temporally and spatially related to the sedimentary rocks of the Beniah Formation (Figure 7). It is plausible that fault systems due to extension acted as conduits for the mafic dykes that fed the subaqueous mafic volcanic flows that cap the formation. Although indisputable outcrops of interstratified mafic flows and sedimentary rocks and upward-coarsening cycles have not been found in the Bell Lake Formation, the abundance of mafic dykes and sills supports rifting.

Conclusion

The Beniah and Bell Lake formations contain mineralogically mature sedimentary rocks that were deposited in a shallow marine shelf-type environment. In a transitional offshore to shoreface setting, sediments were influenced by tide-, wave- and possible storm-activity, resulting in the formation of the composite bedforms that are recorded in the rocks. Lithofacies stacking reveals coarsening-upward parasequences (lithofacies association), interpreted to reflect the attenuation of a protocontinental crust under the influence of rifting. Pillowed flows that conformably overlie the sedimentary rocks support this inference. Figure 8 illustrates two simplified stratigraphic sections of both the Beniah and Bell Lake formations showing the corresponding lithofacies, the basement/cover relationships and contacts between the mafic flows and underlying sedimentary rocks.

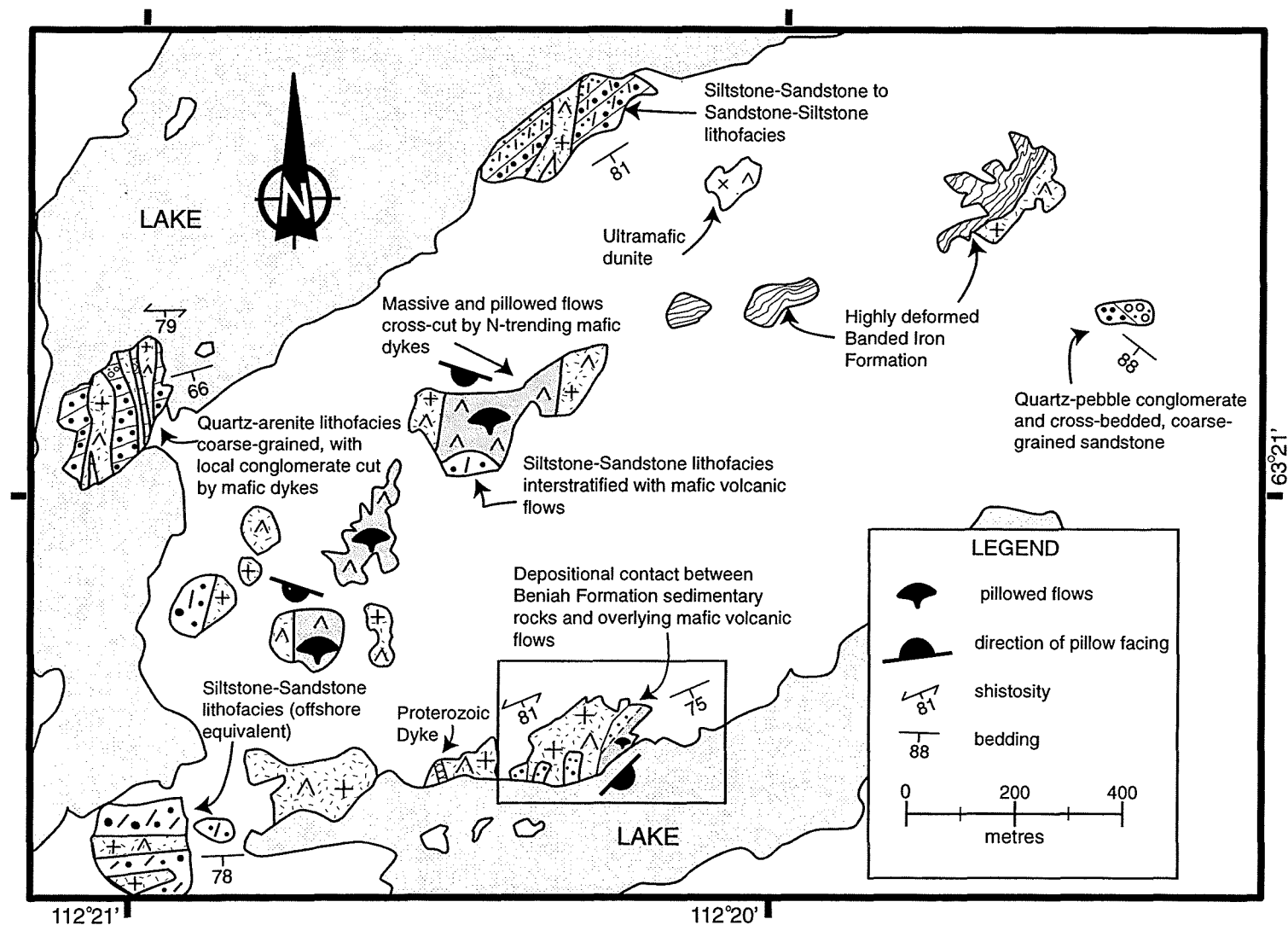


Figure 7. Map of the central Beniah Lake area revealing the location of the depositional contact between the siltstone-sandstone lithofacies and the overlying pillowed flows. Also illustrated are the various lithofacies comprising the Beniah Lake Formation including the conglomerate, quartz-arenite, sandstone-siltstone lithofacies and the banded iron formation sublithofacies, as well as older mafic to ultramafic intrusions.

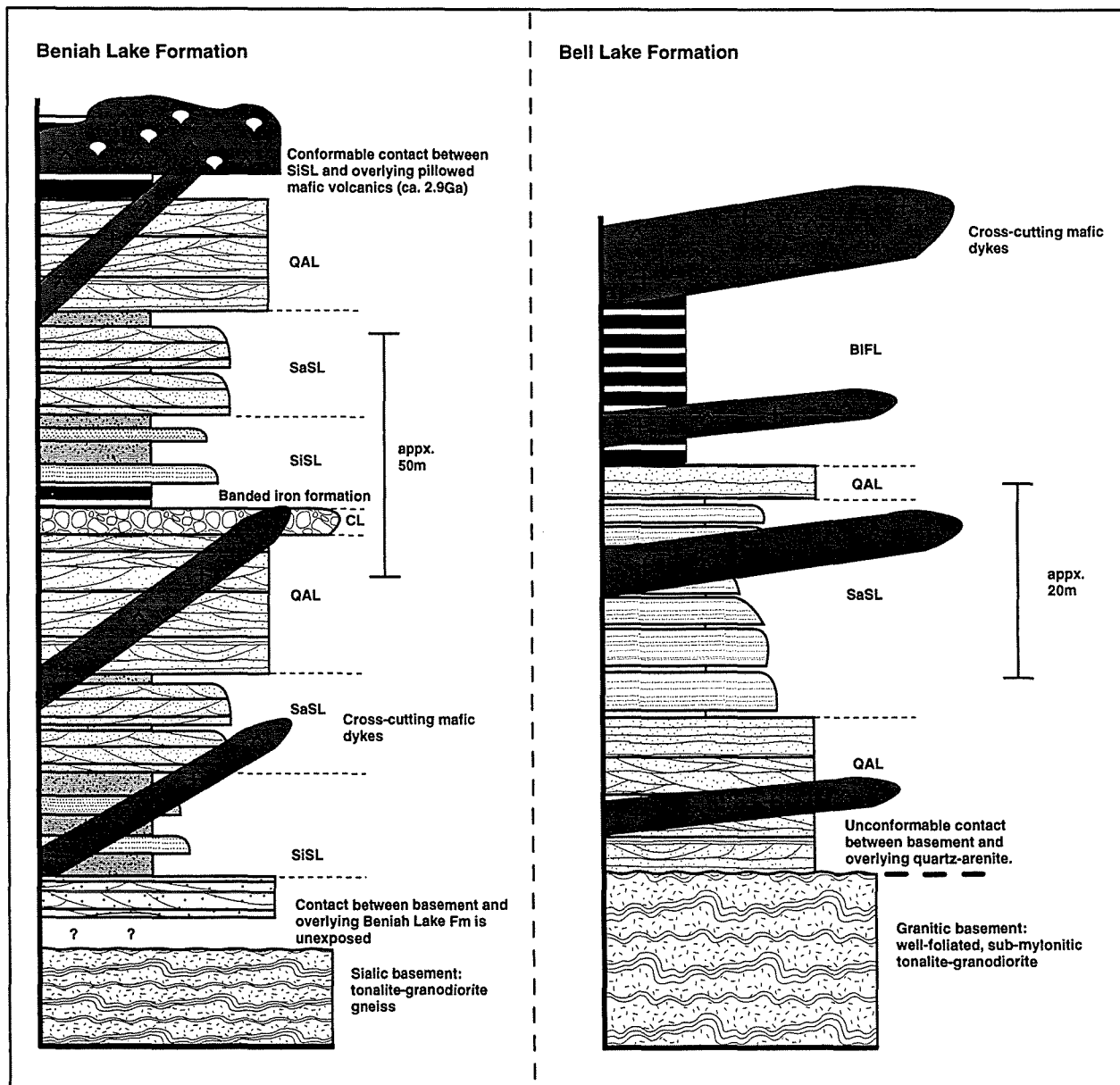


Figure 8. Simplified stratigraphic section of the Beniah Lake and Bell Lake formations. CL=conglomerate lithofacies, QAL=quartz-arenite lithofacies, SaSL=sandstone-siltstone lithofacies, SiSL=siltstone-sandstone lithofacies, and BIFL=banded iron formation lithofacies.

References

- Bleeker, W., Ketchum, J.W.F, Jackson, V.A. and Villeneuve, M.E.** 1999. The Central Slave Basement Complex, Part I: its structural topology and autochthonous cover. *Canadian Journal of Earth Sciences*, **36**, pp. 1083-1109.
- Dalrymple, R.W.** 1992. Tidal Depositional Systems. *In* *Facies Models: Response to Sea Level Change*. Edited by R.G. Walker and N.P. James, Geological Association of Canada, 3rd Ed., pp. 195-218.
- de Mowbray, T. and Visser, M. J.** 1984. Reactivation surfaces in subtidal channel deposits, Oosterschelde, Southwest Netherlands. *Journal of Sedimentary Petrology*, **54**, pp. 811-824.
- Duke, W.L. and Prave, A.R.** 1991. Storm- and tide-influenced prograding shoreline sequences in the Middle Devonian Mahantango Formation, Pennsylvania. *In* *Clastic Tidal Sedimentology*. Edited by D.G. Smith, G.E. Reinson, B.A. Zaitlin and R.A. Rahmani, Canadian Society of Petroleum Geologists, Memoir, **16**, pp. 349-370.
- Isachsen, C.E. and Bowring, S.A.** 1997. The Bell Lake group and Anton Complex: a basement-cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formations. *Canadian Journal of Earth Sciences*, **34**, pp. 169-189.
- Johnson, H.D. and Baldwin, C.T.** 1996. Shallow clastic seas. *In* *Sedimentary Environments: Processes, Facies and Stratigraphy*. Edited by H.G. Reading, Blackwell Science Ltd. 3rd Ed., pp. 232-280.
- Mueller, W. and Dimroth, E.** 1987. A terrestrial-shallow marine transition in the Archean Opemisca Group east of Chapais, Quebec. *Precambrian Research*, **37**, pp. 29-55.
- Nio, S.D. and Yang, C.S.** 1991. Diagnostic attributes of clastic tidal deposits: A review. *In* *Clastic Tidal Sedimentology*. Edited by Smith, D.G., Reinson, G.E. Zaitlin, B.A. and Rahmani, R.A., Canadian Society of Petroleum Geologists, Memoir, **16**, pp. 3-28.
- Okazaki, H. and Masuda, F.** 1995. Sequence stratigraphy of the late Pleistocene Palaeo-Tokyo Bay: barrier islands and associated tidal delta and inlet. *In* *Tidal Signatures in Modern and Ancient Sediments*. Edited by B.W. Flemming and A. Bartholomä, Blackwell Science, pp. 275-288.
- Reading, H. G. and Collinson, J. D.** 1996. Clastic coasts. *In* *Sedimentary Environments: Processes, Facies and Stratigraphy*. Edited by H.G. Reading, Blackwell Science Ltd., pp. 154-231.
- Soegaard, K. and Eriksson, K.A.** 1985. Evidence of tide, storm and wave interaction on a Precambrian siliciclastic shelf: the 1700 M.Y. Ortega Group, New Mexico. *Journal of Sedimentary Petrology*, **55**, pp. 672-684.
- Strachan, R.A.,** 1986. Shallow marine sedimentation in the Proterozoic Moine succession, Northern Scotland. *Precambrian Research*, **32**, pp. 17-33.
- Streckeisen, A.** 1979. Classification and nomenclature of volcanic rocks Lamprophyres, carbonatites and metalitic rocks: Recommendations and suggestions of the IUGS Subcommittee on the Systematics of Igneous Rocks. *Geology*, **7**, pp. 331-335.
- Visser, M.J.,** 1980. Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits: a preliminary note. *Geology*, **8**, pp. 542-546.
- Walker, R.G and Plint, A.G.** 1992. Wave- and storm-dominated shallow marine systems. *In* *Facies Models: Response to Sea Level Change*. Edited by R. G. Walker and N.P. James. Geological Association of Canada, 3rd Ed., pp. 219-238.
- Williams, H., Turner, F.J. and Gilbert, C.M.** 1982. *Petrography*. W.H. Freeman, San Francisco, 2nd Ed, 626p.

Crustal Architecture of the Slave Craton

Wouter Bleeker¹, John Ketchum², Richard Stern¹, Keith Sircombe¹, and Bill Davis¹

¹*Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8 (wbleeker@nrcan.gc.ca)*

²*Memorial University of Newfoundland, St. John's, NF, A1B 3X5*

Recent work has shown that a regionally contiguous, Meso- to Paleoproterozoic basement complex underlies much of the central and west-central parts of the Slave Province (Fig. 1; see [1,2]; cf. [3]). This ancient nucleus of the Slave craton, the Central Slave Basement Complex, is overlain by a thin but diagnostic cover sequence, the Central Slave Cover Group [1]. Although continuity of this basement and autochthonous cover had been documented as far north as the Point Lake area, an important question remained whether these entities could be extended into the realm of the northwestern Slave, including the Acasta River area [4].

To address this question, we have mapped selected areas between Point Lake and Acasta and demonstrated that both basement and cover are continuous, thus uniting all Meso- and Paleoproterozoic basement of the Slave into a single cratonic nucleus by as early as ca 2.9 Ga [5]. The diagnostic Central Slave Cover Group, two horizons of which have now been dated precisely at 2853 ± 2 Ma and 2826 ± 2 Ma [6], overlies ca. 2.9 Ga basement in the Grenville Lake area and from there can be mapped on both limbs of the Emile River greenstone belt, around the Scotstoun Anticline, and further west into the immediate hanging wall of the Acasta Gneiss Complex [5]. The ca. 4.0 Ga Acasta gneisses are therefore an integral part of the Central Slave Basement Complex, thus enhancing their importance for the overall evolution of the craton (e.g., see [7]).

In the Acasta area, and around the Exmouth Anticline, quartzites and BIF of the Central Slave Cover Group, and overlying mafic volcanic rocks, had been previously correlated with the Paleoproterozoic Epworth Group [8]. Our reinterpretation of this critical stratigraphy, which is supported by detrital zircon data [5], suggests that much of central Wopmay Orogen may in fact be Archean.

Our findings have important implications for the crustal architecture of the Slave craton. Along much of the SNORCLE transect, and into the central part of the Slave, the craton is largely underlain by the Central Slave Basement Complex. Hence, geophysical datasets can now be interpreted against the background of a single, albeit complex geological terrane, rather than a collage of different microterranes. At the latitude of Point Lake, this ancient basement complex extends westward all the way to the Wopmay Fault Zone [5]. Further south, the extent of the Central Slave Basement Complex west of Yellowknife remains less constrained. Extreme thickness variations of the basement complex from ≥ 40 km in basement-cored antiforms to ≤ 20 km underneath structural basins must be tectonic in origin. This crustal-scale “pinch and swell” structure may relate to either ca. 2680 Ma opening (extension) of the Burwash turbidite basin or to subsequent collapse of this basin during D1 folding (ca. 2630 Ma), the latter possibly accompanied by blind thrusts in the basement. The resulting structural relief was further amplified during D2 and D3 regional shortening, and large-scale advection of granitic magmas from the lower crust to higher crustal levels. The craton-scale architecture will be illustrated by two cross-sections (see poster).

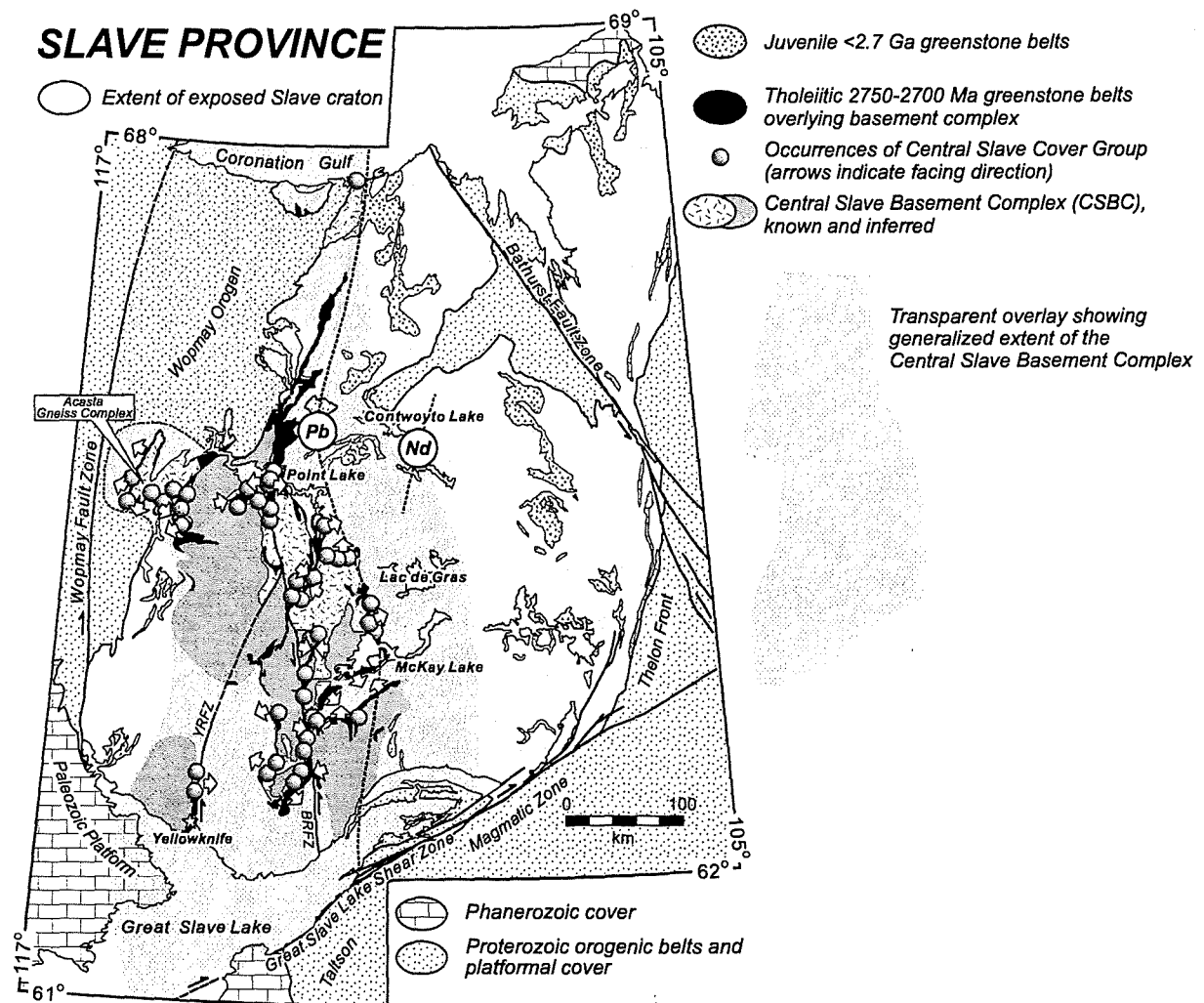


Figure 1: Simplified map of the Slave craton, highlighting the distribution of Meso- and Paleoproterozoic basement rocks of the Central Slave Basement Complex, both known and inferred, and localities where the diagnostic cover sequence has been documented. Transparent overlay (medium grey) marks the generalized extent of the basement complex.

References

- [1] Bleeker et al., 1999. The Central Slave Basement Complex, Part I: Its structural topology and autochthonous cover sequence. *Canadian Journal of Earth Sciences*, vol. 39, pp. 1083-1109.
- [2] Bleeker et al., 1999. The Central Slave Basement Complex, Part II: High-strain zones along the basement/cover contact. *Canadian Journal of Earth Sciences*, vol. 39, pp. 1111-1130.
- [3] Kusky, 1989. Accretion of the Archean Slave province. *Geology*, vol. 17, pp. 63-67.
- [4] Bleeker and Davis, 1999. The 1991-1996 Natmap Slave Province Project: Introduction. *Canadian Journal of Earth Sciences*, vol. 39, pp. 1033-1042.
- [5] Bleeker et al., 2000. Why the Slave Province, Northwest Territories, got a little bigger. *Current Research 2000-C*, Geological Survey of Canada, *in press*.
- [6] Ketchum et al., 2000. This volume.
- [7] see *Science*, vol. 286, no. 5448, pp. 2254-2256.
- [8] St-Onge et al., 1991. Geology, east-central Wopmay orogen, District of MacKenzie, Northwest Territories. Geological Survey of Canada, Map 1754A, scale 1:125 000.

New field and U-Pb data from the Central Slave Cover Group near Yellowknife and the Central Slave Basement Complex at Point Lake

John Ketchum¹

*Department of Earth Sciences, Memorial University, St. John's, Newfoundland, A1B 3X5
ketch@sparky2.esd.mun.ca*

Wouter Bleeker

*Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, K1A 0E8
wbleeker@NRCan.gc.ca*

Introduction

The deposition age of a thin, dominantly siliciclastic succession at the base of numerous greenstone belts throughout the western Slave Province has long been a subject of speculation. Similarly, knowledge of the age and tectonothermal history of an older, largely plutonic terrane beneath this succession has been hampered by a paucity of data. Our work over the past few years has mainly focused on these rocks, which collectively record >1.1 billion years of early earth history. LITHOPROBE, GSC, and EXTECH-funded U-Pb geochronology and detailed fieldwork now provide us with a better understanding of these rocks and allow us to propose new ideas on the tectonic, magmatic, metamorphic, and depositional events that shaped the early Slave Province. An understanding of this pre-2.73 Ga history is critical for evaluating subsequent pan-Slave crustal events that dominate the rock and seismic records.

The thin sedimentary sequence at the base of western Slave greenstone belts is called the Central Slave Cover Group (CSCG; Bleeker et al. 1999a). It is sparsely preserved and generally consists of a <200 m-thick package of quartz-rich clastic rocks, banded iron formation (BIF), and lesser ultramafic and felsic volcanic rocks. The sequence was deposited prior to the onset of widespread volcanism, sedimentation, granitoid plutonism, and deformation between 2.73-2.58 Ga, and typically overlies basement rocks along a high-strain zone or unconformity. It has been interpreted by several authors (e.g., Padgham 1992) as the remnants of a continental platform sequence, and a ca. 2.82 Ga U-Pb minimum age for a felsic volcanic unit within it (Isachsen and Bowring 1997) is consistent with this interpretation. The sequence is interpreted as a cover stratigraphy to underlying basement gneisses and foliated plutons of the Central Slave Basement Complex (CSBC; Bleeker et al. 1999a). The CSBC represents an old cratonic nucleus which occurs only in the western region of the present-day craton (e.g., Kusky 1989). Juvenile crust younger than 2.73 Ga is found east and southwest of the CSBC.

Below we report new U-Pb data for two formations of the CSCG in the Yellowknife greenstone belt, and discuss the results of detailed mapping and U-Pb dating of the CSBC at Point Lake. The data contribute to a growing awareness of an important thermotectonic event that affected the Slave Province between 2.9-2.8 Ga.

¹ as of April 2000: Jack Satterly Geochronology Lab, Royal Ontario Museum, 100 Queen's Park, Toronto, Ontario, M5S 2C6.

U-Pb data for the Central Slave Cover Group, Yellowknife greenstone belt

Dwyer Lake: Two volcanosedimentary packages correlated with the CSCG occur at the base of the Yellowknife greenstone belt. North of Yellowknife at Dwyer Lake, the Dwyer Lake Formation (Bleeker et al. 1999a) consists of a basal unit of fuchsitic quartzite with minor arkose and pelitic or semipelitic schist, an intermediate unit of felsic volcanic and volcanoclastic rocks, and an upper unit of BIF. A previous U-Pb study gave a tentative age of 2835 ± 4 Ma for the felsic volcanic unit (Isachsen and Bowring 1997), and detrital zircons in the underlying quartzite yield ages between 3920–2880 Ma (Bleeker et al. 2000). We re-dated the felsic volcanic unit, specifically a quartz-porphyrific tuff (with possible flattened pumice fragments) at the base of this unit, in order to clarify its age.

The new U-Pb data provide an unequivocal age for the felsic tuff. Three single-grain zircon fractions (one concordant within uncertainty) yield an upper intercept age of **$2853 \pm 2/-1$ Ma**, with no evidence of zircon inheritance or multistage Pb loss. A single monazite grain is much younger at **2708 ± 1.5 Ma**, likely recording metamorphism. The zircon age is older than that proposed by Isachsen and Bowring (1997), but their discordant data array also allow an older age to be proposed, so we see no conflict between their dataset and ours. Along with the SHRIMP U-Pb data of Bleeker et al. (2000), the 2853 Ma age indicates that the basal quartzite and overlying felsic volcanic unit at Dwyer Lake were deposited in the interval ~2880–2853 Ma. The overlying BIF is younger than 2853 Ma.

Bell Lake: The Bell Lake Formation, north of Dwyer Lake, is lithologically and stratigraphically similar to the Dwyer Lake Formation. However, felsic volcanic and volcanoclastic rocks mainly occur as thin homogeneous or heterogeneous layers within quartzite and BIF, rather than as a distinct, separate unit as at Dwyer Lake (Jackson 1998). We dated two felsic volcanic layers from the Bell Lake Formation. The stratigraphically lowest layer is a heterogeneous, strongly-sheared felsic volcanic unit beneath the BIF. The age of this unit is not yet firmly established, but a concordant, 2954 Ma zircon grain is similar in age to underlying basement rocks (see Isachsen and Bowring 1997), and another single grain is concordant at 3511 Ma. These ages and the heterogeneity of the sample indicate that this volcanic unit contains detrital zircons and is reworked. Additional dating is in progress.

Approximately 20 m above this unit, a 3 m-wide layer of quartz-porphyrific felsic tuff within a 40 m-thick BIF unit was also dated. Single and multigrain zircon analyses provide an unambiguous age of **2826 ± 1.5 Ma**, again with simple zircon systematics. The analyses are concordant or very nearly so. This is interpreted as the depositional age of the tuff, and its stratigraphic position indicates that this may also be the age of the enclosing BIF. If this interpretation is correct, then the BIF has a clear temporal link with the CSCG and not with earliest volcanism associated with the Yellowknife greenstone belt.

The Octopus Formation, Yellowknife greenstone belt: not part of the CSCG

At the southern end of the Yellowknife greenstone belt, Helmstaedt and Padgham (1986) described a 750 m-wide package of amphibolite and clastic sedimentary rocks that they

tentatively placed at the same stratigraphic level as the Bell Lake and Dwyer Lake formations. This north-trending package, which they called the Octopus Formation, is dominated by foliated amphibolite derived from pillowed flows and mafic sills and/or massive flows. Sedimentary rocks consist of metamorphosed pebble conglomerate, quartzite, wacke, siltstone, and siliceous fine-grained rock interpreted as felsic volcanic tuff. The lack of typical CSCG lithologies (fuchsitic quartzite, BIF) suggested to Bleeker et al. (1999a) that the Octopus Formation was unlikely to be part of the CSCG. Our U-Pb data now confirm this.

A fine-grained, siliceous unit with graded bedding (reworked felsic tuff?) within mafic volcanic rocks was sampled for dating. Analysed single and multigrain zircon fractions yield a discordant but roughly colinear array, and a best-fit discordia line through this array has an upper intercept age of 2702 ± 8 – 6 Ma. This is interpreted as the age of felsic volcanism that generated the tuff, and indicates that the Octopus Formation is much younger than the Central Slave Cover Group. Correlation with the Yellowknife Bay Formation of the Kam Group is tentatively suggested based on the location of the Octopus Formation (along strike from this formation) and available U-Pb data for the Yellowknife greenstone belt (see Isachsen and Bowring 1997).

The Central Slave Basement Complex, Point Lake: mapping and U-Pb results

The Central Slave Basement Complex is well exposed at Point Lake where it is structurally overlain by the ca. 2.7 Ga Point Lake greenstone belt. Thin, tectonized units of the CSCG occur along the basement-cover contact south of the lake (Easton 1985). Detailed mapping of the basement complex has revealed the presence of two distinctive early gneiss packages, one dominated by tonalite and diorite orthogneiss, and the other dominated by granite and granodiorite orthogneiss. These gneiss associations are separated by an up to 30 m-thick supracrustal package of amphibolite, ultramafic schist, quartzite, and biotite quartzofeldspathic paragneiss which can be traced discontinuously for at least 11 km. We infer on the basis of its field setting that this amphibolite-rich package is older than both the Point Lake greenstone belt and the CSCG. Migmatitic tonalite gneiss from the tonalite-diorite gneiss association is dated at 3150 ± 3 Ma (this study), and the granite-granodiorite gneiss association contains a ca. 3090 Ma component (Northrup et al. 1999).

Younger events that influenced the gneiss complex include volumetrically significant granitoid plutonism (in part 2818 ± 2 Ma; Northrup et al. 1999), and folding of an originally southeast-striking gneissic foliation during heterogeneous structural reworking. The supracrustal marker unit between gneiss packages outlines broad northeast-trending basement folds that are also present in the Point Lake greenstone belt. Reworking is related in part to west-directed thrusting of the greenstone belt over basement, although we agree with Northrup et al. (1999) that this event is not linked to emplacement of an allochthonous thrust sheet (Kusky 1991). The younger plutonic and tectonic events resulted in greatly-increased structural and lithologic diversity within the basement complex. A unit of migmatitic pelitic gneiss within this complex has an uncertain primary age, but two single monazite grains have ages of 2584 ± 1 Ma and 2563 ± 1 Ma. These non-overlapping ages do not date the migmatization, but rather may indicate variable isotopic resetting of older monazite during emplacement of a nearby batholith.

Discussion and related U-Pb data from Brown Lake

We have confirmed the age of the Central Slave Cover Group in one area of the western Slave Province. Taking our data with that of Bleeker et al. (2000), this sequence was deposited on a metamorphosed and deformed, polycyclic, dominantly plutonic basement terrane (the Central Slave Basement Complex) between ca. 2880 Ma and 2826 ± 1.5 Ma in the region now occupied by the Yellowknife greenstone belt. This is unlikely to be the exact age bracket for the CSCG everywhere in the western Slave, as evidenced by a ca. 2823 Ma detrital zircon from a basal quartzite in the Acasta River area (Bleeker et al. 2000). Our data does however provide the ages of two felsic volcanic episodes associated with CSCG deposition. Unfortunately, felsic volcanic rocks are absent from most occurrences of this package, so direct dating of the CSCG across the basement complex is not easily done.

To our knowledge, the basement-cover section with the best-preserved unconformity is at Brown Lake, on the northwestern flank of the Sleepy Dragon basement complex. We now have a depositional age constraint for the CSCG in this area. A basal quartz pebble conglomerate is in contact with foliated, paleoweathered tonalite along a deformed unconformity (Bleeker et al. 1999a). The tonalite is dated at 2908 ± 2 Ma, which represents the maximum age of CSCG deposition in this region. South of here at Patterson Lake, the youngest grain in a graded grit is 2943 ± 1 Ma (Bleeker et al. 1999a), providing a similar maximum age constraint. The CSCG at Patterson Lake is no older than 2734 ± 2 Ma, the age of a cross-cutting mafic dyke (Bleeker et al. 1999b). These data broadly demonstrate that deposition of the cover group east of the Yellowknife area occurred at roughly the same time as in the west.

The CSBC at Point Lake records a complex, high-grade tectonometamorphic history prior to uplift, erosion, and deposition of the CSCG. Of particular note is the juxtaposition of distinctive gneiss packages along a thin horizon of mafic volcanic and sedimentary rocks. This relationship is perhaps best accounted for by tectonic activity as it is difficult to appeal to other processes to explain it. This postulated tectonic activity must be younger than ~3.1 Ga but older than 2.82 Ga based on field relationships and the U-Pb data of Northrup et al. (1999). The distinctive gneiss packages or gneiss associations likely represent separate lithotectonic blocks, and the intervening supracrustal rocks were either deposited on one of these blocks or originated as a separate lithotectonic unit. Highly-deformed mafic dykes that are conspicuous in the granite-granodiorite package do not appear to be present in the tonalite-diorite package, suggesting a possible association of the supracrustal package with the granite-granodiorite gneiss. However, this problem requires additional field work. The distribution and map pattern of all these rocks is reminiscent of areas of basement-over-basement thrusting with the involvement of minor cover rocks (e.g., northern Makkovik Province; Ketchum et al. 1997).

Tectonic implications

The CSCG, with its characteristic and regionally-persistent lithologies, was deposited across the CSBC between 2.9-2.8 Ga. The package has been interpreted as a continental shelf sequence, and we broadly agree with this assessment but point out that ultramafic and felsic volcanism also marked its deposition. Additionally, limited U-Pb data indicate that plutonic and

metamorphic activity occurred in the CSBC at this time. Granitoid plutonism and high-grade metamorphism between 2.84-2.82 Ga (Henderson et al. 1987; Northrup et al. 1999; Ketchum, unpublished data) is potentially linked to the same tectonothermal event that was responsible for this (bimodal?) volcanism. Bleeker et al. (2000) propose that a mantle plume beneath the CSBC was responsible for an regional uplift-subsidence cycle. This plume-related cycle yielded a regional unconformity, ultramafic volcanism, and finally thermal subsidence and deposition of the CSCG. We can extend this idea further here by proposing that felsic volcanism, granitoid plutonism, and high-grade metamorphism in the basement between 2.85-2.82 Ga was linked to this tectonothermal event. Subsequent rifting of the thermally weakened crust gave rise to voluminous mafic volcanism that marked the initiation of greenstone belt development (Bleeker et al. 2000). These belts and the overlying turbidite sequences dominate the supracrustal record in the Slave Province, but it is now evident that the volumetrically minor CSCG provides evidence of major older cratonic events.

References

- Bleeker, W., Ketchum, J.W.F., Jackson, V.A., and Villeneuve, M. 1999a. The Central Slave Basement Complex, Part I: its structural topology and autochthonous cover. *Canadian Journal of Earth Sciences*, 36: 1083-1109.
- Bleeker, W., Ketchum, J.W.F., and Davis, W.J. 1999b. The Central Slave Basement Complex, Part II: high-strain zones along the basement/cover contact. *Canadian Journal of Earth Sciences*, 36: 1111-1130.
- Bleeker, W., Stern, R., and Sircombe, K. 2000. Why the Slave Province got a little bigger. In *Current Research 2000-C*, Geological Survey of Canada.
- Easton, M. 1985. The nature and significance of pre-Yellowknife Supergroup rocks in the Point Lake area, Slave Structural Province, Canada. In *Geological Association of Canada, Special Paper 28*, pp. 153-167.
- Helmstaedt, H., and Padgham, W.A. 1986. A new look at the stratigraphy of the Yellowknife Supergroup at Yellowknife, NWT. Implications for the age of gold-bearing shear zones and Archean basin evolution. *Canadian Journal of Earth Sciences*, 23: 454-475.
- Henderson, J.B., van Breemen, O., and Loveridge, W.D. 1987. Some U-Pb zircon ages from Archean basement, supracrustal and intrusive rocks, Yellowknife-Hearne Lake area, District of MacKenzie. In *Radiogenic Age and Isotopic Studies: Report 1*, Geological Survey of Canada, Paper 87-2, pp. 111-121.
- Isachsen, C.E., and Bowring, S.A. 1997. The Bell Lake group and Anton Complex: a basement-cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation. *Canadian Journal of Earth Sciences*, 34: 169-189.
- Jackson, V. A. 1998. Preliminary geology of part of the lower supracrustal successions in the Bell Lake area (parts of 85J/09 and 85J/16), Northwest Territories. EGS 1998-12, Department of Indian and Northern Development, Yellowknife, Northwest Territories.
- Ketchum, J.W.F., Culshaw, N.G., and Dunning, G.R. 1997. U-Pb geochronologic constraints on Paleoproterozoic orogenesis in the northwestern Makkovik Province, Labrador, Canada. *Canadian Journal of Earth Sciences*, 34: 1072-1088.
- Kusky, T.M. 1989. Accretion of the Archean Slave province. *Geology*, 17: 6367.
- Kusky, T.M. 1991. Structural development of an Archean orogen, western Point Lake, Northwest Territories. *Tectonics*, 10: 820-841.
- Northrup, C.J., Isachsen, C., and Bowring, S.A. 1999. Field relations, U-Pb geochronology, and Sm-Nd isotope geochemistry of the Point Lake greenstone belt and adjacent gneisses, central Slave craton, N.W.T., Canada. *Canadian Journal of Earth Sciences*, 36: 1043-1059.
- Padgham, W.A. 1992. Mineral deposits in the Archean Slave Structural Province; lithological and tectonic setting. *Precambrian Research*, 58: 1-24.

Archean collisional tectonics imaged on Lithoprobe SNORCLE line 1

Arie J. van der Velden and Frederick A. Cook

Dept. of Geology and Geophysics, University of Calgary,
2500 University Dr. N.W., Calgary, AB, T2N 1N4
arie@litho.ucalgary.ca

Lithoprobe SNORCLE line 1 crosses the southwestern tip of the Archean Slave province in northwestern Canada (Figure 1). Reprocessing of the seismic data has revealed a series of reflection truncations which, along with correlation of reflections to the known geology of the Slave province, have provided insights into the evolution of the Slave province at ca. 2.69-2.65 Ga. Reflection fabrics are interpreted as products of collisional tectonics involving tectonic wedging of one lithospheric plate into another.

West of Yellowknife, reflections A1-A5 truncate reflections within wedge AW (Figure 2). Reflections within AW are concordant with faint reflections M that dip into the upper mantle. This reflection pattern, consisting of west-dipping reflections truncating a wedge of east-dipping reflections which in turn are conformable with east-dipping reflections that project into the upper mantle, is similar to that of the Fort Simpson - Hottah collision zone, imaged further to the west on SNORCLE line 1. There, the western plate (Fort Simpson-Nahanni terrane) is interpreted to have been delaminated as the eastern plate (Hottah-Coronation terrane) was inserted into it (Cook et al., 1999). This similarity provides support for the interpretation that the reflection patterns beneath this part of the Slave province are also products of collisional tectonics.

On the east side of Yellowknife, reflections B1-B5 have similar dips as reflections A1-A4. Their correlation is complicated by the fact that (1) the data quality near Yellowknife is poor due to noise from the city and a nearby mine; (2) there is a 6 km S-N along-strike offset between the data west and east of Yellowknife, respectively; and (3) the Yellowknife River fault zone, a late Archean to Proterozoic N-S trending strike-slip fault with a maximum sinistral displacement of a few 10s of kilometers (Bleeker, 1999), may offset the reflections. Nevertheless, reflections A1-A4 probably do correlate with B1-B5 because the interpreted collision zone is likely of regional extent, although individual reflections may be offset. Since the latest major deformational event in the Yellowknife area is Archean, the interpreted collision zone is likely to be of Archean age.

Rocks within the Slave province preserve evidence of a ca. 2.69-2.65 Ga pan-Slave orogenic event, in which the Central Slave Basement complex, a block of continental crust containing gneisses as old as 4.0 Ga, collided with the Hackett River juvenile island arc terrane. Reflections B4 or B5 may be associated with the boundary between the Central Slave Basement complex and the Hackett River arc. This boundary may project east of the Sleepy Dragon complex to the vicinity of the Pb isotope line of Thorpe et al., (1992) (Figure 3). Shear zones at the base of the mafic volcanic sections were active prior to 2.687 Ga (Bleeker et al., 1999), indicating that the basins containing the greenstone belts collapsed prior to final collision with the Hackett River arc. At the north end of the Slave province, where the arc-continent collision appears narrower and less complicated, the boundary between the arc and the continent is a west-dipping suture (Relf et al., 1999). The proposed collisional model is similar to that of Kusky, 1989, which also involves delamination of the Central Slave Basement complex (Figure x). One difference between these models is that in Kusky's model, the accretionary wedge is exposed on the east and the west of the Sleepy dragon complex, whereas in the present model, the accretionary wedge is located in the lower crust beneath Yellowknife.

These results provide tantalizing evidence that processes similar to those of modern convergent zones were operational at 2.69-2.65 Ga. However, enigmatic 2.7 Ga greenstone belts that were caught up in the collision apparently have no modern counterparts.

References

- Bleeker, W., J.W.F. Ketchum and W.J. Davis, 1999, the Central Slave Basement Complex, Part II: age and tectonic significance of high-strain zones along the basement-cover contact. *Can. J. Earth Sci.* p. 1111-1130.
- Cook, F.A., A.J. van der Velden, K.W. Hall and B.J. Roberts, 1999, Frozen subduction in Canada's Northwest Territories: Lithoprobe deep lithospheric reflection profiling of the western Canadian Shield. *Tectonics*, p. 1-24.
- Davis, W.J., and E. Hegner, Neodymium isotopic evidence for the tectonic assembly of Late Archean crust in the Slave province, northwest Canada. *Contrib. to Mineral. and Petr.*, p. 493-504..
- Kusky, T.M., 1989, Accretion of the Slave Province. *Geology*, p. 63-67.
- Relf, C., H.A. Sandeman and M.E. Villeneuve, 1999, Tectonic and thermal history of the Aniak River area, northwestern Slave Province, Canada. *Can. J. Earth Sci.*, p. 1207-1226.
- Thorpe, R.I., G.L. Cumming and J.K. Mortensen, 1992, A significant Pb-isotope boundary in the Slave province and its probable relation to ancient basement in the western Slave Province. *GSC Open File 2484*, p. 179-184.

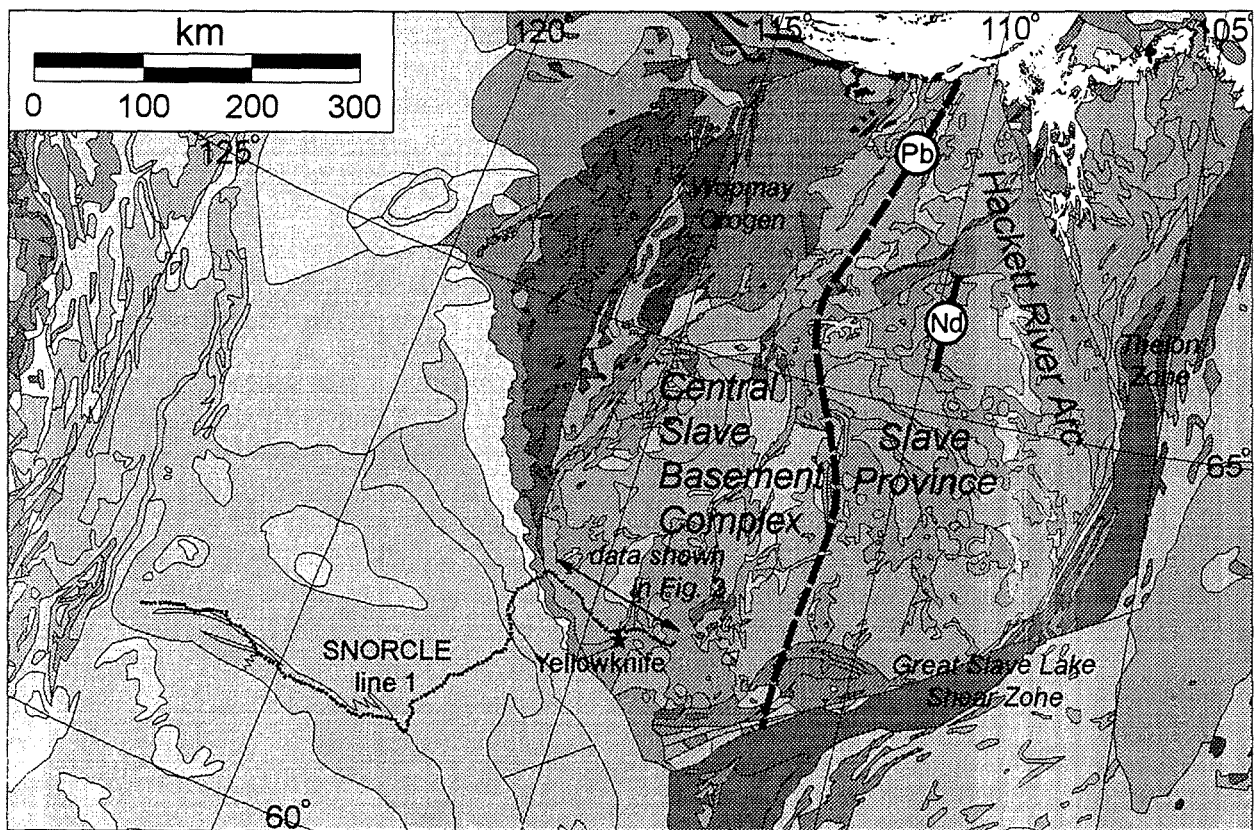


Figure 1. Map of the Slave province. The eastern part of SNORCLE reflection line 1 (dotted line) is shown in Figure 2. The Pb and Nd isotope lines are from Thorpe et al. (1992) and Davis and Hegner (1992).

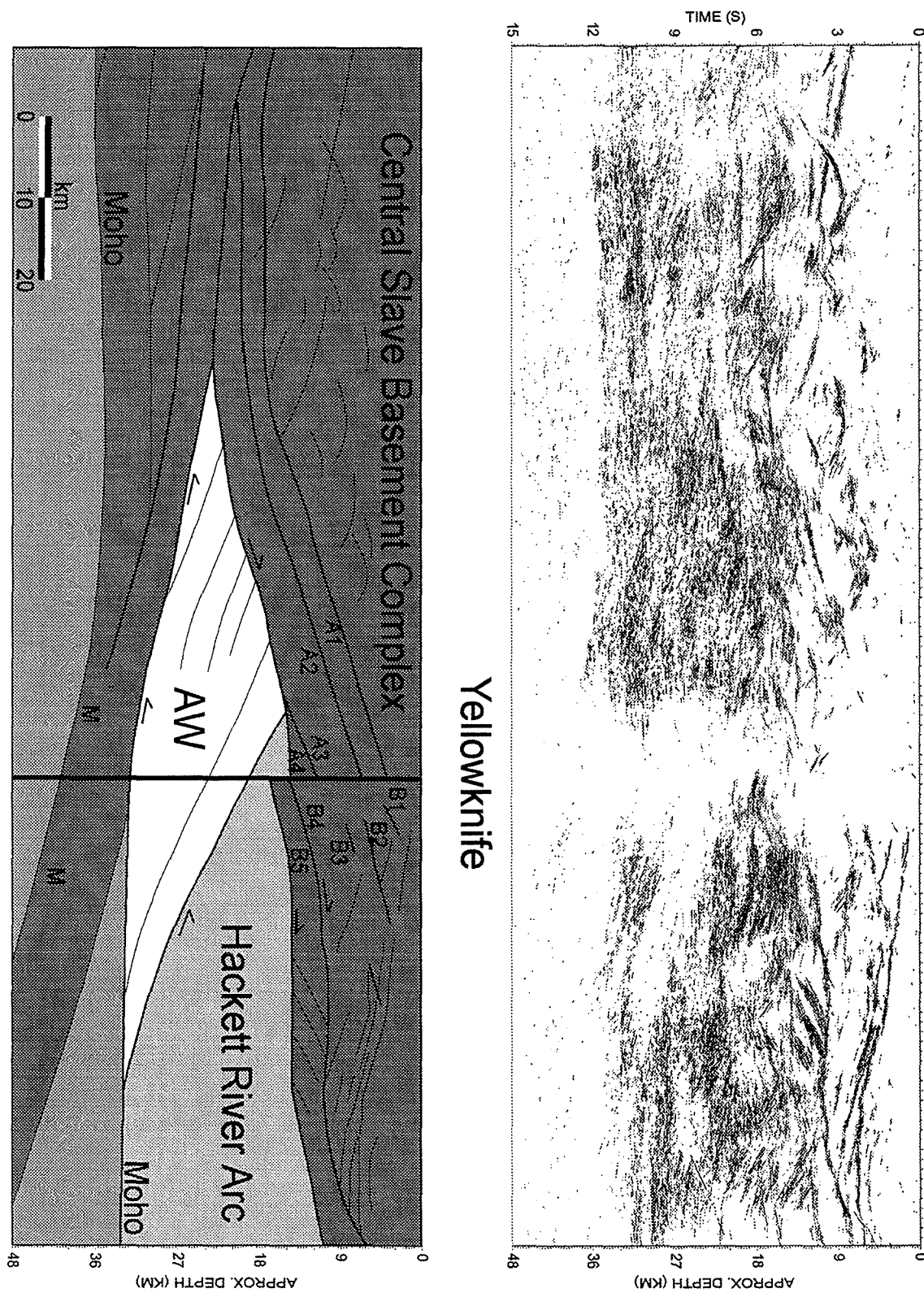


Figure 2. SNORCLE line 1 seismic data and interpretation. The reflections outline a lithospheric delamination structure beneath the Yellowknife area.

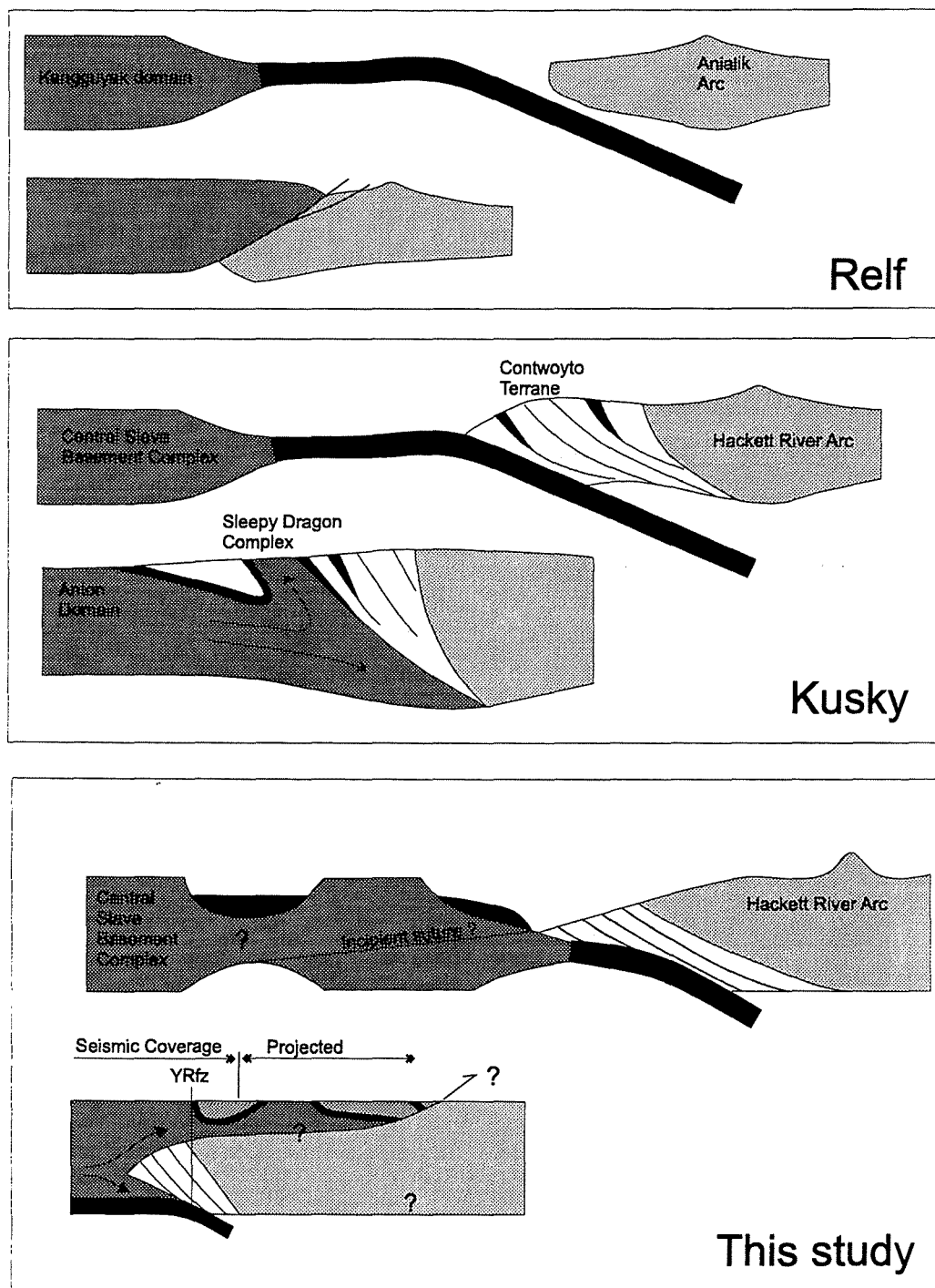


Figure 3. Models for the tectonic development of the Slave province. Top and middle sections redrawn from Relf (1999) and Kusky (1989), respectively.

The electric Slave craton

Alan G. Jones*, 615 Booth St., Ottawa, Ontario, K1A 0E9, ajones@cg.nrcan.gc.ca
Ian Ferguson (University of Manitoba), Rob Evans and Alan Chave (Woods Hole
Oceanographic Institution)

The Slave craton in northern Canada is one of the world's smallest Archean cratons (surface exposure of 300,000 km²), but makes up for this diminutive stature with excellent exposure and by hosting the oldest dated rocks on Earth (4.03 Ga, Stern and Bleeker 1998). It records continental accretion processes, albeit cryptically, and potentially offers the best opportunity worldwide to address the question of the validity of applying plate tectonic theory in the early Archean.

Studies of the Slave craton and its relationship to the Proterozoic terranes to the east are being undertaken as part of SNORCLE transect LITHOPROBE investigations. These studies included reflection profiling, a refraction experiment, a series of electromagnetic (EM) experiments, and additional geochemical and geological activities. The EM experiments used natural sources for obtaining lithospheric information. At each location time series were recorded of the time varying horizontal north (E_x) and east (E_y) electric field components and the north (H_x), east (H_y) and vertical (H_z) magnetic field components in one or more of various frequency bands: audio-magnetotelluric (AMT) band of 10,000 - 100 Hz, magnetotelluric (MT) band of 100 Hz - 1000 s, and long period magnetotelluric (LMT) band of 20 s - 10,000 s.

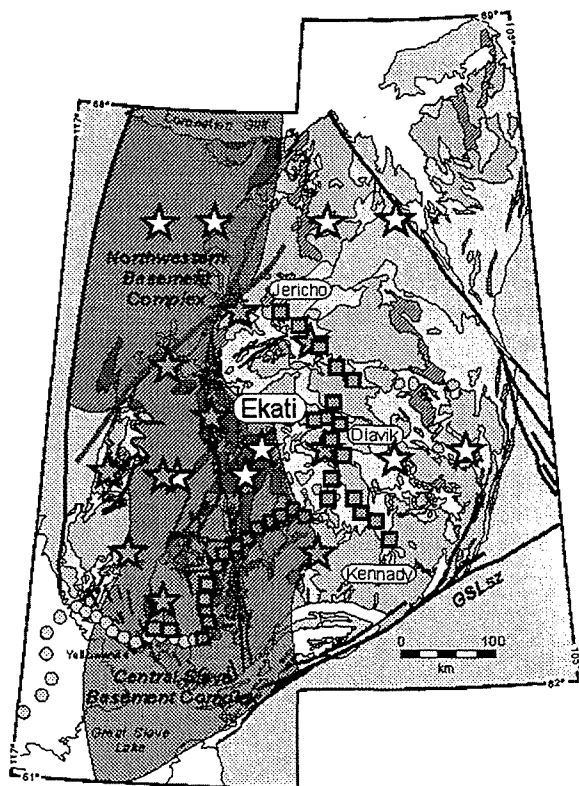


Figure 1: MT site locations on the Slave craton geology basemap from Bleeker and Davis (1999)

Electrifying images of the Slave

The three experiments were:

- 1) conventional AMT, MT and LMT acquisition during Fall 1996 along the all-weather road from Tibbit Lake to Rae in the southwest corner of the craton (yellow dots on Fig. 1);
- 2) MT and LMT acquisition in the winter along the ice road from Tibbit Lake to Lupin mine on Contwoyto Lake, including along the road to Kennady Lake (light green squares in Fig. 1 recorded in March 1998; dark green squares in March 1999), and
- 3) LMT acquisition in lakes around the Slave using instrumentation designed for the ocean-bottom (blue stars in Fig. 1 recorded from August 1998 to August 1999; white stars recording from August 1999 to August 2000).

MT Data Processing and Analysis

MT data processing involved rotation of the time series to geographic coordinates, then estimation of the MT transfer functions relating the horizontal electric field components to the horizontal magnetic field components and estimation of the magnetic transfer functions (TF) between the vertical magnetic field component and the horizontal magnetic field components. The code used was a multi-remote reference variant of the Jones-Joedicke scheme (method 6 in Jones et al., 1989). In addition, data segments were selected with low vertical field variations in order to avoid source field effects on the data (see, e.g., Garcia et al., 1997).

Subsequently, the MT response function estimates were analysed for electric-field distortions caused by local, near-surface inhomogeneities, and the appropriate geoelectric strike direction for interpretation. These steps were accomplished using the multi-site, multi-frequency tensor decomposition code of McNeice and Jones (1996). The data showed a low dependence on geoelectric strike, i.e., the MT phases are virtually direction-independent, which requires the conductivity structure of the crust and mantle to vary slowly with lateral distance in both the crust and mantle.

MT Phase Map

Given the low dependence on rotation, one can obtain qualitative information from a map of the averaged phase at a given period. Figure 2 shows a map of the phases for a period of 300 s. At 300 s periodicity the EM waves are penetrating some 150-200 km down into the lithosphere. The averaged phases show a distinct high of almost 80° at the sites in the Lac de Gras region. Phases decrease monotonically with distance away from this region along all three roads, to the north towards the Jericho pipe, to the southeast towards the Kennady pipe, and to the southwest to Yellowknife. The phase difference between Yellowknife and Lac de Gras is over 10° , and between Kennady and Jericho and Lac de Gras is over 6° . We have only undertaken preliminary processing of three lake bottom sites, namely Big, Lac de Gras and Wheeler. The averaged phases at 300 s for these three are consistent with the data from the winter road, with high phases for Big and Lac de Gras, and low phases for Wheeler. This suggests that the phase maximum extends to the west to at least Big Lake, and perhaps beyond.

Electrifying images of the Slave

A qualitative interpretation of the phase map is of either a higher conductivity of the mantle, or that the depth to the base of the lithosphere is closer to the surface, beneath Lac de Gras compared to neighbouring areas.

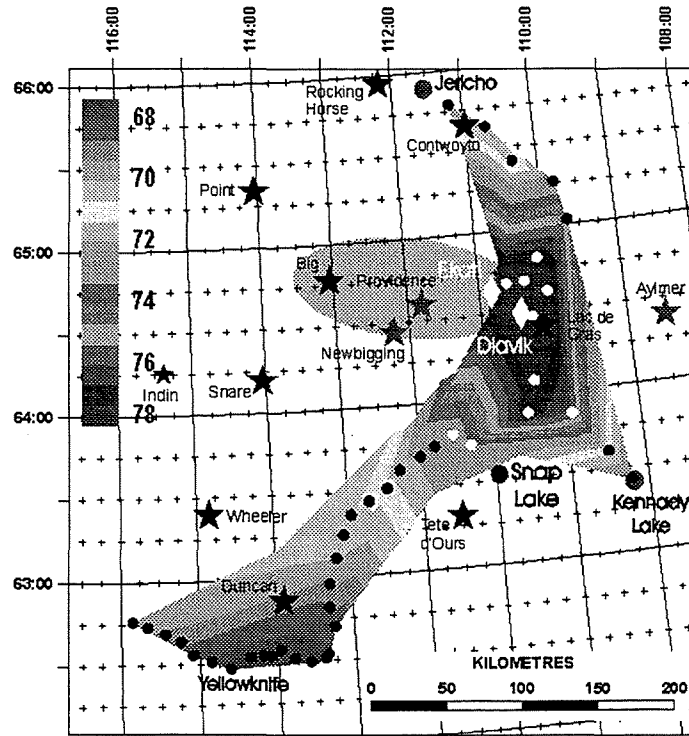


Figure 2: MT average phases at 300 s

MT Modelling

The MT responses, rotated into a strike direction of NE-SW, were objectively modelled using the 2D inversion code of Rodi and Mackie and Rodi (2000). The best-fitting model obtained is shown in Fig. 3.

The dominant feature of the resistivity model is the shallowing high conducting upper mantle region ($\rho < 30 \Omega.m$) beginning at a depth of ~ 80 km beneath Lac de Gras. This anomaly is consistent with the phase map of Fig. 2. The anomaly does not exist north of site 217, i.e., at the start of Contwoyto Lake, nor south of site 205, which is at Nuna's Lockhart Lake camp. Due to the attenuating effects of the anomaly, it is not possible to image the resistivity structure below it. This would require much longer periods than in the present dataset, and would require a specialised experiment such as undertaken by Schultz et al. (1993). In addition to the mantle feature, note that the crust of the Lac de Gras region contains more conducting features than to the south.

A resistivity model (not shown) for a line from Contwoyto Lake to Kennady Lake is consistent with imaging an anomaly at ~ 80 km beneath Lac de Gras, and the anomaly ceases half-way down the Kennady Lake road.

Electrifying images of the Slave

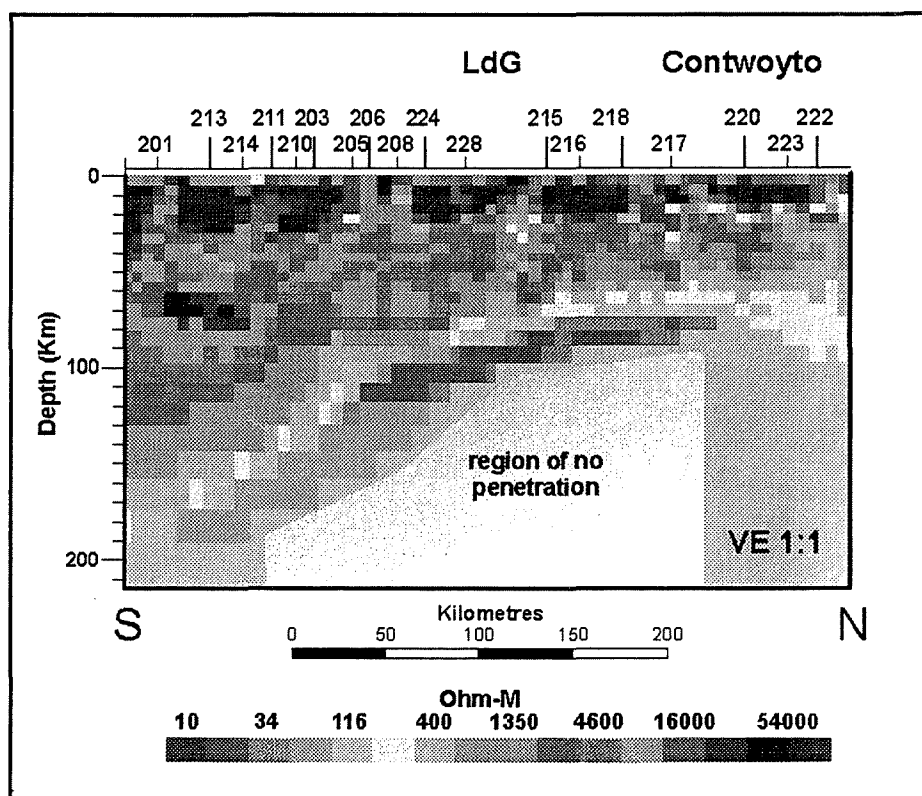


Figure 3: Resistivity model of Slave lithosphere

Inferences and Comparison with Geochemical Results

A map of the conducting mantle region is shown in Fig. 4 (left). The region mapped by the work along the winter road is shown in dark green. Given the high phase value observed at Big Lake, from preliminary processing of the lake bottom instrument, there is the suggestion that this region extends to the west (light green) beyond both the north-south Pb and Nd isotope boundaries (Thorpe et al., 1992; Davis and Hegner, 1992; Davis et al., 1996). These boundaries are considered to indicate that the mantle beneath the western Slave is fundamentally different than beneath the eastern Slave. Verification of the existence of the mantle conductor to the west requires complete analysis of the lake bottom data, including the data that will not be available until the retrieval of the second deployment in August 2000.

Griffin et al. (1999), studying the geochemistry of mantle xenoliths from 21 kimberlites in the Lac de Gras region, mapped the composition, structure and thermal state of the mantle. They discovered a unique two-layered lithospheric mantle, with an ultra-depleted, harburgitic upper layer separated sharply at 140-150 km depth from a less depleted, lherzolitic lower layer, extending over >9,000 km² (Fig. 4: right). This ultra-depleted layer was not found at pipes north of the Lac de Gras kimberlite field (Jericho (J), Ranch Lake (RL), Torrie (T)), nor at pipes to the south (Cross Lake (CrL), Drybones (DB), Camsell lake (CL)).

Electrifying images of the Slave

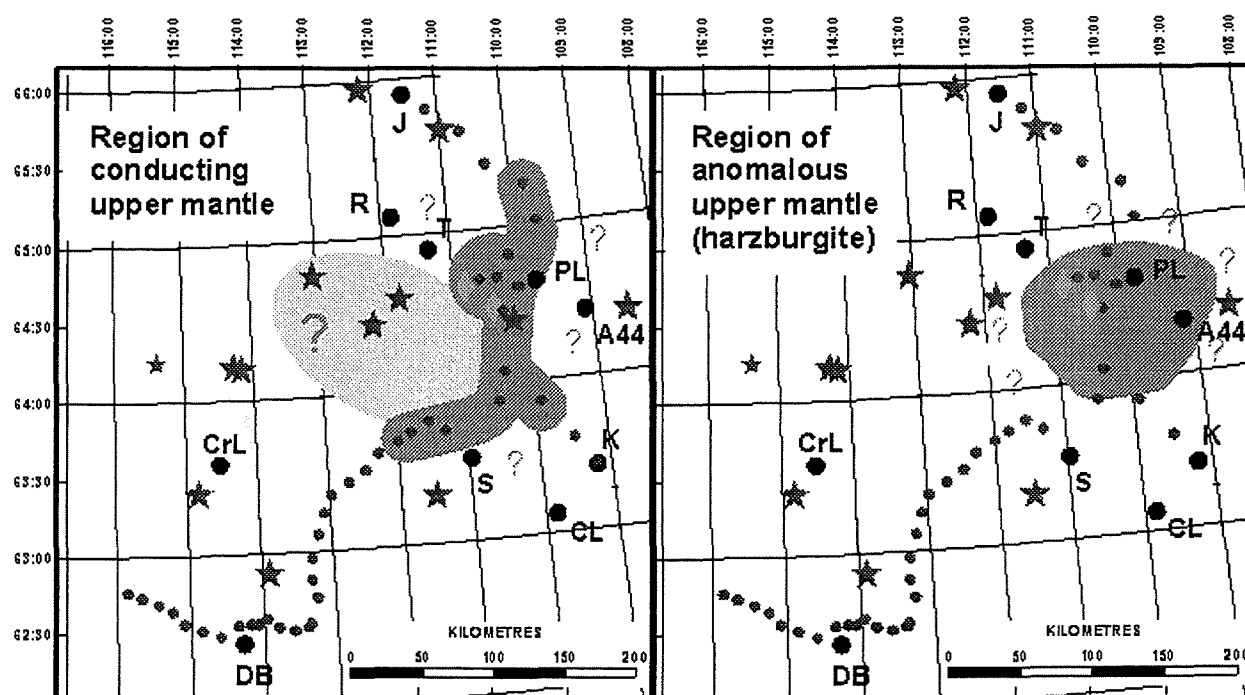


Figure 4: Location of conducting upper mantle (left) compared to region of anomalous geochemical mantle (right). Blue dots show the locations of major kimberlite pipes: DB: Drybones; CrL: Cross Lake; S: Snap Lake; CL: Camsell Lake; K: Kennady Lake; PL: Pellet Lake; T: Torrie; RL: Ranch Lake; J: Jericho.

Comparison of the spatial extent, location and depth of the mapped mantle conductor and the mapped ultra-depleted harzburgitic layer shows remarkable coincidence between the two. As olivine and harzburgite have very high electrical resistivity, then there must be other phases in the rocks to provide the conducting pathways. Processes of emplacement of the ultra-depleted layer must have resulted in this connected conducting phase.

Possible Conductivity Enhancement Mechanisms

There are two dominant mechanisms for the flow of current in the mantle: ionic conduction and electronic conduction. For the former, one can appeal to partial melt in the asthenosphere region and suggest, heroically, that there has been an upwarping of the lithosphere-asthenosphere boundary (LAB) since the emplacement of the Eocene-aged kimberlites in Lac de Gras. This thesis is untenable, given the lack of uplift and high heat flow in the central Slave craton. A free aqueous fluid (H_2O) phase will enhance conductivity at depths greater than 60 km (2 GPa) as the fluid can interconnect due to the dihedral wetting angle dropping below 60° (Mibe et al., 1998), and the conductor begins at ~80 km depth. Alternatively, following Karato (1990; see also Lizarralde et al., 1995), one can appeal to diffusion of hydrogen in the mantle. Both of these hypotheses suffer from requiring an explanation for a lateral boundary.

For electronic conduction, Boerner et al. (1999) invoke hydrous mantle minerals, specifically phlogopite, generated by metasomatising events as a possible explanation of conducting Archean mantle. The arduous and detailed laboratory work has yet to be undertaken on such rocks (A.

Electrifying images of the Slave

Duba, pers. comm., 1999), but hydrous mineral phases in the crust were demonstrated not to enhance conductivity once outgassing was controlled (Olhoeft, 1981). Alternatively, carbon in the mantle may be possible. Above the diamond stability field (<150 km), the carbon would be in the form of graphite, which is highly conducting. Below the stability field it would be in the form of diamond, and diamonds from those depths have been found in the Lac de Gras kimberlite pipes. In the laboratory carbon has been observed at crustal conditions to be deposited in graphite form on mineral surfaces during fracturing (Roberts et al., 1999), leading to the speculation that enhanced carbon in the Lac de Gras region could have been deposited as a continuous graphite film during tectonic processes associated with the Central Slave Basement Complex and the Eastern Slave Province (Bleeker et al., 1999a, b).

Given these scenarios, our preferred explanation is the role of enhanced carbon. This thesis must be tested by observations of carbon on grain-boundary surfaces in the ultra-depleted mantle xenolith material from the kimberlites in the Lac de Gras region, but not other regions. Alternatively, following Griffin et al. (1999) who interpret the ultra-depleted layer as trapped, hydrated oceanic or arc-related lithosphere, the hydrogen diffusion hypothesis (Karato, 1990) may be valid. In either case, the conducting layer was likely emplaced by tectonic processes, and therefore its interpretation will contribute to unravelling the complex history of the formation and development of the Slave craton.

Acknowledgements

Financial support for the Slave EM activities came from LITHOPROBE, GSC, DIAND, the National Science Foundation, Monopros, Kennecott and BHP, and accommodation was provided along the winter roads by Diavik, and in Yellowknife by Giant. Data acquisition along the all-weather and winter roads in 1996, 1998 and 1999 was undertaken by Phoenix Geophysics Ltd., who are thanked for their support in terms of reduced survey rates and access to new generation 24-bit recorders. Gary McNeice in particular, who was the crew chief of the winter road work, ensured the highest possible data recovery in the harsh conditions of a northern Canadian winter. The staff of the Yellowknife Seismological Observatory are thanked for their support and for providing essential preparation facilities. The lake bottom sites were deployed and retrieved from a Twin Otter float plane with a specially-designed winch built for us by Air Tindi. Finally, Garth Eggenberger and Alex Arychuk brought to surface an errant lake bottom instrument that was reluctant to free itself from its anchor.

References

- Bleeker, W. and W.J. Davis, 1999. The 1991-1996 NATMAP Slave Province Project: Introduction. *Can. J. Earth Sci.*, **36**, 1033-1042.
- Bleeker, W., J.W.F. Ketchum, V.A. Jackson and M.E. Villeneuve, 1999a. The Central Slave Basement Complex, Part I: its structural topology and autochthonous cover. *Can. J. Earth Sci.*, **36**, 1083-1109.
- Bleeker, W., J.W.F. Ketchum and W.J. Davis, 1999b. The Central Slave Basement Complex, Part II: age and tectonic significance of high-strain zones along the basement-cover contact. *Can. J. Earth Sci.*, **36**, 1111-1130.

Electrifying images of the Slave

- Boerner, D.E., R.D. Kurtz, J.A. Craven, G.M. Ross, F.W. Jones and W.J. Davis, 1999. Electrical conductivity in the Precambrian lithosphere of Western Canada. *Science*, **283**, 668-670.
- Davis, W.J., C. Gariépy and O. van Breeman, 1996. Pb isotopic composition of late Archean granites and the extent of recycling early Archean crust in the Slave Province, northwest Canada. *Chem. Geology*, **130**, 255-269.
- Davis, W.J. and E. Hegner, Neodymium isotopic evidence for the accretionary development of the Late Archean Slave Province. *Contrib. Min. Pet.*, **111**, 493-504, 1992.
- Garcia, X., Chave, A.D. and Jones, A.G., 1997. Robust processing of magnetotelluric data from the auroral zone. *J. Geomagn. Geoelectr.*, **49**, 1451-1468.
- Griffin, W.L., B.J. Doyle, C.G. Ryan, N.J. Pearson, S. O'Reilly, R. Davies, K. Kivi, E. van Achterbergh and L.M. Natapov, 1999. Layered mantle lithosphere in the Lac de Gras area, Slave craton: composition, structure and origin. *J. Petrology*, **40**, 705-727.
- Groom, R.W. and Bailey, R.C., 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. *J. Geophys. Res.*, **94**: 1913-1925.
- Jones, A.G., Chave, A.D., Egbert, G., Auld, D., and Bahr, K. 1989 A comparison of techniques for magnetotelluric response function estimation. *J. Geophys. Res.*, **94**: 14,201-14,213.
- Karato, S., 1990. The role of hydrogen in the electrical conductivity of the upper mantle. *Nature*, **347**, 272-273.
- Lizarralde, D., A. Chave, G. Hirth, and A. Schultz, 1995. Northeastern Pacific mantle conductivity profile from long-period magnetotelluric sounding using Hawaii-to-California submarine cable data, *J. Geophys. Res.*, **100**, 17,837-17,854.
- McNeice, G. and A.G. Jones, 1996. Multi-site, multi-frequency tensor decomposition of magnetotelluric data Contributed paper at 66th Society of Exploration Geophysicists Annual General Meeting, Denver, Colorado, 10-15 November.
- Mibe, K., T. Fujii and A. Yasuda, 1998. Connectivity of aqueous fluid in the Earth's upper mantle. *Geophys. Res. Lett.*, **25**, 1233-1236.
- Olhoeft, G.R., 1981. Electrical properties of granite with implications for the lower crust. *J. Geophys. Res.*, **86**: 931-936.
- Roberts, J.J., A.G. Duba, E.A. Mathez, T.J. Shankland and R. Kinzler, 1999. Carbon-enhanced electrical conductivity during fracture of rocks. *J. Geophys. Res.*, **104**, 737-747.
- Rodi, W., and Mackie, R.L., 2000. Nonlinear Conjugate Gradients algorithm for 2-D magnetotelluric inversion, *Geophysics*, accepted.
- Schultz, A., Kurtz, R.D., Chave, A.D. and Jones, A.G., 1993. Conductivity discontinuities in the upper mantle beneath a stable craton. *Geophys. Res. Lett.*, **20**: 2941-2944.
- Stern, R.A. and W. Bleeker, 1998. Age of the World's oldest rocks refined using Canada's SHRIMP: The Acasta Gneiss Complex, Northwest Territories, Canada. *Geoscience Canada*, **25**, 27-31.
- Thorpe, R.I., Cumming, G.L., and J.K. Mortensen, A significant Pb isotope boundary in the Slave Province and its probable relation to ancient basement in the western Slave Province, in Project Summaries, Canada-Northwest Territories mineral development subsidiary agreement, Geol. Surv. Canada Open-File Report 2484, 279-284, 1992.

Magnetotelluric Response and Geoelectric Structure of Southwestern Northwest Territories, Canada

X. Wu, I.J. Ferguson

Department of Geological Sciences, University of Manitoba,
Winnipeg, Manitoba, R3T 2N2, Canada

Alan, G. Jones

Geological Survey of Canada
615 Booth St, Ottawa, K1A 0E9, Canada

ABSTRACT

Magnetotelluric soundings were made at 45 sites in the southwestern Northwest Territories, Canada along the LITHOPROBE SNORCLE Transect Corridor 1. The sites cross the Archean Slave Province and the Proterozoic Great Bear, Hottah, Fort Simpson and Nahanni terranes. Phanerozoic sedimentary rocks overlie the Proterozoic terranes. Magnetotelluric results indicate the conductivity structure is close to 1D at shallow depth, 2D with strike of $\sim N35^{\circ}E$ at crustal depths in the Fort Simpson and Hottah terranes, and 2D with the various strikes along the profile at greater depth. The thickness of the Phanerozoic rocks increases from 0 m in the eastern Great Bear magmatic arc to ~ 1000 m in the Fort Simpson terrane. The conductive Phanerozoic surface layer can be subdivided into a moderately resistive upper layer dominated by sandy and/or silty limestone and a conductive lower layer dominated by shale. Two-dimensional inversion and modelling reveals a number of significant crustal conductivity structures. In the west of the corridor, the results delineate a relatively resistive body with a base that dips west to a maximum depth of about 20 km. This structure is interpreted to be the Fort Simpson moncline basin. The underlying middle to lower crust is relatively conductive ($\sim 250 \Omega m$). There is a sub-vertical conductive anomaly ($\sim 10 \Omega m$) near the boundary of the Fort Simpson and Hottah terranes, extending from 5 km depth to the base of the crust. It is interpreted to represent a structure formed during the collision of the Fort Simpson terrane with the western Hottah terrane. The upper crust of the Hottah terrane is resistive ($>3000 \Omega m$). There is a broad conductive zone in the mantle beneath the Hottah terrane. This zone appears to connect with a more conductive zone in the middle to lower crust beneath the eastern part of the Hottah terrane and the western part of the Great Bear magmatic arc. The location of the mid-crustal conductor does not correlate with the gravity anomaly and its tectonic interpretation is still being developed.

Introduction

The LITHOPROBE SNORCLE (Slave-Northern Cordillera Lithospheric Evolution) Transect Corridor 1 is located in the southwestern Northwest Territories. Previous magnetotelluric (MT) surveys completed in this general area include studies by Camfield et al. (1989) and Jones et al. (1995). Camfield et al. (1989) indicated the Wopmay orogen (~ 400 km north of the present survey) contained a very resistive upper crust. Jones et al. (1995) indicated the southern Cordillera (around 950 km south of the present survey) had a variably conductive upper crust, a generally conductive middle crust and a quite

conductive lower crust. Analysis of MT data from the present survey from the Slave Province reveals an absence of a conducting lower crust in the Anton terrane (Jones and Ferguson, 1997). The seismic reflection (Cook et. al., 1992, 1998) and seismic refraction (Viejo et. al. 1999) data as well as gravity and magnetic data collected along the present survey line provide constraints for the interpretation of the MT data.

The Setting of Geology and Geophysics

The SNORCLE Transect Corridor 1 crosses three geological structure elements (Figure 1) (1) the western Archean Slave Province (Anton and Contwoyto terranes) (Clowes, 1993), (2) the Proterozoic Wopmay orogen (Great Bear magmatic arc and Hottah terrane), and (3) the Fort Simpson and Nahanni terranes. The Archean Slave province comprises gneissic to massive granitoid rocks including the gneissic basement (3.1 Ga and 3.96 Ga), younger granitic plutons (2.7-2.6 Ga), and interspersed turbidite-volcanic (greenstone) assemblages (2.72-2.66 Ga) (Goodwin, 1996). The Proterozoic Wopmay orogen consists of a metamorphic-plutonic complex, a volcano-plutonic depression, and a continental margin depositional prism (2.1-1.9 Ga) (Hoffman, 1989). The Fort Simpson and Nahanni terranes are located in the Fort Simpson structural trend, a north-northwest-striking middle Proterozoic anticlinal culmination (Cook et al., 1998).

The Fort Simpson terrane and Great Bear magmatic arc have associated magnetic highs. The Hottah terrane has a magnetic low, gravity high, and anomalous velocity zone (Viejo et al., 1999), which is interpreted to represent the suturing of the Fort Simpson terrane with Hottah terrane as proposed by Hoffman (1989). The magnetic and gravity lows in the west of Fort Simpson terrane are associated with the Fort Simpson Basin. This basin also is also resolved by the seismic reflection and refraction result (Cook et al. 1998, Viejo et al., 1999).

MT Survey and Data Processing

Soundings at 45 MT sites were completed along SNORCLE transect Corridor 1 in the southwestern Northwest Territories, Canada in the summer of 1996 (Fig. 1). There were 24 sites on the Hottah, Fort Simpson and Nahanni terranes, 9 sites on the Great Bear magmatic arc, and 12 sites on the exposed Slave craton. At each site the recordings include Phoenix V5 measurements (10^{-4} s - 100 s) and Geological Survey of Canada LiMS measurements (20 - 30,000 s) (Jones and Ferguson, 1997). Phoenix Geophysics provided the MT responses (V5 data) for each site in the form of auto- and cross-power spectra of the seven EM components in Society of Exploration Geophysicists Electronic Data Interchange, SEG EDI, format. The cross-spectra were computed using robust statistical techniques based on the Jones-Jodicke approach (Jones and Jodicke, 1984, Jones *et al.*, 1989).

The SNORCLE area is located at high latitudes (60° - 63° N) where the long-period MT responses (LiMS data) may be distorted by non-uniform source fields associated with auroral geomagnetic activity. Methods applied to extract the regional earth response from the recorded time-series are the Jones-Jodicke approach (single-station-weighted cascade decimation and all-station-weighted cascade decimation) (Jones and Jodicke, 1984; Jones *et al.*, 1989) and the Chave approach (robust remote reference impedance estimation) (Chave *et al.*, 1987; 1989) methods. In order to obtain an eight-decade

period range (10^{-4} - 10^4 s), we merged the V5 and LiMS data collected at each site. The V5 data was used to define the response at periods <20 s, and LiMS data is used at periods >20 s.

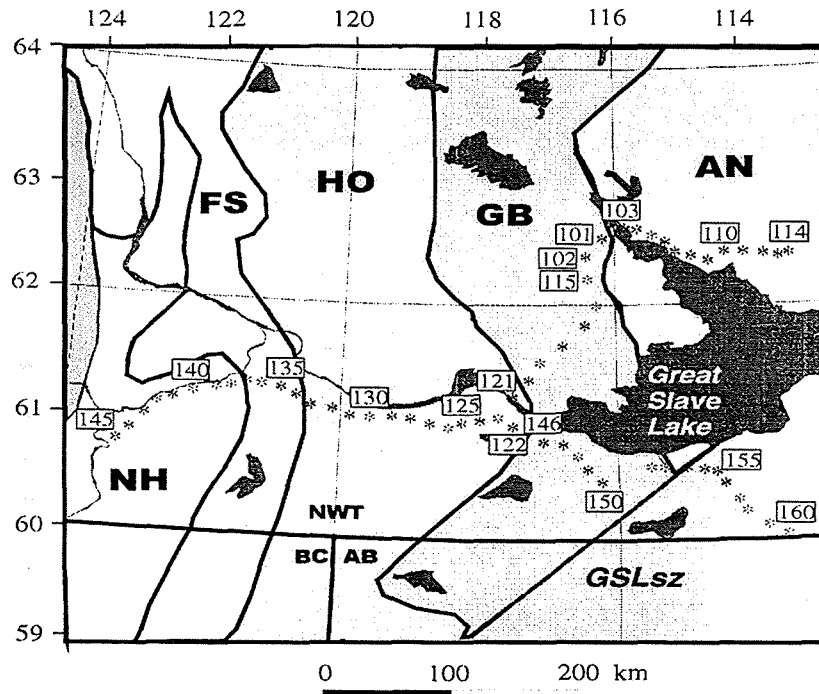


Figure 1. MT survey stations (symbol stars) along Corridor 1. Na: Nahanni terrane, FS: Fort Simpson terrane, Ho: Hottah terrane, GB: Great Bear magmatic arc, AN: Anton terrane, GSLsz: Great Slave Lake shear zone.

Geoelectric Strike Directions

A variety of methods can be used to define the geoelectric strike, including induction vectors, maximum phase split directions and Groom-Bailey (GB) regional strike. The direction of the reserved real component of the induction vector will be orthogonal to the local geoelectric strike and for simple 2D structures will point towards more conductive regions (Jones, 1986). The maximum phase split method can also be used to examine the strike angle. The larger-phase direction will usually (but not always) correspond to the geoelectric strike when there are isolated conductors in resistive background rocks. GB decomposition can also provide the regional strike direction. With both the maximum phase split and GB regional strike, there is a $\pm 90^\circ$ ambiguity in the strike orientation.

Figure 2 shows the geoelectric strike from these three parameters at periods of 0.01 s, 10 s, 100 s and 2500 s. The results show significant differences between the near-surface and deeper resistivity structures, and between the east and west ends of the profile.

Short-periods (near-surface response): At short periods, the real induction vectors and maximum phase splits are small. These indicate the resistivity structure of the Phanerozoic sedimentary rocks is almost 1D. There is a consistent of strike direction $\sim N60^\circ E$ ($\pm 90^\circ$ ambiguity) in the Fort Simpson and Hottah terranes. The strike is irregular in Great Bear magmatic arc and Slave Craton.

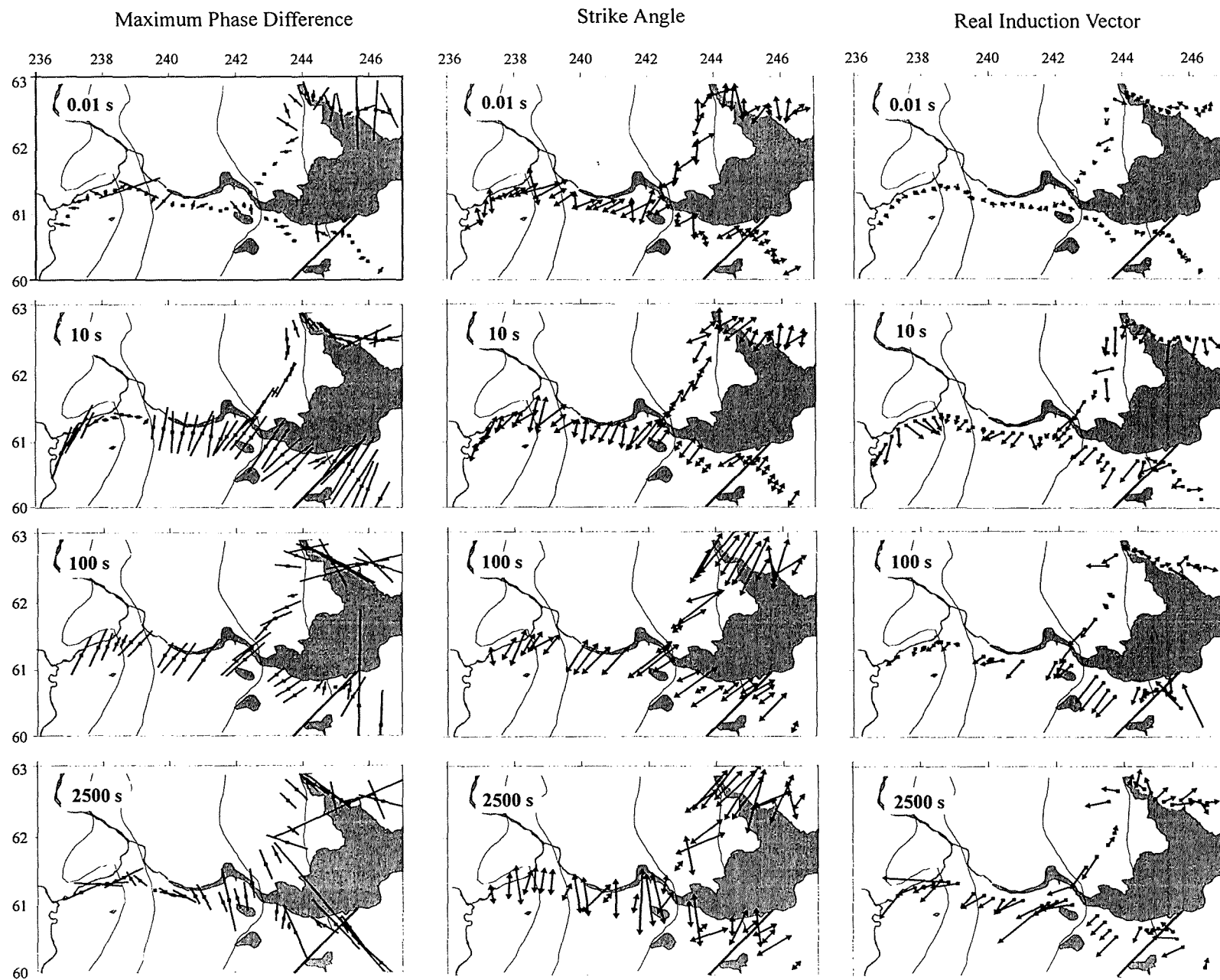


Figure 2. The maximum phase split, Groom-Bailey regional strike and real induction vector along the SNORCLE Transect Corridor 1 at 0.01 s, 10 s, 100 s and 2500 s. There is 90 degree ambiguity between the direction of the maximum phase split and the regional strike.

At Period of 10 s: This period corresponds to signal penetration deep into the upper/middle crust. The induction vectors have an overall southward component that may be caused by the location and thickness of the Phanerozoic sedimentary rocks. Induction vectors have been interpreted as being related to nearby sedimentary rocks in other locations where thick sequences of sedimentary rocks occur adjacent to exposed Precambrian shield. For example, the long period response on the LITHOPROBE THO line includes induction vectors that point towards thick sediments in the Williston Basin (Stevens 1998). There is a reversal in the east-west component of the vectors across the Fort Simpson terrane indicating a presence of a conductor in this area. The maximum phase split directions and strike angles are consistent and close to N20°E, except for the maximum phase split in the Slave Craton.

At Period of 100 s: This period corresponds to signal penetration deep into the middle/lower crust. The vectors are generally small except at sites near the boundary of the Great Bear and Hottah terranes where the vectors point to the southwest (~S30-60°W). The directions of the larger maximum phase split and regional strike are ~N30°E in the west of profile, and about N60°E in the Great Bear magmatic arc. The directions of maximum phase-split are variable in Anton terrane, but the regional strike is about N30°E.

At Periods >10³ s: This period corresponds to signal penetration into the deepest crust and lithospheric mantle. The strike is north-south in the west and changes to ~N30°E in the east, indicating that there is significant differences in the deep resistivity structure across the study area. The direction of phase split is east-west at the western end of the profile, and is N45°W in the Great Bear magmatic arc. Examination of the apparent resistivity and phase values suggests the correct strike in the western portion of the profile (where there is a 90° shift between the regional strike and maximum phase split direction) is north-south.

MT Apparent Resistivity and Phase Responses

The MT responses are separated into two independent modes: TE mode (the electric current flow parallel to the geo-electric strike) and TM mode (the electric current flow perpendicular to the strike). Based on the analyses of geoelectric strike, the average strike angle for the period range of 0.01 to 200 s will be used in subsequent modelling. For the Proterozoic terranes, N34°E is adopted as the strike. Figure 3 shows pseudosections of the apparent resistivity and phase along Corridor 1. The western segment of the profile is perpendicular to the regional strike so the figure shows the TE and TM responses. The eastern and middle sections are for profiles approximately parallel to the survey line and do not represent true TE and TM responses. The phase and apparent resistivity pseudosections clearly show the effect of the Phanerozoic sedimentary rocks extending from the highest frequencies to around 1 Hz. The responses in the Slave Province are much more resistive and characterized by the static shift in the apparent resistivity.

Short period (<1 s): The most conductive short-period response is near site station 131 and the most resistive responses are observed on the Slave craton. The conductive response is observed at

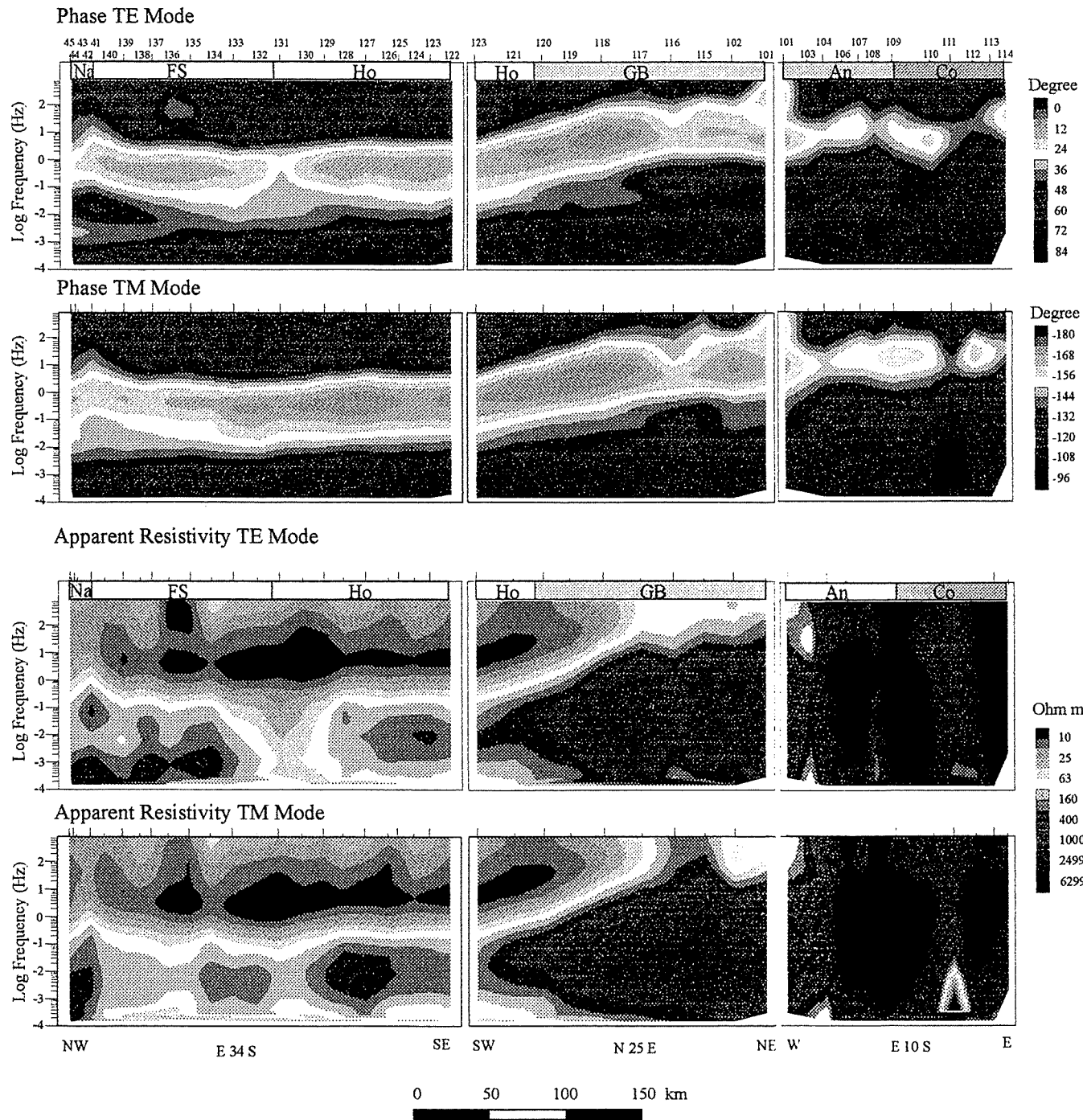


Figure 3. Apparent resistivity and phase pseudosections for TE and TM modes along Corridor 1. It is divided into three profiles. The western one is perpendicular to regional geoelectrical strike. E34S means the direction of profile is east 34 degree south. The other two profiles are approximately parallel to the survey line. Na: Nahanni, FS: Fort Simpson, Ho: Hottah, GB: Great Bear magmatic arc, An: Anton, Co: Contwoyto.

progressively higher frequencies in the southwest to northeast crossing of the Great Bear magmatic arc reflecting the thinning of the sedimentary cover in this direction. There is a discontinuity in the short period response near station 142 at the extreme western end of the Corridor and near station 136 there is enhanced conductivity response in the high frequency response.

Intermediate periods (1-1000 s): The apparent resistivity values in this period range increase from ~200 Ωm in the west to ~2000 Ωm beneath the Great Bear to >5000 Ωm in the Slave province. There is a discontinuity, particularly evident in the TE phase and apparent resistivity response, at stations 131 and 130. This conductive anomaly extends from the periods corresponding to penetration into the upper crust to the periods corresponding to penetrate into the mantle.

Long period (>1000 s): At the longest periods there is a decrease in apparent resistivity beneath the Fort Simpson and Hottah terranes. This feature is not visible in the data (at periods <10⁴ s) in the northern part of the crossing of the Great Bear magmatic arc nor in the Slave Province.

Distortion

Groom-Bailey (GB) decomposition (Groom & Bailey, 1989) was used to examine the galvanic distortion from near-surface inhomogeneities. For Phanerozoic sites, the shear and twist angles are very small (close to 0°) at shorter periods (<10 s). Although the shear and twist angles are larger (<10°) at longer periods (>10 s), the distortion is still small. The results indicate an absence of near-surface heterogeneities at Phanerozoic sites, as expected for the flat-lying sedimentary rocks. The shear and twist of the Slave province are larger at all periods (shear and twist are typically to ~20°) but still smaller than noted in many Precambrian shield settings. The MT response used in subsequent modelling is based on a GB analysis in which the response is constrained for the period range 10⁻³-3×10⁴ s using the average shear and twist at each site, and a constant strike azimuth for the whole profile.

Structure of Surface Sedimentary Rocks

The Phanerozoic sediments form a relatively thick conductive layer at the surface (Figure 3). At short periods (<1 s), the similarity of the TE and TM apparent resistivity responses, and the small induction vector and maximum phase split all imply an approximately 1D near-surface structure. One-dimensional Occam (Constable et al. 1987) and Fischer (Fischer et al. 1981) inversions were used to determine the shallow conductive structure. The data were truncated at period 10 s corresponding approximately to signal penetration through the sediments.

Figure 4 shows the 1D modelling reveals significant resistivity variations within the sedimentary rocks. There is a moderately resistive upper layer (>50 Ωm) with a depth to the base of 20-100 m. At most stations the most conductive rocks (~10 Ωm) occur at 200-900 m depth. The depth to the base of this layer decreases from 1150 m at station 139 to 200 m at station 117 at Great Bear. The results for station 142 shows strong differences with the surrounding stations. The sedimentary rocks are much thinner at this site. Comparing the MT results with the nearby borehole logs, we can interpret that:

- First layer: The relatively resistive surface (~50-100 Ωm) corresponds to sandy and/or silty limestone dominated units. It has a thickness of 20 m to 100 m.
- Second layer: The more conductive layer (~10 Ωm) is associated with conductive shale deposits found mainly in the Phanerozoic rocks overlying the Fort Simpson and Hottah terranes. The thickness of this layer is about 750-850 m in the Fort Simpson terrane, and decreases to the east.

The total thickness of the conductive Phanerozoic sedimentary rocks thins from ~1000 m in the Fort Simpson terrane to 0 m in the east of the Great Bear magmatic arc. The total thickness determined from the MT response is in agreement with borehole results (National Energy Board, 1980). Future work will include comparison of MT data with geophysical logs from the boreholes. Station 142 corresponds to a resistive boundary between the Fort Simpson and Nahanni terranes.

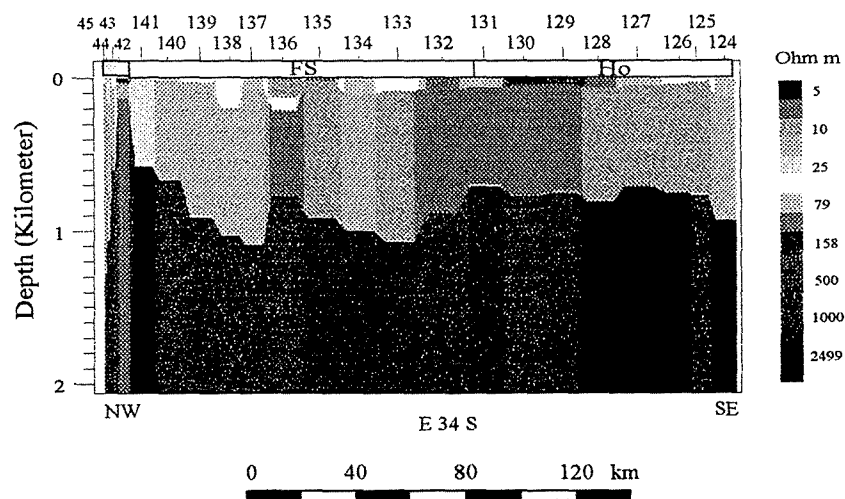


Figure 4. Determinant 1D shallow inversion model from the Fort Simpson terrane to Hottah terrane.

Structure of the Crust

At longer periods, the TE and TM apparent resistivity and phase pseudosections (Figure 3) show both lateral changes and variation with period, indicating the presence of significant crustal and lithospheric resistivity structures. The analysis of geoelectric strike directions indicates that the Corridor 1 survey line is sub-parallel to the structure strike in the Great Bear magmatic arc (Fig. 2), so it is very hard to make a profile that is perpendicular to the strike angle. To extend the modelling results into the Great Bear we have included some sites from Corridor 1a (Wu *et al.* 2000).

2D Inversions

The two-dimensional inversion methods used included 2D Occam inversion (deGroot-Hedlin and Constable, 1990) and 2D Mackie inversion (Mackie, et al., 1993, 1997). Occam inversion determines the smoothest model that fits the observed data to within a prescribed error, and is most useful for identifying which features are principal elements of the true resistivity structure since Occam models include only those features actually required by the data (Constable et al. 1987). Because of uncertainties in the spectral error estimates, constant error estimates were applied to the data. Smaller errors were assigned to

the TM mode since it was the largest (and best therefore determined) component. The error for the TM mode is $\pm 10\%$ for the resistivity and $\pm 2.86^\circ$ for the phase. For the TE mode it is $\pm 20\%$ for the resistivity, and $\pm 5.73^\circ$ for the phase. Mackie inversion uses the non-linear conjugate gradient method. It is much faster than the Occam method. The inversion error used is 5% for the resistivity and 2.5% for the phase in $\ln$ space.

Figure 5 shows the fit of the inversion model response to the data at representative stations. The TM response fits the data better than the TE responses (as expected for the assigned errors). The fit is not as good at periods > 100 s for some stations (for example, station 130, 126). Overall, for both modes, the model responses fit the data well.

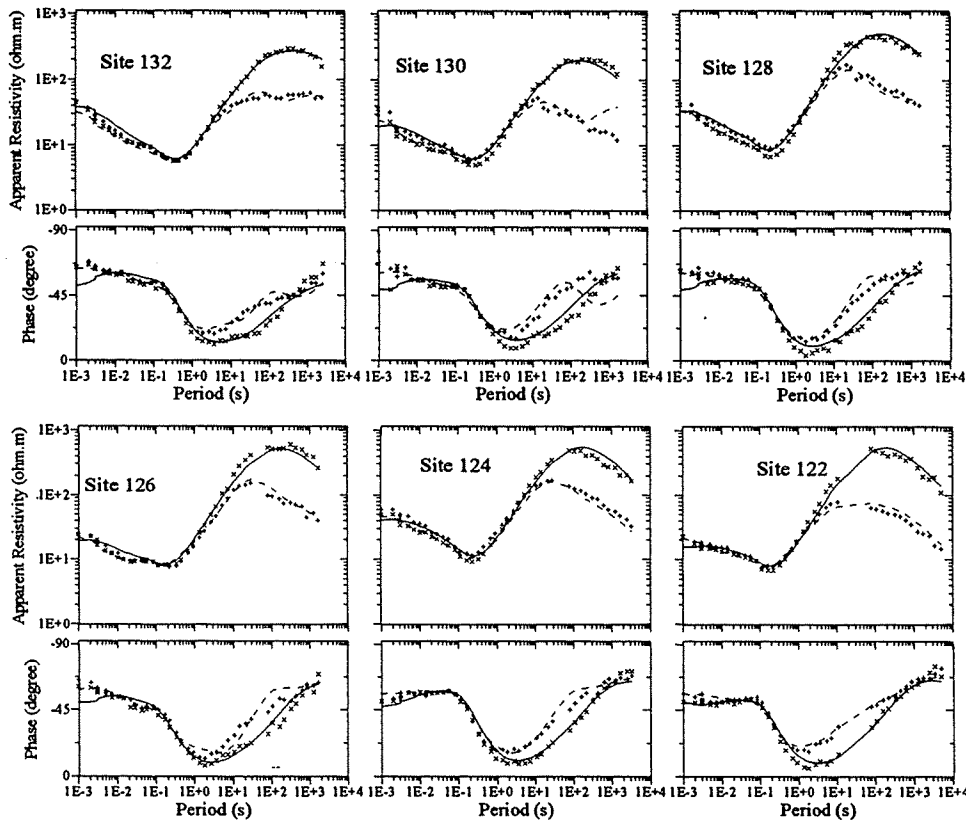


Figure 5. Comparing the apparent resistivity and phase from inversion model responses with the observed data at some stations. Solid line: TM response, dash line: TE response, x: TM observed data, +: TE mode observed data.

Figure 6 and 7 show the 2D inversion models from Occam and Mackie inversion method. The shallow structure from Occam inversion (Figure 6a) is similar to that from the 1D inversion (Figure 4). The crustal structure from both inversion methods (Figure 6b and 7) shows significant lateral variations. There is a good agreement between the results from two methods indicating that these features are well resolved. We will now consider the features in the model moving from west to east.

- There is a resistivity boundary beneath stations 143 and 142 in the Nahanni terrane in which a relatively conductive body extending to 20 km depth separates more resistive zone to the east and west.

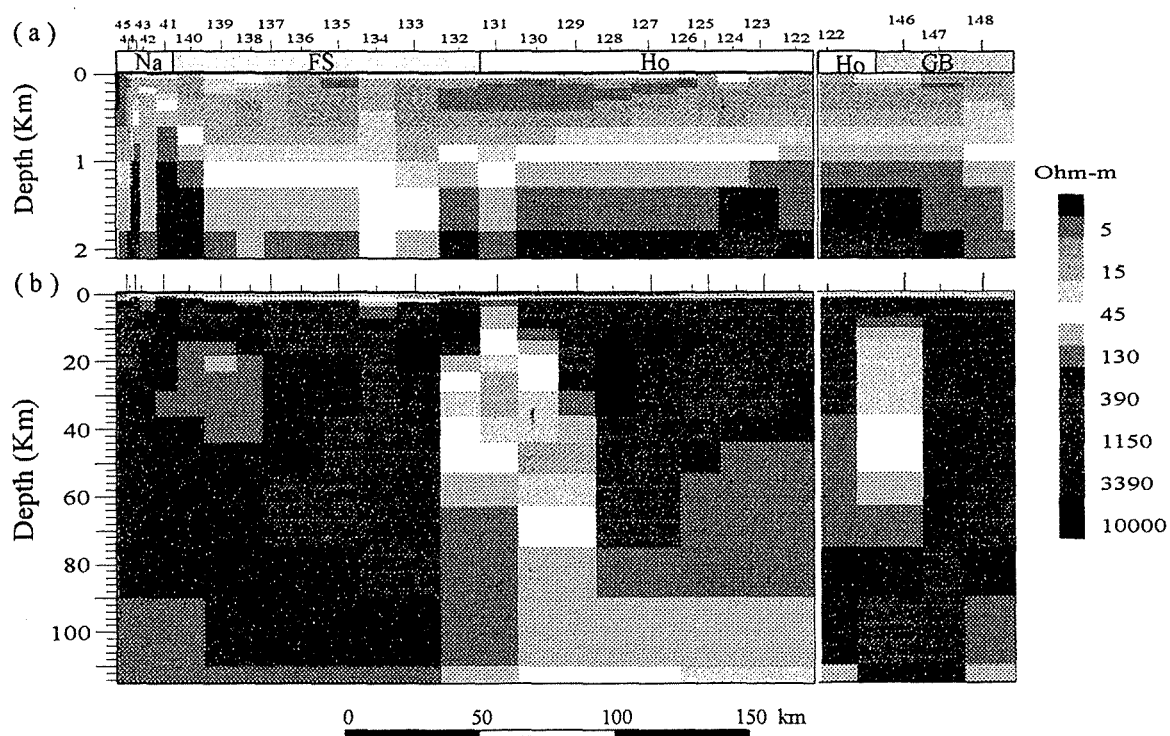


Figure 6. 2D Occam inversion models from Fort Simpson terrane, Hottah terrane to Great Bear magmatic arc in Corridor 1. (a) shallow structure, (b) deeper structure.

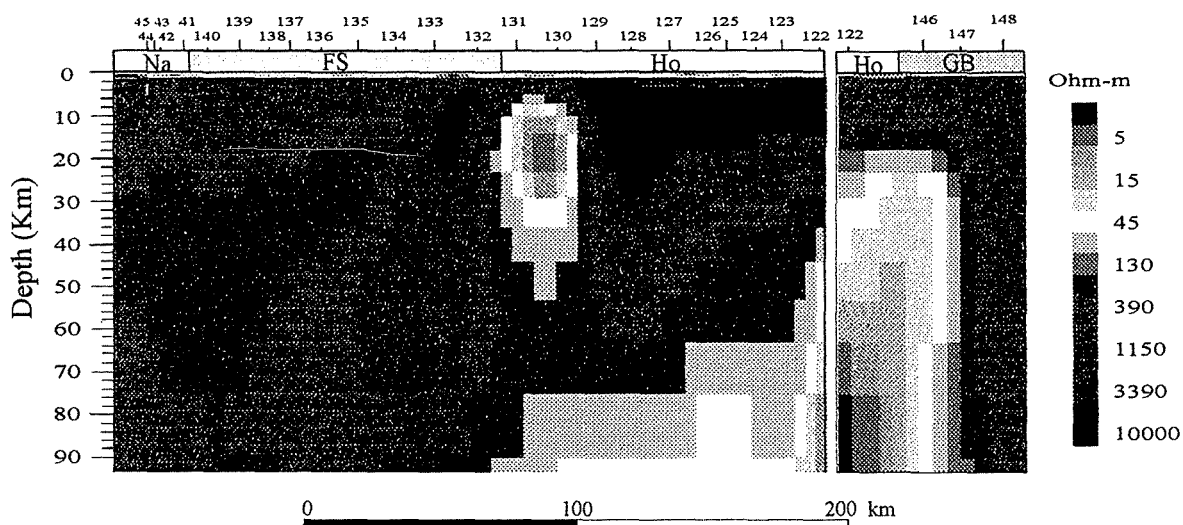


Figure 7. 2D Mackie inversion model from Fort Simpson terrane, Hottah terrane to Great Bear magmatic arc in Corridor 1.

- A relatively resistive body ($>1000 \Omega\text{m}$) is present in the Fort Simpson terrane. The depth to the base of the body decreases from about 20 km under station 141 to ~1 km under station 133. This body is underlain by more conductive middle to lower crust ($\sim 250 \Omega\text{m}$).
- A clear sub-vertical conductive zone is present under station 131 and 130. The resistivity is about $<100 \Omega\text{m}$. This zone extends from several kilometers depth to the lower crust.
- There is a broad conductive zone ($< 100 \Omega\text{m}$) in the mantle beneath the whole Hottah terrane. This zone appears to connect to a more conductive zone ($<20 \Omega\text{m}$) in the middle to lower crust beneath the boundary of the Hottah and Great Bear terranes. There is sharp western edge to this zone at station 147.

Interpretation

- The resistivity boundary at station 143 and 142 corresponds to the Nahanni and Fort Simpson terrane boundary. The feature coincides with a decrease in the thickness of the Phanerozoic sedimentary rocks (Fig. 4, Fig. 6a).
- The resistive body in the Fort Simpson terrane corresponds to the Fort Simpson basin, which is a west dipping ($\sim 20^\circ$) monocline basin. The western side of the Fort Simpson monocline is overlain by Proterozoic (meta-) sedimentary rocks and/or sills (Cook, et al, 1992, 1998), the depth is about 20 km. The basin thins to the east, and disappears near the boundary between Fort Simpson and Hottah terranes. This Proterozoic sedimentary basin is also well defined by seismic reflection and refraction data (Cook et al. 1998, Viejo et al., 1999).
- The sub-vertical conductive zone at station 131 and 130 corresponds to the gravity high, magnetic low and an anomalous velocity zone (Viejo et. al, 1999) in the Hottah terrane. The conductivity anomaly indicates the presence of a structural boundary associated with the collision between the Fort Simpson and the western Hottah terranes (Cook et. al 1998).
- The conductive middle to lower crust under the Hottah terrane is related to the boundary between the Hottah terrane and Great Bear magmatic arc. The conductivity anomaly does not appear to coincide with the gravity response and it is at sufficient depth that direct correlation with the magnetic response would not be expected. The seismic refraction result shows that the Hottah terrane has higher velocity in the east (Viejo et. al., 1999). Tectonic interpretations for the resistivity structure are still being developed.

Conclusions

The MT data set from the SNORCLE Transect Corridor 1 reveals information on both the Phanerozoic sedimentary rocks and the structures of the underlying Proterozoic crust and lithosphere:

1. The conductive Phanerozoic surface layer can be subdivided into a moderately resistive upper layer dominated by sandy and/or silty limestone and a conductive lower layer dominated by shale. The thickness of the sedimentary rocks thins from ~1000 m in Fort Simpson terrane to 0 m in the eastern Great Bear magmatic arc.

2. The geoelectric strike is $\sim N34^{\circ}E$ in the upper crust of the Proterozoic terranes. In the Great Bear magmatic arc it is oriented closer to $N60^{\circ}E$. At the longest periods, corresponding to mantle penetration, the strike is approximately north-south.
3. The MT data resolves significant resistivity variations in the crust and mantle. In the west of the corridor, the MT results image a structure at the boundary of the Nahanni and Fort Simpson terranes and the resistive west-dipping Fort Simpson monocline basin. Further east the MT results image a conductive structure apparently associated with the collision of the Fort Simpson terrane with the western Hottah terrane, and a conductive zone in the middle and lower crust beneath the boundary of the Hottah terrane and the Great Bear magmatic arc.

Acknowledgements

The financial support for this project came from LITHOPROBE and NSERC grants. The data from the contracted MT V5 survey were collected by Phoenix Geophysics. The LiMS data were collected by Mr. Nick Grant, with assistance of researchers from the Geological Survey of Canada (GSC), the University of British Columbia, and the University of Manitoba. Processing of LiMS data was performed using software provided by the GSC. We would like to thank Mr. R. Mackie for advice on the use of his 2D inversion program. We used the 2D Occam inversion program from S. Constable and C. deGroot-Hedlin that is packaged in Geotools software.

References

- Camfield, P.A., Gupta, J.C., Jones, A.G., Kurtz, R.D., Krentz, D.H., Ostrowski, J.A. and Craven J.A., 1989. Electromagnetic sounding and crustal electrical conductivity in the region of the Wopmay Orogen, Northwest Territories, Canada. *Can. J. Earth Sci.*, **26**, p. 2385-2395.
- Chave, A.D., Thomson, D.J. and Ander M.E., 1987. On the robust estimation of power spectra, coherences, and transfer functions. *J. Geophys. Res.*, **92**, 633-648.
- Chave, A.D. and Thomson, D.J., 1989. Some comments on magnetotelluric response function estimation. *J. Geophys. Res.*, **94**, 14215-14225.
- Clowes, R.M. (editor), 1993, LITHOPROBE Phase IV proposal: Studies of the Evolution of a Continent. Published by LITHOPROBE Secretariat, The University of British Columbia, Vancouver, B.C. 290 pp.
- Constable, S.C., Parker, R.L. and Constable, C.G., 1987., Occam's inversion: A practical algorithm for generating smooth models from electromagnetic sounding data. *Geophys.*, **52**, 289-300.
- Cook, F.A., Dredge, M. and Clark, E.A., 1992. The Proterozoic Fort Simpson structural trend in northwestern Canada. *Geological Society of America Bulletin*, v. **104**, p. 1121-1137.
- Cook, F. A., van der Velden, A. J., Hall, K. W., Roberts, B. J., 1998. Tectonic delamination and subcrustal imbrication of the Precambrian lithosphere in northwestern Canada mapped by Lithoprobe. *Geology (Boulder)*, **26** (9), p. 839-842.
- deGroot-Hedlin, C. and Constable, S., 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophys.*, **55**, 1613-1624.

- Fischer, G., Schnegg, P. and Peguiron, M. 1981. An analytic one-dimensional magnetotelluric inversion scheme. *Geophys. J. R. astr. Soc.*, **67**, 257-278.
- Goodwin, A.M. 1996. Principles of Precambrian Geology, Academic Press, pp. 327.
- Groom R.W. and Bailey, R.C. 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. *J. Geophys. Res.*, vol. **94**, 1913-1925.
- Hoffman, P.F., 1989. Precambrian geology and tectonic history of North American, in *The Geology of North American*, Vol. A, The Geology of North American - An overview, The Geological Society of American.
- Jones, A.G. and Jödicke, 1984. Magnetotelluric transfer function estimation improvement by a coherence-based rejection technique. Contributed paper at *54th Annual International Meeting, Society of Exploration Geophysics*, Atlanta, Georgia, U.S.A., Dec. 2-6. Expanded abstracts 51-55.
- Jones, A.G., 1986. Parkinson's pointers' potential perfidy. *Geophys. J. R. Astr. Soc.*, **87**, 1215-1224.
- Jones, A.G., Chave, A.D., Egbert, G., Auld, D. and Bahr, K., 1989. A comparison of techniques for Magnetotelluric response function estimation. *J. Geophys. Res.*, **94**, 14201-14213.
- Jones, A.G. and Gough D. I., 1995. Electromagnetic images of crustal structures in southern and central Canadian Cordillera. *Can. J. Earth Sci.*, **32**, 1541-1563.
- Jones A.G. and Ferguson, I.J. 1997. Results from 1996 MT studies along SNORCLE profiles 1 and 1A. In *Lithoprobe 1997 Report*, pp. 6.
- Mackie, R.L. and Madden, T.R., 1993. Three-dimensional magnetotelluric inversion using conjugate gradients. *Geophys. J. Int.*, **115**, 215-229.
- Mackie, R., Rieven, S. and Rodi, W., 1997. Users Manual and software Documentation for Two-Dimensional Inversion of Magnetotelluric Data.
- National Energy Board, 1980. Schedule of wells north of 60 NWT & Yukon. Published under the authority of The Minister of Indian Affairs and Northern Development.
- Stevens, K.M. 1998. The interpretation of magnetotelluric measurements from the Glennie domain to the Flin Flon belt, eastern Saskatchewan: part of the LITHOPROBE, Trans-Hudson orogen transect. Thesis, University of Manitoba, pp.274.
- Viejo, G.F., Clowes, R.M., Amor, J.R. and the SNORE Working Group, 1999. Lithospheric velocity structure beneath the Slave province and Wopmay orogen from the SNORCLE refraction experiment. In *Lithoprobe SNORCLE and Cordilleran tectonic Workshop Meeting, Lithoprobe Report*, No. **69**, edited by Cook, F. and Erdmer, P., 73-80.
- Wu, X. Ferguson, I. and Jones, A., 2000. Magnetotelluric response and geoelectric structure of Great Slave Lake shear zone along SNORCLE transect Corridor 1a. In *LITHOPROBE Report, 2000 SNORCLE Workshop Meeting (this volume)*.

Mantle Strain beneath the Great Slave Lake Shear Zone, NWT from Measurements of Seismic and Electrical Anisotropy

*David W. Eaton, University of Western Ontario
Isa Asudeh and Alan G. Jones, Geological Survey of Canada*

Introduction

Observations of seismic and electrical anisotropy provide complementary proxy measurements of the degree and orientation of strain in the subcontinental mantle. Seismic anisotropy in the mantle is generally believed to be controlled by strain-induced lattice-preferred orientation of olivine crystals (e.g., Vauchez and Nicolas, 1991; Kern, 1993). Measurements of shear-wave splitting parameters (fast polarization direction ϕ and delay time δt) for teleseismic phases, such as SKS, have been used extensively to characterize seismic anisotropy in the mantle (Silver, 1996). Similarly, magnetotelluric methods can be used to determine electrical anisotropy of the mantle, which is characterized by measurements of the most conductive direction (ϕ_{MT}) and phase difference between the most conductive and orthogonal directions ($\delta\theta$). Strong electrical anisotropy of the upper mantle has been attributed to preferred interconnection of a highly conducting mineral phase (such as graphite) within foliation planes (Jones, 1992; Mareschal et al., 1995). In a recent study across the Grenville front, Ji et al. (1996) noted a conspicuous and systematic discrepancy of about 23° between δt and $\delta\theta$. They proposed that this obliquity represents a fabric asymmetry produced in a non-coaxial strain regime, reflecting the difference between lattice-preferred orientation (seismic anisotropy) and shape-preferred orientation (electrical anisotropy) of mantle minerals.

In the present study, new shear-wave splitting measurements across the Great Slave Lake shear zone (GSLsz), NWT, are compared with previously reported electrical anisotropy parameters (Jones and Ferguson, 1997) as a direct test of the hypothesis of Ji et al. (1996). In addition to the known electrical anisotropy in the upper mantle, this location was chosen because the well defined kinematic regime, non-coaxial ductile strain and tectonic quiescence since ca. 1.86 Ga limit the number of possible interpretations of mantle strain patterns. The GSLsz is a major continental transform fault, linked to the Paleoproterozoic convergence and collision between the Slave and Rae provinces (Gibb, 1978; Hoffman, 1987). It is exposed along the southeast shore of Great Slave Lake within a 25-km wide, northeast-trending subvertical mylonite corridor that produces one of the most spectacular linear magnetic anomalies in North America (Fig. 1). Based on its magnetic expression, the GSLsz can be correlated for at least 1300 km, mostly in the subsurface. In its early, ductile phase (ca. 1.97 Ga), the GSLsz accommodated up to 700 km of dextral strike-slip motion (Hoffman, 1987) in a regime of non-coaxial strain (Hanmer et al., 1992). A later phase of brittle strike-slip motion (post 1.87-1.86 Ga) occurred along the parallel McDonald fault, accounting for an additional 75-125 km of offset (Hanmer et al., 1992).

Teleseismic data acquisition

For this experiment, thirteen temporary seismograph stations were deployed from mid-May to early October, 1999. Nine of these stations used Nanometrics Orion-3 digital seismographs with Guralp CMG-40T sensors (0.03 - 50 Hz). The remaining four stations used Reftek 72A-05 seismographs

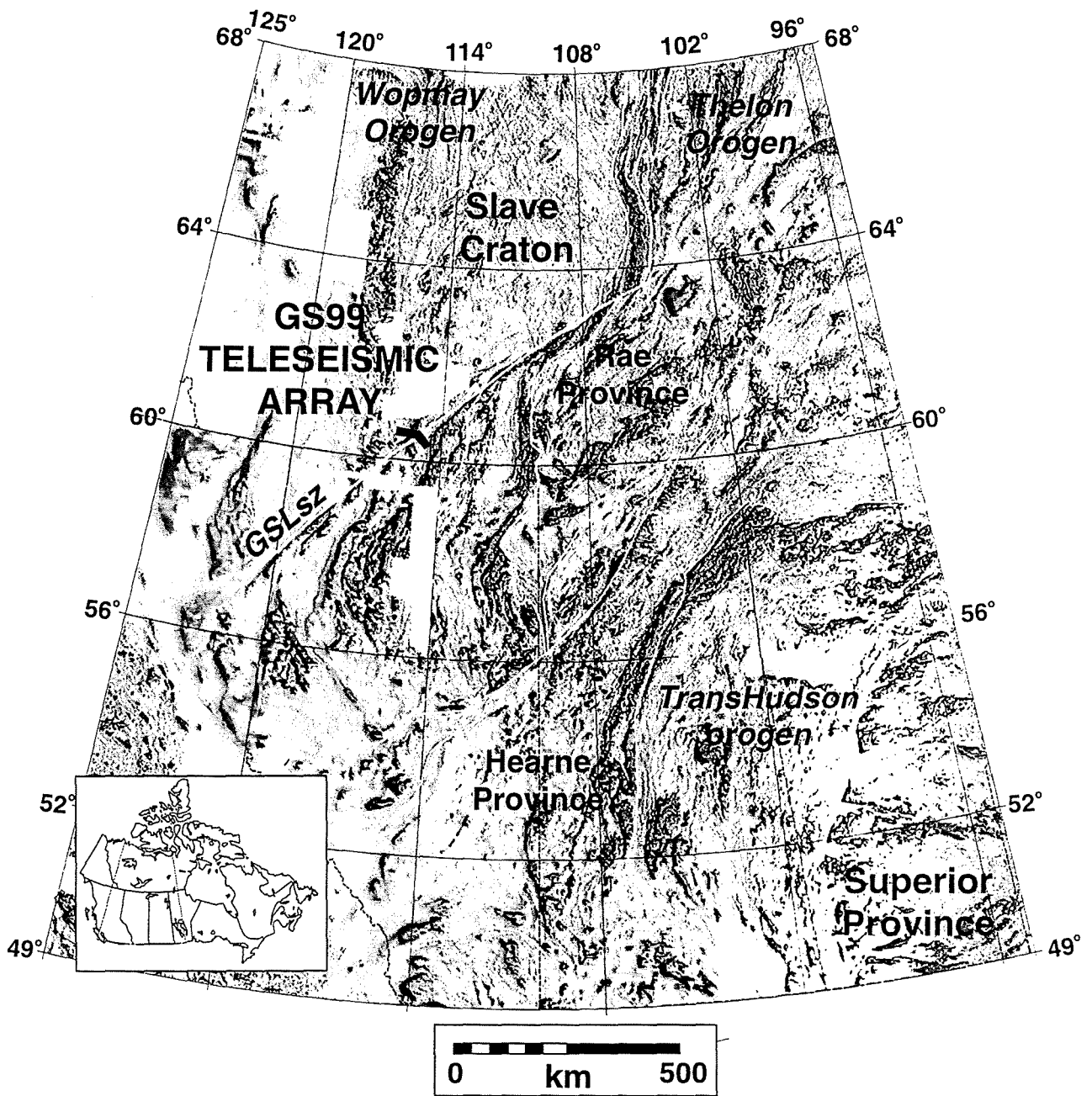


Fig. 1. Aeromagnetic anomaly map for western Canada showing the trend of the Great Slave Lake shear zone (GSLSZ) and the present study (GS99). This figure was compiled using data from the Geophysical Data Centre, Geological Survey of Canada.

Table 1. Earthquakes used in this study.

Date	Time (UT) (hh:mm:ss)	Latitude (° N)	Longitude (° E)	Depth (km)	Magnitude	Δ (°)	Baz (°)	Event Number	Location
5/22/1999	10:08:53	-20.731	169.881	33	6.1	100	247	1	Vanuatu
6/18/1999	10:55:25	5.514	126.639	33	6.4	98	297	2	Celebes Sea
7/9/1999	05:04:42	-6.514	154.944	29	6.3	95	266	3	Solomon Is.
7/26/1999	01:33:20	-5.151	151.942	69.4	6.2	95	269	4	New Britain
8/14/1999	00:16:52	-5.885	104.711	101.4	6.5	117	313	5	Sumatra
8/22/1999	09:35:39	-40.509	-74.756	33	6.4	106	148	6	Chile
8/22/1999	12:40:46	-16.117	168.039	33	6.5	97	250	7	Vanuatu
8/26/1999	01:24:42	10.376	126.006	62.6	6.1	94	299	8	Phillipines
8/26/1999	07:39:28	-3.522	145.657	33	6.3	97	275	9	PNG
9/17/1999	14:54:48	-13.74	167.163	197.3	6.3	95	252	10	Vanuatu

and Guralp CMG-40T sensors provided by the IRIS Program for Array Seismic Studies of the Continental Lithosphere (IRIS-PASSCAL). Wherever possible, the stations were located in abandoned gravel pits, which provided concealment from the road and good ground-coupling conditions. The sensors were oriented according to magnetic north, and buried in shallow cement-based enclosures just above the water table. Two 75-Watt solar panels provided power for each site. Considerable effort was devoted to encasing all cables in PVC tubing, for protection from the elements and inquisitive wildlife. The four Reftek stations were configured in a dense cross-arm array (~ 2 km station spacing) near the centre of the main array, with the objective of testing teleseismic signal enhancement using beam-forming techniques. Monthly service visits were conducted by staff from the GSC Yellowknife Observatory, with additional service visits by workers who were hired locally.

During the 5-month recording period, 44 earthquakes above magnitude 6.0 occurred, all at epicentral distances (Δ) of greater than 13.5° (Figure 2). Of these, 19 events fell within the epicentral distance range most suitable for SKS studies (85° - 140°), but only 10 had sufficient signal-to-noise ratio for detailed analysis (Table 1). In this range of epicentral distances, the SKS phase arrives at nearly vertical incidence and thus provides excellent horizontal resolution of mantle structure beneath the recording site, but poor vertical resolution.

Teleseismic Data Analysis

In general, a shear wave that passes through an anisotropic region will split into fast and slow modes of propagation. The polarization directions of the split shear waves record the orientation of the elastic symmetry system (Crampin, 1981). For SKS waves, the polarization of the S wave as it enters the lower mantle is known, to a very good approximation, to be radial (i.e., parallel to the backazimuth). This assumed initial polarization direction implies that for small delay time (δt) relative to the period of the wave, the transverse SKS component will approximate a scaled time-derivative of the radial component. If observed, this property of SKS phases is diagnostic of passage through an anisotropic layer.

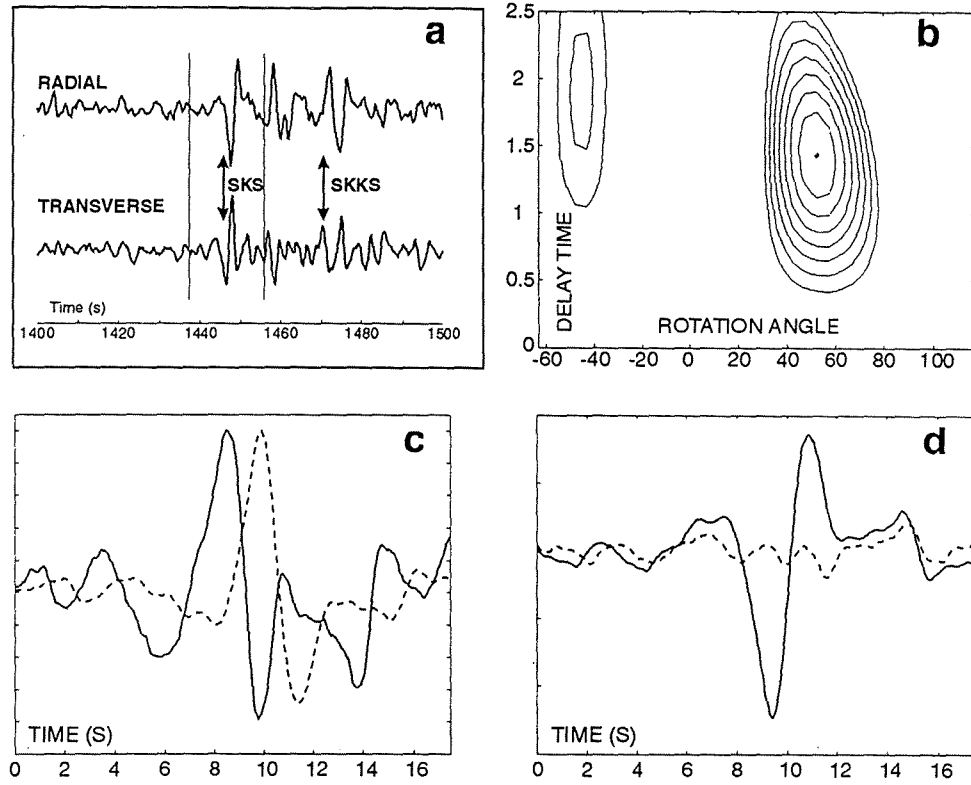


Figure 3. Example of S-wave splitting analysis for event 2 at station GS09. a) Filtered radial and transverse components, showing SKS and SKKS arrivals. Vertical lines show the analysis time window used for parts b-d. b) Misfit surface (energy of reconstructed transverse component). Contour interval is 5% of the maximum energy value. Minimum point is indicated by the dot. c) Horizontal traces after rotation. Note the similarity of the fast (solid line) and slow (dashed line) waveforms. d) Reconstructed radial (solid line) and transverse (dashed line) components.

Table 2. Estimated splitting parameters.

Station	Latitude (° N)	Longitude (° W)	Number of events ¹	δt (s)	ϕ (°)	Baz Range ² (°)	Evidence for multi- layers? ³
GS01	60.7342	115.5775	7(4)	1.5+/-0.2	58+/-3	44	NO
GS02	60.73	115.313	7(5)	1.3+/-0.3	57+/-3	47	NO
GS03	60.7142	115.0911	8(5)	1.2+/-0.3	52+/-1	44	NO
GS05	60.742	114.812	8(8)	1.1+/-0.5	36+/-52	63	YES
GS09	60.6703	114.594	9(5)	1.3+/-0.3	47+/-10	44	YES
GS10	60.5657	114.4293	8(6)	1.2+/-0.2	53+/-4	47	NO
GS13	60.278	114.0263	8(5)	1.2+/-0.3	60+/-4	47	NO

¹ Number of well recorded SKS arrivals, followed by the number of non-null events in parentheses.

² Range of backazimuth directions for all non-null events.

³ i.e., significant (within 95% confidence intervals) azimuthal variation in splitting parameters.

generally SW backazimuth produced null results (no observed transverse component). Stations GS05 and GS09 had a more complex response, with splitting parameters that varied significantly with backazimuth. Because of technical difficulties during the experiment, only 1 or 2 SKS events were recorded at stations GS11 and GS12. Therefore, these stations are not considered in the interpretation.

Electrical anisotropy

Jones and Ferguson (1997) have investigated electrical anisotropy of the upper mantle near the GSLsz, based on data from a regional magnetotelluric (MT) program. Some of their results are plotted in Fig. 4, in a combined presentation of seismic and electrical anisotropy parameters superimposed on the magnetic anomaly map. The GSLsz is clearly delineated by a strong magnetic low (Fig. 4), which indicates a generally NE strike direction for the shear zone. There is some additional evidence for a lozenge-like structural element southwest of the array. The electrical anisotropy is represented by a vector of magnitude $\delta\theta$ in the direction ϕ_{MT} (most conductive direction). A period of 30 s was used to compute these vectors, corresponding to maximum sensitivity depth of roughly 50 km. The MT results show evidence of strong localized electrical anisotropy in the mantle within the GSLsz. The orientation of the most conductive direction ($\sim 35^\circ$) is approximately parallel to the local strike direction of the shear zone.

Preliminary Interpretation

With the exception of stations located within the GSLsz (GS05 and GS09), the splitting parameters exhibit a relatively simple trend. The consistency of splitting parameters with respect to backazimuth, and the presence of a strong null parallel to the fast polarization direction, suggest that the splitting is caused by a single anisotropic layer. The average orientation of the fast polarization direction for these stations is 57° , clockwise-oblique to the most conductive direction. This obliquity is consistent with the sense of obliquity proposed by Ji et al. (1996) for dextral strike-slip deformation of the mantle. However, the splitting results are also generally consistent with fast-splitting directions recently reported for the entire Slave Province (Bank et al., 2000), hinting that the dominant cause of anisotropy may not be directly related to the GSLsz.

Aside from stations GS05 and GS09, the values of δt appear to increase systematically across the GSLsz toward the NW, from 1.2 to 1.5 s. In contrast with the pattern of electrical anisotropy described above, the maximum splitting time does not coincide with the axis of the GSLsz. Taken together with splitting parameters for the Slave Province (Bank et al., 2000), the results of this study are consistent with the presence of a single anisotropic layer in the mantle that extends far to the north beneath the Slave Province. Local deviations, within the GSLsz at stations GS05 and GS09, are described below.

SKS splitting trends are commonly interpreted as indicative of either fossil anisotropy in the mantle (Silver and Chan, 1991; Silver, 1996), or the direction of absolute plate motion (APM) due to present-day asthenospheric flow (Vinnik et al., 1992). Using the position of the North American pole of rotation for model NUVEL-1 (Gripp and Gordon, 1990), the APM vector is locally oriented SW. Since this is nearly parallel to the strike direction of the GSLsz, a potential ambiguity exists for

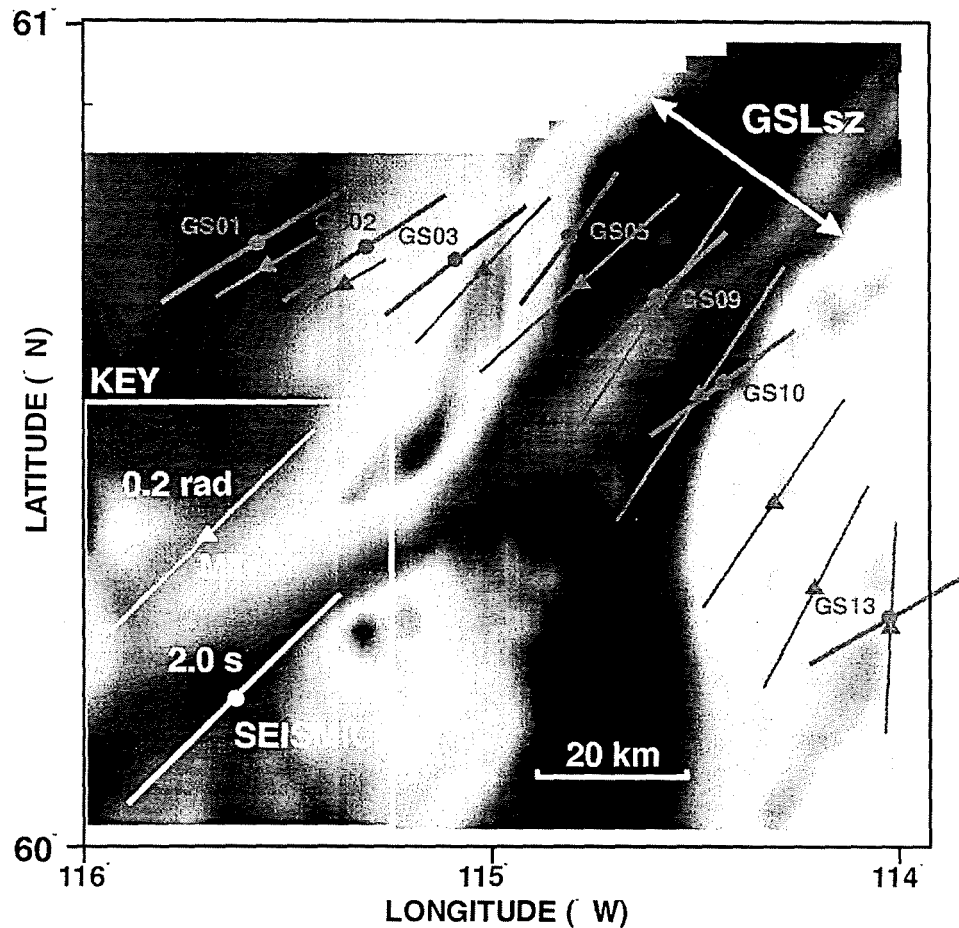


Fig. 4. Summary of magnetotelluric (MT) anisotropy vectors (lines with triangles) and average seismic fast polarization directions (lines with circles), superimposed on a magnetic anomaly map. Dark regions of the map correlate with magnetic lows. Reference vectors inside the key indicate the direction of absolute plate motion. Seismic anisotropy vectors for GS05 and GS09 should be considered as apparent directions, since these stations exhibit characteristics of multi-layer anisotropy (see text). GSLsz = Great Slave Lake shear zone.

the interpretation of the fast polarization direction. However, given the similarity in splitting parameters for this study with the overall results for the Slave Province (Bank et al., 2000), as well as the absence of a change across the GSLsz, it seems likely that the fast polarization direction for these stations is indicative of the present-day asthenospheric flow direction. If so, the obliquity between the splitting direction and the APM vector could be the result of localized deflection from topography at the base of the lithosphere (Bormann et al., 1996).

For the stations within the GSLsz, observed azimuthal variations in splitting parameters furnish evidence for multi-layered anisotropy, especially for station GS05. The localized nature of this effect (strong variations over 10's of km) suggests that the upper anisotropic layer is relatively shallow,

perhaps in the crust or uppermost mantle. As a working hypothesis, it is assumed that the anisotropic layer observed at other stations continues beneath station GS05, with secondary splitting related to deformation in the GSLsz. Ongoing modelling studies are seeking to characterize the anisotropy parameters for both two layers and relate the parameters for the shallower layer to the electrical anisotropy.

Acknowledgements

Noel Barstow and other staff of the IRIS-PASSCAL data management centre are sincerely thanked for the support they provided during this experiment. Stephane Rondenay provided essential Reftek training “on the job”, and his experience was invaluable for station deployment. We are also grateful to the staff of the Ecosystem Secretariat at Wood Buffalo National Park. The assistance of Chris John and George Jensen of the GSC Yellowknife observatory, as well as Greg Mayer, Jackie Hope and Sandrine Sage, is gratefully acknowledged as well. Gerry Ross provided graphics for figure 1. Finally, we thank Charly Bank for providing a preprint and results from the Slave experiment.

References

- Bank, C-G., Bostock, M.G., Ellis, R.M. and Cassidy, J.F. 2000. A reconnaissance teleseismic study of the upper mantle and transition zone beneath the Archean Slave craton in NW Canada. *Tectonophysics*, in review.
- Bormann, P., Grünthal, G., Kind, R. and Montag, H., 1996. Upper mantle anisotropy beneath central Europe from SKS wave splitting: Effects of absolute plate motion and lithosphere-asthenosphere boundary topography? *J. Geodynamics*, **22**, 11-32.
- Crampin, S., 1981. A review of wave motion in anisotropic and cracked elastic-media. *Wave Motion*, **3**, 343-391.
- Gibb, R.A., 1978. Slave-Churchill collision tectonics. *Nature*, **271**, 50-52.
- Gripp, A.E. and Gordon, R.G. 1990. Current plate velocities relative to the hotspots incorporating the NUVEL-1 global plate motion model. *Geophys. Res. Lett.*, **17**, 1109-1112.
- Hanmer, S., Bowring, S., van Breemen, O. and Parrish, R. 1992. Great Slave Lake shear zone, NW Canada: mylonitic record of Early Proterozoic continental convergence, collision and indentation. *J. Struct. Geol.*, **14**, 757-773.
- Hoffman, P.F., 1987. Continental transform tectonics: Great Slave Lake shear zone (ca. 1.9 Ga), northwest Canada. *Geology*, **15**, 785-788.
- Ji, S., Rondenay, S., Mareschal, M. and Senechal, G., 1996. Obliquity between seismic and electrical anisotropies as a potential indicator of movement sense for ductile shear zones in the upper mantle. *Geology*, **24**, 1033-1036.

Jones, A.G., 1992. Electrical properties of the lower continental crust. In, Fountain, D. et al., eds., *Continental Lower Crust*: Elsevier, p. 81-143.

Jones, A.G. and Ferguson, I.J., 1997. Results from 1996 MT studies along SNORCLE profiles 1 and 1A. In, Cook, F. and Erdmer, P. (compilers), 1997 *Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) Transect and Cordilleran Tectonics Workshop Meeting (March 7-9)*, University of Calgary, Lithoprobe Report No. 56, p. 42-47.

Kern, H., 1993. P- and S-wave anisotropy and shear-wave splitting at pressure and temperature in possible mantle rocks and their relation to the rock fabric. *Physics of the Earth and Planetary Interiors*, **78**, 245-256.

Mareschal, M., et al., 1995. Archean cratonic roots, mantle shear zones and deep electrical anisotropy. *Nature*, **375**, 134-137.

Silver, P.G., 1996. Seismic anisotropy beneath the continents: Probing the depths of geology. *Ann. Rev. Earth Planet. Sci.*, **24**, 385-432.

Silver, P.G. and Chan, W.W. 1991. Shear wave splitting and subcontinental mantle deformation. *J. Geophys. Res.*, **96**, 16,429-16,454.

Vaucher, A. and Nicolas, A., 1991. Mountain building, strike-parallel motion and mantle anisotropy. *Tectonophysics*, **185**, 183-201.

Origin of chemical stratification of the Slave peridotitic mantle.

Maya G. Kopylova* and James K. Russell

Earth and Ocean Sciences Dept., The University of British Columbia,
6339 Stores Road, Vancouver, Canada, V6T 1R9

Introduction

Our recent studies of the mineralogical and chemical composition of the Slave mantle (Kopylova and Russell, Lithoprobe 1999a, Kopylova and Russell, 1999b) elucidated differences and similarities between the Slave craton and other worldwide cratons and constrained the nature of events that contributed to the stabilization of the Slave lithosphere. The composition of the Slave peridotitic mantle was deduced from xenoliths of peridotite within the Jericho kimberlite, Northwest Territories (Cookenboo, 1998). Our chemical datasets includes major, trace and rare earth element compositions of bulk samples of spinel peridotite, low-T and high-T garnet peridotite and minor pyroxenite. Mineral modes for individual samples are based on computer-aided image analysis of conventional thin sections and on recalculation of bulk chemistry to a mineral equivalent basis reflecting the constituent phases (Kopylova and Russell, 1999a). Compared to primitive upper mantle, Slave peridotite shows depletion in the major elements and enrichment in incompatible elements (except for HREE) (Kopylova and Russell, 1999b). The Slave mantle is also uniquely stratified; the nature and origin of this stratification is the subject of the work presented here.

Stratification of the Slave Mantle

Figure 1 summarizes the mineralogical and chemical traits of Slave peridotite as a function of stratigraphic position. The whole-rock data have been grouped and averaged (Table 1) according to their mineralogy which represents different depth facies (Fig. 1, left panel). In addition, we divided peridotite into fertile and depleted types; samples containing more than 10% of clinopyroxene or garnet were considered fertile. On the basis of geothermobarometry, most samples of fertile peridotite derive from the deepest parts of the low-T peridotitic mantle. They overlie pyroxenite and appear to either overlie (the Finnerty-Boyd - MacGregor thermobarometry) or coincide (the Brey-Köhler thermobarometry) with high-T peridotite (Fig. 1). Average compositions and modes of fertile peridotite are also given in Table 1.

The Slave peridotitic mantle shows a strong chemical and mineralogical zonation with depth. The major chemical variation found in the Slave peridotitic mantle is a pronounced decrease in Mg# with depth that reflects the strong increase in FeO(τ) content of the deeper mantle (Fig. 1-2). Figure 2 is a histogram of FeO(τ) contents for Slave peridotite and shows unequivocally that deeper mantle rocks are enriched in iron relative to shallow peridotite. This progressive Fe-enrichment with depth is consistent with the trend of Mg-depletion described in olivine from Jericho peridotite (Kopylova et al., 1999). Al₂O₃ and CaO contents below Jericho show a gradual increase with depth although it may not be statistically significant. This is also reflected in a 3-fold

Table 1.
Average compositions of peridotite layers in the Slave mantle under the Jericho kimberlite pipe.

Sample	Spinel Peridotite		Spinel-Garnet Low-T Peridotite		Garnet Low-T Peridotite		Fertile Garnet Peridotite		Pyroxenite		High-T Garnet Peridotite	
	Av. of 14	St Dev	Av. of 7	St Dev	Av. of 6	St Dev	Av. of 5	St Dev	Av. of 2	St Dev	Av. of 9	St Dev
SiO ₂	44.47	1.85	44.00	0.85	42.81	1.79	42.05	1.27	48.11	1.99	42.03	0.74
TiO ₂	0.03	0.01	0.06	0.03	0.05	0.02	0.13	0.04	0.33	0.15	0.09	0.05
Al ₂ O ₃	0.77	0.38	1.18	0.28	1.08	0.53	3.88	1.11	5.75	4.29	1.44	1.00
FeO	5.29	0.28	5.72	0.17	5.81	0.45	5.87	0.48	5.72	0.60	6.59	0.50
Fe ₂ O ₃	0.97	0.28	1.41	0.36	1.84	0.86	2.52	0.85	1.27	0.34	1.74	0.33
MnO	0.10	0.00	0.12	0.00	0.12	0.01	0.14	0.01	0.17	0.02	0.13	0.01
MgO	45.40	1.58	43.47	1.02	43.06	2.01	35.33	3.92	28.84	2.41	43.17	2.68
CaO	0.51	0.22	0.94	0.23	1.14	0.38	3.17	1.33	5.88	0.52	1.21	0.95
Na ₂ O	0.16	0.06	0.23	0.05	0.24	0.02	0.33	0.08	0.76	0.15	0.28	0.13
K ₂ O	0.10	0.04	0.25	0.10	0.12	0.02	0.27	0.11	0.24	0.04	0.23	0.20
P ₂ O ₅	0.02	0.01	0.03	0.01	0.03	0.01	0.03	0.01	0.07	0.03	0.04	0.03
LOI	1.48	0.56	1.57	0.60	3.00	2.11	5.16	2.34	1.91	1.26	1.71	0.68
Total	99.29		99.65		100.03		99.73		99.87		98.65	
Cr ₂ O ₃	0.369	0.088	0.395	0.039	0.447	0.158	0.577	0.170	0.437	0.287	0.463	0.157
NiO	0.288	0.026	0.283	0.009	0.292	0.026	0.255	0.017	0.102	0.030	0.293	0.039
FeO _T	6.10	0.45	6.98	0.32	7.46	0.76	8.139	0.636	6.86	0.30	8.05	0.60
Mg/Mg+Fe	0.931	0.004	0.920	0.006	0.918	0.014	0.890	0.02			0.906	0.010
Ca/Al	0.986	0.371	1.088	0.178	1.528	0.449	1.182	0.633			1.104	0.318
Mg/Si	1.316	0.095	1.281	0.056	1.291	0.059	1.080	0.138			1.321	0.088
Ol (%)	71.7	6.3	70.8	6.5	72.8	5.3	59.9	5.7	22.1	1.3	76.9	5.6
Opx (%)	25.8	6.5	21.4	5.8	17.4	6.1	16.7	4.8	28.8	20.3	15.3	4.5
Cpx (%)	1.5	0.9	3.3	1.5	4.7	1.4	10.9	3.9	31.3	8.0	2.6	1.7
Spl (%)	1.0	0.6	0.6	0.4	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
Gar (%)			3.9	1.8	5.1	2.2	12.5	3.4	17.7	10.9	5.1	2.5

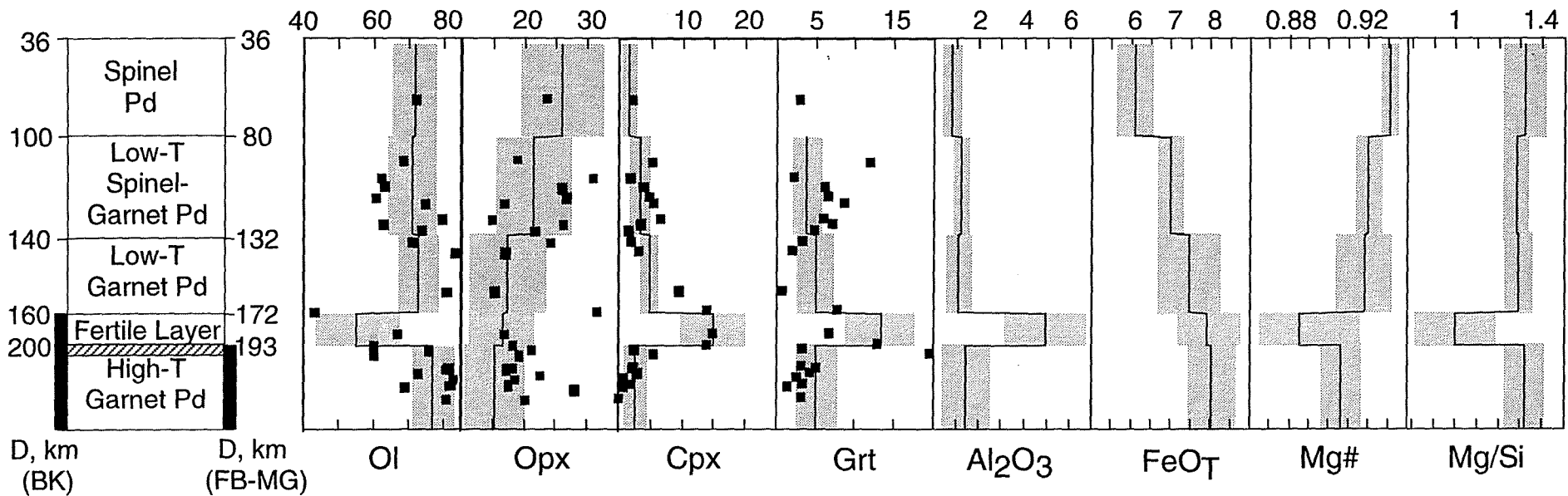


Fig. 1. Compositional characteristics of peridotitic mantle below the Jericho kimberlite plotted against depth. The stratigraphic framework is constructed on the basis of geothermobarometry (Kopylova et al., 1999). Note that thicknesses and positions of stratigraphic units are dependent on the thermobarometric solutions. The scale to the left of the stratigraphic column represents depths based on Brey-Kohler thermobarometry (Brey and Kohler, 1990); right-hand scale represents the Finnerty-Boyd (Finnerty and Boyd, 1987) & MacGregor solution (MacGregor, 1974). Solid bars on the sides of the stratigraphic column denote the depths to the petrological asthenosphere according to these two thermobarometric solutions. A striped pattern represents a layer of pyroxenites that are localized at 180-195 km depth according to the Finnerty-Boyd (Finnerty and Boyd, 1987) & MacGregor (MacGregor, 1974) thermobarometry, or at 195-215 km depth according to the Brey-Kohler thermobarometry (Brey and Kohler, 1990). Chemical characteristics of the Slave mantle are plotted according to the Finnerty-Boyd & MacGregor solution. Solid symbols correspond to mineral modes of samples for which equilibrium P-T conditions are known (Kopylova et al., 1999); not all samples have been analyzed for major element compositions. Solid lines in each panel show mean value established for each type of peridotite and shaded bar denotes 1 standard deviation for each suite.

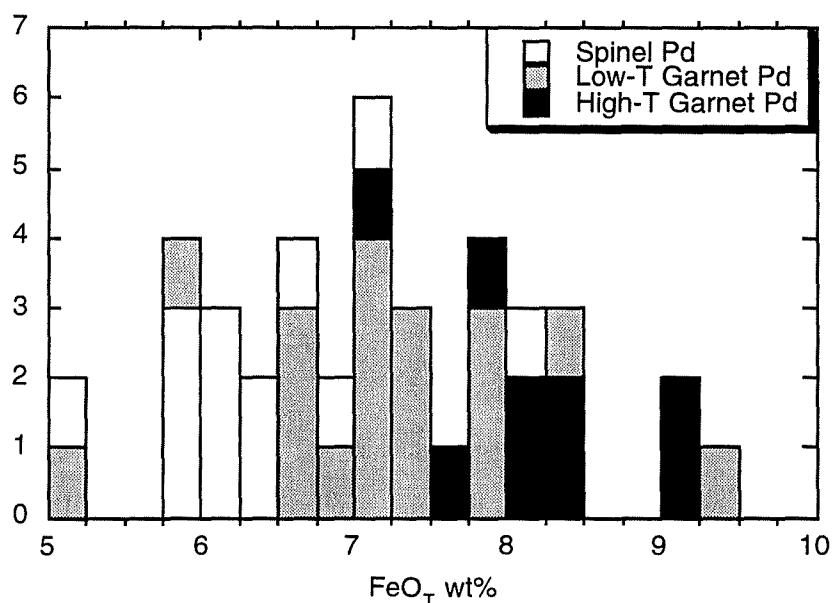


Fig. 2. Histogram showing compositional diversity (wt. % FeO_T) of individual types of peridotite xenolith from the Slave lithosphere.

increase in clinopyroxene mode from spinel peridotite (1.5%) to low-T garnet peridotite (4.7%). Our data show that modal olivine is relatively constant with depth, but deeper mantle (high-T peridotite) appears to have the highest olivine content (Fig. 1). Average orthopyroxene modes decrease with depth throughout the Slave mantle from 26 vol. % in spinel peridotite to 15 vol. % in high-T peridotite. However, the within-group variation of modal orthopyroxene is large and the apparent decrease in orthopyroxene content may not be statistically significant (Fig. 1, Table 1).

Three major, relatively sharp chemical boundaries are identified within the peridotitic mantle below Jericho. Two boundaries coincide with the upper and lower bounds of the fertile layer and are marked by significant changes in Al₂O₃, CaO and SiO₂, Mg/Si and Mg#, and modal clinopyroxene (up to 6%), garnet (up to 10%) and olivine (Fig. 1, Table 1). The only other major sharp chemical boundary within the Slave mantle coincides with the interface between spinel peridotite and spinel-garnet peridotite and is manifested mainly by a step-wise increase in FeO_T (Fig. 1).

Growth of the Slave cratonic mantle

Stratification in cratonic mantle

The mineralogical stratification of the Slave mantle is defined by a shallow layer of depleted spinel peridotite underlain by garnet peridotite, and a thin layer of fertile peridotite and pyroxenite situated at the base of the lithosphere. The upper layer of depleted spinel peridotite (36-80 km) can be

equated with the ultra-depleted shallow mantle identified elsewhere beneath the central Slave craton (Griffin et al., 1999). On the basis of compositions of garnet from kimberlite concentrate, Griffin et al. (1999; in press) argued for ultra-depleted peridotite at depths of 150 km below the Lac-de-Gras region; their inferred distribution showed the depleted mantle layer to thin towards the north, south and southwest. Based on our results, we suggest a correlation between our layer of depleted spinel peridotite and the ultra-depleted mantle layer defined by Griffin and coworkers. This would imply that, rather than disappearing, the depleted upper mantle layer thins to a depth of 80-100 kms in the northern part of the Slave craton.

In contrast to the stratified mantle beneath the Slave craton, spinel peridotite and garnet peridotite from the Kaapvaal and Siberian cratons show no substantial variations in bulk composition or mineralogy (Boyd, 1998). Griffin et al., (in press) have shown that garnet composition and the abundance of harzburgitic rocks change gradually over relatively restricted depth intervals below cratons in Kaapvaal, Siberia and China. However, relative to the Slave cratonic mantle, this stratification is more localized and less sharply-defined. The Tanzanian craton (Lee and Rudnick, in press) is, presently, the only other mantle to show a pronounced step-wise chemical enrichment; at a depth of 120 km there is a change from more depleted garnet-free to less depleted garnet-bearing peridotite.

Timing and Origins of Stratification

The chemical stratification of the Slave peridotitic mantle is consistent with the density profile of a long-stabilized peridotite. The most depleted, Mg-rich, less dense peridotite (Jordan, 1988) sits buoyantly on top of less depleted peridotite. This gravitationally stable system could have formed in two ways. Firstly, the present structure of the Slave mantle may be inherited from the original processes causing chemical depletion. In this case, the shallow mantle is more depleted and less dense due to greater degrees of partial melting. A second way to account for chemical stratification of the Slave mantle is purely mechanical. The stratification results from the gradual sinking of denser, less depleted portions of the peridotitic lithosphere and replacement by ascent of more buoyant (more depleted) segments of the mantle. This model implies that the present depth positions of the peridotitic mantle are not primary but represent a secondary mechanical segregation required to achieve a gravitationally stable configuration.

Recent radiometric age determinations on peridotitic mantle xenoliths from the Jericho kimberlite (Irvine et al., 1999) provide a means of discriminating between these two models. Re-Os ages of the Slave peridotite imply that shallow-seated spinel peridotite formed 3.2-2.9 Ga. and that deeper garnet peridotite formed 2-1.7 Ga. These data show that the Slave mantle is also stratified in age; the layers in the Slave mantle column have unique ages and the boundaries correspond to discrete events. On this basis, we prefer to interpret the chemical stratification of the Slave mantle as a primary feature

related to original melting events, rather than resulting from later-stage mechanical segregation.

These model ages for the Slave mantle are also inconsistent with “top-down” models of growth for early Archean continents, via over-stacking processes (de Wit, 1998) because they require shallow mantle to be younger. Conversely, these ages favour growth of the lithosphere by accretion of mantle material to the base of the continental keel. Accretion could be driven by conductive cooling of the asthenosphere or by diapiric underplating of plume material to the older lithosphere (Clark and Ringwood, 1964; Jordan, 1981). Griffin et al. (1999) argue that, for the Slave, the plume material is fertile in composition which contrasts the depleted character of diapirs beneath other continents (McDonough, 1990).

The gradual increase in fertility found in the deeper and older layer of garnet peridotite (Fig. 1) places constraints on its origin. It cannot be attributed to subduction- and collision-related imbrication or tectonic thickening (e.g. Helmstaedt and Schulze, 1989). This layer of garnet peridotite may derive from a single melting event but requires polybaric melting associated with adiabatic decompression of upwelling mantle. Such melting produces slightly depleted residues at high pressure (low-productivity melting), and highly depleted residues at lower pressure (major-melting regime) (Asimow et al., 1997; Hirth and Kohlstedt, 1996; Kelemen et al., 1998; Hirschmann et al., 1999). Such melting must have been less intense than the melting events below other cratons, as implied by lower Mg# of the Slave residues (Kopylova and Russell, 1999b). This is further corroborated by the absence of komatiite magmas and the lower volume of volcanic rocks within the Slave craton (Pandham and Fyson, 1992). Alternatively, the gradual change in composition of the deeper mantle may have resulted from recent metasomatism that enriched high-T peridotite and deeper horizons of low-T peridotite adjacent to it. A young metasomatic event is supported by the presence of pronounced zoning in low-T garnet peridotite.

One of the most prominent features in the stratification of the Slave mantle is that fertile peridotite and pyroxenite samples appear over a restricted depth interval. Together they form a thin (20-40 km) layer situated at the base of the lithosphere (Fig. 1). We think that the spatial closeness of fertile peridotite and pyroxenite is not accidental. They are both younger than the surrounding mantle and may have formed together. Wehrlite from the fertile layer is Phanerozoic in age (Irvine, pers. comm.) and pyroxenite, on the basis of mineralogical and textural data, probably represents relatively young magmatic intrusions (Kopylova et al., 1999). Fertile peridotite directly overlying pyroxenite may result from chemical interaction between originally depleted peridotitic mantle and younger pyroxenitic magma or associated fluids.

Two types of cratons based on chemical and age stratification

Our experience suggests that there are two end-member types of cratonic mantle that are distinguished by the presence or absence of stratification. The first type of craton represented by the Tanzanian (Chesley et

al., 1999) and Slave cratons has a chemically stratified mantle; from the deepest seated garnet peridotite to the most shallow spinel peridotite, there is gradual increase in depletion. This stratification was stabilized through incremental downward growth of mantle lithosphere with time as suggested by systematic changes in Re-Os ages (Irvine et al., 1999; Chesley et al., 1999). The Kaapvaal and Siberian cratons are representative of a second type of cratonic mantle. They are not chemically stratified (Boyd, 1998) and their roots do not show any systematic pattern of stabilization age with depth (Pearson et al., 1995; Pearson et al., 1996).

We suggest that the presence of stratification within cratonic mantle relates to the nature of melting events in the earliest stages of craton stabilization. If the initial, thin cratonic mantle is subjected to a particularly intense melt extraction event, a highly depleted, relatively buoyant mantle residue is produced. This older, highly depleted mantle layer would remain buoyant, with respect to newly stabilized portions of the deeper mantle, if the subsequent, deeper-seated melting events were less intense. This idealized sequence of events results in a chemical and age stratification consistent with that observed in the Slave mantle.

Cratonic mantle that is unstratified with depth implies a different style of stabilization. The lack of correlation between mantle age and depth could indicate a single stabilization event followed by heterogeneous, random melting of the root. Conversely, the cratonic root may have lost its stratification by mixing of mantle blocks with different ages and degrees of depletion induced by gravitational instabilities. Such a process would be natural if an older, shallow mantle layer was not depleted enough during early melting to maintain its buoyancy relative to deeper, younger mantle.

Acknowledgements

Funding (1998-1999) for this research derived from LITHOPROBE and the Natural Sciences and Engineering Research Council (NSERC) of Canada. We are indebted to Canamera Geological, Lytton and personally to Harrison Cookenboo for generous access to materials. Jennifer Owen is thanked for sample preparation and estimation of mineral modes by image analysis.

References:

- P.D. Asimow, M.M. Hirschmann, E.M. Stolper, An analysis of variations in isentropic melt productivity. *Philosophical Transactions of the Royal Society of London, Series A*, 3355, 255-281, 1997.
- F.R. Boyd, The origin of cratonic peridotites: a major element approach. *Intern. Geology Review*, 755-764, 1998.
- G.P. Brey, T. Köhler. Geothermobarometry in Four-phase lherzolites. II. New thermobarometers, and practical assessment of existing thermobarometers. *Journal of Petrology*, 31, 6, 1353-1378, 1990.
- J.T. Chesley, R.T. Rudnick, C.T. Lee, Re-Os systematics of mantle xenoliths from the East African rift: Age, structure, and history of the Tanzanian craton. *Geoch. et Cosmoch. Acta*, 63, 5, 1999.
- S.P. Clark, A.E. Ringwood, Density distribution and constitution of the mantle. *Rev. Geophys.*, 2, 35-88, 1964.

- H. Cookenboo. Emplacement history of the Jericho kimberlite pipe, northern Canada. In: Ext. Abstracts of the 7th Intern. Kimb. Conf., 13-18 April, Cape Town, 161-163, 1998.
- M.J. de Wit, On Archean granites, greenstones, cratons and tectonics: does the evidence demand a verdict? *Precamb. Res.*, 91, 181-226, 1998.
- A.A. Finnerty, J.J. Boyd, Thermobarometry for garnet peridotites: basis for the determination of thermal and compositional structure of the upper mantle. In: Nixon, P.H. (ed.) *Mantle Xenoliths*, New York: John Wiley and Sons, 381-402, 1987
- W.L. Griffin, B.J. Doyle, C.G. Ryan, N.J. Pearson, S.Y. O'Reilly, R. Davies, K. Kivi, E. van Achterbergh, L.M. Natapov, 1999. Layered mantle lithosphere in the Lac de Gras Area, Slave Craton: Composition, Structure and origin. *J. of Petrology*, 40, 5, 705-728
- W.L. Griffin, B.J. Doyle, C.G. Ryan, N.J. Pearson, S.Y. O'Reilly, L. Natapov, K. Kivi, U. Kretschmar, J. Ward, Lithosphere structure and Mantle Terranes: Slave Craton, Canada. In: Proc. 7th Int. Kimberlite Conference, J.J. Gurney, S.R. Richardson, eds., Red Roof Designs, Cape Town, in press.
- H. Helmstaedt, D.J. Schulze, Southern African kimberlites and their mantle sample: Implications for Archean tectonics and lithosphere evolution. In: J. Ross (Ed.) *Kimberlites and Related Rocks*, vol. 1, Geol. Soc. Aust. Spec. Publ., 14, 358-368, 1989.
- M.M. Hirschmann, P.D. Asimow, M.S. Ghiorso, E.M. Stolper, Calculation of peridotite partial melting from thermodynamic models of minerals and melts. III. Controls on isobaric melt production and the effect of water on melt production. *J. of Petrology*, 40, 5, 831-851, 1999.
- G.H. Hirth, D.L. Kohlstedt, Water in the oceanic upper mantle: implications for rheology, melt extraction, and evolution of the lithosphere. *Earth and Planet. Science Letters*, 144, 93-108, 1996.
- G. Irvine, M. G. Kopylova, R. W. Carlson, D. G. Pearson, S. B. Shirey, and B. A. Kjarsgaard Age of the lithospheric mantle beneath and around the Slave craton: A Re-Os isotope study of peridotite xenoliths from the Jericho and Somerset Island kimberlites. Abstract, Goldschmidt Conference, 1999.
- T.H. Jordan, Continents as a chemical boundary layer. *Phil. Trans. R. Soc. Lond.* A301, 359-373, 1981
- T.H. Jordan, Structure and formation of the continental lithosphere. *J. Petrol. Sec. Lithosphere Issue*, 11-37, 1988
- P.B. Kelemen, S.R. Hart, and S. Bernstein, Silica enrichment in the continental upper mantle via melt/rock reaction. *Earth and Planet. Sci. Lett.*, 164, 387-406, 1998.
- M.G. Kopylova, J. K. Russell and H. Cookenboo, Petrology of peridotite and pyroxenite xenoliths from the Jericho kimberlite: Implications for the thermal state of the mantle beneath the Slave craton, Northern Canada. *J. of Petrology*, 40, 1, 79-104, 1999
- M.G. Kopylova, J. K. Russell, Composition of peridotitic mantle from below the Slave craton. In: Cook F. and Erdmer (compilers) *Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) transect and Cordilleran Tectonics Workshop Meeting* (March 5-7), University of Calgary, LITHOPROBE Report No. 69: 288-295, 1999a.
- M.G. Kopylova, J. K. Russell, Composition and stratification of the Slave cratonic upper mantle. Abstract, AGU Fall Meeting, San Francisco, 12-17 December, 1999, Suppl. to Eos, Transactions, AGU Volume 80, 46, F1177, 1999b.
- C-T. Lee, R.L. Rudnick, Compositionally stratified cratonic lithosphere: petrology and geochemistry of peridotite xenoliths from the Labait tuff cone, Tanzania. In: Proc. 7th Int. Kimberlite Conference, J.J. Gurney and S.R. Richardson, eds., Red Roof Designs, Cape Town, in press.
- W.F. McDonough, Constraints on the composition of the continental lithospheric mantle. *Earth and Planet. Sci. Lett.*, 101, 1-18, 1990.
- I.D. McGregor, The system $\text{MgO-Al}_2\text{O}_3\text{-SiO}_2$: solubility of Al_2O_3 in enstatite for spinel and garnet peridotite compositions. *American Mineralogist*, 59, 110-119, 1974
- W.A. Padgham, and W.K. Fyson, The Slave Province: a distinct craton. *Canadian J. of Earth Sci.*, 29: 2072-2086, 1992

- D.G. Pearson, R.W. Carlson et al., Stabilisation of Archean lithospheric mantle: A Re-Os isotope study of peridotite xenoliths from the Kaapvaal craton. *Earth Planet. Sci. Lett.* 134, 341-357, 1995.
- D.G. Pearson, S.B. Shirey et al., Re-Os, Sm-Nd, and Rb-Sr isotope evidence for thick Archean lithospheric mantle beneath the Siberian craton modified by multistage metasomatism. *Geoch. Cosmoch. Acta* 59 5, 959-977, 1995.

Interpretation of Mantle Structure and Lithology Using Kimberlite-Borne Garnets from the Slave Province and Other Locations in North America

D. Canil¹, D.J. Schulze², G.B. Carbo¹, K. Scully¹

1. School of Earth and Ocean Sciences, University of Victoria, Victoria, BC.
2. Department of Geology, Erindale College, University of Toronto, Toronto, ON

A total of 45 garnets, including 9 garnet-diopside pairs were collected from xenoliths and concentrate from the Drybones Bay kimberlite, located in the southwest Slave Province, Northwest Territories, Canada. These garnets were analyzed for a suite of 25 trace elements using a LAM-ICP-MS. The Ni-in-garnet geothermometer was used to estimate the temperature and when projected to a regionally constrained paleogeotherm [1,2], allows an estimate of the *relative* depth of equilibration of the garnets, assuming they equilibrated along the paleogeotherm. Trace element data from the garnets shows that deeper parts of the lithospheric mantle beneath Drybones Bay have undergone carbonatite metasomatism. Two distinct sets of garnets are recognized in the population based on their rare earth element (REE) patterns – normal (LREE depleted, HREE-enriched) which show no signs of metasomatism, and sinuous (LREE-enriched), which show evidence of carbonatite metasomatism. These two contrasting types of garnets are sharply separated at a depth of ~110-130 km, with many trace elements and trace element ratios in the garnet population showing a profound change at the same depth. Results from teleseismic studies ~50 km north of Drybones Bay [3] show a structural discontinuity at a ~120 km depth in the mantle lithosphere characterized by ‘multiple layers’ beneath the southwest Slave craton that may represent the stacking of ancient subducted lithosphere [3]. The ~120 km discontinuity recognized by seismology is identical to the discontinuity recognized geochemically in garnets from Drybones Bay, and may represent a change in lithology from unmetasomatized wehrlite to interlayered, metasomatized wehrlite and lherzolite.

We are undertaking similar geochemical studies of mantle garnet populations in kimberlites from elsewhere in North America [4] and using them to unravel specific lithologic patterns in the mantle lithosphere beneath these regions. Specifically, certain key element ratios and patterns in the datasets for each kimberlite can be quite revealing of the spinel - garnet lherzolite transformation, the modal mineralogy and the location of possible eclogite horizons in the mantle lithosphere beneath some regions. These preliminary images are being refined with further data collection and ultimately with other datasets [5] may serve as a basis for interpretation of higher resolution electromagnetic and seismic images of cratonic mantle lithosphere being conducted in Canada and elsewhere.

- [1] MacKenzie and Canil (1999) Contrib. Mineral. Petrol., 134, 313-324.
- [2] Russell and Kopylova (1999) J. Geophys. Res., 104, 7089-7101.
- [3] Bostock (1998) J Geophys. Res. 103, 21183-21200.
- [4] Schulze (1993) Proc. PDAC Short Course, 361-377.
- [5] Griffin et al (1999) J. Petrol., 40, 705-727.

Wedge geometries in arc-continent convergence tectonics of the Wopmay, Svecofennian orogens and beyond

David B. Snyder

Geological Survey of Canada, 615 Booth Street, Ottawa K1A 0E9 (snyder@cg.nrcan.gc.ca)

A number of deep seismic reflection profiles have now imaged Paleoproterozoic arc-continent collision zones within several of the world's cratonic regions. Prominent examples include the accretion of the 2.0-1.8 Ga Svecofennian terrane to the Baltic craton (BABEL Working Group 1993), the accretion of the 1.92-1.83 Reindeer zone of the Trans-Hudson orogen to the Superior craton (White et al. 1999) and the accretion of the 1.92-1.90 Hottah terrane of the Wopmay Orogen to the Slave craton (Cook et al. 1999). Each example reveals new details of and variations in this accretion process, but the fundamental role of a wedge-shaped older craton flaking off parts of the crust of the juvenile terrane emerges in all cases studied to date. The crustal level at which the cratonic wedge causes detachment within the colliding terrane varies from the mid-crust to the Moho, with the implication that a significant portion of the colliding lithosphere is underthrust beneath the leading edge of the lower plate. Underplating, or underthrusting, of these deep crust and mantle portions of colliding terranes (typically intra-oceanic and continental arcs) against the lower plate lithosphere represents one possible mechanism for growing the lithospheric roots of continents.

This tectonic wedging process may be best documented to date by some of the mantle reflectors imaged by SNORCLE in the Hottah-Slave (Wopmay orogen) collision zone, and also in the Fort Simpson-Hottah collision zone. Many of the most prominent crustal and mantle reflections, and significantly the ones that outline wedge geometry, have direct correspondence to similar reflections observed beneath the Svecofennian orogen of the Baltic Shield (Snyder et al. 1995). These include: (1) outward (from the craton) dipping reflections throughout most of the crust, (2) craton-ward dipping reflections within the uppermost few tens of kilometers of the mantle located approximately 100 km outboard of the crustal reflections, and (3) higher amplitude reflections associated with the Moho in the interval between (1) and (2). These reflections are interpreted to coincide with major shear zones where deformation, alteration and possibly anisotropy enhance the reflectivity of the rocks.

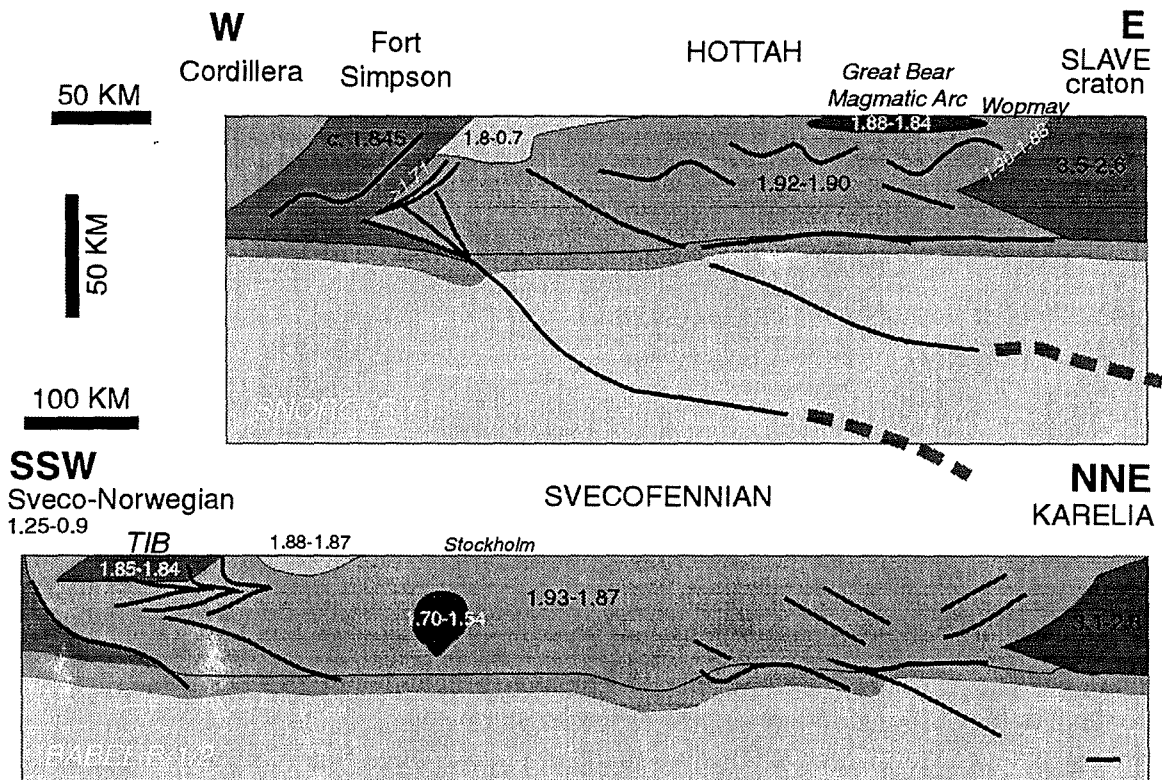
Late transpression often plays a major role in modifying the original collisional structures. More modern analogue studies from the Banda arc of Indonesia (Snyder et al. 1996) and the Caledonides of the UK, also anchored by deep seismic reflection profiles, provide insight into how the final wedge geometry develops. Late stage polarity reversal appears to play a key role and usually results in the prominent reflector geometry observed in the ancient examples. The ramp and wedge geometry is also important in understanding many of the geochemical and isotopic patterns observed in late or post-orogenic plutons in the ancient orogens. In places, highly evolved isotopic signatures are found in plutons that intrude juvenile rocks at the surface but that overlie lower plate cratonic lithosphere at depth.

References

BABEL Working Group, 1993, Integrated seismic studies of the Baltic Shield using data in the Gulf of Bothnia region, *Geophys. J. Int.*, **112**, 305–324.

- Cook, F.A., van der Velden, A.J., Hall, K.W. & Roberts, B.J., 1999. Frozen subduction in Canada's Northwest Territories: Lithoprobe deep lithospheric reflection profiling of the western Canadian Shield. *Tectonics*, **18**, 1-24.
- Snyder, D. B., S. B. Lucas, & J. H. McBride, 1996, Crustal and mantle reflectors from Paleoproterozoic orogens and their relation to arc-continent convergence, in Brewer, T. S. (ed.), *Precambrian Crustal Evolution in the North Atlantic Region*, Spec. Pub. Geol. Soc. London No. 112, 1-23.
- Snyder, D. B., H. Prasetyo, D. J. Blundell, C. J. Pigram, A. J. Barber, A. Richardson, & S. Tjokosaproetro, 1996, A dual doubly vergent orogen in the Banda Arc continent-arc collision zone as observed on deep seismic reflection profiles, *Tectonics*, **15**, 34-53
- White, D.J., Jones, A.G., Lucas, S.B., & Hajnal, Z., 1999. Tectonic evolution of the Superior Boundary Zone from coincident seismic reflection and magnetotelluric profiles. *Tectonics*, **18**, 430-451.

Figure 1. Cartoon representations of parts of the SNORCLE 1 (above) and BABEL B deep seismic reflection profiles. Dark lines represent prominent reflections; numbers on the various grey-shaded terranes indicate the known age of that terrane. In both examples, the younger tectonic unit is wedged apart (delaminated) by the older terrane (here shown on the right in all cases). This wedging occurs at several different levels in the lithosphere.



Lithology and U-Pb Geochronology of Shallow Basement Along The SNORCLE Line, Southwest Northwest Territories: A Preliminary Report

**Gerald M. Ross, GSC-Calgary (gmross@nrcan.gc.ca); Heidi C. Annell, University of Calgary (hcannell@ucalgary.ca),
Mike A. Hamilton, GSC-Ottawa (hamilton@nrcan.gc.ca)**

The western two-thirds of the SNORCLE reflection line recorded in 1998 crossed basement domains in the southwest NWT assigned to Wopmay Orogen, based largely on the extrapolation of the magnetic signatures of the exposed Wopmay Orogen more than 400 km south into the covered basement west of Great Slave Lake. In order to ground truth this correlation and perhaps provide better age constraints closer to the SNORCLE line we examined the composition of drill core and cuttings in this region. We used public domain aeromagnetic anomaly data to provide a basis for tectonic subdivision and refinement of earlier domains. Only 9 wells recovered drill core from this region. To supplement this meager data base we examined cuttings identified as "Precambrian" from well data bases provided by Shell Canada and the GSC. Of more than 120 wells with industry picks from well logs as "Precambrian" only 94 wells contained crystalline material with the rest composed of pre-Devonian sandstones of uncertain age ("pre-identifiable Paleozoic" of Williams, 1990). Of these 94 wells, 44 were available for sampling from unwashed cuttings held in curation at the GSC in Calgary. Cuttings were cleaned of drilling mud and carefully picked to remove cave-in material which resulted in samples that ranged from 16-2 grams in size. 25 of these samples were sent to University of Victoria for nondestructive heat generation measurements. Key samples are presently being analyzed for U-Pb geochronology of igneous material and apatite fission track analysis. The U-Pb geochronology is being conducted at the SHRIMP II ion microprobe facility at GSC-Ottawa in order to make the best use of the small size of most samples and locally poor quality of the zircons. This suite of both destructive and nondestructive tests will result in better characterization of the Precambrian history of this region as well as characterization of thermal properties and thermal history of relevance to the petroleum industry and geodynamic models.

The sediment cover in the study area increases in thickness from the circa 700 m on the west shore of Great Slave Lake to more than 2300 m near Fort Simpson. The westward thickening character of the sedimentary section results in an attendant loss in the wavenumber content of the aeromagnetic data. In addition, the zero-edge of Precambrian sedimentary cover occurs close to the Fort Simpson terrane and comprises a westward-thickening wedge between the Phanerozoic and the underlying crystalline basement. Fabric recognition in phaneritic crystalline rocks from small samples of cuttings is challenging and hence difficult to discriminate coarse-grained orthogneiss from undeformed plutonic material. Additionally, it is impossible to completely exclude the possibility that some of the cuttings were derived from cobbles with sedimentary material. However, lithologic homogeneity in each sample and no evidence of a sedimentary matrix makes it unlikely that this is the case. Expanding upon existing work (Hoffman, 1989) we recognize the following geophysical domains.

Hay River Terrane (tentative new name) is an aeromagnetic low that lies along the south shore of Great Slave Lake but east of the Great Bear Magmatic Zone and north of Great Slave Lake shear zone. A lack of aeromagnetic anomaly data in Great Slave Lake precludes correlation of this domain with exposed crust although Slave Province and Simpson Islands Terrane (both Archean in age), Coronation margin (1970 -1878 Ma) or sedimentary and igneous rocks of the East Arm of Great Slave Lake are all possible equivalents. A single cutting from this domain consists of granitic material.

Great Bear Magmatic Zone is a composite continental magmatic arc characterized by epizonal magnetite-bearing plutons and coeval volcanic material dated at 1875-1840 Ma (Hildebrand et al., 1987). It is identified by positive magnetic signatures with little internal fabric, consistent with the general lack of penetrative strain in the exposed GBMZ east of Great Bear Lake. The magnetic anomaly pattern of the GBMZ is continuous as a curvilinear concave-westwards arc that extends for more than 900 km from south of the Arctic coast to the Great Slave Lake shear zone in northern Alberta and northeast British Columbia. It is truncated by the GSLSZ/Hay River fault and has no counterpart preserved along the south side of this structure. It appears to have at least one right-stepping deflection in its western boundary west of Great Slave Lake, previously interpreted as right-lateral strike slip fault that feeds into the MacDonald fault system of Great Slave Lake. Cuttings and drill core from this terrane consist of plutonic granitic material (monzonite-syenogranite) and felsic porphyries of shallow intrusive to extrusive origin, similar to what is described from the shield.

Hottah Terrane in the exposed shield consists of volcanic, plutonic and subordinate metasedimentary rocks that are older than circa. 1914 Ma and are characterized by a negative aeromagnetic signature (Hildebrand et al., 1983). In the subsurface the Hottah Terrane extends from Great Bear Lake south into northeast British Columbia where, like GBMZ, it is truncated by the Hay River fault. In the subsurface we have subdivided the Hottah terrane into three subdomains: *Eastern Hottah terrane* is characterized by a negative magnetic anomaly signature and lies immediately west of GBMZ along a magnetic gradient that ranges from sharp to rather irregular; *Central Hottah high* is an irregularly-shaped aeromagnetic high that is ca. 40 km wide and at least 300 in strike length that occurs in the middle of the Hottah Terrane; *Western Hottah terrane* is an aeromagnetic low lying between the central Hottah high and Fort Simpson high. Eastern Hottah terrane appears to consist largely of felsic plutonic/metaplutonic rocks and subordinate felsic porphyries and metasedimentary(?) schists. The central Hottah high also consists of phaneritic granitic crystalline material. The western Hottah terrane contains a mix of plutonic rocks and biotite-bearing schistose rocks (metasediments?).

Collectively the Hottah terrane is cut by a suite of northwest-trending positive linear aeromagnetic anomalies that superficially resemble a dyke swarm. The magnetic linears are characteristic of the Hottah terrane throughout the southern NWT and northeastern British Columbia but their presence cannot be confirmed in either the GBMZ or the adjacent Fort Simpson terrane. Fortunately, several drill core and cuttings of fine to medium grained diabase confirm the dyke interpretation.

Fort Simpson terrane is a prominent aeromagnetic high that extends along much of the strike length of the Cordilleran deformation front. Previously sampled drill core in

the NWT and northeast British Columbia demonstrated that the Fort Simpson terrane was composed of granitic material that crystallized circa. 1845 Ma (Villeneuve et al., 1991). The prominent magnetic signature and presence of plutonic rocks in drill core led Hoffman (1989) to suggest that the Fort Simpson was an outboard arc that collided with western Hottah terrane between 1860 - 1810 Ma. (Note: in early papers an age of 1860 Ma was quoted for the Fort Simpson terrane. This age was based on discordant $^{207}\text{Pb}/^{206}\text{Pb}$ ages and incomplete geochronological analysis. The work of Villeneuve et al. (1991) resolves this with a published age of 1845 Ma. Accordingly the collision must in part post-date 1845 Ma)

Nahanni terrane was a term introduced by Hoffman (1989) for buried crust west of the Fort Simpson trend. Although direct samples were unavailable from this domain, Hoffman inferred an age of circa 2.0-2.4 Ga based on inheritance patterns in Cordilleran granites and $^{207}\text{Pb}/^{206}\text{Pb}$ ages of multigrain fractions of detrital zircons. Subsequently Ross (1991) suggested that such age assignments were premature and that the age and composition of the Nahanni terrane was accordingly assigned as "age unknown". Recently, the SNORCLE line showed that the region of crust that corresponds to the Nahanni terrane coincides with the westward thickening wedge of Precambrian sedimentary strata. Thus the Nahanni terrane is tentatively assigned to this basin (Fort Simpson basin of Cook et al., 1999). Most wells that penetrate preDevonian rocks in this region are assigned to "pre identifiable Paleozoic" (Williams, 1990). In other words sedimentary rocks of uncertain but likely Precambrian age. Fortuitously a single well from the Nahanni terrane registered a pick from the well log of "Precambrian granite". Examination of this well showed the crystalline material to be composed of gabbroic mafic rock, perhaps sampling a sill within the Fort Simpson basin (Cook et al., 1999).

Geochronologic Results

Geochronologic results for 12 samples, including a previously published age from Villeneuve et al. (1991) for well G-50 are presented in table form. Except for well G-50, all ages were generated at the SHRIMP II laboratory at the GSC in Ottawa. Mounted zircon grains were characterized using cathodoluminescence and backscatter SEM imaging to detail the internal structure of grains and isolate robust domains for U-Pb analysis. Results are based on multiple analyses and ages are reported as weighted means of concordant and/or nearly concordant analyses, or as upper intercepts of partially discordant data. All ages are reported with 2 sigma uncertainties.

Perhaps the biggest surprise of the results thus far is the narrow range of ages from circa 1875-1838 Ma, regardless of which terrane the samples come from. In GBMZ, the ages range from 1873-1862 Ma - nearly identical to dates from the older portion (pre-folding plutons) of the exposed magmatic rocks near Great Bear Lake. A single age from the Hay River terrane, at 1838 Ma, is younger than any known rock in this region. In the exposed shield the Hottah terrane is characterized by ages of plutonic rocks older than 1914 Ma; our results thus far suggest that the Hottah terrane has a different range of distinctly younger ages in the subsurface, ranging from 1875-1854 Ma, very similar to ages considered typical of GBMZ. Several samples from the subsurface Hottah terrane and GBMZ do contain evidence of inheritance in the form of concordant and nearly

Well Name and Number	Lithology	Latitude	Longitude	Depth	Weight (g)	U-Pb age
Great Bear Magmatic Zone						
Miami Amoco E Cameron D-16	felsic volcanic	60	116.56	3020'-3070'	10.48	1866 +/- 5
Miami Amoco Kakisa River Block I-52	granite	60.11	117.91	5610'-5650'	10.55	1867 +20-19
Miami Amoco Alexandra Falls Block G-36	rhyolite	60.19	116.61	2620'-2670'	14.85	1873 +/- 6
Shell HB Grumbler F-07	monzogranite	60.36	116.02	2270'-2290'	8.53	1862 +/- 6
Eastern Hottah terrane						
CDR CPOG Chevron Gull Creek A-63	biotite tonalite	60.79	118.19	3100'-3090'	11.38	1863 +/- 6
Briggs Foetus Lake No. 1 D-06	granodiorite	60.93	118.53	2740'	core	1862 +/- 6
CDR Triad Andex et al Mills Lake B-75	bio. granite/syenogranite	61.24	117.48	1810'-1790'	9.89	1874 +/- 5
Imperial Triad Davidson Creek P-02	granite	62.2	118.25	2729'-2731'	core	1875 +/- 8
Central Hottah high						
Gulf et al Redknife H-28	biotite granite	61.43	119.56	2330'-2310'	1.84	1854 +/- 7
Fort Simpson terrane						
UnOil Trout River O-80	biotite granodiorite	60.81	120.48	4500'-4450'	9.59	1854 +/- 9
Imperial Island River No. 1 G-50	granodiorite	60.15	121.14	8230'-8233'	core	1844 +/- 5-3
Hay River terrane						
Horn River et al Hay River B-52	biotite syenogranite	60.85	115.67	2025'-2010'	9.23	1838 +/- 5

concordant single spot analyses that are older than ca. 1940 Ma, consistent with the age of basement inferred to underlie the Hottah terrane (Bowring and Podosek, 1989; Housh et al., 1989). It is worth noting that no inheritance ages >1925 Ma have been found in the GBMZ samples analyzed, suggesting that crust underlying these rocks is markedly younger than under the Hottah terrane, where many of the granites have signs of inheritance from older Paleoproterozoic crust.

Implications For Reflection Interpretation and Regional Tectonics

On the 1998 SNORCLE line, the Great Bear Magmatic Zone was imaged as a relatively thin (circa 3-4.5 km) basin of nonreflective material that lies above strongly reflective crust presumed to be either the Hottah terrane or the imbricated Coronation margin (Cook et al., 1999). The composition and ages of cuttings examined in this study corroborate that interpretation. However one puzzling aspect of this correlation, noted by Cook et al., (1999), is the relative thinness of the GBMZ and the apparent lack of disruption of pre-GBMZ reflections beneath it. This conundrum is not answered in the present study but the presence of granitic, presumably plutonic material, in the cuttings emphasizes this problem.

The young ages within the Hottah terrane, closely overlapping those in GBMZ, were not anticipated. Much of the SNORCLE line that traverses the Hottah terrane imaged a transparent, nonreflective region above strongly reflective, structurally imbricated crust. This basin-shaped nonreflective zone appears to truncate the structures in the underlying crust and thus, like the GBMZ, likely postdates much of the deformation. However, on its western margin this "basin" is imbricated with slivers of both inferred Hottah and Fort Simpson crust. When the well data are plotted relative to the location of the SNORCLE profile it appears that most of the samples we have analyzed in the Hottah terrane may sample this transparent zone or its lateral equivalents. The ages are comparable to the *older* ages of the GBMZ but generally not to the *younger* parts of these arcs (GBMZ - ca. 1840 Ma and Fort Simpson - ca. 1854-1844 Ma). The Fort Simpson terrane has a hint of inheritance ca. 1950 Ma, similar to inheritance in igneous rocks

Hottah terrane. Similarly, there is a general agreement between Hottah and Fort Simpson Nd isotopic signatures which result in Nd model ages between 2.1-2.4 Ga (Bowring and Podosek, 1989; Villeneuve et al., 1991). Is it possible that the nonreflective "basin" is an arc and if so, is it an extension of the GBMZ, Fort Simpson or something altogether different? If the arc interpretation is correct, it may require revision of the tectonic models proposed for this region.

REFERENCES

- Bowring, S.A. and Podosek, F.A., 1989, Nd isotopic evidence from Wopmay Orogen for 2.0 - 2.4 Ga crust in western North America. *Earth Planet. Sci. Letters*, 94, 217-230.
- Cook, F.A., van der Velden, A.J., Hall, K.W., and Roberts, B.J., 1999, Frozen subduction in Canada's Northwest Territories: Lithoprobe deep lithospheric reflection profiling of the western Canadian Shield. *Tectonics*, v. 18, p. 1-24.
- Hildebrand, R.S., Bowring, S.A., Steer, M.E., and van Schmus, W.R., 1983, Geology and U-Pb geochronology of parts of the Leith Peninsula and Riviere Grandin map areas, District of Mackenzie. Geological Survey of Canada, Paper 83-1A, p. 329-342.
- Hildebrand, R.S., Hoffman, P.F., and Bowring, S.A., 1987, Tectonomagmatic evolution of the Great Bear magmatic zone, Wopmay Orogen, northwestern Canada. *Journal of Volcanology and Geothermal Research*, v. 32, p. 99-118.
- Hoffman, P.F., 1987, Continental transform tectonics: Great Slave Lake shear zone (ca. 1.9 Ga) northwest Canada. *Geology*, v. 15, p. 785-788.
- Hoffman, P.F., 1989, Precambrian geology and tectonic history of North America. in *The geology of North America-an overview*, A.W.Bally, A.R.Palmer, eds., Geol. Soc. Amer., The Geology of North America, A, 447-512.
- Housh, T., Bowring, S.A., and Villeneuve, M.E., Lead isotopic study of Early Proterozoic Wopmay orogen. *Journal of Geology*, v. 97, p. 735-747.
- Ross, G.M., 1991, Precambrian basement in the Canadian Cordillera: an introduction. *Canadian Journal of Earth Sciences*, v. 28, p. 133-1139.
- Villeneuve, M.E., Theriault, R.J. and Ross, G.M., 1991, U-Pb ages and Sm-Nd signature of two subsurface granites from the Fort Simpson magnetic high, northwest Canada. *Canadian Journal of Earth Science*, v. 28, p. 1003-1008.
- Villeneuve, M.E., Ross, G.M., Theriault, R.J., Miles, W., Parrish, R.R. and Broome, J., 1993, Geophysical subdivision, U-Pb geochronology and Sm-Nd isotope chemistry of the basement of the Western Canada Sedimentary Basin, Alberta and northeastern British Columbia. Geological Survey of Canada, Bulletin 447, 86 pp.
- Williams, G.K., 1990, Tectonics and structure, Mackenzie Corridor, Northwest Territories. Geological Survey of Canada, Open File 2248.

The Thermal Regime of the SNORCLE Lithoprobe Transect and Tectonic Consequences

R.D. Hyndman

Pacific Geoscience Centre, Geological Survey of Canada
and School of Earth and Ocean Sciences, University of Victoria

T.J. Lewis

Sidney Geophysical Consultants Ltd., Sidney, B.C.,
and Pacific Geoscience Centre, G.S.C.

P. Flueck

School of Earth and Ocean Sciences, University of Victoria

Introduction

Heat flow, radioactive heat generation, and other thermal constraints for the Lithoprobe SNORCLE transect indicate a large contrast in lithosphere temperature between the very hot and weak Cordillera, and the cold and strong Craton, similar to that found in southwestern Canada. From heat flow-heat generation data, and from the other thermal constraints, the estimated temperatures at the Moho in both the north and south are 400-500°C for the Craton. As previously estimated for the Southern Cordillera, the temperatures at the Moho for the northern Cordillera are remarkably hot, 800-1000°C. There are two new surprises. First, the heat flow in the northern Cordillera is as high or higher than that in the south. This is unexpected because the high heat flow in the south can be explained by present subduction-driven advection, but in the north subduction stopped in the Eocene. The second surprise is the very high heat flow measured in the Proterozoic Wopmay orogen, from Ft. Providence west to the mountain front. Such old and stable areas normally have low heat flow. Several tectonic differences between the north and south Rocky Mountain fold and thrust belts may be related to the north-south differences in thermal regimes. (1) the mountains just to the west of the thrust front are lower in the north, (2) the foreland basin is much thinner in the north, and the sediments change from mainly clastics in the south to extensive shales in the north, (3) the foreland continental crust is unusually thin in the north, much thinner than in the south, i.e., ~35 km compared to 40-50 km.

SNORCLE Craton-Cordillera Thermal Regimes

The general Craton-Cordillera thermal contrast for the SNORCLE region is similar to that for the Southern Canadian Cordillera. There is an increase in heat flow from 40-60 mW/m² in the stable Craton (there is limited data in the Slave province) to 80-120 mW/m² in the Cordillera (the

Wopmay orogen is discussed below). The heat flow in the northern Cordillera (avg. 103 ± 24 mW/m²) actually is somewhat higher than in south (avg. 86 mW/m²). The radioactive heat generation is somewhat higher in the north, but the deep temperatures still are inferred to be at least as high as in the south. This is surprising since in the south there is present subduction of the Juan de Fuca plate along the Vancouver Island margin and the high heat flow can be explained by present subduction-driven advection of heat into the backarc region. However, in the north subduction stopped in the Eocene (~42 Ma) with the initiation of the Queen Charlotte-Fairweather transform fault. The backarc high heat flow is expected to have decayed. Several other temperature indicators confirm the Cordillera-Craton lithosphere thermal contrast in both the south and north, (1) temperature-dependent uppermost mantle Pn velocities (Pn~8.2 for the Craton, Pn~7.8 for the Cordillera), (2) mantle xenoliths show much lower temperatures for the Craton, (3) thermally controlled isostasy (discussed below). From heat flow-heat generation data, and from the other thermal constraints, the estimated temperatures at the Moho in both the north and south are 400-500°C for the Craton and 800-1000°C for the Cordillera.

There is a systematic increase in heat flow eastward across the southern Cordillera. The heat flow variation is mainly due to eastward increase in upper crust heat generation, but a small eastward increase in deep temperature is probably present. There is no clear variation across the northern Cordillera, except possibly at the west end. There are only a few heat flow values at the southwestern part of the SNORCLE transect region in the Coast Belt and the Alaska panhandle. They average about 60 mW/m². This average is very similar to that for the Queen Charlotte Basin just to the south where there has been mid-Tertiary extension, but much higher than the values for Vancouver Island where there is present subduction. Thus, the SNORCLE Cordillera heat flow data suggest that the heat sink of the pre-Eocene subducting plate has decayed along the coast, but further to the east asthenosphere flow under the northern Cordillera former backarc has continued to maintain high heat flow.

In the Lithoprobe SNORCLE transect region of the Yukon-NWT, the Craton-Cordillera thermal transition is not yet as well defined as in the south, but it appears to occur near the mountain front. New heat flow and crustal radioactive heat generation data, and other thermal indicators in the north are discussed below.

SNORCLE Heat Flow and New Radioactive Heat Generation Measurements

Heat generation data for the crust of the northern Cordillera are relatively low, although they have somewhat higher average compared to for the south. The high heat flows thus imply high temperatures in the upper mantle. However, there are high heat flow values to the west of Yellowknife across the Proterozoic Wopmay Orogen (for about 500 km west from Ft.

Providence), with an average of 93 mW/m^2 . This is remarkably high for such an old and stable region. Also, high deep crust and upper mantle temperatures are inconsistent with the other thermal constraints that indicate only slightly higher than normal Craton deep temperatures in this region. Another explanation must be sought. One explanation is that the high heat flow results from high radioactive heat generation in the upper crust, such that it has rather little effect on deep temperatures. To confirm this hypothesis, new radioactive heat generation measurements have been made on a number of basement cutting samples from the bottom of hydrocarbon exploration wells, as part of a multidisciplinary analysis of these samples (coordinated by G. Ross). The heat generations are indeed unusually high, but not high enough to explain the very high heat flow. The average for 25 wells is $3.2 \text{ } \mu\text{W/m}^3$. The average for 9 igneous samples that may be more representative of the upper $\sim 10 \text{ km}$ of the crust is $3.5 \text{ } \mu\text{W/m}^3$. The high heat generation in this region may represent the erosive products of strongly upward differentiated adjacent Slave Craton crust. Assuming standard heat flow-heat generation relations for the Canadian Craton, this heat generation corresponds only to a heat flow of $65\text{-}70 \text{ mW/m}^2$. An exceptionally upper crust high heat generation of about $6 \text{ } \mu\text{W/m}^3$ is needed to explain the observed average surface heat flows, assuming normal Craton mantle heat flow. Another possible source of heat is in the wide spread shales within the westward thickening overlying Phanerozoic sediment section. To test this model, measurements of radioactive heat generation in samples from shale drill cuttings are planned.

Thermal Control of Isostatic Balance Across Craton-Cordillera Boundary

In both the southern Canadian Cordillera and SNORCLE transect areas, isostatic balance is maintained across the Craton-Cordillera thermal boundary by thermal expansion and density reduction of the lithosphere beneath the Cordillera. However, there is an important contrast between the north and south. In the south, across the Rocky Mountain Trench there is a large change in crustal thickness with no significant change in elevation. The Craton crust to the east is $40\text{-}50 \text{ km}$ thick, whereas the Cordillera crust to the west is $32\text{-}34 \text{ km}$ thick. Thermal density reduction beneath the Cordillera balances the thinner crust. In the north at the thermal boundary near the mountain front, there is almost no change in crustal thickness, but there is a change to higher elevation in the mountains to the west. Across this boundary, the higher elevation of the Cordilleran mountain belt is maintained in isostatic balance with the lower elevation Craton through the temperature effect on density. More detailed modelling of isostatic balance across the SNORCLE transects is in progress using the newly acquired seismic structure data for crustal thicknesses and for crustal density estimated from velocity.

Foreland-Hinterland Deformation

The Canadian Rocky Mountain fold and thrust belt exhibits the characteristic orogen division into foreland and hinterland deformation. In the foreland the deep crust and upper mantle have remained largely undeformed during late Mesozoic to early Tertiary tectonics. Shortening occurred primarily in overlying sedimentary thrust sheets, mediated by high pore fluid pressures, i.e., thinned skin tectonics. In contrast, Cordillera hinterland shortening deformation (and subsequent extension mainly in the south) involved the crystalline crust, i.e., thick skinned tectonics. The contrast is explained by the pronounced difference in lithosphere temperature and thus strength between the two regions. The lithosphere thicknesses for the Craton and Cordillera, defined by $\sim 450^{\circ}\text{C}$ for crustal and $\sim 750^{\circ}\text{C}$ for mantle compositions, are only the upper ~ 15 km of the crust for the western Cordillera but over 100 km for the Craton. The total Craton lithosphere is at least 10 times stronger than that of the Cordillera. As a consequence, tectonic lithosphere deformation is limited to the high temperature hinterland.

Foreland Basins, South and North

In the southern Canadian Cordillera the thermal transition occurs near the Rocky Mountain Trench about 100 km west of the mountain front. In this area the upper Cordillera crust (i.e., whole Cordillera “lithosphere”) has been both shortened and thrust ~ 100 km over the strong Craton that extends about to the Rocky Mountain Trench (thinned and heated craton mantle lithosphere may extend further west). The thick thrust sheets pushed in front of the advancing Cordilleran upper crust have loaded the strong Craton lithosphere. Because the Craton lithosphere is very cold and thick, it has a long flexural wavelength and a very wide foreland basin resulted. In the north, a much thinner foreland basin has formed which suggests that the thrust thickening of the sedimentary section has not reached and significantly loaded the western edge of the cold Craton lithosphere. This may be because there is less shortening in the north compared to the south. The deep lithosphere thermal boundary is interpreted to be near the mountain front.

**Lithospheric structure across the Canadian
Cordillera of northeastern British Columbia:
Results from the SNoRE '97 Experiment, Line 21**

J. Kim Welford and Ron M. Clowes

Dept. of Earth & Ocean Sciences, Univ. of British Columbia, 6339 Stores Road, Vancouver, BC, V6T 1Z4
kwelford@geop.ubc.ca, clowes@lithoprobe.ubc.ca

ABSTRACT

The SNoRE '97 seismic refraction/wide-angle reflection (R/WAR) survey recorded four separate seismic profiles along the three corridors of the SNorCLE transect. This study focuses on the results for refraction Line 21 which is located in northeastern British Columbia and extends WNW to ESE for 460 km. From east to west, the line begins in the Proterozoic Fort Simpson magmatic arc terrane, crosses the accreted Nahanni terrane, transects the Foreland Belt and samples the edge of the Omineca Belt just west of the Tintina Fault (Fig. 1). A velocity structural model is achieved first through $\tau - p$ analysis, then forward ray trace modelling and 2-d inversion of traveltimes and forward amplitude modelling using RAYINVR, a ray-theory-based algorithm. The main features of the interpreted velocity structural model are (1) a westward thickening package of low upper crustal velocities (6.2 km/s and less) extending to almost 20 km depth along the eastern portion of the profile below the WCSB, (2) a west-facing ramp of higher velocities, resolved in the middle and lower crust, at the edge of cratonic North America, (3) a pinched-out high velocity (7.3 km/s) lower crustal layer at the base of the crust beneath the edge of cratonic North America, (4) high velocity material (6.4 km/s) in the upper five kilometers of the eastern Foreland Belt, (5) a narrow trench of low velocities in the near-surface at the western end of the profile, ~ 20 km to the west of the inferred location of the Tintina Fault, (6) a deepening of the Moho from ~ 34 km to ~ 38 km beneath the Foreland Belt, and (7) a laterally heterogeneous upper mantle with anomalously high velocities (up to 8.3 km/s) beneath the Foreland Belt flanked by regions of low velocities (7.7-7.8 km/s). Results from 3-d inversion of the regional Bouguer gravity data and 2.5-d forward modelling of the Bouguer gravity data are combined with results from previous geophysical studies to constrain the interpretation of the tectonic evolution of northeastern British Columbia.

GEOTECTONIC SETTING

Northeastern British Columbia includes the region of transition from cratonic North America to the deformed Canadian Cordillera. While geological mapping has progressed for over 120 years (reviewed by Monger, 1993) in the northern Cordillera, the subsurface has remained *terra incognita* as few geophysical surveys have been conducted (reviewed by Berry et al., 1971).

The easternmost coverage of Line 21 extends onto the western margin of ancestral North America which developed into a passive margin sequence in Neoproterozoic time. In terms of tectonic elements (Fig. 1), this section of Line 21 begins in the east in the Proterozoic Fort Simpson magmatic arc terrane, extends westward across the accreted Nahanni terrane, and then into the margin of ancestral North America. The Nahanni and Fort Simpson domains were accreted as part of the Wopmay Orogen in Paleoproterozoic times.

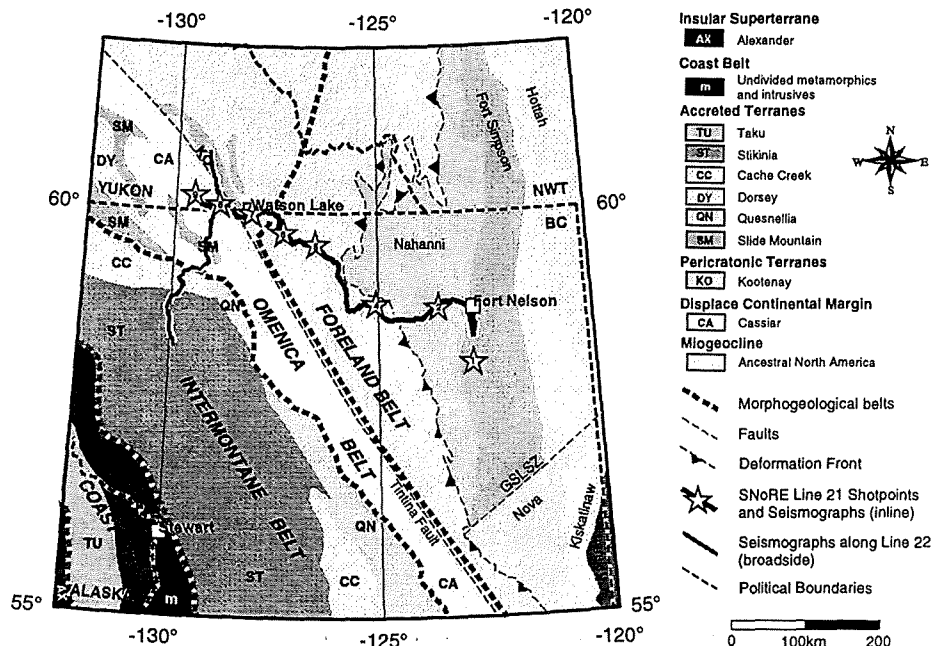


Figure 1: Terrane map of SNorCLE transect surrounding Line 21. Both Line 21 and the northern portion of Line 22, along which receivers for broadside recordings were deployed, are shown. Shot locations along Line 21 are numbered and shown as stars. Morphogeological belt boundaries are superimposed on the map with thick dashed lines. Both the Tintina Fault and the Great Slave Lake Shear Zone (GSLSZ) are indicated as thinner dashed lines. Dashed line with west-pointing triangles delineates the Cordilleran deformation front.

To the west in the Cordilleran Foreland, Line 21 samples the mountainous Foreland Belt. This classic fold and thrust belt is composed of folded miogeoclinal and clastic wedge assemblages of Mesoproterozoic to Jurassic age that were deposited on and along the flank of the western passive margin of ancestral North America. During the compressional events that resulted from the accretion of the western Cordilleran belts during the Middle Jurassic (ca. 170 Ma), the passive margin sequences along the rifted edge of cratonic North America were folded, detached from crystalline basement and upthrust onto the edge of ancestral North America to form the mountain belt.

The westernmost extent of Line 21 crosses the Tintina Fault, a Late Cretaceous to Oligocene brittle structure extending up to 2000 km in length, and samples the Omineca Belt, a mountainous region of uplift underlain by metamorphic and granitic rocks which straddles the boundary between the accreted terranes and the North American miogeocline. Due to overlying drift cover sediments of the Liard Plain, the Tintina Fault's exact location at the Yukon/BC border is uncertain.

EXPERIMENT AND LINE 21 DESCRIPTION

The LITHOPROBE 1997 Slave-Northern Cordillera Refraction Experiment (SNoRE '97) was designed to determine the velocity structure of the crust and the upper mantle from Great Slave Lake in the Northwest Territories to the coast of the Alaska "Panhandle". To achieve this goal, four refraction/wide-angle reflection profiles, numbered 11, 21, 22 and 31, were collected along three corridors of the SNorCLE transect.

Line 21 in Corridor 2 was designed to determine the velocity structure of the crust and upper mantle from the NW portion of the Western Canada Sedimentary Basin (WCSB), across the deformation front of the northern Cordillera into deformed North American rocks and across the Tintina Fault, the eastern boundary of accreted terranes (Fig. 1). The line is 460-km-long and extends along the Alaska Highway from Fort Nelson, BC, northwest to Watson Lake, Yukon. 596 portable seismographs were deployed along Line 21 (station spacing ~ 1.0 km) and along the northern half of Line 22 (station spacing ~ 2.0 km). Eight shot points along Line 21 (shot spacing ~ 60 km) were recorded by all stations, providing inline profiles and broadside coverage across the Tintina Fault south of Watson Lake.

DATA QUALITY AND INTERPRETATION

The refraction data show good signal-to-noise ratios and primary phases [Pg, PmP and Pn] are observable for most shots. Highest signal-to-noise ratios occur for shots at the ends of the line (2101, 2102, 2107, 2108 (Fig. 2) and 2109). Shot 2104 has the noisiest data and only provides reliable Pg for near offsets where arrivals demonstrate high velocities (6.3 km/s) within 5 km of the surface. Shot 2108 shows anomalously slow velocities near the surface ~ 20 km to the west of the inferred location of the Tintina Fault (demonstrated in enlarged segment of Fig. 2).

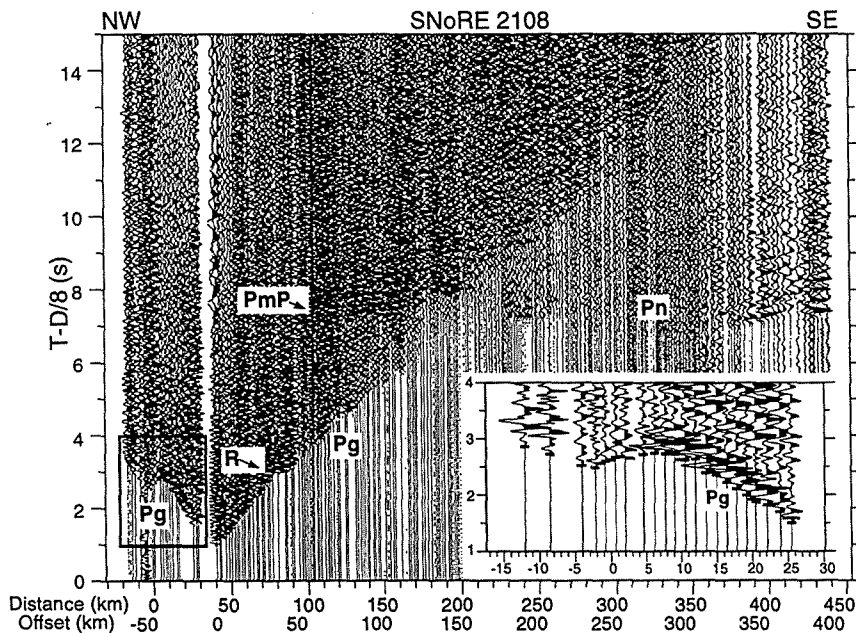


Figure 2: Trace normalized data plot for shot 2108; on the enlarged segment, picks are overlain as horizontal bars. The phases identified on the section are: Pg which represents rays turning in the crust; PmP which represents rays reflecting off the crust-mantle boundary (Moho); Pn which represents rays turning in the upper mantle; and R which represents rays reflecting off a crustal reflector.

A velocity structural model is achieved first through $\tau - p$ analysis (Gorman and Clowes, 1999), then forward ray trace modelling and 2-d inversion of traveltimes and forward amplitude modelling using RAYINVR (Zelt and Smith, 1992), a widely applied, ray-theory-based algorithm developed

for R/WAR studies. The results reveal that the data from Line 21 sampled a laterally heterogeneous region of considerable complexity.

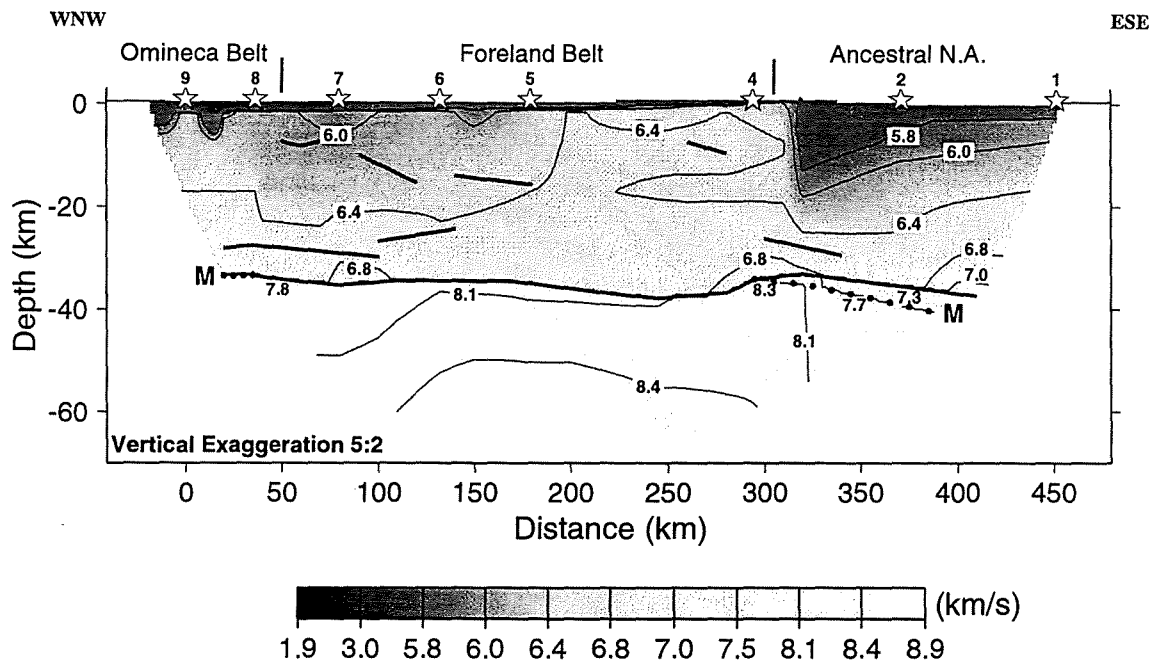


Figure 3: Final interpreted velocity structural model for Line 21 plotted with a vertical exaggeration of 5:2. Shot locations are plotted as stars along the top of the model. Thick lines signify regions constrained by wide-angle reflections. The M indicates the location of the Moho while the dotted M line represents the Moho depths not constrained by wide-angle reflections.

The interpreted velocity structural model (Fig. 3) demonstrates a westward thickening package of low upper crustal velocities (6.2 km/s and less) extending to almost 20 km depth along the eastern portion of the profile below the WCSB. Beneath the westward thickening low velocities, a west-facing ramp of higher velocities, resolved in the middle and lower crust, is interpreted as the rifted margin of cratonic North America, which was overlain by low velocity, passive margin sediments during the mid-to-late Proterozoic and early Paleozoic. Beneath the edge of cratonic North America, a pinched-out high velocity (7.3 km/s) lower crustal layer is imaged at the base of the crust. It is inferred to be the result of magmatic underplating during rifting. The eastern part of the Foreland Belt shows high velocities (6.4 km/s) in the upper five kilometers, indicating rocks up-thrust from deeper in the crust. At the western end of the line, a narrow trench of low velocities in the near-surface of the model is inferred to represent sediments and brecciated surface rocks filling in the scar of the crustal-scale Tintina Fault. The location of the fault is resolved ~ 20 km to the west of its current inferred location. The depth to Moho is resolved at ~ 34 km in the Omineca Belt, deepens to ~ 38 km below the eastern Foreland Belt, and shallows to ~ 34 km at the Cordilleran deformation front. The upper mantle is laterally heterogeneous with anomalously high velocities (up to 8.3 km/s) beneath the Foreland Belt flanked by regions of low velocities (7.7-7.8 km/s).

Results from 3-d inversion of the regional Bouguer gravity data and 2.5-d forward modelling of the Bouguer gravity data are combined with results from heat flow analyses and previous geophysical studies to check the consistency of the resolved velocity model and to constrain the interpretation

of the tectonic evolution of northeastern British Columbia. Generally, the resolved density models show excellent consistency with the interpreted velocity structural model.

TECTONIC EVOLUTION OF NORTHEASTERN BC

The tectonic evolution of northeastern British Columbia (Fig. 4) appears to have been directly affected by the geometry of the rifted western margin of cratonic North America. Following the Proterozoic rifting events, a passive margin sequence was overlain on the west-facing ramp of the cratonic edge. The westernmost Paleozoic passive margin sediments and underlying middle crustal material were subsequently upthrust over the edge of the craton during the formation of the Foreland Belt (Fig. 4); however, since the upthrusting of material occurred outboard of the ramped edge of cratonic North America, over 100 km of Proterozoic passive margin sediments, known as the Fort Simpson Basin, were unaffected by the Cordilleran Orogen. As the Moho was depressed in isostatic response to the thickened crust outboard of the ramped cratonic edge, the crust remained relatively thin compared to the southern Cordillera and a section of thinner crust remained unaffected between the Foreland Belt and the thicker craton to the east. Due to downward heating either from high heat production within the overlying crust or from preferential emplacement of hot upper mantle material beneath the Nahanni terrane (or both), a localized pocket of low velocities and densities developed beneath the western margin of ancestral North America. The formation of large scale right-lateral transcurrent faults such as the Tintina Fault during the Eocene later resulted in the northwestward displacement of the cratonic margin at the western end of Line 21.

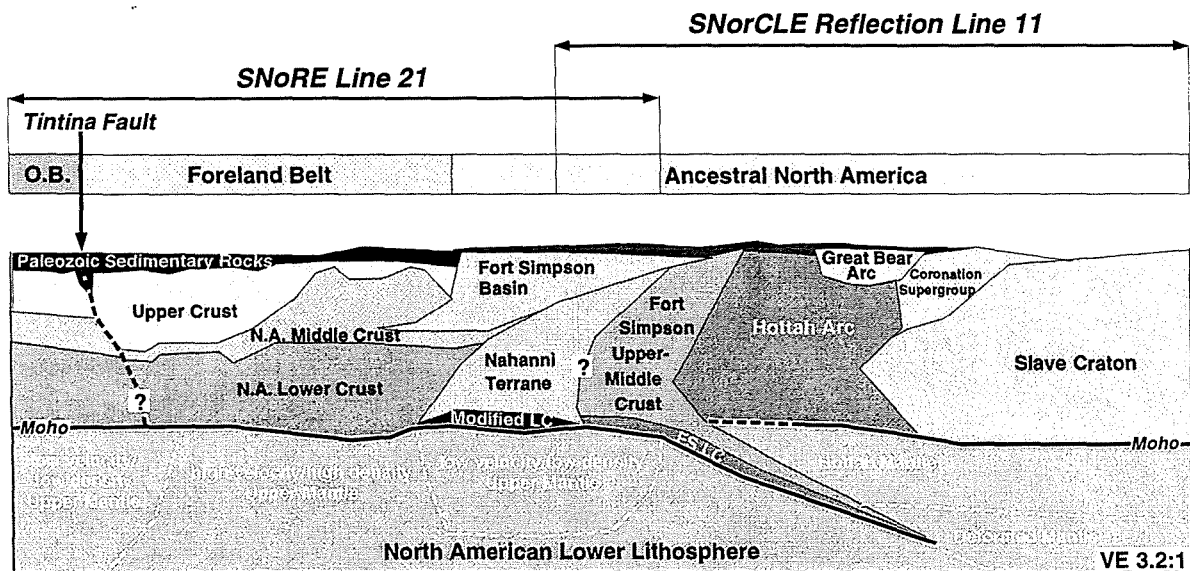


Figure 4: Interpreted cross-section for the Cordilleran-North American craton transition. Locations of SNoRE Line 21 and SNorCLE reflection line 11 (interpreted by Cook et al. (1999)), and the lateral extents of cratonic North America, the Foreland Belt and the Omineca Belt (O.B.) are shown across the top of the diagram. The inferred location of the Tintina Fault is indicated with a thick dashed line at the western end of Line 21. Modified LC and FS LC signify modified lower crust and Fort Simpson lower crust respectively.

ACKNOWLEDGMENTS

The funding for SNoRE 97 was provided by the NSERC Collaborative Special Projects grant to LITHOPROBE, the Geological Survey of Canada, and NSERC Research Grants to R.M. Clowes, R.M. Ellis and G. Spence. J. Kim Welford is the recipient of a CSEG Scholarship.

REFERENCES

- Berry, M.J., W.R. Jacoby, E.R. Niblett, and R.A. Stacey, 1971. A review of Geophysical Studies in the Canadian Cordillera, *Canadian Journal of Earth Sciences*, Vol.8, p.788-801.
- Cook, R.A., A.J. van der Velden and K.W. Hall, 1999. Frozen subduction in Canada's Northwest Territories: LITHOPROBE deep lithospheric reflection profiling of the western Canadian Shield, *Tectonics*, vol. 18, pp. 1-24.
- Gorman, A.R. and R.M. Clowes, 1999. Wave-field tau-p analysis for 2-d velocity models: Application to western North American lithosphere, *Geophysical Research Letters*, vol. 26, pp. 2323-2326.
- Monger, J.W.H., 1993. Canadian Cordilleran Tectonics: from geosynclines to crustal collage, *Canadian Journal of Earth Sciences*, Vol.30, p.209-230.
- Zelt, C.A. and R.B. Smith, 1992. Seismic traveltime inversion for 2-d crustal velocity structure, *Geophysical Journal International*, vol. 108, pp. 16-34.

Mesoproterozoic evolution of Northeastern British Columbia.

D. G. F. Long, (Department of Earth Sciences, Laurentian University, Sudbury, Ont. P3E 2C6, dlong@nickel.laurentian.ca) and **B. R. Pratt**, (Department of Geological Sciences, University of Saskatchewan, Saskatoon, SK, S7N 5E2).

The configuration of the western margin of ancestral North America at the time of deposition of the Muskwa Assemblage and Belt-Purcell Supergroup remains problematic. While these Mesoproterozoic sequences are interpreted by some to represent an early rift-drift sequence, developed within the Kanatia Supercontinent, beginning in the early Mesoproterozoic, others argue that early rifting was followed by thermal relaxation with sag-basin development, and that the sequence was developed entirely on continental crust, with no major continental separation.

The presence of six (exposed) to fifteen (inferred) kilometres of possibly time equivalent strata in the Muskwa Ranges is suggestive of extensional basin development, although there is no clear evidence if this is rift related extension, or might be tied to transtensional strike slip mechanisms. The lower few kilometres of the exposed parts of the sequence appear to have been deposited in distally steepened ramp setting, which appears to deepen to the west. Structures within the carbonate and siliciclastic sand dominated units indicate water depths from shallow sub-tidal to slightly below storm wave-base while mudstone dominated sequences may have been deposited in water depths in excess of 120 m. The transition from shallow-shelf sandstones in the Tuchodi Formation, to mudstones and wackes in the overlying Aida and Gataga Formations suggests a transition to significantly deeper water depths in late Neoproterozoic times.

The depositional style of exposed strata is consistent with the basin forming by intracontinental rifting (extension perpendicular to local structures) associated with widespread intracontinental transtensional wrenching ("extension" oblique to local structures) processes which resulted from long-range (1000-5000 km) transmission of stresses from plate-margin collisional areas. If the Paleoproterozoic Hamersley and Bangermall Provinces in Australia are directly correlated with the Wopmay and Talston Provinces in Canada, then about 2000 km of sinistral movement is required to accommodate the differences between the SWEAT and the AUSWUS reconstructions of Kanatia - Rodinia. There is no evidence for direct influence of NE-SW directed faults during deposition of the Muskwa Assemblage.

Inferred NW-SE paleo-shorelines roughly parallel the strike of the modern Cordillera and are consistent with both extensional and transtensional models.

Closure of the Muskwa basin, in response to far-field tectonic stress, may have occurred during the Racklan orogeny at ~ 1.2 Ga, but is as yet unconfirmed by direct dating. Closure led to uplift and erosion during deposition of the overlying Mackenzie Mountains Supergroup and its equivalents north of the study area. This latter group also appears to have developed in an extensional basin setting with little to no evidence of a drift phase. The absence of equivalent strata in northeastern B.C. may indicate that the MacDonald platform acted as a high or horst, controlled by deep-seated faults inherited from the earlier basin or initiated during a rifting-spreading event. Extension in both the Mackenzie Mountains and Muskwa Ranges is marked by the intrusion of 799 ± 2 diabase dikes along high angle faults.

A second phase of folding, the ~ 0.8 Ga Hayhook orogeny, separates the above strata from a well defined continental margin sequence which reflects rift and drift conditions in the late Neoproterozoic. It is uncertain if this phase involved only minor separation of Australia-South China and Laurentia, or if a broad ocean basin was developed. This phase may be reflected in the Muskwa Assemblage by reactivation and shearing along the trend of the high-angle faults which host the diabase dikes. Local dolomitization of the George Formation adjacent to high-angle reverse faults may have occurred at this time.

It has been suggested that renewed rifting along the Cordilleran margin occurred in Early Cambrian time and is best modeled using a crustal-attenuation model involving asymmetrical extensional break-up, delamination and sub-crustal shear. In this model, upper plate segments (crust above a deep detachment fault) may alternate with lower plate segments (consisting of the footwall of detachment, overlain by faulted upper plate remnants). While there is some evidence to suggest that this framework existed during deposition of the Rapitan and Windermere Supergroups and possibly the underlying Mackenzie Mountain Supergroup, there is no clear evidence as yet to support the concept that upper and lower plate segmentation had developed in early Mesoproterozoic time.

ISOTOPIC PROVENANCE OF THE LOWER MUSKWA ASSEMBLAGE,
(MESOPROTEROZOIC, ROCKY MOUNTAINS, BRITISH COLUMBIA): NEW
CLUES TO CORRELATION AND SOURCE AREAS

G.M. ROSS Geological Survey of Canada – Calgary, 3303 33rd Street N.W.,
Calgary AB. T2L 2A7; M.E. VILLENEUVE and R.J. THERIAULT Geological
Survey of Canada - Ottawa, 601 Booth Street, Ottawa, ON. K1A 0E8

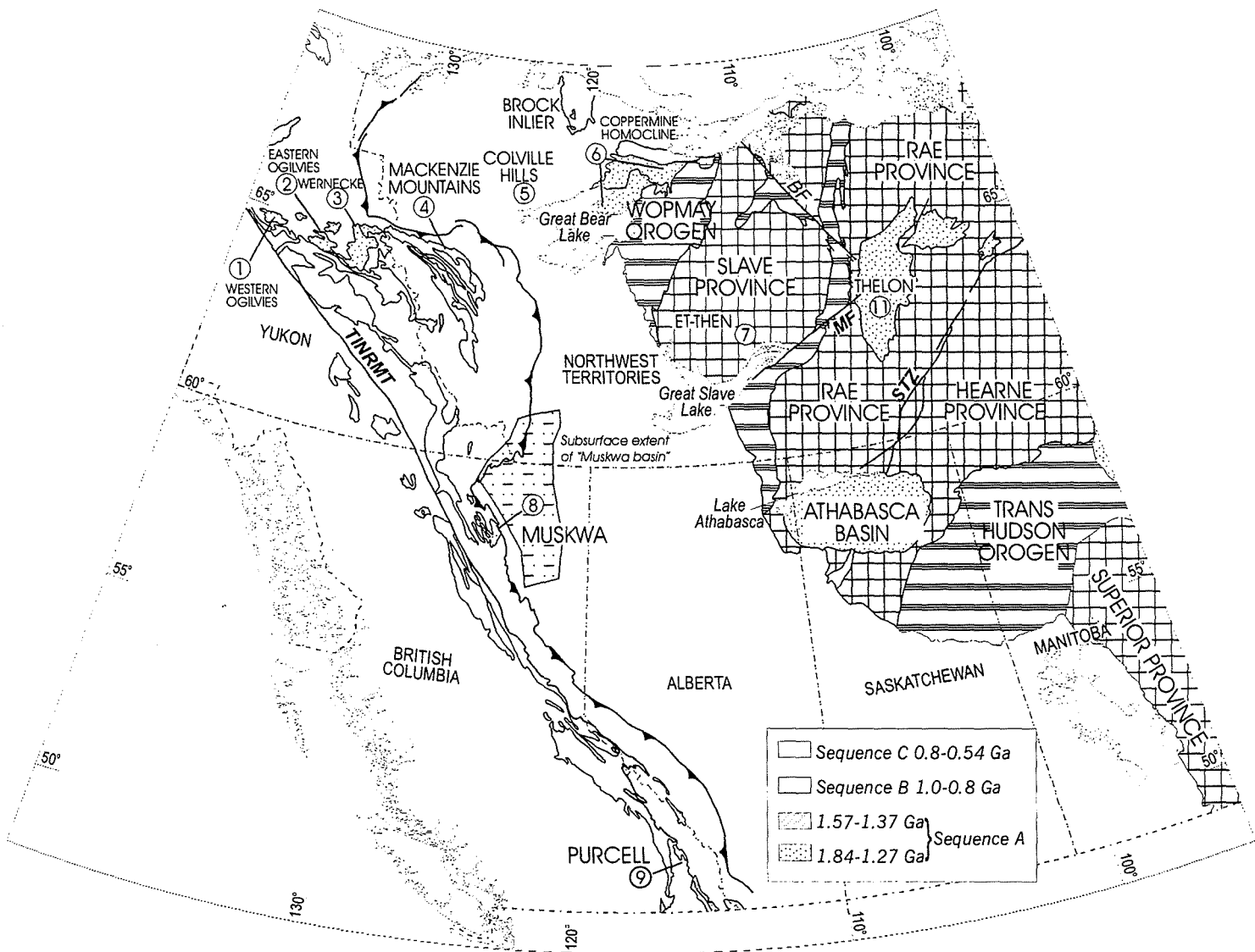
** this is an excerpt from a paper submitted to Precambrian Research. Preprints may be obtained
by request to gmross@nrcan.gc.ca*

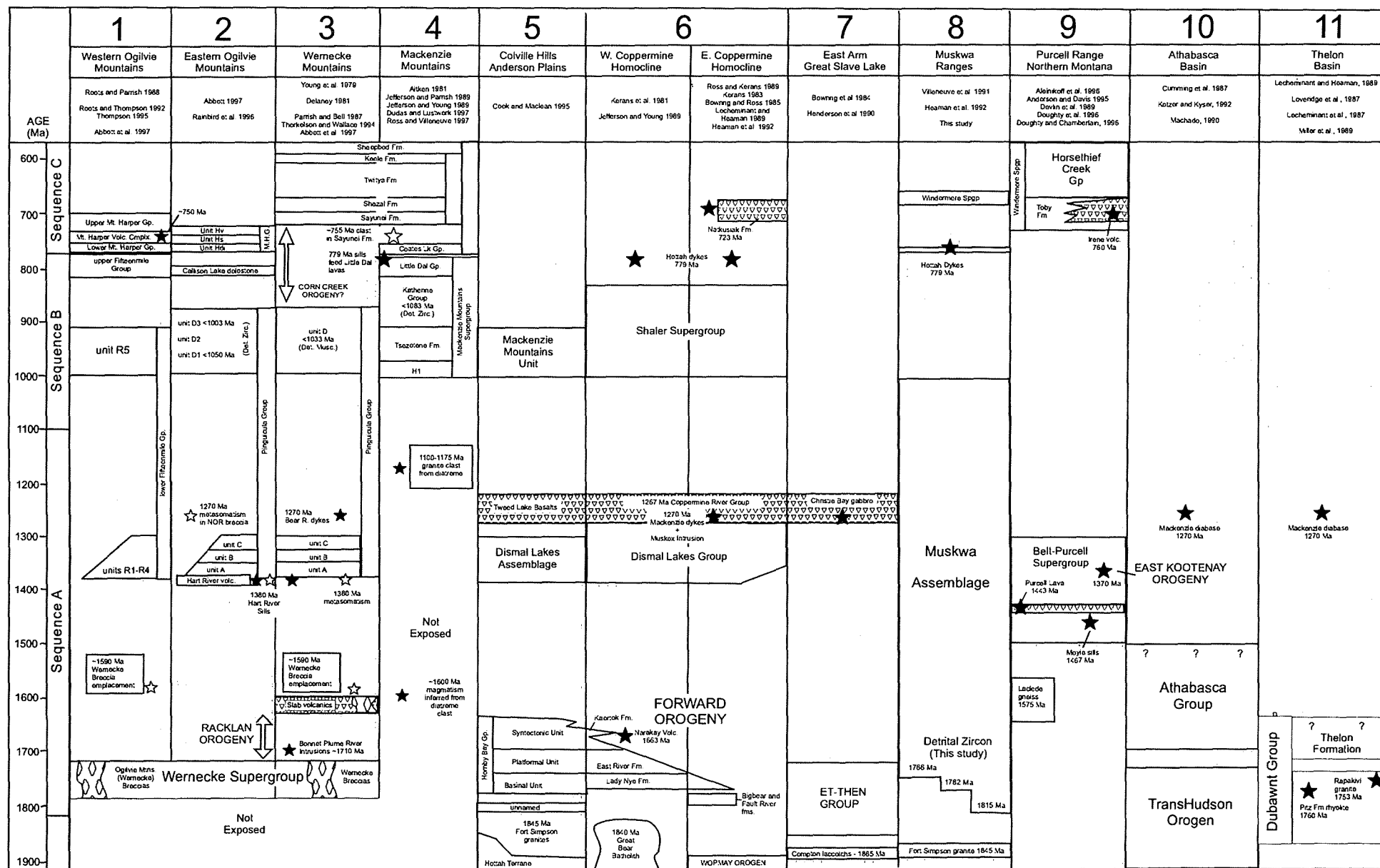
The Muskwa assemblage is a thick (6 km) sequence of essentially unmetamorphosed, predominantly fine-grained siliciclastic and carbonate strata carried within thrust sheets of the Canadian Rocky Mountains of northeast British Columbia. It is inferred to be widespread in the subsurface of the autochthon to the east on the basis of industry seismic sections and the SNORCLE seismic reflection profile. The age and stratigraphic affinities of this succession are uncertain although it is known to be older than 779 Ma based on the age of cross-cutting dykes. Based on extrapolation into the subsurface it is younger than the age of crystalline basement of the Fort Simpson terrane (1845 Ma) which underlies inferred Muskwa reflections seen on seismic profiles. We report U-Pb SHRIMP ages for detrital zircons from four sandstone units and Sm-Nd data for interbedded shales which refine stratigraphic ages and correlation (Figure 1).

$^{207}\text{Pb}/^{206}\text{Pb}$ ages determined by SHRIMP analysis of 94 detrital zircon grains from 4 sandstone samples range from ca. 3075 - 1766 Ma with a pronounced concentration of ages at ca. 1850 Ma. The youngest, most concordant analysis constrains the maximum age of the Muskwa assemblage to 1766 ± 14 Ma (99.5% concordant; 1 sigma error). Recent geochronology in the subsurface of southern NWT along the SNORCLE transect suggests that grains as young as ca. 1840 Ma could have been derived from this region. However, sources younger than that have not been found in basement proximal to the Muskwa basin. The pattern of U-Pb ages is similar to that of the western

Canadian Shield and the abundance of grains with young ages (1850-1770 Ma) implies derivation from similar aged rocks of the Rimbey granite belt, Hearne Province and possibly the internides of the TransHudson orogen.. Sm-Nd analysis of associated mudrocks result in a range of ϵ_{Nd} values that overlap with western Canadian Shield sources but result in T_{DM} model ages of 2.30-2.45 and 2.18-2.33 Ga, using Goldstein et al. or DePaolo models, respectively. The calculated Nd model ages are too young to have been derived exclusively from typical western Canadian Shield with the exception of the Rimbey granites in the basement beneath central Alberta, Hottah terrane of western Wopmay orogen or the internides of TransHudson orogen.

The provenance characteristics of the Muskwa assemblage are distinct from those considered typical of sequence B strata that are characterized by detrital zircons and Sm-Nd signatures derived from the Grenville Province of eastern North America. Hence the Muskwa assemblage is assigned to sequence A although it cannot be demonstrated which of the sequence A successions in western Canada are direct correlatives, if any. The provenance of the Muskwa assemblage is dramatically different than the Belt-Purcell, for example, one of the proposed correlatives. Regional considerations suggest that most likely correlation is with cratonic sand sheets of the Amundsen, Thelon and Athabasa Basin that developed immediately after assembly of the core of Laurentia.





GEOLOGY OF LOWER CAMBRIAN STRATA AT MUNCHO LAKE, NORTHERN BRITISH COLUMBIA

Ryan T. POST, and Darrel G.F. LONG,

(Department of Earth Sciences, Laurentian University, Sudbury, Ontario. P3E 2C6,
(rt_post@nickel.laurentian.ca, dlong@nickle.laurentian.ca)

Stratigraphic observations on Lower Cambrian strata in the Terminal Range, near Muncho Lake (58°59'N; 15°47'W), can be interpreted in terms of a clastic-carbonate depositional regime within a rift related, fault controlled basin, associated with the early development of the Paleozoic Cordilleran margin. The basal member of this 1300m thick succession is a 65 m unit of muddy siltstone and fine grained sandstone, with interbedded with oöid-bearing, carbonate-rich strata (Fig. 1). These are interpreted as part of a relatively large, shallow playa lake which developed on the emergent MacDonald High. The basal strata are overlain by about 900 m of massive cobbly-pebble conglomerate, with minor discontinuous lenses of pebbly sandstone. These are interpreted as products of a high gradient, ephemeral, gravelly braided river system, analogous in part to the modern Scott River in Alaska. Overlying this unit is a sequence of mixed carbonate rich siliciclastics sandstones and mudstones which are characterised by locally developed, incomplete carbonate-enriched soil profiles. Predominant textures of these aridisols include displacive and amalgamated carbonate nodules, displaced oxide-rich lamellae, small-scale desiccation cracks, and micro-slump structures. The stratigraphic position of the paleosols between fluvial conglomerates and marine sandstones is analogous to a wadi-sabkha transition. 250 m of thick-bedded, massive, carbonate cemented sandstones overlie the soils and conglomerates and in places are locally interbedded with conglomerates and recrystallized oncolite-bearing carbonate beds. This package is interpreted as the subaqueous marine component of a small, coarse-grain braid-delta. The Lower Cambrian strata are conformably overlain by at least 200 m of non-fossiliferous grey calcareous mudrocks of the Kechika Group.

The sedimentary framework of the Lower Cambrian, clastic-carbonate succession exposed at Muncho Lake is consistent with deposition within a fault-controlled basin during an early stage of rifting in a low latitude setting. The basal lacustrine strata on this segment of the MacDonald High were overwhelmed by progradation of a thick, predominantly axial, fluvial package. Following deposition of the cobbly-pebble conglomerates, a marked reduction in subsidence rates led to deposition of a fluvial-marine transition zone within the

basin. Exceptionally low accretion rates allowed for the production and preservation of aridisols in the peritidal and supra-tidal sabkha. With continued subsidence, possibly during an early drift stage, the margin was transgressed by shallow, storm-agitated marine waters, to produce a relatively narrow coastal plain in part analogous to the modern Red Sea.

The Cambrian strata near Muncho Lake, previously assigned to the Atan Group, display no physical similarity to the type section of this group, which is located 250 km to the west, on the far side of the Tintina - Northern Rocky Mountain trench. The paucity of fossil-bearing carbonates, in combination with the development of a thick fluvial package, is similar to other rift- to drift packages along the paleo-margin of the Cordillera, including the MacNaughton Formation of the Gog Group in areas well to the south.

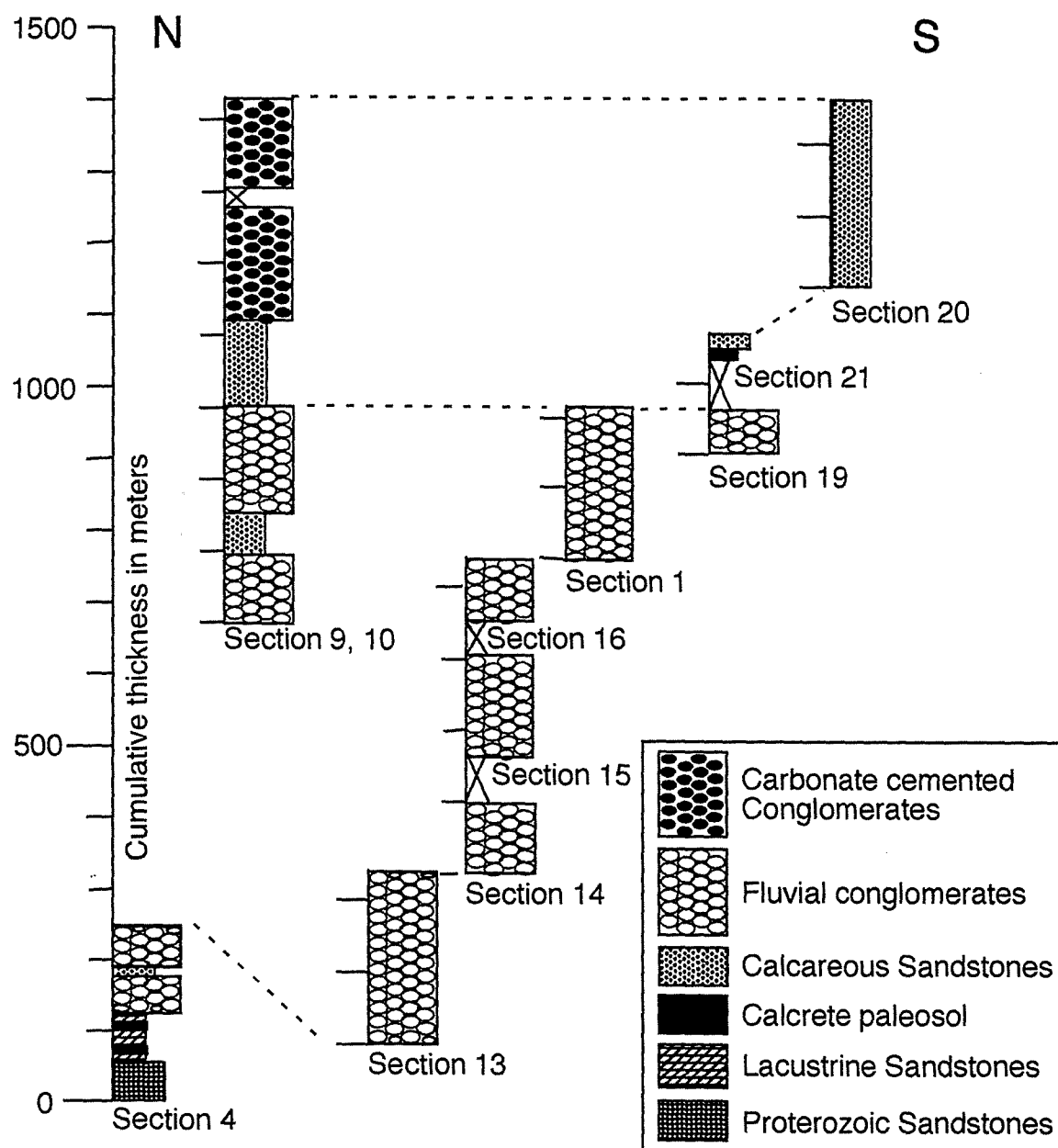


Figure 1: Preliminary correlation of measured sections of Lower Cambrian strata at Muncho Lake.

Section Locations:

- 1: 59°00.12'N, 125°47.73'W to 59°03.02'N, 125°48.12'W;
- 4: 59°02.14'N, 125°53.35'W to 59°03.00'N, 125°50.54'W;
- 9: 59°01.86'N, 125°49.15'W;
- 10: 59°01.37'N, 125°48.62'W to 59°01.48'N, 125°49.54'W;
- 13: 59°00.78'N, 125°47.61'W to 59°00.49'N, 125°48.40'W;
- 14: 59°00.00'N, 125°48.12'W;
- 15: 59°00.61'N, 125°48.15'W;
- 16: 59°00.39'N, 125°47.88'W;
- 19: 58°59.59'N, 125°48.15'W;
- 20: 58°59.59'N, 125°47.88'W;
- 21: 58°59.39'N, 125°47.06'W.

**Joint Subfabrics and Their Tectonic Significance in Sedimentary
Rocks of the Cordilleran Shelf-Miogeocline, Southwestern Inualuit,
Canada**

D.K. Norris*, B.R. Pelletier and L.D. Dyke****

Abstract

The Cordilleran shelf-miogeocline in southwestern Inualuit comprises a succession of layered sedimentary rocks ranging in age from Precambrian Helikian to Paleozoic Carboniferous, resting with profound unconformity on Precambrian, mostly crystalline rocks of the Hudsonian basement. The succession is an integral part of the supracrustal wedge, ranging in thickness from zero at the western edge of the Canadian Shield to approximately 7 km along the interface between the Interior Platform and the Cordilleran Orogen, to more than 20 km within the orogen.

The most striking feature of this relatively undeformed, succession of the shelf-miogeocline is the regionally pervasive, unconformity-bounded joint systems oriented perpendicular and sub-perpendicular to the lithologic layering. These systems can be subdivided into sets of different orientations and ages, that are traceable from the platform into the orogen, and that may bear no dynamic relationship to folding and faulting in the adjacent Cordilleran Orogen. Few systematic joints show any evidence of shearing movement across them although locally some of them have been dilated and mineralized with calcium carbonate.

The fact that many of the joint sets in the Frontal Belt of the Cordilleran Orogen assumed about the same orientation as those in the undisturbed rocks of the Interior Platform after the beds hosting them have been unfolded and unfaulted would suggest that systematic jointing was superposed on the rocks prior to their being uplifted, externally rotated and eroded. The remarkable coincidence in orientation of joint systems of diverse ages over areas of continental dimensions tends to support the hypothesis that the causal forces may have been global in application. One possibility is that systematic joints could be due to earth tides (Hodgson, 1961, p. 37), with concomitant brittle failure by rock fatigue. Another is that they may be due to epeirogenesis (Babcock, 1973, p. 1779). Whatever the mechanism, those joints of Paleozoic or older age in the Cordilleran shelf-miogeocline must have been inherited from Pangaea prior to breakup, some 150 to 180 million years ago.

*444 Okaview Rd., Kelowna, B.C. Canada, V1W 4L4

** Geological Survey of Canada, 601 Booth St., Ottawa, Canada K1A 0E8

**Evolution of the Laurentian margin during the late Cambrian to early Silurian:
Stratigraphy and conodont biostratigraphy of a platform to basin transect,
northeastern British Columbia**

Leanne J. Pyle and Christopher R. Barnes, School of Earth and Ocean Sciences,
University of Victoria, P. O. Box 3055, Victoria, BC V8W 3P6
leanne@uvic.ca; crbarnes@uvic.ca

Lower Paleozoic strata of the Canadian Cordilleran Miogeocline have been examined across a platform to basin transect, which addresses the nature of the rifted margin of Laurentia and its evolution from the late Cambrian to early Silurian. Regionally, renewed phases of extension of the margin throughout the Lower Paleozoic are recorded in abrupt lateral and vertical facies changes and pulses of volcanism. The transect spans over 500 km in the Ware, Tuchodi Lakes and Kechika (94F, K, L) and McDame (104P) map areas and lies within an interpreted upper plate of an asymmetrically rifted margin (Cecile et al., 1997). The study provides detailed stratigraphic descriptions of over 12,000 m of strata from the Kechika Formation (late Cambrian to lower Arenig), Skoki Formation (lower to middle Arenig), and Road River Group (lower Arenig to Llandovery) from nine principal sections across the Macdonald Platform to Kechika Trough and three sections from an east-west transect of the parautochthonous Cassiar Terrane. The line of transect approximates to part of Line 2 of the LITHOPROBE/SNORCLE transect and complements similar studies in the southern Cordillera and in Newfoundland now being addressed by a Pan-LITHOPROBE Project.

Revised stratigraphic terminology has been proposed (Pyle and Barnes, in press) in which the Kechika Formation is divided into 5 new formal members: the Lloyd George, Quentin, Grey Peak, Haworth and Mt. Sheffield members. The Skoki Formation comprises the new Sikanni Chief, Keily and Redfern members. The Road River Group is divided into three new formations: the Ospika, Pesika and Kwadacha formations. The Ospika Formation is further subdivided into five formal members: the Cloudmaker, Finlay Limestone, Chesterfield, Finbow Shale and Ware members.

Over 40,000 identifiable conodont elements have been recovered from 405 (4-5 kg each) samples which range from high species diversity and abundance in the platform and miogeocline facies to low in the deep basinal environments. The total fauna comprises over 100 multielement species representing over 50 genera from both the

Midcontinent and North Atlantic realms. Conodont zones recognized in the Kechika Formation range in age from the *Eoconodontus notchpeakensis* Zone (late Cambrian) through Faunas B, C and D (Tremadoc to early Arenig) recognized for the Midcontinent succession. The thick carbonate and shale ramp succession of Kechika suggests that a phase of post-rift thermal subsidence or extension was initiated in the late Cambrian and continued until the lower Arenig (*Oepikodus communis* Zone). A deepening phase during the early Arenig is recorded by the initial deposition of the black shale of the Ospika Formation of the Road River Group. This second phase of extension is marked by early Middle Ordovician volcanics observed at the Kechika-Road River boundary in the Kechika Trough. The base of the Skoki lies within the *O. communis* Zone and the formation ranges into the *Jumudontus ganada* and *Tripodus laevis* zones (lower to middle Arenig). Abrupt lateral facies changes occur from the Skoki, representing a broad subtidal platform facies that is transitional through debris flows at a well defined shelfbreak into the basinal lower Road River. The lower Skoki correlates with the lower part of its offshore equivalents in the Ospika Formation which ranges from the *Tetragraptus approximatus* (base Arenig) graptolite Zone into the *Paroistodus horridus* Subzone of the *Lenodus variabilis* Zone (base of the Llanvirn). The upper members of the Road River range into the Caradoc and Ashgill based on graptolite biostratigraphy. The overlying Pesika Formation lies within the *Distomodus staurognathoides* Zone of middle Llandovery age.

Conodonts from the parautochthonous Cassiar Terrane indicate the base of the Road River Group is older than that in the Kechika Trough, being within the *Rossodus manitouensis* Zone (Tremadoc) and with the unit ranging into the *Phagmodus undatus* Zone (middle Caradoc).

Several additional unnamed shelfbreak and basinal Road River units are the subject of a new study along a North-Central Rockies transect as part of the GSC Central Foreland NATMAP Project. This study involves 11 stratigraphic sections totaling 8850 m from which 257 (4-5 kg) conodont samples have been collected and are presently under processing and initial study. The biozonation for the Kechika, Skoki and Ordovician to Lower Silurian Road River Group provides a foundation for further studies in order to apply this zonation to the North-Central transect and further study of younger

strata of the Road River (Unnamed Upper Ordovician Shale and Quartzite, Carbonaceous Limestone and Lower Silurian Breccia Unit) and their platformal equivalents, namely the Beaverfoot, Lower Silurian Limestone and Nonda formations. In this area, the Middle Ordovician to Lower Silurian sequence is complicated by significant facies changes, influx of siliciclastics and prominent shelfbreak debris flows into the Ospika Embayment.

As only the general stratigraphic framework is understood from previous regional mapping, the present detailed stratigraphic and conodont biostratigraphic work across the Northern Rockies Transect has substantially clarified east-west temporal and facies relationships for the ancient margin. Refinement of the zonation for the thick ramp succession of the Kechika Formation (over 1000 m) and time equivalency of the lower part of the Skoki to the lower part of the basinal Ospika Formation has been established. Two phases of post-rift subsidence are suggested, one at the base of the Kechika and one at the base of the Ospika Formation and constrained as late Cambrian and early Arenig, respectively. Thompson (1989) has suggested a migrating carbonate shelfbreak through the early Paleozoic. Our study is providing refined dates and a redefined stratigraphy for the complex facies across the margin through much of the early Paleozoic that reflect both extensional events on the margin and flexures of the platform.

References

- Cecile, M. P., Morrow, D. W. and Williams, G. K. 1997. Early Paleozoic (Cambrian to Early Devonian) tectonic framework, Canadian Cordillera. *Bulletin of Canadian Petroleum Geology*, 45, p. 54-74.
- Davies, E. J. L. 1966. Ordovician and Silurian of the northern Rocky Mountains between Peace and Muskwa Rivers, British Columbia. Unpublished Ph. D. Thesis. University of Alberta.
- Pyle, L. J. and Barnes, C. R. (in press). Upper Cambrian to Lower Silurian stratigraphic framework of platform to basin facies, Northern British Columbia. *Bulletin of Canadian Petroleum Geology*.
- Thompson, R. I. 1989. Stratigraphy, tectonic evolution and structural analysis of the Halfway River map area (94B), northern Rocky Mountains, British Columbia. Geological Survey of Canada, Memoir 425.

Progress report on Middle and Late Triassic ichthyolith biostratigraphy and regional thermal maturation studies in the Trutch map area of northeastern British Columbia.

Marji J. Johns¹, Christopher R. Barnes², and Michael J. Orchard³

¹Pacific PaleoQuest, P.O. Box 220, Brentwood Bay, B.C. V8M 1R3

²School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055, Victoria, BC V8W 3P6

³Geological Survey of Canada, 101-605 Robson Street, Vancouver, BC V6B 5J3

INTRODUCTION

Ichthyoliths (microscopic fish teeth and scales; Fig. 1) are a new tool for the development of a tectono-stratigraphic framework for Triassic rocks and in future hydrocarbon exploration in northeastern British Columbia (NE BC). Ichthyoliths have utility in biostratigraphic, paleoenvironmental, and thermal maturation assessments. They have a broad distribution in pelagic environments, may be recovered from small samples in both marine and nonmarine sedimentary rocks, and have a long fossil record (Cambrian to Recent).

This report summarizes progress on a new project initiated in 1998 on Triassic ichthyolith biostratigraphy and thermal maturation studies in the Trutch (94G) and Halfway River (93B) map-areas. The study is supported through the LITHOPROBE SNORCLE Program and the Geological Survey of Canada's Central Foreland NATMAP Project.

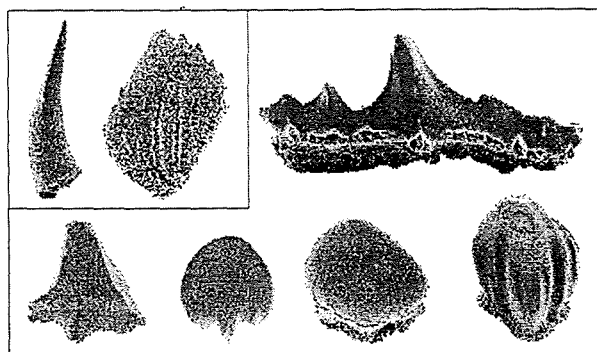


Figure 1. Examples of Late Triassic fish teeth and scales from NE BC.

PROJECT OBJECTIVES

The principal objectives of this project are to:

- 1) test, calibrate, refine, and expand the provisional Middle and Upper Triassic ichthyolith zonation of NE BC (Johns, Barnes, & Orchard, 1997) by sampling and studying faunas from new sections in the Trutch map-area;
- 2) recognize and interpret regional variations in ichthyolith successions and biofacies along and across the strike of the foreland belt;
- 3) develop an ichthyolith colour alteration index and recognize regional thermal maturation patterns;
- 4) investigate key stratigraphic and biological event intervals in the Triassic; and

- 5) combine and integrate these four components with GSC stratigraphic and biostratigraphic work to determine the regional tectono-stratigraphic framework for the western margin of the Western Canada Sedimentary Basin (WCSB).

A new objective is to interpret the pattern of gamma ray highs as observed at surface outcrops (1999 field data), assess their relationship to abundant ichthyolith and bone beds, apply results to surface to subsurface correlation, and explore the causes of the abundant ichthyolith beds that may relate to transgressive/regressive events, sedimentary processes, and (or) biological events.

In addition, comparison of NE BC results with other Triassic ichthyolith data from BC miogeoclinal and outboard terrane sections is important to better understand terrane motions from ichthyolith distributions.

1998 AND 1999 FIELD WORK

Excellent progress on this project has been made based on two successful field seasons (1998 & 1999). Superior field logistic support (helicopter time, student assistants, and field accommodation) from the GSC's Central Foreland NATMAP Project, allowed for collection of over 230 microfossil samples in 1998 and over 245 samples in 1999 from 11 Triassic locations across the Trutch and northern Halfway River map-areas of the central foreland belt (Fig 2). The best and most accessible Triassic exposures were sampled in the Liard, Charlie Lake, Baldonnel, and Pardonet formations (Ladinian, Carnian, and Norian) (Fig. 3). One section included samples from the Lower Triassic Toad and Grayling formations.

Collaborative fieldwork was undertaken with M. Orchard (GSC), J. Dixon (GSC), J.P. Zonneveld (GSC), and M. Cecile and L. Lane (leading several other geologists, mappers, and students as part of the GSC's Central Foreland NATMAP Project). In 1999, students and assistants G. Carrelli, C. Bass, R. Aquilini, & P. Tseng helped with field sample and data collections.

Also in 1999, new Upper Triassic ichthyolith samples were collected in the southern Cordillera at Silver Star Mountain (near Vernon) by Johns and J. Unterschutz. Other collections (Orchard) from the Cordillera include important ichthyoliths from the Nicola Group and the Tyaughton Formation/Cadwallader Group.

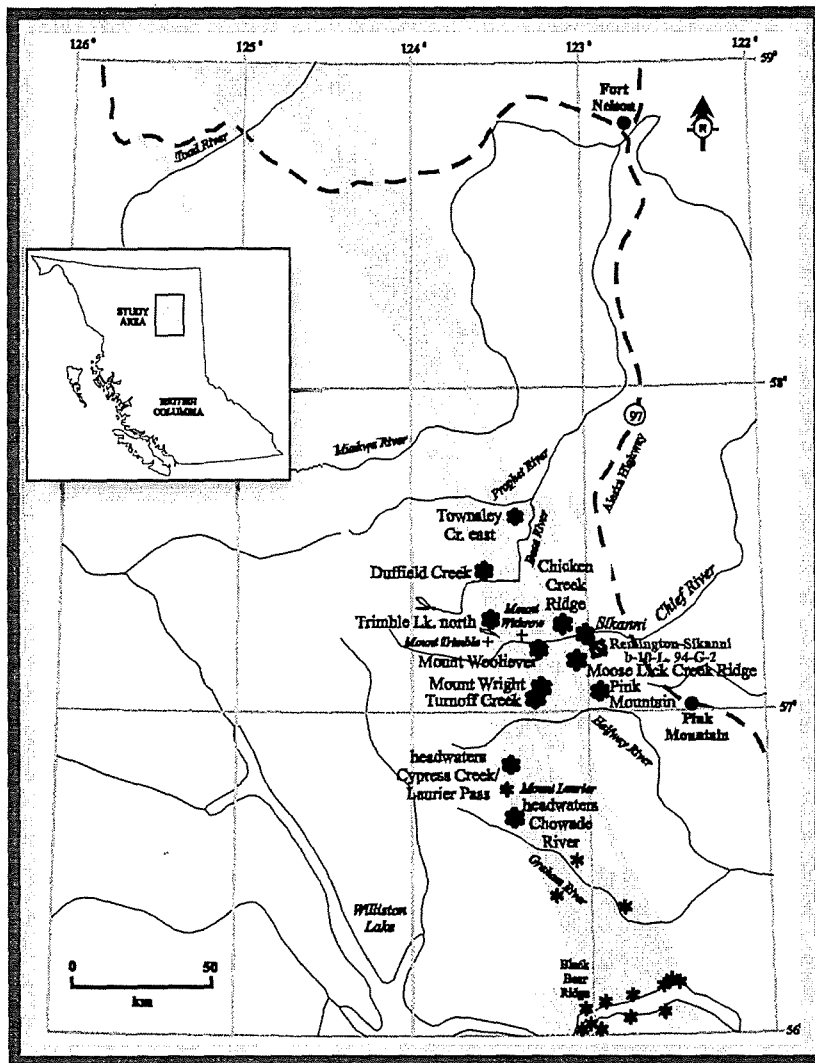


Figure 2. Index map of northeastern British Columbia. Shading shows Triassic exposure.

- ★ Locations where microfossil samples were collected in 1997, 1998, and 1999.
- * Pre-1997 microfossil samples.
- ⊗ Remington-Sikanni well B-10-L, 94-G-2

Figure 3. Triassic stratigraphy of northeastern British Columbia (after Gibson, 1993).

△ Locations and geological formations sampled for ichthyoliths in 1997, 1998, & 1999. Best ichthyoliths have been recovered from the Liard, Baldonnel, and Pardonet formations (Ladinian, Carnian, and Norian).

System / Series / Stage		Foothills Lithostratigraphy after Gibson, 1993		1997 - 1999 Ichthyolith samples								
		Outcrop	Subsurface	headwaters Chowade River	Cypress Creek/Laurier Pass	Trimble Lake north	Duffield Creek	Turnoff Creek	Mount Wright north	Mount Woollever	Chicken Creek ridge	Moose Lick Creek ridge
Triassic	Jurassic	Fernie Fm.	Fernie Fm.									
	Rhaetian	Bocock Fm.										
	Norian	Pardonet Fm.	Pardonet Fm.				△	△	△	△	△	△
	Carnian	Baldonnel Fm.	Baldonnel Fm.				△	△	△	△	△	△
		Dacotia Mbr.	Dacotia Mbr.		△	△		△	△	△	△	△
		Charlie Lake Fm.	Charlie Lake Fm.		△	△		△		△		△
	Ladinian	Liard Fm.	Halfway Fm.			△		△		△		
	Anisian	Toad Fm.	Doig Fm.									
	Spathian											
	Smithian											
Lower Triassic	Dianerian											
	Griesbachian	Grayling Fm.	Montney Fm.	△								

ICHTHYOLITH FAUNAS

A previously developed ichthyolith biostratigraphy is being refined (Fig. 4) and will provide an important biostratigraphy for ancestral North American faunas that can be used as a standard to compare broader distributions of ichthyoliths from outboard terranes and distant basins. Based on results up to and including 1998 samples, new ichthyoliths have been documented in the Upper Carnian, near the Carnian/Norian boundary, Lower Norian, and Upper Norian. Data from 1999 samples will help further document the ranges of these new faunas in each of the sections, refine the regional zonation, and provide additional specimens for taxonomic description and illustration of new species.

LITHOSTRATIGRAPHY

Detailed lithostratigraphy will be compiled by Dixon, Zonneveld, Orchard and Johns. Johns is compiling new stratigraphic data from sections at Mount Wright north, Duffield Creek, and Pink Mountain, and additional data from Moose Lick Creek ridge and

Turnoff Creek. New jointly collected data (Zonneveld, Orchard & Johns) are from Mount Wooliever and north of Trimble Lake.

In 1999, Johns focussed on the upper Charlie Lake and Baldonnel Formation successions, tracking the transition from the shoreface/hypersaline facies of the Charlie Lake Formation to the inner marine shelf/ramp facies of the Baldonnel Formation. The resistant and massive light-gray limestones of the upper Baldonnel Formation are usually easily recognized in the field. However, below this unit, it can be difficult to differentiate the Baldonnel and Charlie Lake formations because the basal Baldonnel succession commonly consists of recessive and mixed lithologies that indicate deepening and shallowing cycles. The lithologies include flaggy and blocky limestone, chert nodules, siltstone, shale, and sandstone.

Marine ichthyoliths are recovered from a dark gray-brown flaggy limestone unit in the lower Baldonnel Formation at Moose Lick Creek ridge. A similar unit found in outcrop

in the Peace River-Sukunka River areas was described by Gibson (1975) and Gibson & Edwards (1990) as the Ducette Member of the Baldonnel Formation and was interpreted as flooding cycles equivalent to the deeper water facies of the Ludington Formation to the west. Davies (1997b) recognizes the Ducette Member just above the Siphon unconformity in the Remington Sikanni B-10-L, 94-G-2 well located to the east of our sections (Figs. 2, 5). Initial evidence from our fieldwork indicates Ducette-like units at several Trutch locations. Results from 1999 microfossil samples will provide more data.

ABUNDANT ICHTHYOLITHS

Ichthyolith-abundant beds are good markers that can be used to correlate surface and subsurface strata. Several of these beds in the study area are widespread, distinctive and appear to correspond to known Western Canada Sedimentary Basin sequence boundary events in the upper Ladinian, Carnian, and Lower, Middle, and Upper Norian (Figure 6). More than one cause for beds with abundant ichthyoliths is probable. In addition to accumulation at the contact of two sedimentary facies, other causes for ichthyolith abundance could include winnowing and concentration of coarser, heavier, and more resistant particles; concentration resulting from long periods of slow deposition; increased productivity such as from upwelling resulting in nutrient enrichment and fauna abundance; and mass mortality resulting from large phytoplankton blooms or

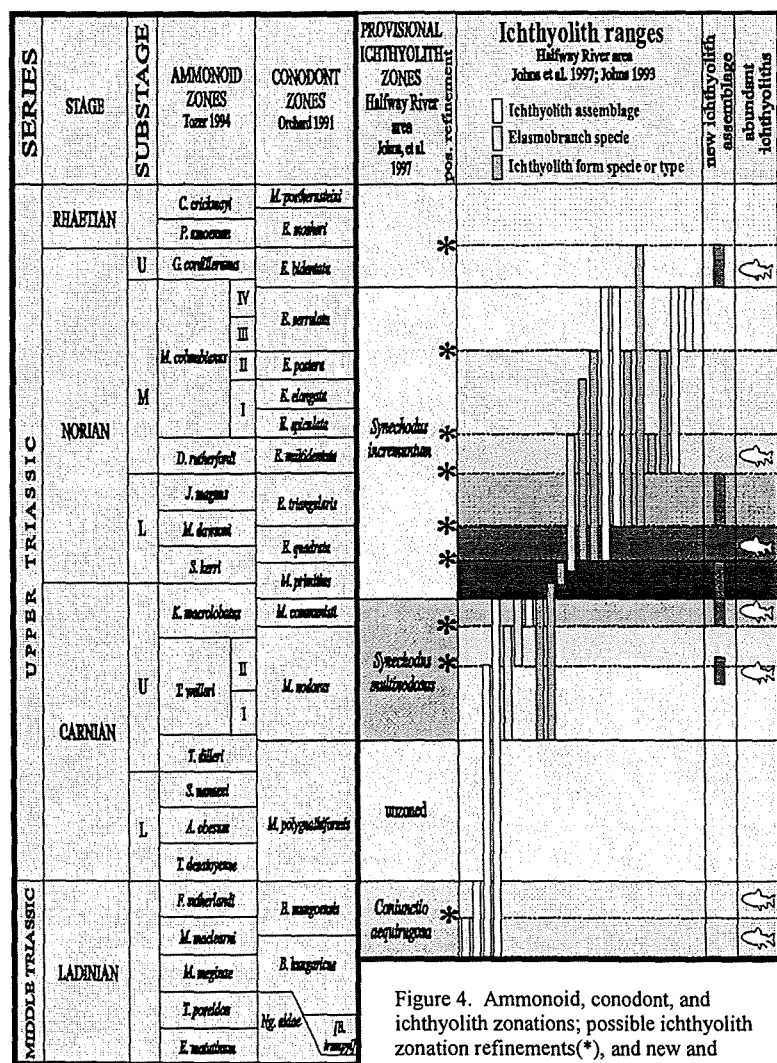


Figure 4. Ammonoid, conodont, and ichthyolith zonation; possible ichthyolith zonation refinements (*), and new and abundant ichthyoliths.

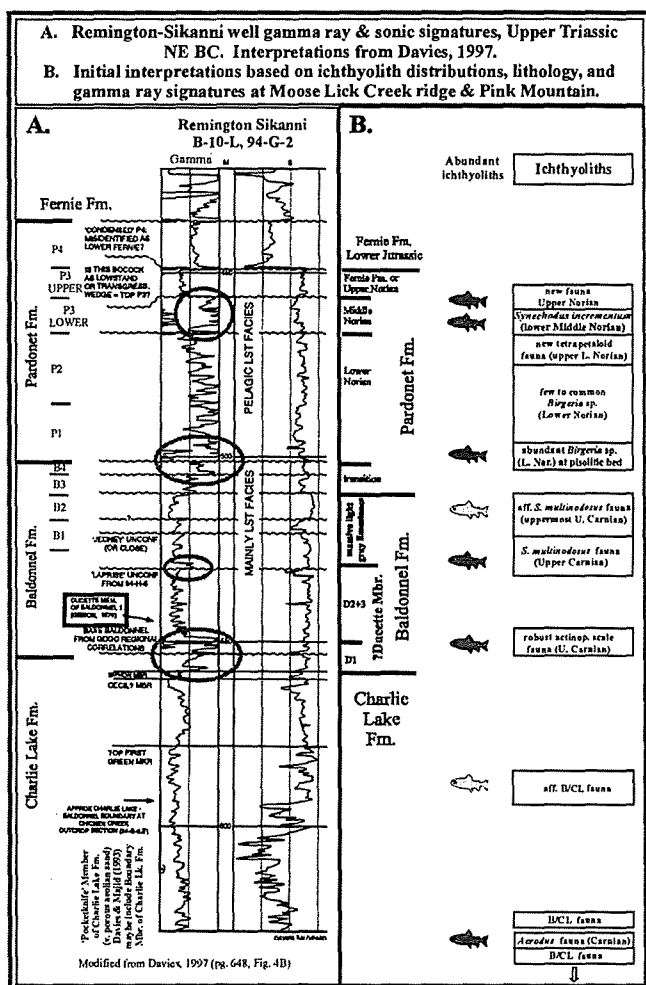


Figure 5. A) Remington-Sikanni well gamma ray and sonic signatures, and geological interpretations, Upper Triassic, NE BC (from Davies, 1997). B) Abundant ichthyoliths and gamma ray data at Moose Lick Creek Ridge, Pink Mountain, and other locations will provide important data to correlated surface and subsurface strata. Abundant ichthyoliths are commonly associated with high gamma ray levels (circled).

sudden basin turnover to an anoxic environment. Ichthyolith preservation in strata can be affected by their hydroxyapatite composition (ichthyoliths are resistant to some diagenetic processes), and their specific gravity (heavier than silicates). Paleo-environments in the Upper Triassic are variable and we are currently interpreting some of the causes.

GAMMA RAY DATA

Ichthyolith-abundant beds may correlate with phosphatic spikes (high gamma-log deflection levels over 100/150 API) from subsurface wells. Davies (1997b) found a variety of phosphatic materials in Baldonnel and Pardonet Formation sedimentary environments and that because of the complexing of uranium with the synsedimentary phosphate and associated organic material, these intervals will show increased gamma ray log profiles. Future subsurface sampling is anticipated and could be focused near rich phosphatic/ichthyolith levels. Subsurface and outcrop units could be correlated and dated using both gamma ray and ichthyolith data (Fig. 5).

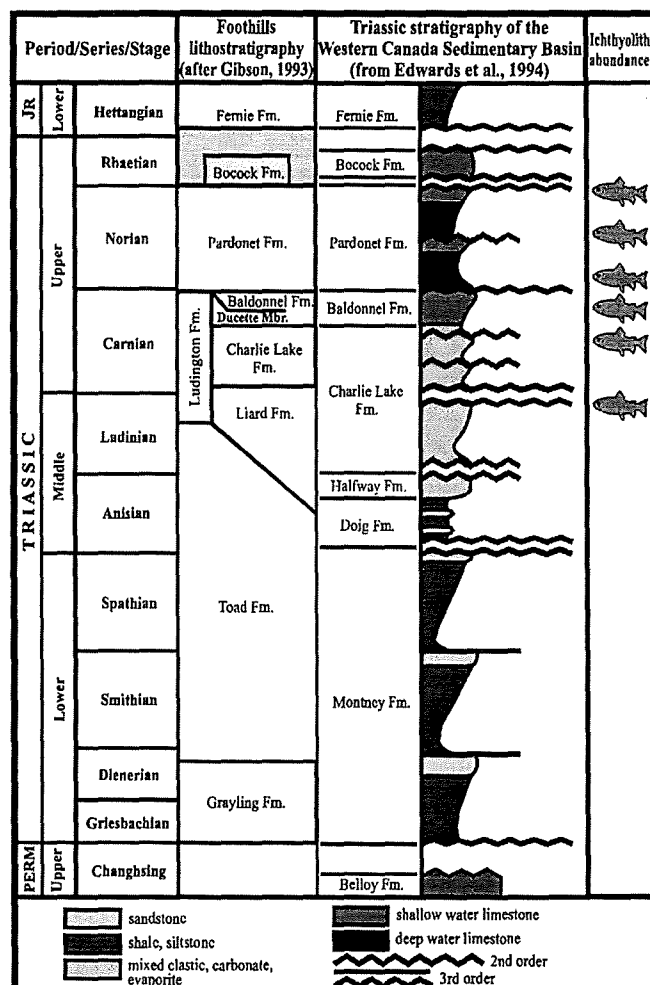
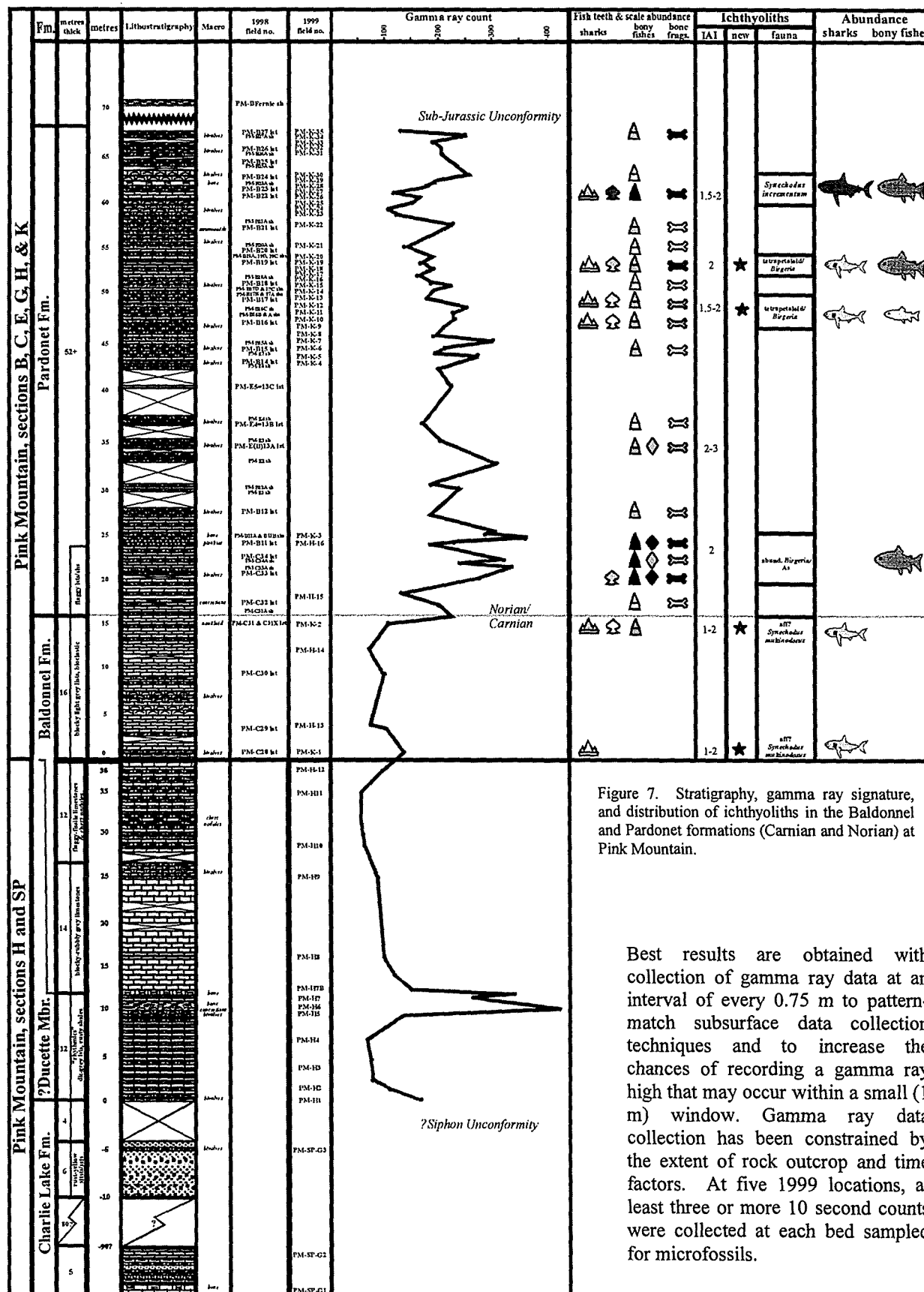


Figure 6. Abundant ichthyolith beds may be correlated with sequence boundaries recognized in the Triassic Peace River Basin subsurface. Second order sequence boundaries in the Upper Triassic are known at the Rhaetian/Norian, Norian/Carnian, and Carnian/Ladinian boundaries. A third order sequence boundary is in the Middle Norian, and two boundaries in the middle Carnian. In the Carnian, these boundaries correlate with the Siphon, Boundary and Coplin unconformities (see Davies, 1997a).

A section selected as an example (Fig. 7), shows the Upper Triassic gamma ray signature at Pink Mountain. A significant gamma ray high was measured at a bone bed in Ducette-like strata near the contact of flaggy dark gray-brown limestones and blocky to massive lighter gray limestones. Overlying, is a repeat of Ducette-like strata but with more chert content, and an increase in the gamma ray level, followed by massive light-gray limestones that are well recognized in the upper part of the Baldonnel Formation. This pattern has been observed at other Trutch locations but the uppermost Baldonnel Formation light-gray limestone unit is thicker (totaling about 50 m) than at Pink Mountain.

The Pardonet Formation is an organic-rich interval and results show high gamma ray counts at Pink Mountain and other locations. Bone and abundant ichthyolith beds occur at the base, middle, and top of the Pardonet Formation.



THERMAL MATURATION STUDIES

Like conodonts, ichthyoliths show similar colour change patterns in response to heating. A bony fish tooth, *Birgeria* sp.1, is useful for colour and thermal analyses; it has a simple form, is abundant, and occurs in most of the samples so far studied in the Middle and Upper Triassic. Using this species in thermal assessments will provide consistent results.

An ichthyolith thermal alteration index (IAI) is in development. Only minor differences in thermal values have been observed within a section. This observation suggests that there was little heating variation during the Middle to the Upper Triassic. However, different locations across the strike of the central foreland belt generally show lower alteration values at the east and higher values to the west (Fig. 8).

In the NE BC sites, ichthyolith colour changes occur within a spectrum of conodont colour alteration indices ranging from about 1 to 5. The Pink Mountain and Moose Lick Creek ridge sites have an IAI value of 1.5 to 2. When correlated with CAI values they are within the oil window. Some anomalies may exist in the Williston Lake area. Samples collected in 1999 will provide thermal data from new sites in Trutch. Collaboration with C. Riediger (Univ. of Calgary) and G. Carrelli (M.Sc. student) has been initiated to undertake geochemical (total organic carbon and other) analyses on 1998 & 1999 samples and to provide comparative data to test the ichthyolith alteration index.

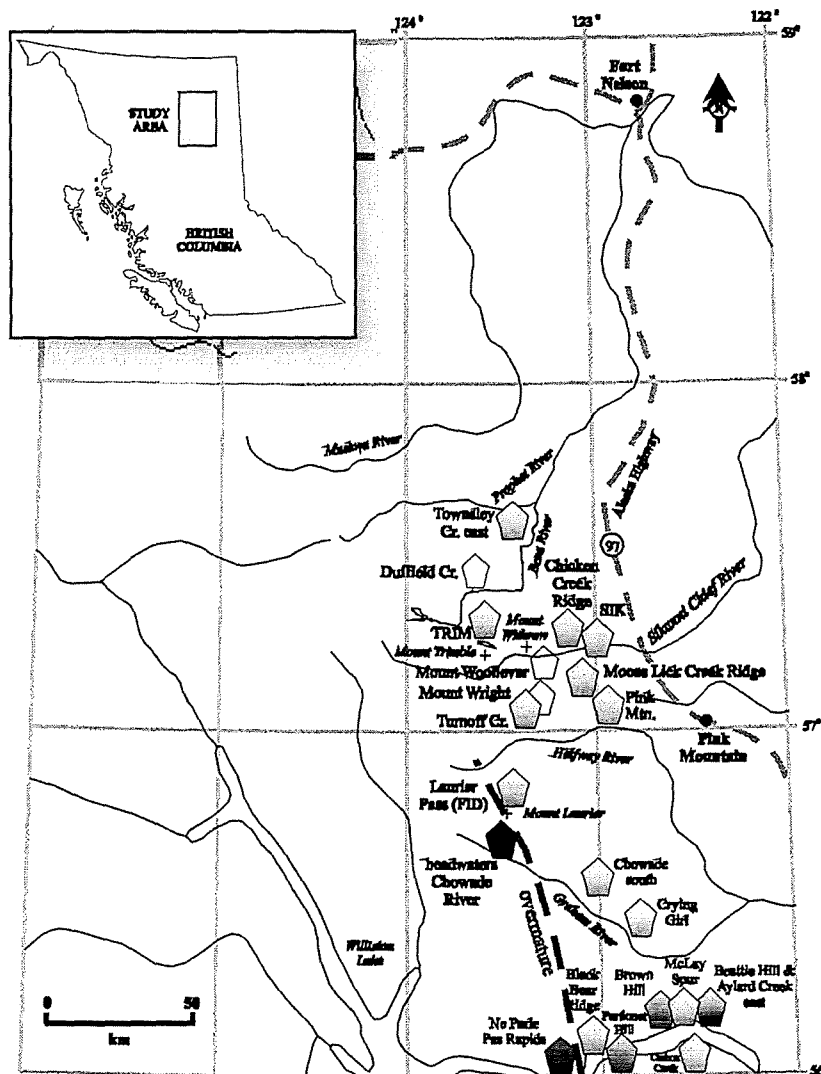


Figure 8. Index map of northeastern British Columbia illustrating ichthyolith colour alteration values and locations. Lighter shaded symbols indicate values within the oil & gas window. Open symbols are 1999 locations/samples yet to be analyzed.

REFERENCES

- Davies, G.R. 1997a. The Triassic of the Western Canada Sedimentary Basin: tectonic and stratigraphic framework, paleogeography, paleoclimate, and biota. *Bulletin of Canadian Petroleum Geology*, v. 45, no. 4, p. 434-460.
- 1997b. The Upper Triassic Baldonnel and Pardonet formations, Western Canada Sedimentary Basin. *Bulletin of Canadian Petroleum Geology*, v. 45, no. 4, p. 643-674.
- Edwards, D.E., Barclay, J.E., Gibson, D.W., Kvill, G.E., and Halton, E. 1994. Chapter 16. Triassic strata of the Western Canada Sedimentary Basin, p. 259-275; in *Geological Atlas of the Western Canada Sedimentary Basin*, G.D. Mossop, and R.I. Shetsen (compilers), Canadian Society of Petroleum Geologists and Alberta Research Council, 510 p.
- Gibson, D.W. 1975. Triassic rocks of the Rocky Mountain Foothills and Front Ranges of northeastern British Columbia and west-central Alberta. *Geological Survey of Canada Bulletin* 247, 61p.
- 1993. Upper Triassic coquina channel complexes, Rocky Mountain foothills, northeastern British Columbia; *Bulletin of Canadian Petroleum Geology*, v. 41, no. 1, p. 57-69.
- Gibson, D.W. and Edwards, D.E. 1990. An overview of Triassic stratigraphy and depositional environments in the Rocky Mountain Foothills and Western Interior Plains, Peace River Arch area, northeastern British Columbia. *Bulletin of Canadian Petroleum Geology*, v. 38A, p. 146-158.
- Johns, M.J., Barnes, C.R., and Orchard, M.J. 1997. Taxonomy and biostratigraphy of Middle and Late Triassic elasmobranch ichthyoliths from northeastern British Columbia; *Geological Survey of Canada, Bulletin* 502, 235 p., 38 pl., 14 fig.
- Orchard, M.J. 1991. Upper Triassic conodont biochronology and new index species from the Canadian Cordillera; in *Ordovician to Triassic Conodont Paleontology of the Canadian Cordillera*, M.J. Orchard and A.D. McCracken (eds.), *Geological Survey of Canada, Bulletin* 417, p. 299-335.
- 1999. Triassic conodont biostratigraphy and Upper Triassic stratigraphy, Trutch map area, British Columbia; in *Current Research 1999-A*, *Geological Survey of Canada*, p. 45-50.
- Tozer, E.T. 1994. Canadian Triassic ammonoid fauna; *Geological Survey of Canada, Bulletin* 467, 663 p., 148 pl.

CRUSTAL SEISMIC VELOCITY STRUCTURE OF THE NORTHERN CORDILLERA, SOUTHERN YUKON TERRITORY - LITHOPROBE SNoRE LINE 31

Brian Creaser and George Spence

*School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055, Victoria, BC,
V8W 3P6, Phone: (250)721-6120, Fax: (250)472-4620, E-mail: bcreaser@uvic.ca*

ABSTRACT

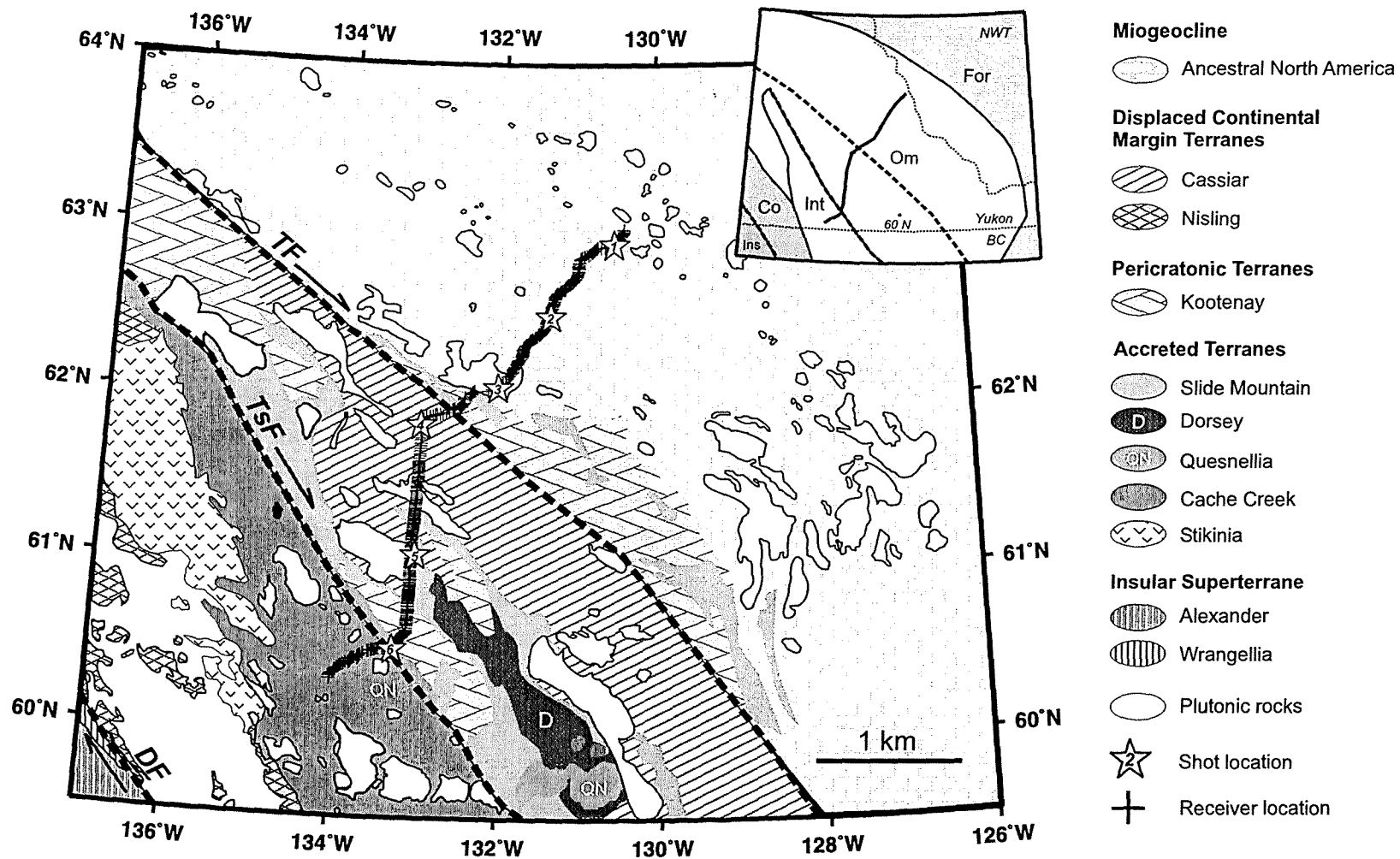
A seismic refraction/wide-angle reflection profile was collected in the summer of 1997 across the southern Yukon Territory in northwestern Canada. The data were acquired by LITHOPROBE as part of the Slave-Northern Cordillera Lithospheric Evolution (SNorCLE) transect Refraction Experiment (SNoRE). From east to west, Line 31 extends from the deformed miogeocline of ancestral North America (Omineca belt), across the Tintina fault (TF), through displaced continental margin terranes, and into pericratonic and accreted terranes of the Cordillera (Intermontane superterrane). The Tintina fault is a major intercontinental transform characterized by at least 450 km of late Cretaceous to Oligocene dextral strike-slip movement. Little is known about the subsurface expression of this feature. The profiled region has a complex geologic history, including phases of extension, contraction, accretion and lateral displacement. Models of crustal structure are essential to advance our understanding of the tectonic evolution of the northern Cordillera.

The 360 km-long seismic profile was comprised of 7 shot points (1000 - 2000 kg of T3 explosive). Data were recorded by 403 seismographs (PRS, REFTEK and SGR) spaced approximately 0.8 km apart. The Line 31 data quality is excellent. Numerous refracted and reflected phases are easily identified, including refracted energy from the shallow crust (Ps), upper crust (Pg) and upper mantle (Pn), as well as reflected energy from a mid-lower crustal reflector (R1) and the base of the crust (PmP).

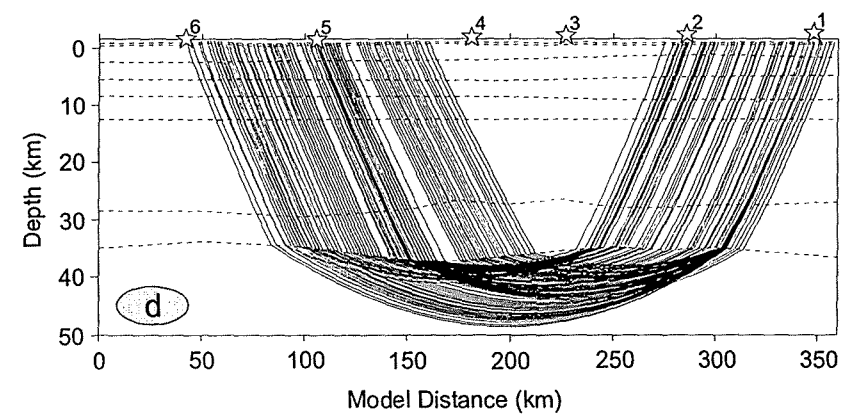
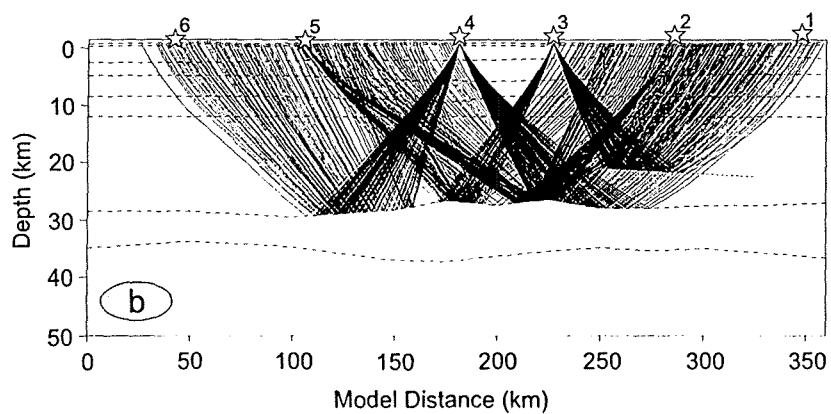
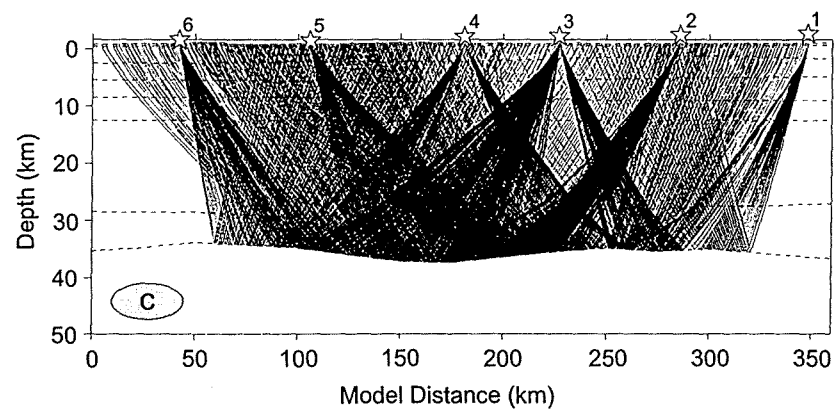
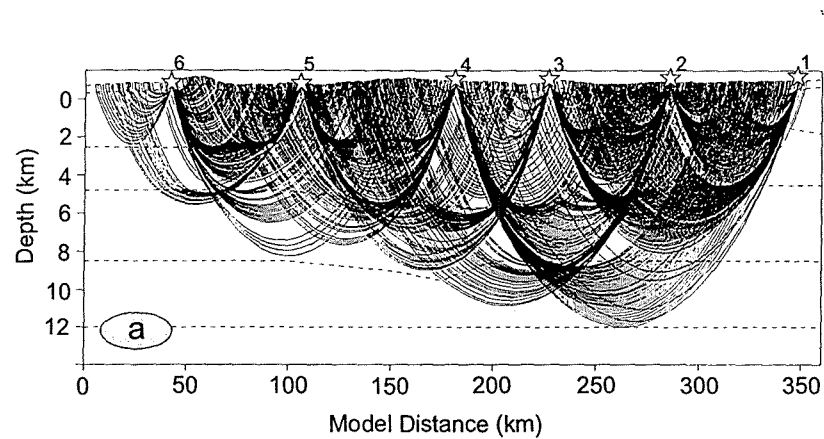
Forward and inverse modelling of traveltimes, combined with forward amplitude modelling indicates that the TF is a major crustal-scale structure across which significant structural differences occur. The upper-middle crust east of the TF is characterized by velocities (<6.3 km/s) slower than those to the west (<6.4 km/s). A mid-crustal reflector terminates to the east of the TF. The crust immediately west of the TF is thicker (~37 km) than the crust to the east (~34 km). Lower crustal velocities range from 6.4-6.7 km/s, with the lowest velocities located near the center of the model (thickest crust). Upper mantle velocities just below the Moho range from 7.8-7.9 km/s, consistent with the high heat flow in the region.

A reflector that may correspond to Proterozoic basement characterizes the base of the middle crust. Difficulty arises in tracing the TF through this reflector and to the base the lower crust, possibly due to the changing physical state of the fault zone with depth. However, thickening of the crust immediately to the west suggests movement along the fault in the lower crust.

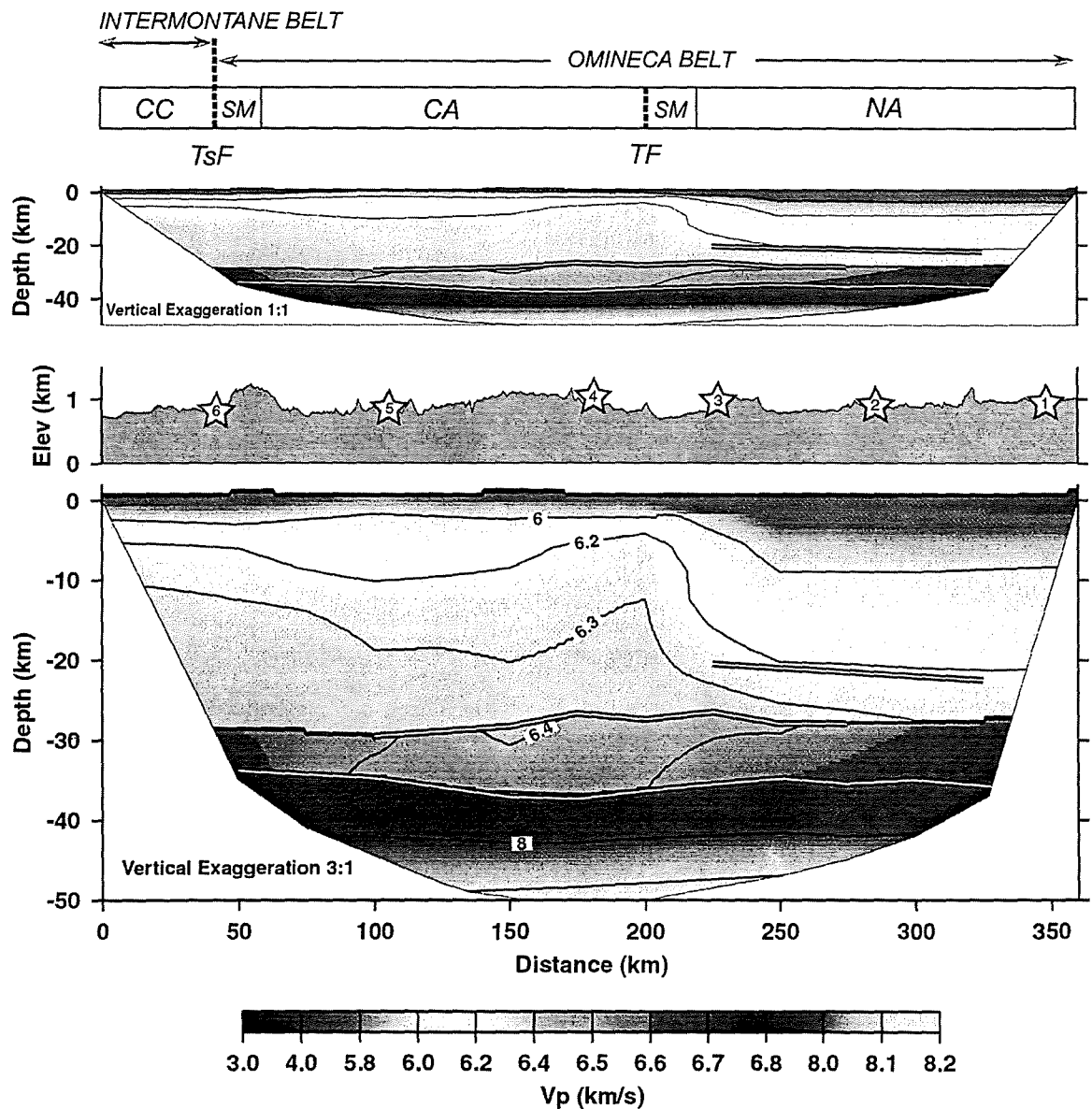
Additional data confirm the structure implied by the refraction modelling results. A simple density model confirms that the crust east of the TF is underlain by rocks of lower density than those to the west. A crude two-way traveltime section derived from the wide-angle data displays similar crustal structure as well as a reflective crust-mantle transition zone.



Tectonostratigraphic map of the study area showing the location of the SNoRE 31 R/WAR profile and major dextral faults (dashed lines). TF, Tintina Fault; TsF, Teslin Fault; DF, Denali Fault. Upper right map shows the profile with respect to morphogeological belts in the southern Yukon Territory. NWT, Northwest Territories; BC, British Columbia; For, Foreland Belt; Om, Omineca Belt; Int, Intermontane Belt; Co, Coast Belt; Ins, Insular Belt.



Ray coverage of the Pg (a), PcP (b), PmP (c) and Pn (d) phases. Dashed lines indicate layer boundaries used in modelling.



Final velocity model obtained from modelling refraction data. The velocity field is plotted with vertical exaggerations of 3:1 and 1:1. Double solid lines indicate where reflective boundaries are constrained by ray coverage. Stars indicate shot point locations. Simplified terrane and morphogeological boundaries are plotted on top: NA, Ancestral North America; SM, Slide Mountain terrane; CA, Cassiar terrane; CC, Cache Creek terrane; TsF, Teslin Fault; TF, Tintina Fault.

Reflections on Lithoprobe-SNORCLE Line 31 in light of the structure of the Teslin zone in the Last Peak area (NTS map 105E/9), southern Yukon Territory

Martin de Keijzer^{1,a}, Paul F. Williams¹, and Sharon D. Carr²

¹ Department of Geology, University of New Brunswick, Fredericton, NB, ^a de_keijzer@unb.ca

² Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, ON

The primary purpose of the Omineca belt section of seismic profile Line 31, once fully processed (preliminary results presented by Creaser and Spence [1999]), is to serve as the basis for an interpretation of the crustal structure in the Omineca belt of southern Yukon Territory. Line 31 runs ca. 100 km to the south of the study area along the Canol Road (Fig. 1), where it crosses the Teslin zone (TZ) (i.e. the northerly trending belt of rocks between post-accretionary faults; the Big Salmon/Teslin fault system to the west and the d'Abbadie fault system to the east). As such, the structure in the Last Peak area (NTS map 105E/9) established by de Keijzer and Williams (1998, 1999) and de Keijzer et al. (1999) as part of the SNORCLE project cannot be directly linked to the seismic profile. Nevertheless, as originally intended (Brown et al. 1995), the results of these studies, some of which are outlined below, provide important constraints on viable interpretations of the crustal structure in southern Yukon Territory.

Although their nature is unclear at present, a number of shallow seismic reflectors at depths between 20 and 40 km (including the Moho discontinuity at ca. 35 km) are visible in the preliminary velocity model of Line 31 in the subsurface of the TZ and the Cassiar terrane (Creaser and Spence 1999). Apart from some aspects of the structure of Stevens and Erdmer (1996), who inferred a shallow detachment in the subsurface of the TZ, these preliminary results are incompatible do not support the structure proposed by other previous workers in the TZ (e.g., Tempelman-Kluit 1979; Erdmer 1985; Hansen 1989; Stevens 1994). They suggested that the TZ comprises a discrete zone of steeply dipping rocks, with a steep foliation unique to the zone, that extends into the mantle. A prediction of their geometric models is an absence of good seismic reflectors in the TZ since layering and/or major structures (e.g., a km-wide shear zone) in a steep orientation typically lack(s) seismic reflectivity (e.g., McQuillin et al. 1984, p. 211).

The structure of the TZ described by de Keijzer et al. (1999) is substantially different to that of previous workers. Most importantly, the steep orientation of the transposition foliation (S_T ; defined by transposed compositional layering and S_1 and S_2 cleavages that are axial planar to F_1 and F_2 transposition folds, respectively; **Note 1**) in the TZ, in contrast to adjacent rocks to the east, is the result of F_3 folding (i.e. occurred late in the deformational history, rather than having

formed in a steep orientation, as proposed by other workers); most TZ rocks in the Last Peak area form the steep limb of the regional F_3 Grizzly synform. This fold has a shallow limb in the easternmost part of the zone and immediately east of the zone. According to this interpretation, North American rocks pass under the eastern TZ and outcrop to the west of the Nisutlin and Anvil assemblages. This geometry precludes the generally accepted notion that the zone is the root zone (i.e. location of initial detachment; western limit of the North American continental margin) of klippen to the east of the TZ. In other words, contrary to that proposed by, for example, Tempelman-Kluit (1979), Erdmer (1985) and Hansen (1989), the TZ does not mark the position of closure of the Anvil ocean/marginal basin. The root zone was somewhere to the west of the TZ. Its location, however, is unknown; the North American plate to the west of the TZ has been significantly modified by complex accretionary tectonics from the latest Permian onwards (e.g., Mihalynuk et al. 1994) and continental crust has been disrupted and translated along post-accretionary transcurrent faults such as the Teslin fault.

It appears that the geometrical framework described by de Keijzer and Williams (1998, 1999) and de Keijzer et al. (1999) is in agreement with the preliminary results of Creaser and Spence (1999). Various types of structures recognized by the authors could result in reflections, and assuming continuity of the regional structure (supported by the regional map [Wheeler and McFeely 1991]), are likely to have their counterpart in the subsurface near the Canol Road.

(1) Enveloping contacts between rock packages with sufficiently different reflection coefficients.

Principal candidates are the contact between the dominantly (ultra)mafic Anvil assemblage and siliceous and calcareous metasedimentary rocks of North America (i.e. the obduction boundary) and between the Anvil assemblage and dominantly siliceous metasedimentary rocks of the Nisutlin assemblage, as well as some contacts within the Nisutlin assemblage and North America (e.g., the contact between quartz-muscovite phyllite and graphitic siliceous phyllite). Whereas outcrop-scale transposed compositional layering in the TZ generally dips steeply at the surface, the enveloping surfaces of these contacts are believed to be relatively shallow under much of the TZ (de Keijzer et al. 1999; Fig.2). This type of reflector has also been suggested by Brown et al. (1998) and Gallagher (1999).

(2) Shear zones and/or flattening zones of more intense fabric development in which layering and earlier tectonic fabrics have been transposed into a shallow orientation. An example is the development of zones of more intense axial planar S_3 development close to the Grizzly synformal hinge. Such zones, whether related to the Grizzly synform or to similar, as yet unrecognized large-scale folds to the south may act as (laterally restricted?) seismic reflectors. The Two Cub antiform (Gallagher 1999), a km-scale post-transposition fold that has steepened S_T south of the study area and conceivably postdates the Grizzly synform (Gallagher 1999), is not associated with significant axial plane fabric development. Consequently, it does not fall in this category.

(3) One or more low-angle detachment zones (Fig. 2) related to mid-Cretaceous (**Note 2**) southwest-northeast-directed ductile extension (de Keijzer and Williams 1999; de Keijzer et al. 1999). In the study area, extension involved reactivation of the basal ductile thrust/obduction boundary, as well as the formation of more steeply east- and west-dipping normal faults dissecting structures that were formed during crustal thickening. We would like to emphasize the probability of significant crustal reworking elsewhere in southern Yukon Territory as a result of mid-Cretaceous extension; late-stage (brittle-)ductile (Roots et al. 2000) and brittle (e.g., Tempelman-Kluit 1977; Gordey 1981; Roots et al. 2000) normal faults have also been recorded in other parts of the Omineca belt in southern Yukon Territory. This suggests that extension late in the deformational history is a regional phenomenon. It is probable that as yet unrecognized extensional detachments are present in the area between the Tintina and Teslin faults near the Canol Road. If so, the nature (geometry, extent, and kinematics) of the extensional structures there should be studied in detail prior to interpretation of the Omineca belt part of Line 31.

Note 1: A 3 m-wide biotite-muscovite-bearing leucocratic augen orthogneiss in the Cassiar terrane and a dm-wide deformed granitic dyke in the western Dunite klippe apparently experienced similar ductile deformation and finite strain as the rocks they intruded (Carr et al. 1999). (Near) concordant U-Pb zircon ages of 331 ± 2 Ma and 267 ± 10 Ma obtained from the orthogneiss and the deformed granite, respectively (Fig. 3), provide lower age limits in the Cassiar terrane and the klippen for the high-strain portion of S_T development. Since the nature of F_1 - F_2 transposition is similar in the Anvil and Nisutlin assemblages and North America, (i) S_T development is attributed primarily to easterly directed obduction/ductile thrusting of the two assemblages onto North America (cf. de Keijzer et al. 1999), and (ii) penetrative fabric development in the orthogneiss and surrounding Cassiar terrane rocks is interpreted as having occurred at approximately the same time as in the Dunite klippen (i.e. also at 267 ± 10 Ma or later). The 267 ± 10 Ma age may, but need not, define a maximum age for the onset of S_T development (or the age of 'early' structures that subsequently were transposed during S_T development) since the klippe granite may have intruded during the early stages of this deformation. The 267 ± 10 Ma age is in agreement with the concordant 269 ± 2 Ma U-Pb age of a metamorphic zircon in the Last Peak eclogite in the western TZ (Creaser et al. 1997). This zircon is believed to have grown prior to amphibolite grade metamorphism of the eclogite during regional S_T development and shearing. If the ca. 236 Ma cooling age of a white mica (Erdmer et al. 1998; cooling below ca. 350°C) in the Last Peak eclogite is reliable (in view of the fact that excess argon is common in white mica) it implies that S_T development in the rocks surrounding the Last Peak eclogite is older than ca. 236 Ma. Thus, similar to de Keijzer et al. (1999), it is proposed that the abovementioned obduction and associated penetrative deformation in both the footwall and hanging wall rocks took

place between the middle Early Permian and late Middle Triassic. This differs from most other regional studies (e.g., Hansen et al. 1991; Plint and Gordon 1997; Stevens et al. 1996; Monger 1997; Hansen and Dusel-Bacon 1998), in which collision of the Yukon-Tanana terrane and North America, and emplacement of the former onto the latter by thrust faulting (discrete thrusts), occurred in the Late Triassic–Early Jurassic in the northern Canadian Cordillera. Largely brittle thrust faulting in the Late Triassic–Early Jurassic is believed to record ‘reshuffling’ of the crustal structure of the Omineca belt after initial obduction/ductile thrusting. The former may record higher crustal level convergent tectonism unrelated to, or a continuation of, pre-Late Triassic mid-crustal obduction-related ductile flow.

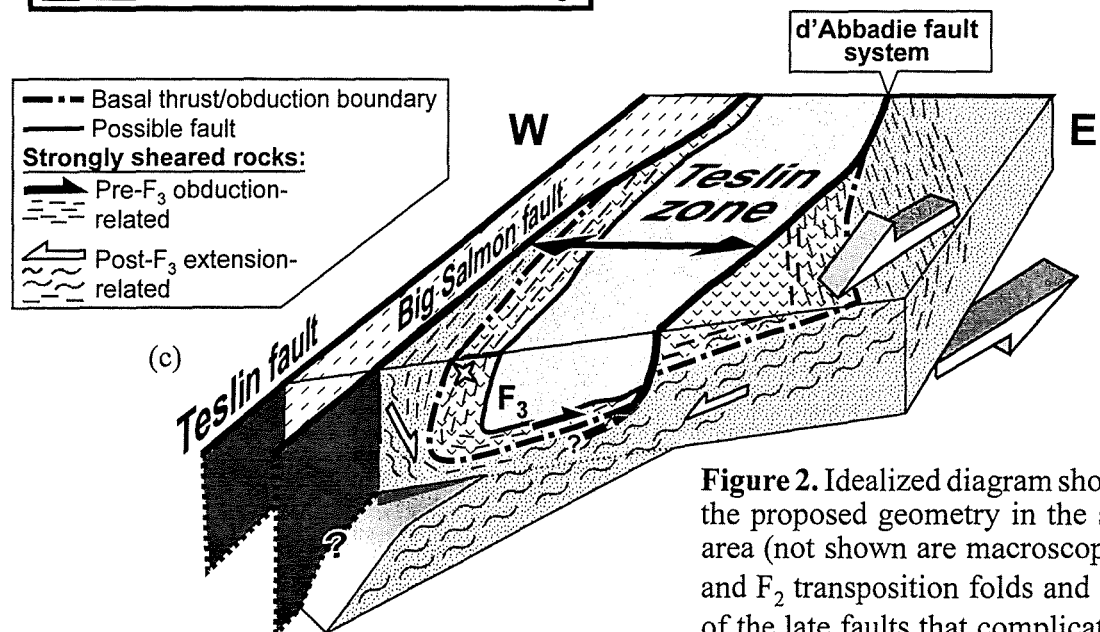
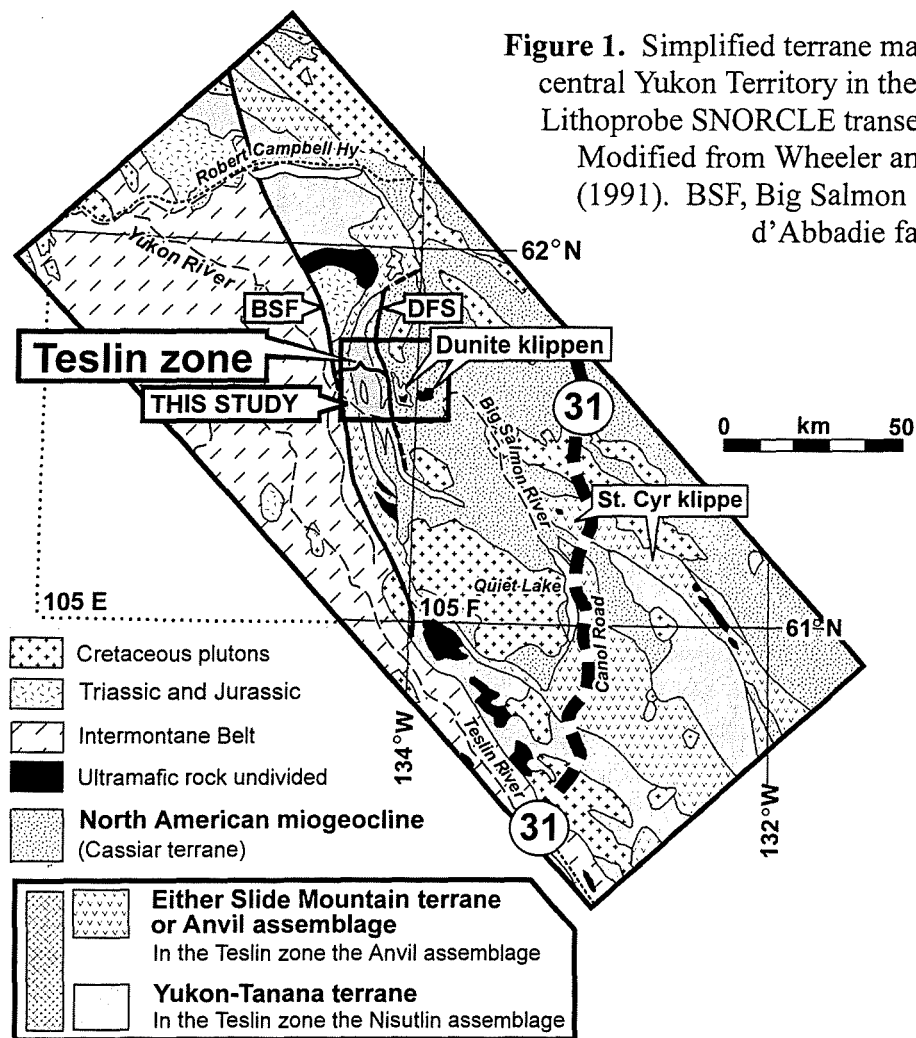
Note 2: The d’Abbadie pluton and a medium-grained andesitic dyke, both largely undeformed (the pluton has a weak margin-parallel fabric), cross-cut S_T at high angles in Cassiar terrane rocks. A medium-grained muscovite-biotite-bearing (1–2 %) granite sample of the former, collected ca. 10 m from the southern margin, yielded an average $^{207}\text{Pb}/^{235}\text{U}$ monazite age of 109 ± 3 Ma (zircon shows strong inheritance) (Fig. 4a), interpreted as the crystallization age of the pluton. Intrusion and crystallization of the andesite dyke are interpreted as having taken place also at 109 ± 3 Ma (Fig. 4b) based on the lower intercept of discordia lines through zircon fractions A, D, and E (109.5 ± 0.5 Ma), and through B, D, and E (108 ± 1.5 Ma) (same lower intercept of D and E). The error is assigned on the basis of the range generated by adding the errors to the older age and subtracting them from the younger age.

At first glance, the 109 ± 3 Ma age of the two intrusives defines the upper age limit of the ductile part of extension. There is no indication that the andesite dyke, or any other similarly steep, cross-cutting late dykes in the part of the Cassiar terrane studied, occur in macroscopic post-dyke boudins. However, localized extensional deformation was ongoing around this time and (at least shortly) thereafter as evidenced by (i) retrograde shear bands that formed at temperatures below ca. 300°C (unannealed biotite and muscovite) (i.e. after temperatures in the contact aureole of the d’Abbadie pluton, which reached a minimum of 525°C as indicated by cordierite-andalusite-biotite growth, had significantly declined), and (ii) ductilely extended andalusite porphyroblasts in the contact aureole. Considering the above and the ca. 115–109 Ma mica cooling ages in the western Cassiar terrane (Hansen et al. 1991), extensional deformation above ca. 300°C is interpreted as having occurred at ca. 115–108 Ma or older, and ductile extension below ca. 300°C is believed to have ceased at ca. 109–108 Ma, or shortly thereafter.

References

- Brown, R. L., Carr, S.D., Harvey, J.L., Williams, P.F., and de Keijzer, M. 1998. Lithoprobe Report 44, pp. 56–62.
Brown, R. L., de Keijzer, M., Carr, S. D., Williams, P.F., and Gallagher, C.S. 1998. Lithoprobe Report 64, pp. 152–157.

- Carr, S.D., de Keijzer, M., and Gallagher, C. 1999. Lithoprobe Report 69, pp.219-220.
- Creaser, B., and Spence, G. 1999. Lithoprobe Report 69, pp. 163-167.
- Creaser, R.A., Heaman, L.M., and Erdmer, P. 1997b. Canadian Journal of Earth Sciences, **34**: 709-715.
- de Keijzer, M., and Williams, P.F. 1998. Lithoprobe Report 64, p. 13.
- de Keijzer, M., and Williams, P.F. 1999. Lithoprobe Report 69, 122-129.
- de Keijzer, M., Williams, P.F., and Brown, R.L. 1999. Canadian Journal of Earth Sciences, **36**: 479-494.
- Erdmer, P. 1985. Journal of Structural Geology, **7**: 57-72.
- Erdmer, P., Ghent, E.D., Archibald, D.A., and Stout, M.Z., 1998. Geological Society of America, Bulletin, **110**: 615-629.
- Gallagher, C.S. 1999. M.Sc. thesis, Carleton University, Ottawa, Ontario, pp. 179.
- Gordey, S.P. 1981. Geological Survey of Canada, Bulletin **318**, pp. 41.
- Hansen, V.L. 1989. Journal of Structural Geology, **11**: 717-733.
- Hansen, V.L., and Dusel-Bacon, C. 1998. Geological Society of America, Bulletin, **110**: 211-230.
- Hansen, V.L., Heizler, M.T., and Harrison, T.M. 1991. Tectonics, **10**: 51-76.
- McQuillin, R.M., Bacon, M., and Barclay, W. 1984. Gulf Publishing Company, Houston, pp. 287.
- Mihalynuk, M.G., Nelson, J.L., and Diakow, L.J. 1994. Tectonics, **13**: 575-595.
- Monger, J.W.H. 1997. Geoscience Canada, **24**: 189-198.
- Plint, H.E., and Gordon, T.M. 1997. Canadian Journal of Earth Sciences, **34**: 105-126.
- Roots, C.F., de Keijzer, M., Nelson, J.L., and Mihalynuk, M.G. 2000. Geological Survey of Canada, Current Research 2000-A.
- Stevens, R.A. 1994. Ph.D. thesis, University of Alberta, Edmonton, pp. 252.
- Stevens, R.A. and Erdmer, P. 1996. Tectonics, **15**: 1342-1363.
- Tempelman-Kluit, D.J. 1977. Geological Survey of Canada, Open file 486.
- Tempelman-Kluit, D.J. 1979. Geological Survey of Canada, Paper 79-14, pp. 27.
- Wheeler, J.O., and McFeely, P. (compilers) 1991. Geological Survey of Canada, Map 1712A, scale 1:2 000 000.



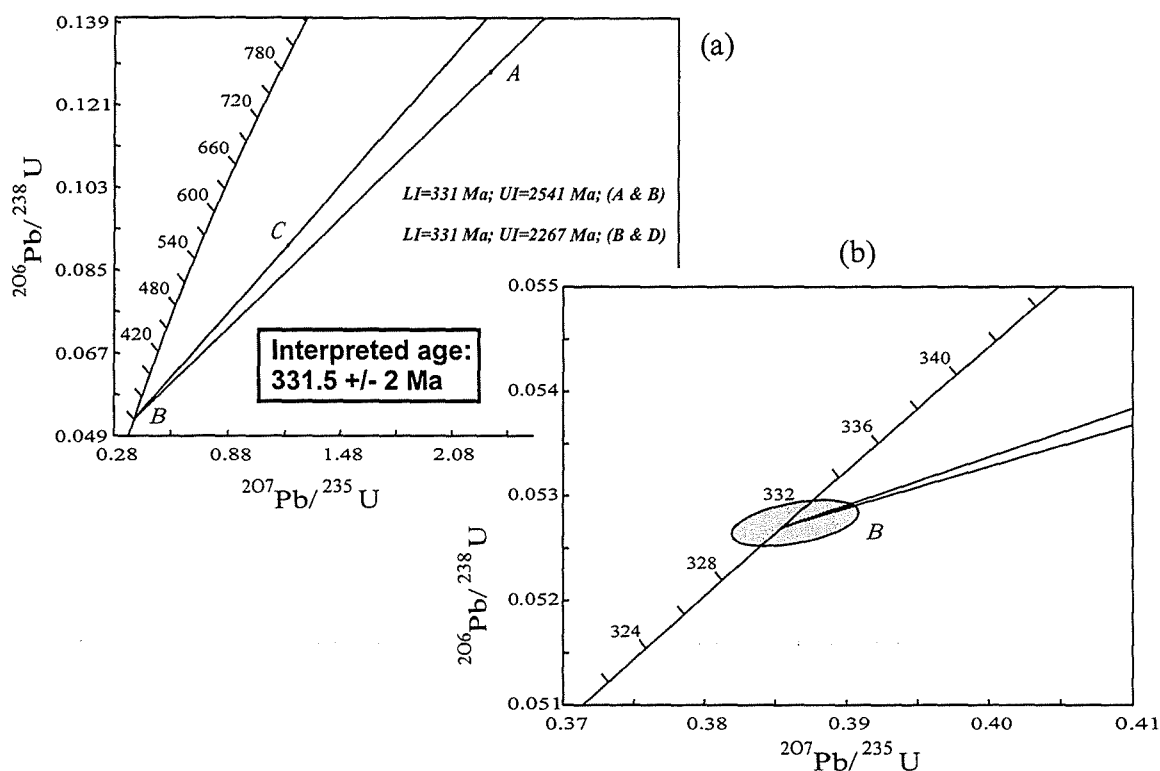


Figure 3. (a) Concordia diagram showing U–Pb zircon data from a ca. 3 m-wide foliated and lineated augen orthogneiss body at the contact of unit PM and unit QFM, Cassiar terrane. (b) Detail of concordia diagram in (a) showing near-concordant single zircon fraction B.

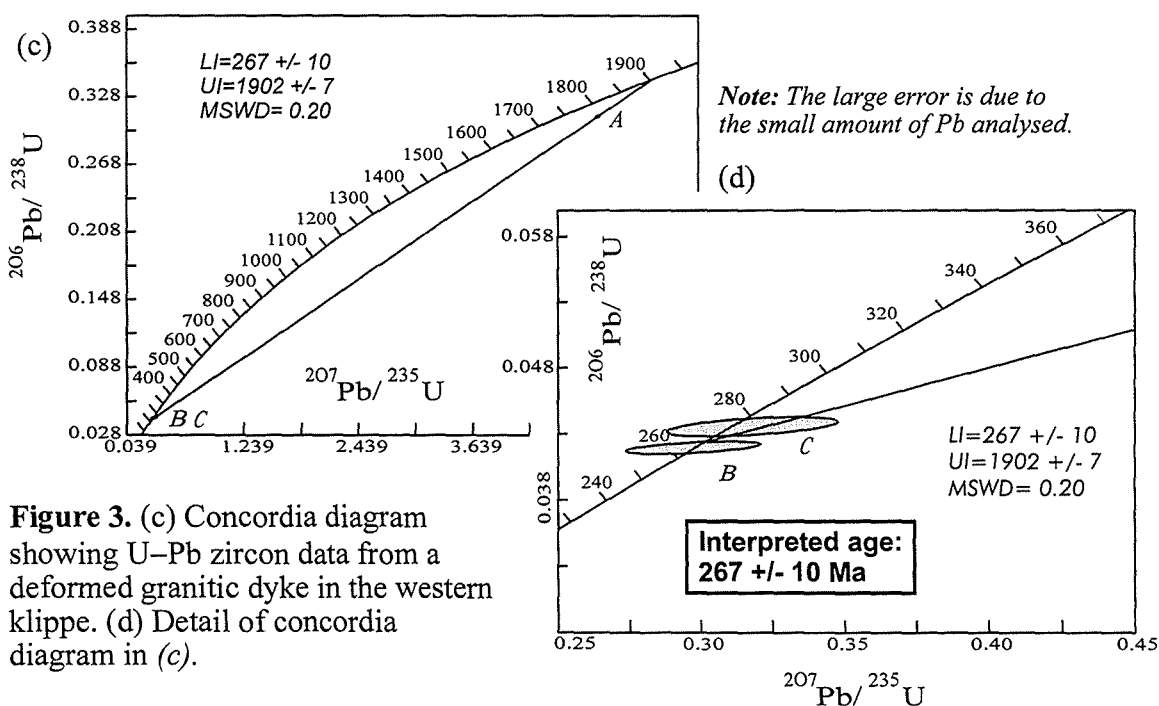


Figure 3. (c) Concordia diagram showing U–Pb zircon data from a deformed granitic dyke in the western klippe. (d) Detail of concordia diagram in (c).

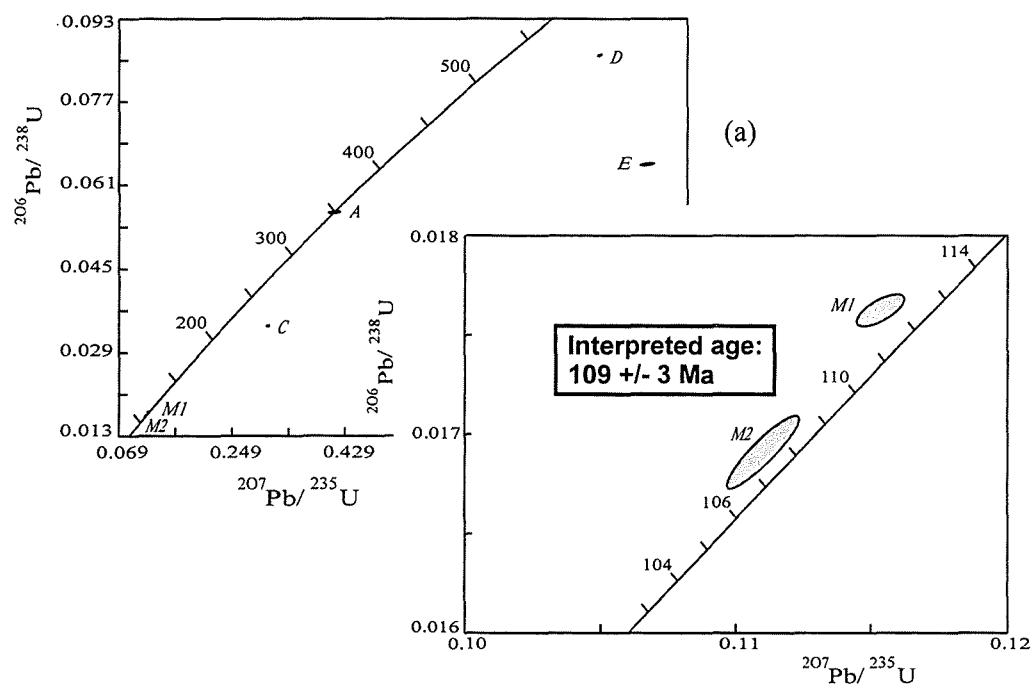


Figure 4a. U-Pb zircon (fractions A–D) and monazite (fractions E and F) data from the d'Abbadie pluton.

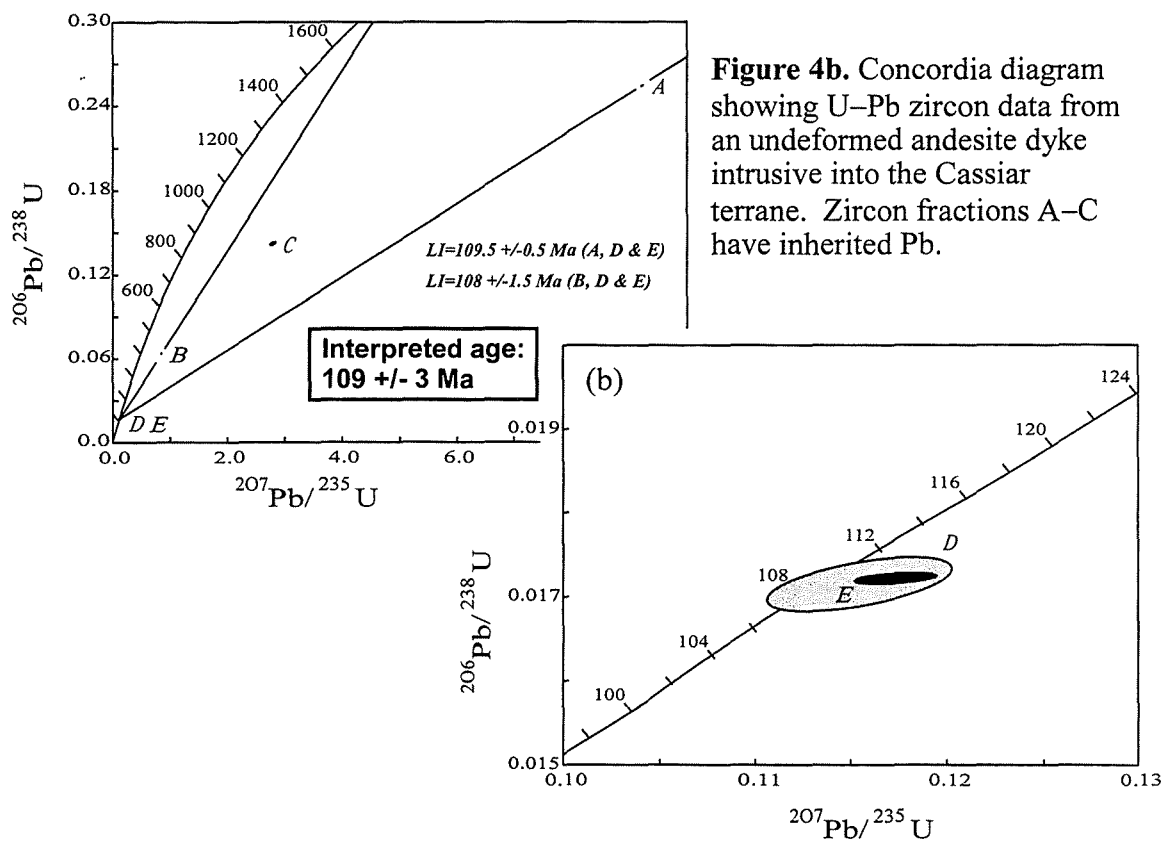


Figure 4b. Concordia diagram showing U-Pb zircon data from an undeformed andesite dyke intrusive into the Cassiar terrane. Zircon fractions A–C have inherited Pb.

SNORCLE Reflection Survey 1999-2000: Corridors 2 and 3

F. A. Cook⁽¹⁾, R. M. Clowes⁽²⁾, D. B. Snyder⁽³⁾, A. J. van der Velden⁽¹⁾, K. W. Hall⁽¹⁾ and K. Vasudevan⁽¹⁾.

(1) Department of Geology and Geophysics
University of Calgary
Calgary, AB T2N 1N4

(2) LITHOPROBE and Department of Earth & Ocean Sciences
357 Geological Sciences Centre
University of British Columbia
Vancouver, BC V6T 1Z4

(3) Continental Geoscience Division
Geological Survey of Canada
615 Booth St.
Ottawa, ON K1A 0E9

The final phase of the SNORCLE reflection program began at Macmillan Pass on the Yukon-Northwest Territories border in August, 1999 and was completed near Ft. Nelson, BC in February, 2000. Due to a favorable bid, we were able to complete Profile 3 to White Pass, BC (near Skagway, AK), and to separate Profile 2 into two parts that cross in the vicinity of the Tintina fault near Watson Lake, Yukon; this will provide some three-dimensional coverage in the area. In the Yukon, Profile 3 (ca. 650 km) follows the south Canol road from the deformed Selwyn Basin sedimentary rocks near Macmillan Pass, across the Tintina trench near Ross River, accreted rocks of the Cassiar and Cache Creek terranes, and ends east of the Denali fault near White Pass. Profile 2A (ca. 675 km) begins at Stewart, British Columbia and follows highway 37 to north of Watson Lake, Yukon. It crosses the Stikine, Cache Creek, and Cassiar terranes, passes in the vicinity of Quaternary- volcanic rocks near Mount Edziza, crosses the Liard Plain in the vicinity of the Tintina fault, and ends about 35 km north of Watson Lake. Profile 2B (ca. 570 km) follows the Alaska highway from about 60 km west of Watson Lake to Ft. Nelson, British Columbia. It provides a second crossing of the Tintina in the Liard Plain, and then crosses deformed Foreland fold and thrust belt rocks before ending in the Western Canada Sedimentary Basin.

Both stacked and unstacked data were recorded, in uncorrelated format, with 576 channels, 50 m station spacing, 75 m vibrator point spacing, 10-80 Hz sweeps, 20 s sweep length, 32 s listen time, with either 8 or 6 sweeps per vibrator point, for 4 or 5 vibrators, respectively. Recording both stacked (8 or 6 summed records) and unstacked (no summing) data at each source location provides extreme flexibility for later processing and testing because noise analyses and reduction processes can be applied prior to summing of the records. Testing of the infield stacking and stacking at the LITHOPROBE Seismic Processing Facility indicates little difference, thus allowing the initial processing to be facilitated by using field-stacked records.

At the present time, about one half of Profile 3 has been processed to a preliminary brute stack. Some key features that are visible at this time are:

1) A prominent surface can be followed from about 3.0 s beneath Macmillan Pass to about 5.0 s on the east side of the Tintina fault. This surface separates the uppermost crust, in which layers generally dip westward and flatten into it, from the very reflective lower crust.

2) The mapped surface position of the Tintina fault about 10 km west of Ross River is underlain by reflections at ca. 1.0-1.5 s (about 3-4.5 km) that dip westward.

Most of Profile 3 will be processed by the time of the transect meeting and will be presented in preliminary form. Processing for Lines 2A and 2B will not be complete until summer.

Acknowledgements: We would like to thank Kinetex Inc., the seismic acquisition contractor, for their sterling efforts to acquire quality data in spite of some very challenging and demanding problems. We also wish to thank John Amor, Kate Bone, Phil Hammer, Jeff Schragge and Kim Welford of The University of British Columbia and Gervais Perron of the Geological Survey of Canada who volunteered to undertake a period of birddogging during this survey.

New SNORCLE magnetotelluric data: preliminary implications

Juanjo Ledo*, Alan G. Jones

(Geological Survey of Ottawa, 615 Booth St., Ottawa, On K1A 0E9)

Ian J. Ferguson

(University of Manitoba)

Introduction

The Slave-Northern Cordillera Lithospheric Evolution (SNORCLE) Trancset addresses LITHOPROBE's theme of crustal evolution through an integrated program of geological and geophysical studies across this geologically diverse region and through four billion years of Earth's history. The application of the magnetotelluric (MT) method to the study of the northern Cordillera has three principal objectives. The first concerns characterization of the regional conductivity properties of the northern Cordillera in relation to the major tectonic units. The second thrust involves upper mantle features: determination of the depth extent and internal variation within the lithosphere beneath the Cordillera the fate of the vast amount of pacific lithosphere overridden by North America during the past. The third specific goal is determination of the subsurface geometry and character of the Tintina strike-slip fault zone for comparison with the reflection data and a better understanding of reasons for conductivity enhancement at faults.

Geological setting

The northern Cordillera consists of a great variety of rock types ranging in age from early Proterozoic to recent and representing different tectonic episodes, among them: epicratonic basins, subsiding shelves, foreland basins, island arcs and deep ocean basins. These rocks have been submitted to different episodes of compressional and extensional deformation, transcurrent faulting, metamorphism and plutonism. This complex geological record has been described in terms of interactions of several terranes with each other and with the margin of ancestral North America. The ancestral North America is a passive continental margin assemblage, where strata had been deposited since Early Proterozoic to Lower Cretaceous, and reflect a broad range of depositional environments. The Cassiar Terrane is considered to be a portion of the North American miogeocline that was displaced dextrally along the Tintina-Northern Rocky Mountain system. To the west of the Tintina Fault, the crust is comprised of several terranes that were accreted to the continental margin. The nature and evolution of the terranes and its boundaries are complex and still controversial (e.g., Wheeler et al. 1991; Gabrielse and Yorath, 1992; Gordey and Makepeace, 1999).

Magnetotelluric method

The magnetotelluric method uses the fluctuations of the natural electromagnetic field at the Earth's surface to study the lateral and vertical variation of the electrical conductivity of the Earth's interior. The physical parameter being sensed is the electrical conductivity, which varies over a range of eight orders of magnitude. Most rock-forming minerals in the crust have very low conductivity and they are classed as insulators. The enhancement in electrical conductivity of the Earth's crust is due to ionic conduction and/or electronic conduction. The first one occurs when ions are free to move through fluids (i.e. water, partial melt) and the second one occurs when electrons move through electronically-conductive solids (i.e. graphite, sulphides, iron oxide's). Moreover, the bulk electrical conductivity depends not only on the amount of ionic fluids and/or electronic conductors, but also on their geometric distribution within the host rock. These are useful tracers of tectonic and geodynamic processes that are difficult or impossible to sense remotely by other techniques. Penetration to all depths is assured by the skin depth phenomenon. The depth of penetration of an electromagnetic wave into the Earth depends onto

the Earth's conductivity and the periodicity of the electromagnetic wave. The analysis of different periods allows us to obtain information at different depths, and to determine the dimensionality of the geological structures (2D or 3D), strike direction and its depth dependence. The interested reader is referred to Jones (1992) in which the fundamentals and applications of the MT method is explained with more detail.

The fieldwork began in August 1999 and finished at the end of October 1999. In total more than two hundred MT sites (AMT, broad band and long period) have been acquired. The data are presented as a pseudosection of the phases determinant (figure 2) of the broad band data, that is invariant under rotation, and shows the main regional structures. Phases values higher than 45 degrees are associated to the presence of conductive structures, and phases below 45 degrees correspond with the response of more resistive structures. The main characteristic of the data is the presence of a resistive upper crust (low periods) in relationship with a more conductive lower crust (high periods). Moreover, some vertical conductive structures can be observed at lower periods that could be related to the presence of fault systems.

Preliminary results

Here we present the preliminary results obtained across the Tintina fault at Ross River. The Tintina Fault is a major transcurrent fault along which an estimated 450 km or more of Cretaceous-tertiary dextral displacement. The period range of the data used is 0.01-8000 s, which allows us to image the earth structure from near surface (hundred meters depth) to deep into the mantle (> 50 km). 2D Objective modelling of the apparent resistivity and phases for the two principal electromagnetic directions, parallel and perpendicular to the fault was done using the algorithm of Mackie and Rodi (1996) (figure 3). The main results are the presence of several subvertical contacts both near surface (e.g. Tintina Fault) and deep in the crust (e.g. St. Cyr Fault). The trace in surface of the Tintina Fault coincides with an important lateral contrast in the electrical properties up to 4-5 km deep. To the southeast, there is another vertical contact that correlates with the surface trace of the St. Cyr Fault. This structure penetrates deep into the crust, although the bottom of this structure is not well constrained. To the northwest a high resistive structure is imaged up to 20 km deep. The analysis and decomposition of the whole magnetotelluric data set will be the preceding step to obtaining an electrical resistivity distribution of the subsurface structures. The correlation between the electrical structures with other geological and geophysical parameters will be one of the main objectives for future research activities.

References:

- Gordey, S.P. and Makepeace, A.J., 1999. Yukon digital geology. Geological Survey of Canada Open File D3826.
- Gabrielse, H. and Yorath, C.J. (ed), 1992. Geology of the Cordilleran orogen in Canada; Geological Survey of Canada, Geology of Canada, no. 4, 844 p.
- Jones, A.G., 1992. Electrical properties of the lower continental crust in Continental Lower Crust. Fountain, D.M., Arculus, R. and Kay, R.W. (eds). Elsevier, Amsterdam.
- Mackie, R.L. and Rodi, W., 1996. A non-linear conjugate gradients algorithm for 2D magnetotelluric inversion. AGU Fall meeting 1996.

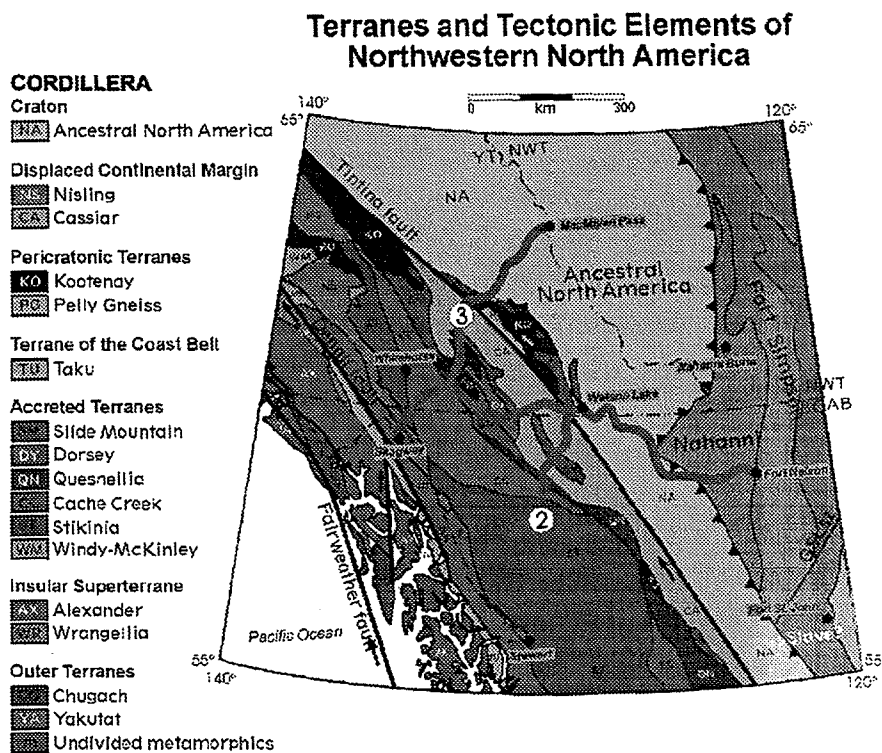


Figure 1. Snorchle MT transect (red line) on a map of the terranes and tectonic elements of northwestern North America. Faults are heavy dark lines.

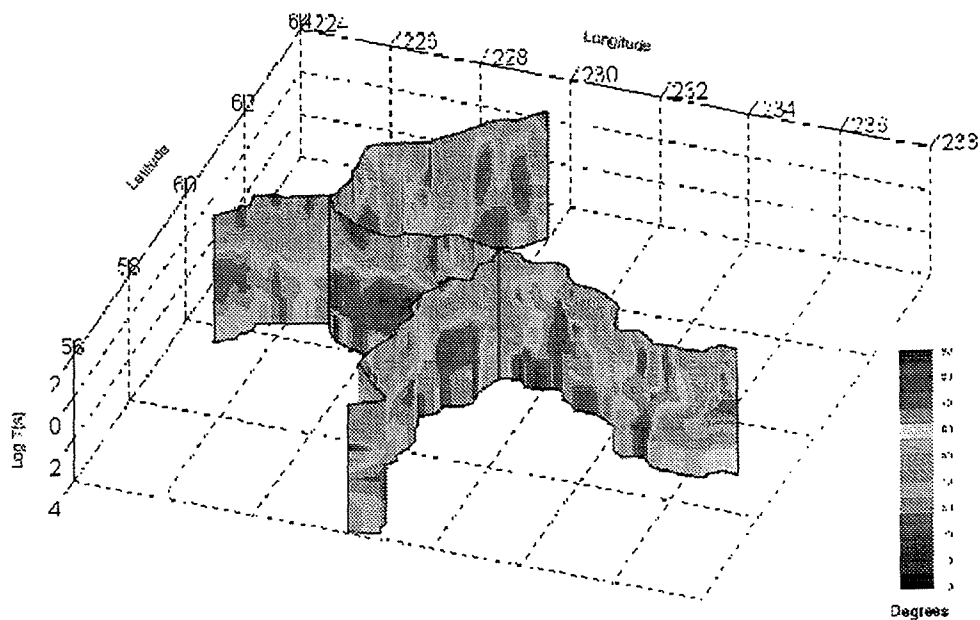


Figure 2. Pseudosection of the phases determinant for the broad band MT data.

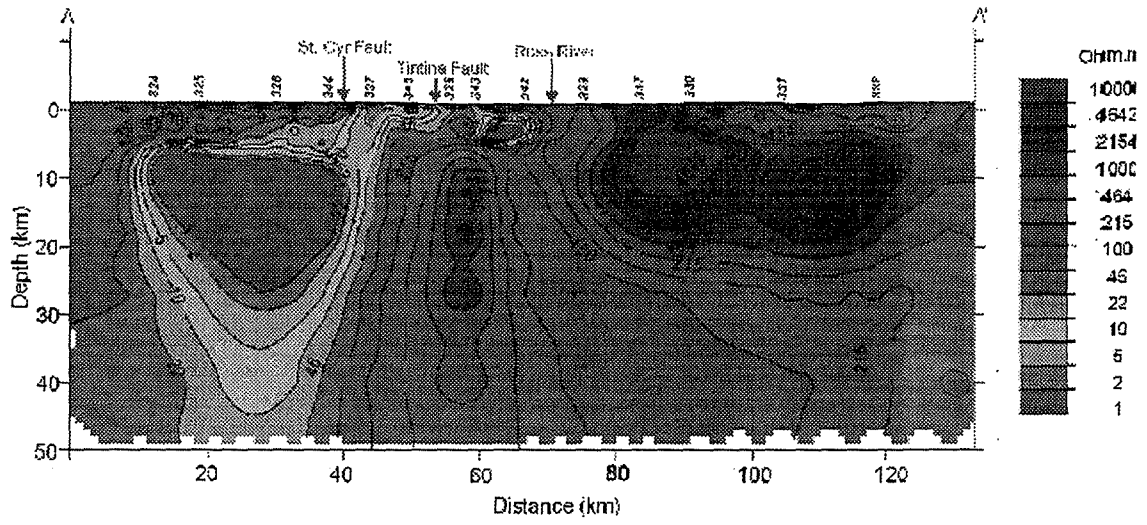


Figure 3. 2D model across the Tintina Fault at Ross River.

NEW DIGITAL COMPILATION OF YUKON GEOLOGY

S.P. Gordey and A.J. Makepeace
Geological Survey of Canada
101-605 Robson Street, Vancouver, B.C. V6B 5J3
(email: sgordey@gsc.nrcan.gc.ca)

A new digital compilation of Yukon geology is now available as a double CD-ROM set. These CD-ROMs include new syntheses of bedrock geology and glacial limits, compilations of geochronology, paleontology, and mineral occurrences (Yukon Minfile), a compendium of coloured aeromagnetic images, and data sets on Yukon park boundaries and physiography. None of the data was previously available in digital format; much resided in previously unpublished databases. A subset of a public domain topographic data set (Digital Chart of the World, by ESRI, Inc.) is included for georeference purposes.

For ease of use, data sets (themes) are divided geographically into 45 map tiles corresponding to the National Topographic System (NTS) 1:250,000 quadrangles. Data sets spanning the entire Yukon Territory are also included for use on sufficiently powerful computers and GIS software.

Each theme for all of the 45 map tiles is presented in two projections. An Albers equal area projection is provided on disc 1 to allow seamless integration of adjoining tiles throughout the Yukon. The complete data set is also provided on disc 2 in the UTM coordinate system, which is commonly used for accurately plotting data at the local scale. Several different formats are presented for vector data files (Arc/Info coverages, interchange (*.e00), dBase (*.dbf), shapefiles (*.shp)), and image data files (band interleaved by line (*.bil), tagged image file format (*.tif)) to allow easy importing of data into commercial GIS software.

Documentation for each data set includes a summary describing its contents and a detailed outline of the data structure. Documentation is viewed through extensively interlinked HTML files on a web browser.

The CD-ROMs also include a viewing application for Microsoft Windows (SurView) that provides an opportunity for those without specialized GIS software to display, print, and query the Yukon Digital Geology databases on their own PC.

Arc-Rifting and Ensialic Back-Arc Basin Magmatism in the Northern Canadian Cordillera: Evidence from the Yukon-Tanana Terrane, Finlayson Lake Region, Yukon.

Stephen J. Piercey¹, Donald C. Murphy², James K. Mortensen¹, and Suzanne Paradis³

1-Mineral Deposit Research Unit, Department of Earth and Ocean Sciences
University of British Columbia, Vancouver, British Columbia, V6T 1Z4
spiercey@eos.ubc.ca, jmortens@eos.ubc.ca

2-Yukon Geology Program, P.O. Box 2703 (F-3)
Whitehorse, Yukon, Y1A 2C6
don.murphy@gov.yk.ca

3-Mineral Resources Division, Geological Survey of Canada
9860 West Saanich Road, Sidney, British Columbia, V8L 4B2
paradis@pgc-gsc.nrcan.gc.ca

Introduction

The discovery of volcanogenic massive sulphide (VMS) mineralization within volcano-sedimentary rocks of the Yukon-Tanana terrane (YTT) in the Finlayson Lake region in 1994 has led to a renewed interest in the geological, tectonic and metallogenic setting of the YTT both in the Finlayson Lake region and elsewhere in the Cordillera (e.g., Ancient Pacific Margin NATMAP project). Numerous paradigms exist for the evolution of the YTT in the northern Cordillera (e.g., Templeman-Kluit, 1979; Hansen and Dusel-Bacon, 1998 and references therein; Mortensen, 1992 and references therein); however, very few studies have integrated geological, geochemical and metallogenic information to provide insights into the paleotectonic evolution of this terrane. In this paper we provide an integrated database of geology, felsic volcanic geochemistry and metallogenic data to illustrate a Mississippian continental margin arc-rifting and ensialic back-arc basin event is recorded within the YTT of the Finlayson Lake region. This type of tectonism and volcanic activity has yet to be documented within YTT rocks of the Finlayson Lake region or elsewhere in the northern Cordillera and as such represents a new contribution to understanding the tectonic and metallogenic evolution of the pericratonic terranes of the Cordillera.

Regional Geological and Stratigraphic Setting

The geology and stratigraphic setting of the Finlayson Lake VMS district within the YTT has previously been described by Templeman-Kluit (1979), Mortensen and Jilson (1985), Mortensen (1992), and more recently by Murphy (1998), Murphy and Timmerman (1998), Murphy and Piercey (1999a,b,c, 2000) and Piercey and Murphy (2000) and is summarized below.

The Finlayson Lake district consists of variably metamorphosed (greenschist and locally amphibolite facies) and deformed sedimentary, volcanic, and intrusive rocks. This district has been deformed and/or metamorphosed during three events, including a Mississippian event of uncertain kinematics (Colpron et al., in press), a post-Permian and pre-Jurassic north-northeasterly directed thrusting event along the Money Creek Thrust (Murphy and Piercey, 2000), and a predominant Cretaceous south-southeasterly directed folding and thrusting that has overprinted many of the rocks with a ductile deformation fabric (Murphy, 1998). Although these rocks have been deformed and metamorphosed there are abundant locations where protolith textures and rock classifications can be undertaken (e.g., Piercey and Murphy, 2000), and as a

result we have omitted the prefix “meta” in this paper when discussing volcanic rocks where protolith affinities and textures are readily discernable.

The Finlayson Lake district consists of a seven component stratigraphy for which many units have internal subdivisions. The lowermost stratigraphic unit (unit 1) consists of a pre-Devonian biotite-rich non-carbonaceous metasedimentary package that is overlain by a package of ~365-360 Ma arc-derived (Grant et al., 1996; Grant, 1997; Piercey et al., 1999a,b) package of predominantly mafic volcanic rocks with lesser felsic volcanic rocks, sedimentary rocks and associated mafic and ultramafic plutonic rocks (unit 2; Figs. 2 and 3). This package exhibits significant lateral thickness changes, due to syvolcanic faults, and where thickest hosts the ~8.5 Mt Besshi-style Fyre Lake Cu-Co-Au VMS deposit (Figs. 2 and 3; Murphy, 1998; Murphy and Piercey, 2000).

The mafic dominated unit 2 is overlain by a package of variably carbonaceous package of felsic volcanic and sedimentary rocks (unit 3=Kudz Ze Kayah succession). This unit is heterogeneous consisting of abundant rhyolitic to dacitic rocks, and related felsic tuffs and resedimented felsic material that are laterally gradationally into carbonaceous phyllites and quartzites. Other sedimentary rocks consisting of calcareous quartz psammite, siliceous carbonaceous schist and quartzite with local quartz-muscovite schist and marble, are interlayered with the dominantly felsic metavolcanic succession (Fig. 2). Volcanic rocks have yielded predominantly Early Mississippian U-Pb zircon ages (Mortensen, 1983; Mortensen and Jilson, 1985; Mortensen, 1992). Rhyolite flows and tuffs near the top of unit 3 host the 13 million tonne Kudz Ze Kayah (KZK) Zn-Cu-Pb deposit (5.5% Zn, 1% Cu, 1.3% Pb, 125g/t Ag, 1.2 g/tAu; Shultze (1996); Figs. 2 and 3).

The Kudz Ze Kayah succession is overlain by carbonaceous phyllitic rocks which are associated with rift-alkaline to tholeiitic mafic dykes and intrusive rocks with minor quartzofeldspathic sandstone, conglomerate and clean white quartzite of uncertain origin (unit 4; Figs. 2 and 3).

Unconformably overlying parts of unit 4 and 3 is a quartz-feldspar pebble conglomerate and gritty quartzofeldspathic sandstone of unit 5l. This subunit contains abundant K-feldspar clasts akin to those in the Grass Lakes granitoid suite (see below), and abundant carbonaceous phyllite chips on the bedding surfaces of the grits. Murphy and Piercey (1999a) and Murphy (1999) interpreted this unit to represent an unconformity between the underlying succession (units 1 to 4) and the overlying succession (units 5 to 6 = Wolverine succession). Subunit 5l grades laterally into a succession of blue quartz-feldspar phyric rhyolites, porphyritic felsic tuffs, and associated quartz-feldspar porphyritic subvolcanic intrusives (subunits 5qfp,f), and are overlain by a package of grey carbonaceous argillite/phyllite (subunit 5cp) (Figs. 2 and 3). It is conformably overlain by a thin but laterally persistent unit of white aphyric rhyolites and chert-barite-magnetite-iron formation, interbedded with some muscovite-quartz phyllite and minor carbonaceous phyllite (unit 6) (Murphy and Piercey, 1999a) (Figs 2 and 3). Unit 6 hosts the 6.2 million tonne Wolverine Zn-Cu-Pb VMS deposit (12.96% Zn, 1.41% Cu, 1.53% Pb, 359.1 g/t Ag, 1.81 g/t Au; Tucker et al. (1997); Fig. 1), which lies at the contact between underlying black to grey carbonaceous argillite/phyllite and overlying felsic volcanic rocks. Although not tightly constrained, a U-Pb zircon age of 356 ± 1 Ma has been obtained on felsic metavolcanic rocks of units 5qfp,f (Mortensen, 1992), and it is interpreted that unit 6 is temporally equivalent.

The Wolverine succession is overlain by rocks of the Campbell Range belt which consists of two basaltic packages separated by carbonaceous argillite, sandstone, mafic tuff (?), with local diamictite and olistostromal carbonate blocks (Murphy and Piercey, 1999a,b). More detailed descriptions of the geology of the Campbell Range Belt are given by Plint and Gordon (1997) and Murphy and Piercey (1999a,b,c).

Several granitoid bodies intrude the aforementioned units. The Grass Lakes suite, consists of variably sheared peraluminous K-feldspar megacrystic to K-feldspar porphyritic granitoids that are interpreted to be the subvolcanic equivalents to felsic volcanic rocks of unit 3.

U-Pb ages for the Grass Lakes granitoids and the felsic volcanic rocks (unit 3) indicate an Early Mississippian age (Figs. 2 and 3; Mortensen, 1983, 1992, and personal communication 1999). Numerous ~357-361 Ma (Mortensen, 1992; Grant, 1997) metaluminous (?) quartz (+feldspar) porphyritic subvolcanic granitoid intrusives are coeval with parts of unit 2, and are the subvolcanic equivalents of the aforementioned unit 2 rhyolites. Post-dating much of the above sequence, and possibly the Wolverine sequence rocks, are the ~345-350 Ma calc-alkalic metaluminous granitoids of the Simpson Range Plutonic Suite (SRPS; Figs 2 and 3; Mortensen, 1992 and personal communication 1999; Grant, 1997).

Geochemistry

Geochemical features of least altered rhyolitic to dacitic metavolcanic rocks from units 3 and 5 are presented in Figures 2 and 3. The felsic metavolcanic rocks have variable SiO_2 contents (67.90-79.90 wt%) with weakly to moderately peraluminous A/NK (1.08-2.34) and A/CNK (1.02-2.15) ratios. The Zr/TiO₂-Nb/Y systematics (Fig. 2a) support the silica-based rhyolite-rhyodacite composition and exhibit a transitional subalkalic-alkalic affinity.

The immobile trace element systematics of the Finlayson Lake felsic metavolcanic rocks provide the most petrotextonic information about the felsic rocks. All of the felsic metavolcanic rocks are characterized by variably fractionated REE and LREE enrichment ($\text{Ce/Yb}_n = 3.47-17.87$) with variably negative Eu ($\text{Eu/Eu}^* = 0.12-0.73$) and Ti anomalies ($\text{Ti/Ti}^* = 0.03-0.11$), coupled with elevated Th/Nb values (0.66-1.75) and negative Nb anomalies ($\text{Nb/Nb}^* = 0.11-0.33$; Fig 3). The felsic volcanic rocks are also characterized by elevated Zr (130-572 ppm), Hf (3.8-13.0 ppm), Nb (11.0-40.0 ppm), Y (19.0-68.0 ppm), Ga (12.0-24.0 ppm), and REE (except Eu $\Sigma\text{REE} = 114-471$ ppm) values, coupled with low Sr (18-207 ppm), Eu (0.36-2.20 ppm), Al_2O_3 (10.60-15.30 wt%), CaO (0.11-3.01 wt%), TiO_2 (0.14-0.76 wt%), and transition metal (Cr, Ni, V, Co) contents. The elevated HFSE contents are also reflected by the elevated Nb/Y (0.49-1.13; Fig. 2b) and Ga/Al ($10^4\text{Ga/Al} = 1.9-3.5$; Fig. 2c) ratios, and Nb-Ce-Y systematics (Fig. 2d). On Figure 2b, the samples plot transitionally between fractionated volcanic arc granitoids (~I-type) and within plate (~A-type) granitoids, with HFSE systematics typical of A-type granitoids (Fig. 2c and 2d).

Discussion

Yukon-Tanana terrane has been interpreted in large part as the product of mid-Paleozoic continental (margin?) arc magmatism (Mortensen and Jilson, 1985; Mortensen, 1992; Creaser et al., 1997). Published geochemical and isotopic data are in support of this hypothesis (e.g., Mortensen, 1992; Creaser et al., 1997; Grant, 1997; Grant et al., 1996; Piercey et al., 1999a,b). However, we invoke a refinement to the continental arc models, one involving arc-rifting, asthenospheric upwelling and subsequent ensialic back-arc basin generation.

To begin we feel it appropriate to discuss the salient geochemical features of felsic volcanism from the Finlayson Lake district for which most of our subsequent discussions are based. The low contents of Sr, Eu, Al_2O_3 , CaO and TiO_2 , Cr, Ni, V, Co can be readily accommodated by either high level fractionation of feldspars (Sr, Eu, Al_2O_3 , CaO) and oxide minerals (TiO_2 , Cr, Ni, V, Co), respectively, or retention of these minerals as a restite phase at the source of crustal melting (e.g., Whalen et al., 1996, 1998; Lentz, 1996, 1998, 1999). The aforementioned can also explain the negative Eu and Ti anomalies on primitive mantle normalized plots in Figure 3. The high Th/Nb and low Nb/Nb* ratios typically reflect a negative Nb anomaly, which can be variously interpreted. For instance, some workers suggest that the negative Nb anomaly is a source feature of rocks derived from arc source regions or contaminated by arc crustal basement (e.g., Jenner, 1996; Whalen et al., 1998). Lentz (1996, 1998, 1999) suggests that negative Nb anomalies may reflect titanite and/or oxide magnetite/ilmenite crystallization during felsic magma evolution since Nb has a high partition coefficient for these minerals (cf. Green and Pearson, 1987). The inverse relationship between Th/Nb and TiO_2 and

Sc (Fig. 4a-b) and the sympathetic relationship between Nb and TiO₂ and Sc (Fig. 4c-d) support this hypothesis and cast doubt that the negative Nb anomaly actually reflects an “arc” signature. The elevated HFSE contents, Nb/Y and Ga/Al ratios, and Nb-Ce-Y systematics are also atypical of arc-derived magmatism but are more akin to within plate environments (e.g., Pearce et al., 1984; Eby, 1992; Whalen et al., 1998).

Any model for the origin of the felsic magmatism in the Finlayson Lake district must account for the above geochemical characteristics and the volume of felsic volcanism in this region (e.g., Fig. 1). A method of accommodating the volume of volcanism and its HFSE enrichment is by arc-rifting and ensialic back-arc basin generation. In this scenario, the arc that was built in the lower stratigraphic unit (e.g., unit 2) was rifted due to slab roll back and was underplated by enriched (back-arc related?) asthenosphere (Fig. 9). In this paradigm, the underplate would induce crustal partial melting crustal block which the arc was situated upon and generate the volumes of volcanism observed within the Finlayson Lake district. The HFSE-enrichment could either be accommodated by the felsic volcanic rocks being mantle-crust hybrids in which the HFSE budget was inherited from the enriched underplate. Alternatively, the elevated heat flow associated with the asthenospheric underplate could dissolve HFSE-enriched phases (e.g., monazite, titanite, zircon, rutile) within the crustal reservoir leading to HFSE enrichments (e.g., Lentz, 1996, 1998, 1999). The latter case seems more likely in light of published isotopic data for this region. Although isotopic data for the felsic volcanics is lacking, peraluminous granitoids within the YTT that are coeval with the volcanic rocks have ⁸⁷Sr/⁸⁶Sr_i ratios ranging from 0.716 to 0.728 and εNd_i values of -15±1 (Mortensen, 1992). Furthermore, inherited zircon is ubiquitous in nearly all volcanic and plutonic U-Pb geochronological samples from the Finlayson Lake region (Mortensen, 1992; Grant, 1997; Grant et al., 1996). These isotopic and geochemical features add very little support for a significant mantle component and support a high temperature, crustal partial melt origin within a continental arc rift / ensialic back-arc basin for the volcanics of the Finlayson Lake region.

Possible Modern and Ancient Analogues: Working Hypotheses

Given this sequence of rocks and related geochemical attributes, we suggest possible ancient and modern analogues the Bathurst region of the Canadian Appalachians (van Staal et al., 1991; Lentz, 1999; Whalen et al., 1998), and the Okinawa Trough southwest of Japan (Shinjo et al., 1998; Sibuet et al., 1998), respectively. The stratigraphic and metallogenic characteristics of units 3-5 bear striking resemblance to the Tetagouche Group (van Staal et al., 1991 and Murphy and Piercey, 1999a,b,c). In addition, although smaller in size and number, VMS deposits such as Wolverine and Kudz Ze Kayah have some similarities with deposits in the Brunswick Belt (e.g., Lentz, 1999). Furthermore, the felsic volcanic and plutonic geochemistry of the Tetagouche Group is essentially identical to those from the Finlayson Lake region (e.g., Lentz, 1996, 1999; Whalen et al., 1998). Recent models for felsic magmatism and tectonism in the Tetagouche have suggested generation in an intracontinental rift and analogous to the Cenozoic Okinawa Trough southwest of Japan (e.g., van Staal et al., 1991; Lentz, 1999; Whalen et al., 1998).

We believe that the Okinawa Trough model, in particular the Central Okinawa Trough (COT), is applicable to parts of the Finlayson Lake region and accounts for many of the geological, geochemical and metallogenic attributes of the Finlayson Lake region (Sibuet et al., 1998; Shinjo, 1998, 1999; Shinjo et al., 1999). For example, the COT is an intracontinental back-arc rift centered on the Ryukyu arc system (e.g., Sibuet et al., 1998) with abundant asthenospheric upwelling beneath the continental block (Shinjo, 1998, 1999; Shinjo et al., 1999). Although A-type felsic volcanism has not yet been documented in the COT, the abundant enriched asthenospheric basaltic magmatism (e.g., Shinjo, 1998, 1999; Shinjo et al., 1999) has a OIB-like features akin to those related to the unit 4 rocks (Piercey, unpublished data). Furthermore, the presence of felsic volcanic hosted hydrothermal mounds, related graben structures and basinal sedimentation in the COT (e.g., JADE hydrothermal field; Halbach et al.,

1993) provide analogues to the Wolverine and Kudzu Kayah VMS deposits of the Finlayson Lake region.

References

- Colpron, M., Murphy, D.C., and Mortensen, J.K., in press. GSA Cordilleran Section Meeting, Program with Abstracts.
- Creaser, R. A., Erdmer, P., Stevens, R.A., and Grant, S.L., 1997a. *Tectonics*, v.16, p.107-121.
- Eby, G.N., 1992. *Geology*, v.20, p.641-644.
- Grant, S.L., 1997. Unpublished M.Sc. thesis, University of Alberta, 177 p.
- Grant, S.L., Creaser, R.A., and Erdmer, P., 1996. in Slave-Northern Cordilleran Lithospheric Experiment (SNORCLE), LITHOPROBE Report 50, p. 58-60.
- Green, T.H., and Pearson, N.J. 1987. *Geochemica et Cosmochimica Acta*, v.51, p.55-62.
- Halbach, P., Pracejus, B., and Marten, A., 1993. *Economic Geology*, v.88, p.2210-2225.
- Hansen, V.L., and Dusel-Bacon, C., 1998. *GSA Bulletin*, v.110, p.211-230.
- Jenner, G.A., 1996. in Wyman, D.A., (ed.), Geological Association of Canada, Short Course Notes Volume 12, p.51-77.
- Lentz, D.R., 1996. in Wyman, D.A., ed., Geological Association of Canada, Short Course Notes Volume 12, p.359-402.
- Lentz, D.R., 1998. *Ore Geology Reviews*, v.12, p.289-327.
- Lentz, D.R., 1999. *Economic Geology*, v.94, p.57-86.
- Mortensen, J.K., 1983. Unpublished Ph.D thesis, University of California, Santa Barbara, 155p.
- Mortensen, J.K., 1992. *Tectonics*, v.11, p.836-853.
- Mortensen, J.K., and Jilson, G.A., 1985. *Geology*, v.13, p.806-810.
- Murphy, D.C., 1998. in Yukon Exploration and Geology 1997, p. 51-58.
- Murphy, D.C., 1999. in Slave-Northern Cordillera Lithospheric Experiment (SNORCLE), Lithoprobe Report 69, p. 138-141.
- Murphy, D.C., and Timmerman, J.T., 1997. in Yukon Exploration and Geology 1996, p. 29-32.
- Murphy, D.C., and Piercey, S.J., 1999a. in Yukon Exploration and Geology; p. 47-62.
- Murphy, D.C., and Piercey, S.J., 1999b. Exploration and Geological Sciences Division, Department of Indian and Northern Affairs Canada, Open File 19993 (1:50,000 scale).
- Murphy, D.C., and Piercey, S.J., 1999c. Exploration and Geological Sciences Division, Department of Indian and Northern Affairs Canada, Open File 1999-4 (1:100000 scale).
- Murphy, D.C., and Piercey, S.J., 2000. in Yukon Exploration and Geology 1999, p. XX-XX.
- Pearce, J.A., Harris, N.B.W., and Tindle, A.G., 1984. *Journal of Petrology*, v.25, p.956-983.
- Piercey, S.J., and Murphy, D.C., 2000. in Yukon Exploration and Geology 1999; p. XX-XX.
- Piercey, S.J., Hunt, J.A., and Murphy, D.C., 1999a. in Yukon Exploration and Geology 1998, p. 125-138.
- Piercey, S.J., Murphy, D.C., Mortensen, J.K., and Hunt, J.A., 1999b. in Slave-Northern Cordillera Lithospheric Experiment (SNORCLE), Lithoprobe Report 69, p. 312.
- Plint, H.E., and Gordon, T.M., 1997. *Canadian Journal of Earth Sciences*, v.34, p.105-126.
- Shinjo, R., 1998. *Journal of Volcanology and Geothermal Research*, v.80, p.39-53.
- Shinjo, R., 1999. *Chemical Geology*, v.157, p.69-88.
- Shinjo, R., Chung, S-L, Kato, Y., and Kimura, M., 1999. *Journal of Geophysical Research*, v.104, #B5, p.10591-10608.
- Sibuet, J-C., Deffontaines, B., Hsu, S-K., Thureau, N., Le Formal, J-P., Liu, C-S, and ACT Party, 1998. *Journal of Geophysical Research*, v.103, #B12, p.30245-30267.
- Templeman-Kluit, D.J., 1979. Geological Survey of Canada Paper 79-14, 27 pages.
- van Staal, C.R., Winchester, J.A., and Bédard, J.H., 1991. *Canadian Journal of Earth Sciences*, v.28, p.1031-1049.
- Whalen, J.B., Currie, K.L., and Chappell, B.W., 1987. *Contributions to Mineralogy and Petrology*, v.95, p. 420-436.
- Whalen, J.B., Rogers, N., van Staal, C.R., Longstaffe, F.J., Jenner, G.A., and Winchester, J.A., 1998. *Canadian Journal of Earth Sciences*, v.35, p.237-252.
- Winchester, J.A., and Floyd, P.A., 1977. *Chemical Geology*, v.20, p.325-343.

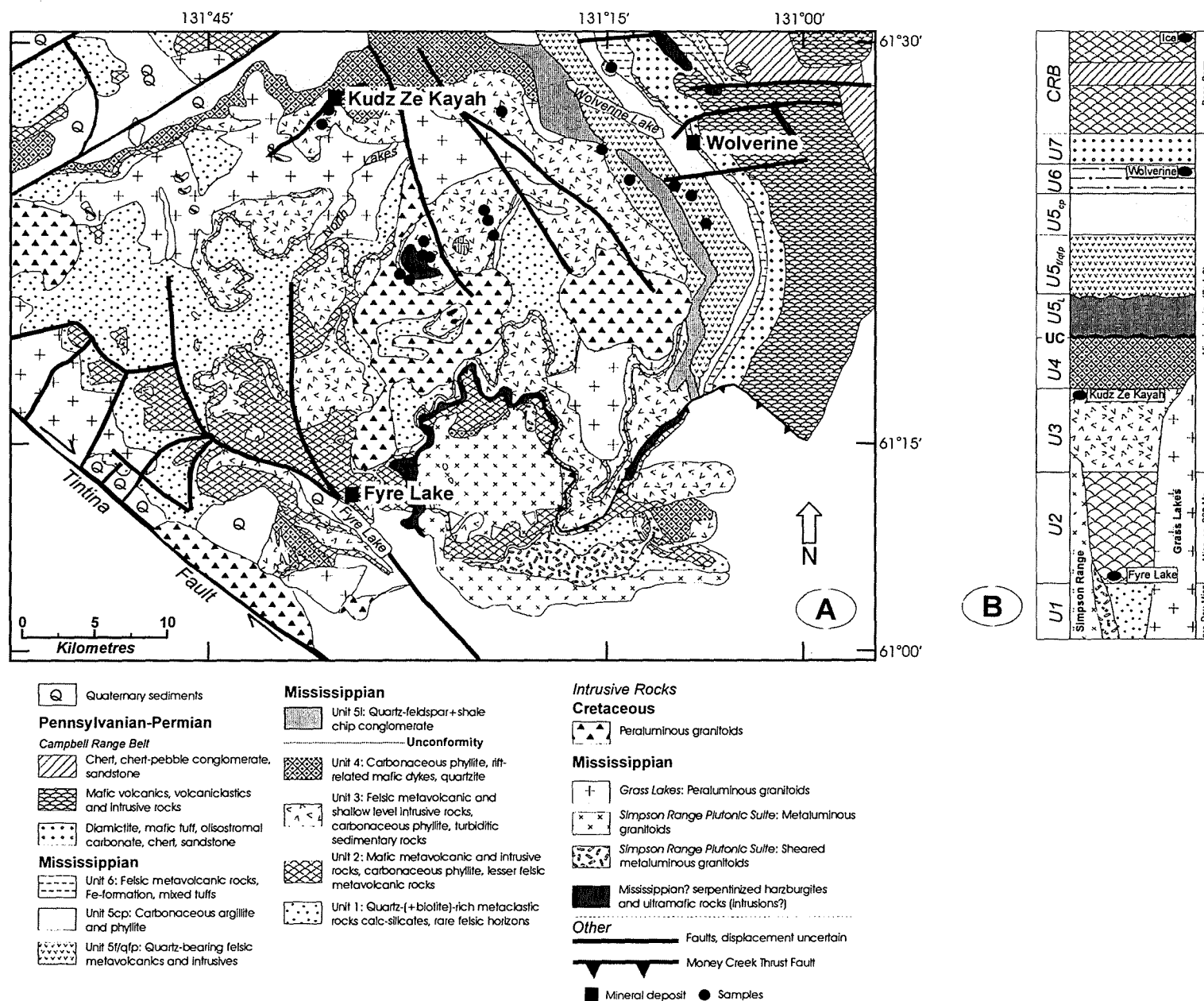


Figure 1. Geological setting of the Yukon-Tanana terrane in the Finlayson Lake region with location of felsic samples presented in this paper (a), and (b) schematic stratigraphic column for the YTT in the Finlayson Lake region. Modified from Murphy (1998), Murphy and Piercey (1999a,b,c), Murphy and Piercey (2000) and Piercey and Murphy (2000).

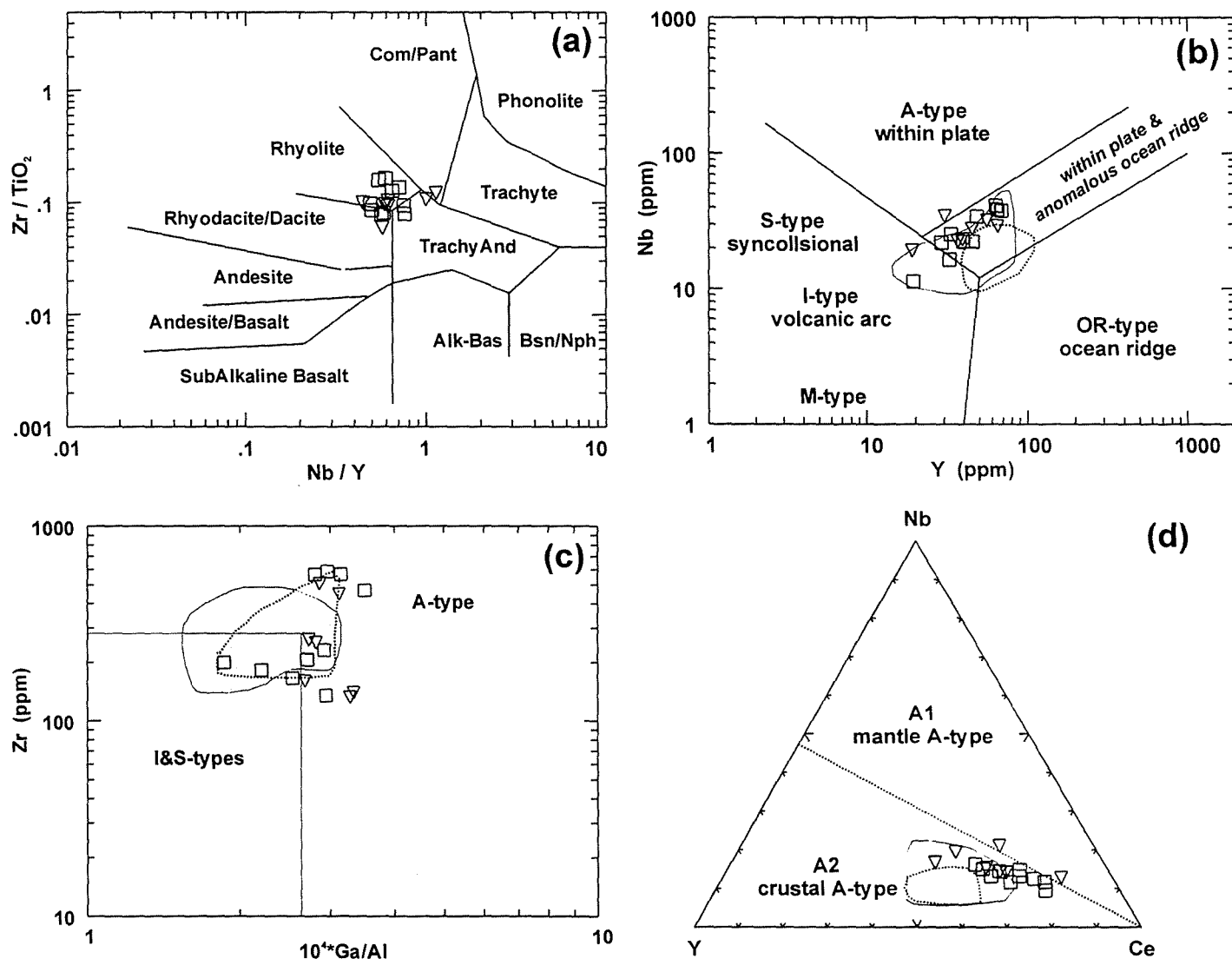


Figure 2. Discrimination diagrams for the YTT felsic rocks from the Finlayson Lake region. In (a) the felsic rocks have a transitional alkaline/non-alkaline affinity based on Winchester and Floyd's (1977) classification. This behaviour is echoed in other HFSE based diagrams as they have elevated Nb/Y (a) transitional between arc and non-arc affinities, and elevated Ga/Al ratios typical of fractionated I-type granitoids and A-type granitoids (c). They also have Nb-Ce-Y systematics typical of crustally derived A-type granitoids (e.g., rifted-arcs +/- ensialic back-arc basins). Fields in (b) from Pearce et al. (1984), in (c) from Whalen et al. (1987) and (d) from Eby (1992). Shown for comparison are volcanic rocks from the Tetagouche Group of the Bathurst VMS district, New Brunswick from Lentz (1996, 1999) and Whalen et al. (1998).

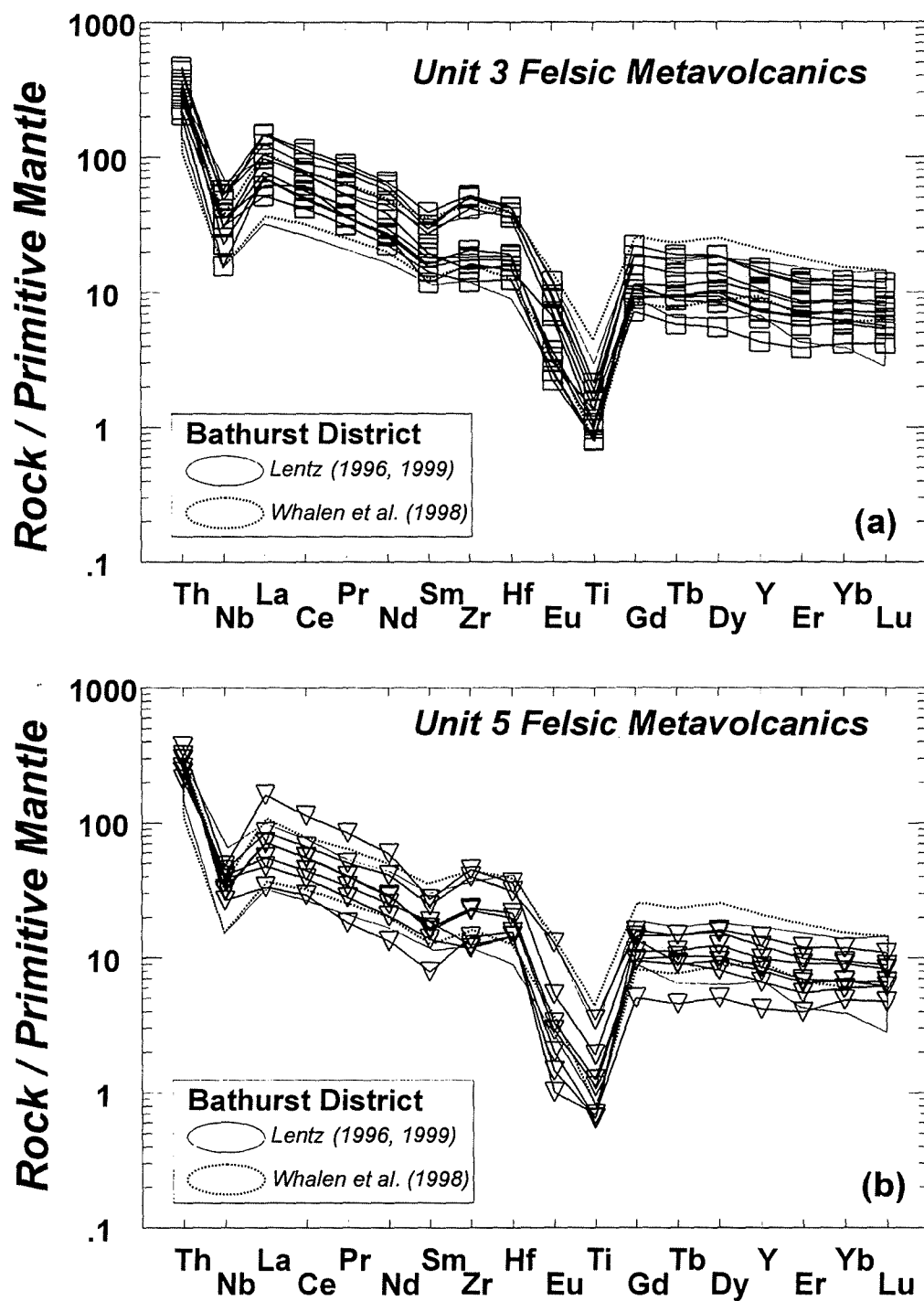


Figure 3. Primitive mantle normalized trace element plots for YTT felsic rocks from the Finlayson Lake region. Details of the plots are provided in the text.

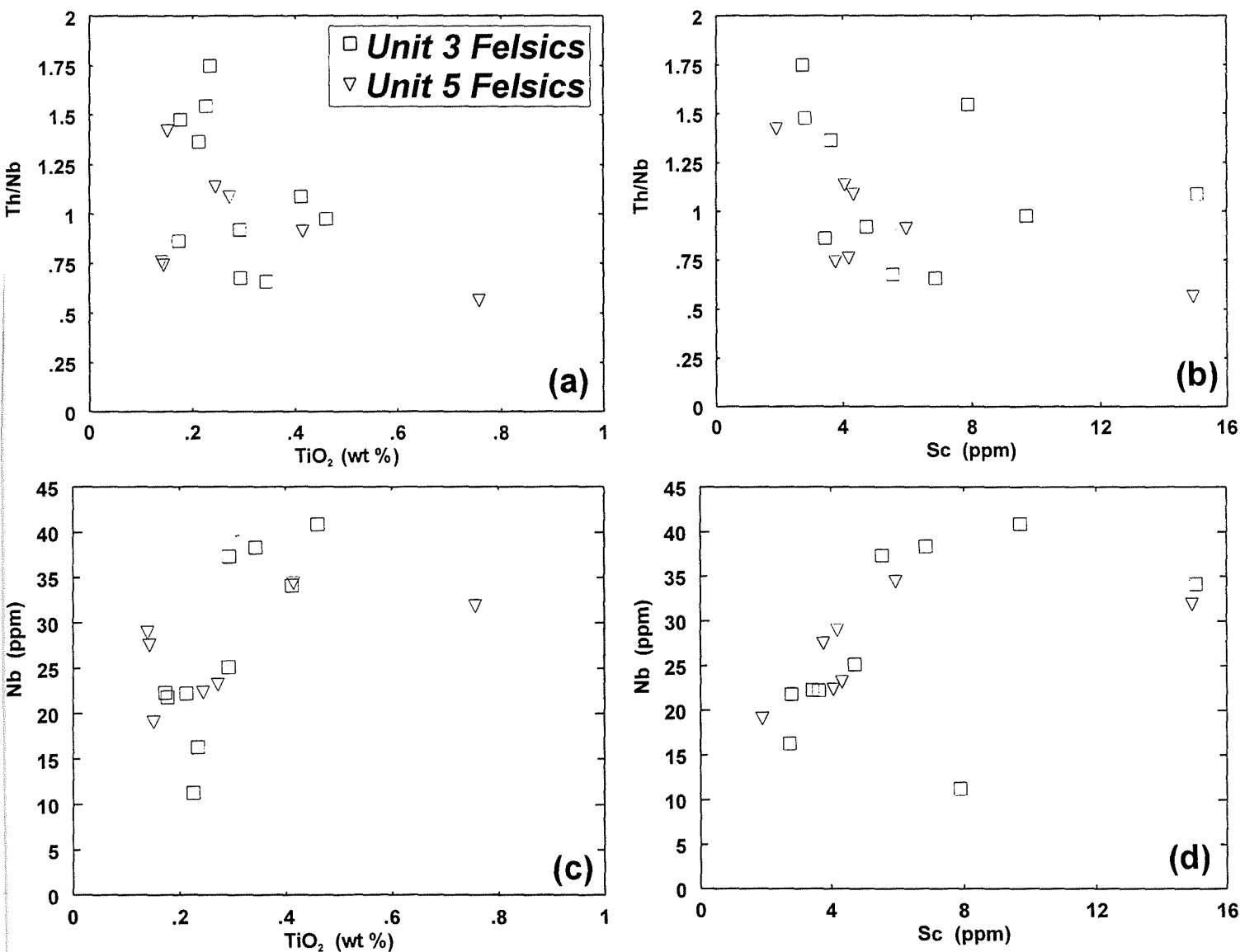


Figure 4. The inverse relationships between Th/Nb and Sc and TiO₂ (a) and (b), and the sympathetic relationship between Nb and TiO₂ and Sc suggest that the negative Nb anomaly in Figure 3 may be related to crystallization (and/or restitic) of Ti-rich phases (e.g., rutile, titanite, magnetite/ilmenite), and not necessarily be a diagnostic "arc" signature.

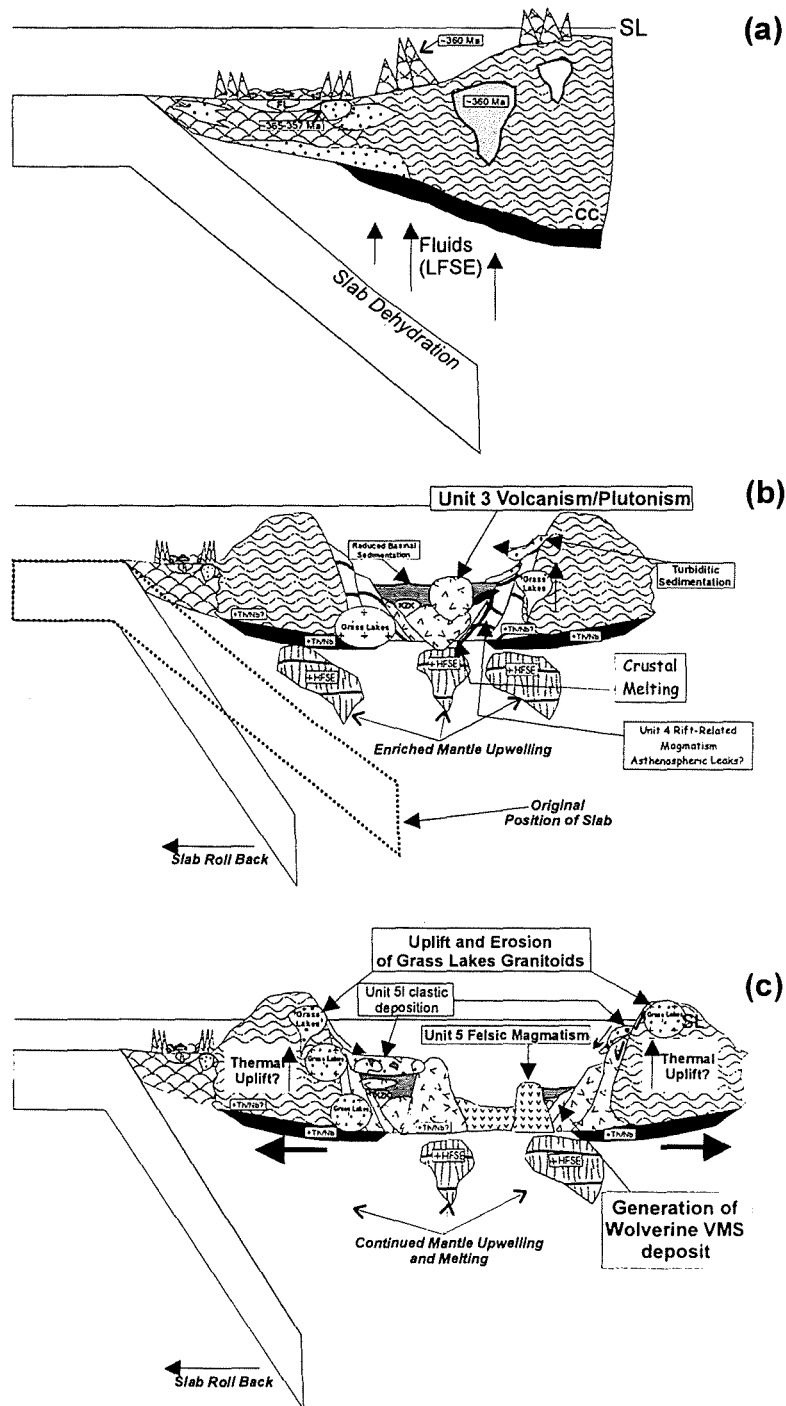


Figure 5. Possible geodynamic model for the setting of the Finlayson Lake VMS district. The early evolution of the Finlayson Lake district is characterized by ~365-360 Ma (Mortensen, 1992; Grant et al., 1996; Grant, 1997) primitive through mature arc magmatism (unit 2) built upon transitional continental crust (Grant et al., 1996; Grant, 1997; Piercey et al., 1999a,b). Mississippian arc rifting was likely induced by a retreating slab which rolled back leaving a void between the mantle wedge, arc crust and subducting slab (b) that was subsequently underplated by enriched asthenospheric mantle that induced melting of the arc-lithosphere and crust forming crustal melts and felsic magmatism associated with unit 3. The stratigraphic progression from unit 4 through 5 represents a stage of uplift and erosion, yet maintenance of similar petrogenetic and metallogenic conditions as the underlying unit 3 volcanics (c). Further details are provided in the text.

MID-PALEOZOIC TECTONISM IN YUKON-TANANA TERRANE, NORTHERN CANADIAN CORDILLERA: RECORD OF INTRA-ARC DEFORMATION

Maurice Colpron¹ *Yukon Geology Program*
Don Murphy *Whitehorse, Yukon Y1A 2C6*

Jim Mortensen *University of British Columbia*
 Vancouver, B.C. V6T 1Z4

Hints of mid-Paleozoic tectonism have been reported from various locations in pericratonic terranes, and locally in basinal strata of the North American miogeocline, along the length of the Canadian Cordillera. The timing of these tectonic events is typically poorly constrained. They have generally been correlated with the Early Mississippian Antler orogeny of the US Cordillera with the implication that a mid-Paleozoic collisional orogeny occurred along the entire North American Cordillera.

In Yukon-Tanana terrane, evidence of mid-Paleozoic tectonism includes: (1) tectonic foliations and associated structures which are cut by late- to post-tectonic intrusions; (2) regional unconformities that are inferred to onlap previously deformed terrain; and (3) eclogite of mid-Mississippian age. On-going U-Pb zircon geochronological studies reveal, however, that deformational events indicated by these relationships are of significantly different ages in different areas and therefore cannot be related to a single collisional event.

In the Finlayson Lake area, NE of Tintina fault, a late-tectonic intrusion dated at ca.357 Ma truncates a tectonic fabric in country rocks. This pluton was uplifted and eroded before deposition of overlying younger Mississippian sequence. In Glenlyon area, SW of Tintina fault, deformation is tightly constrained to mid-Mississippian (Viséan) time. In NW Glenlyon, calc-alkaline volcanic rocks and sub-volcanic intrusions dated at 344-346 Ma were deformed and metamorphosed prior to intrusion of the post-tectonic Tatlain batholith (ca.340 Ma). To the SE, a ca.340 Ma calc-alkaline volcanic sequence, co-magmatic with the Tatlain batholith, unconformably overlies two different clastic sequences, one of which is intruded by a 353 Ma pluton. Eclogitic rocks from SE Yukon, NE of Tintina fault, were exhumed by ca.346 Ma. They record mid-Mississippian subduction, which can be linked to arc volcanism to the west, but do not necessarily imply a collisional orogeny.

In light of these age constraints, we propose that mid-Paleozoic deformational events in Yukon-Tanana terrane record intra-arc tectonism reflecting the intricacies of the geodynamic processes acting in arc/subduction complexes and that local evidence for deformation is not necessarily regionally significant.

¹ maurice.colpron@gov.yk.ca

Geochemical and isotopic constraints on the source terranes of mid-Cretaceous granites in the Teslin area.

George A. Morris¹ and Robert A. Creaser²

¹ Département de Minéralogie, Université de Genève, rue des Maraîchers 13, 1211 Genève 4, Switzerland,
e-mail: morris9@etub.unige.ch

² Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, T6G 2E3,
Canada, e-mail: robert.creaser@ualberta.ca

Igneous rocks have long been recognised as probes of deeper crustal composition as well as providing many clues as to the tectonic and petrogenetic processes through which they were formed. The southern Yukon is formed of a complex assemblage of cratonic, pericratonic and exotic crustal terranes, a part of the northern Canadian Cordillera. The mid-Cretaceous (approx. 120 Ma to 90 Ma) across the southern Yukon was marked by large scale granite intrusion (and occasional extrusion) to form the most numerous post-collisional suite of igneous rocks in a near continuous transect perpendicular to the strike of the Cordillera. As such, these granites provide an excellent tool for examining the assemblage of the Cordillera in the southern Yukon.

As part of an extensive study of granites in the southern Yukon, a number of plutons and batholiths on either side of the Teslin Tectonic Zone (TTZ) were examined. Specifically, these are (from NE to SW) the Quiet Lake batholith, the Deadman Creek batholith, the Mt. McClintock, Point 1775m, Streak Mountain and Hayes Peak plutons (Fig. 1). The TTZ is the boundary between accreted terranes of the Intermontane Belt and pericratonic terranes of the Omineca Belt. As such, granites in this area are of particular interest as they can provide

information as to the architecture of the crust at depth.

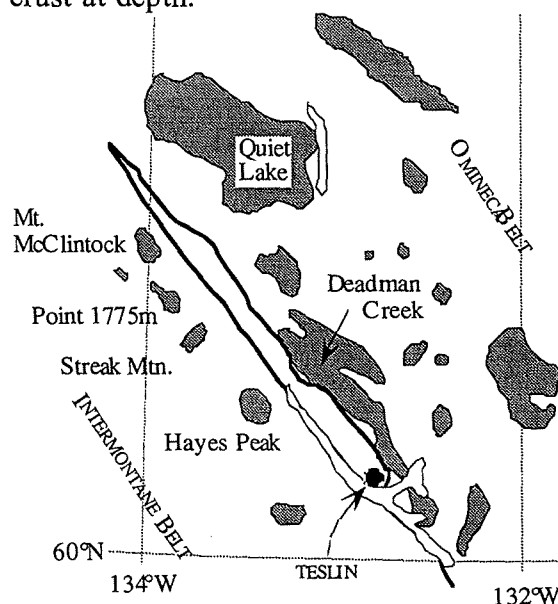


Fig. 1. Mid-Cretaceous granites of the Teslin area with the plutons and batholiths discussed in this contribution labelled. Also labelled are major faults separating the Intermontane and Omineca belts, and the settlement of Teslin.

GEOCHEMICAL AND ISOTOPIC RESULTS

The most significant geochemical observation to come out of this study is the presence, or absence, of the trace element "subduction signature" in granites of the Teslin area. This signature, the enrichment of Large Ion Lithophile (LIL) elements coupled with the depletion of High Field Strength (HFS) elements (see Fig. 2B) is only imparted on a magma

during the subduction process. Therefore, most continental rocks, which were either formed at volcanic arcs, or formed from rocks that were at one stage in their history derived from volcanic arc rocks (sometimes through many intermediate processes) will bear this signature. More significantly, a granite that does not bare this signature, must have been derived from the mantle via processes that do not include subduction. These include direct derivation from a mantle (i.e. basaltic) melt via fractional crystallisation, or AFC processes where the assimilated material does not bare the subduction signature, or by partial melting of oceanic crust, also lacking the subduction signature. The extreme degrees of fractionation required to produce a granitic magma from a mantle melt would produce significant depletion in key trace elements, distinguishing such granites from those derived from purely, or largely crustal sources.

In the Teslin area, granites of the Mt. McClintock, Point 1775m and Streak Mountain plutons, and components of the Quiet Lake batholith bear the subduction signature (Fig. 2B), attesting to their typical continental crust origin. Granites of the Hayes Peak pluton, the Deadman Creek batholith and the remainder of the Quiet Lake batholith, lack the subduction signature (Fig. 2A). There is no significant depletion in the key trace elements normally associated with fractional crystallisation suggesting that their source was either mainly, or entirely oceanic crust.

The non-subduction signature granites generally show primitive isotopic values (Sr_i : 0.7033 to 0.7062, ϵ_{Nd_i} : +0.1 to +5.1, all initial ratios calculated for $t = 100\text{Ma}$), supporting the geochemical evidence for their formation from primitive

oceanic crust. Subduction signature bearing granites are generally more evolved (Sr_i : 0.7051 to 0.7102, ϵ_{Nd_i} : -5.9 to +2.6), in keeping with a more evolved continental crustal origin.

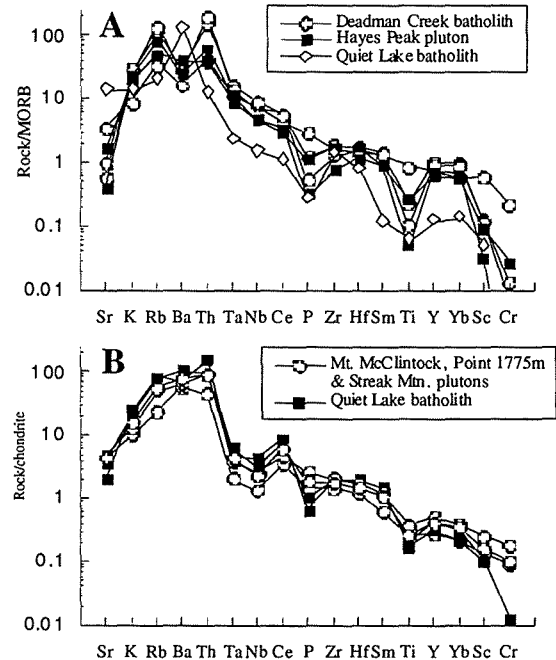


Fig. 2. MORB normalised element plots (after Pearce, 1983) for A: non-subduction signature granites and B: subduction signature granites.

TECTONIC CORRELATIONS

Correlation of granites with their source can be further refined by comparison of ϵ_{Nd} $t=100\text{Ma}$ versus $^{147}\text{Sm}/^{144}\text{Nd}$ data with similar data obtained from host terranes. It should however be noted that while ϵ_{Nd} data should correlate exactly (once terrane data has been recalculated to the same age as the granite data), some variation can take place in $^{147}\text{Sm}/^{144}\text{Nd}$ data due to the effects of fractionation on rare earth elements.

While there are several terranes in the Teslin area within both the Intermontane Belt and the Omineca Belt that could impart a subduction signature on

a magma, only rocks of Quesnellia and Stikinia have similarly high $\epsilon_{\text{Nd}}(t=100\text{Ma})$ and low $^{147}\text{Sm}/^{144}\text{Nd}$ ratios to the granites of this study. Indeed, the Mt. McClintock, Point 1775m and Streak Mountain plutons are hosted by Devonian to lower Jurassic Arc volcanics and arc derived sediments of Stikinia and it is quite feasible that deep seated components of this terrane are the source of these plutons. The Quiet Lake batholith is hosted by metasediments of the Cassiar and Yukon-Tanana terranes that generally return much more evolved $\epsilon_{\text{Nd}}(t=100\text{Ma})$ ratios. A more plausible source for the subduction signature bearing components of the Quiet Lake batholith is arc volcanics and arc sediments of either Quesnellia or Stikinia underlying the Yukon-Tanana and Cassiar Terranes.

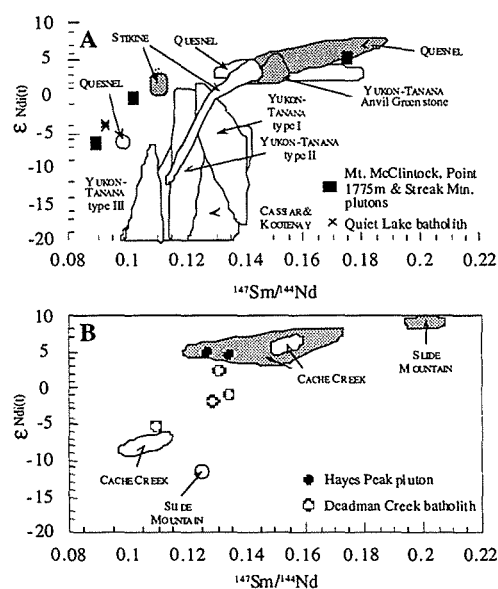


Fig. 3. Neodymium isotopic data for A: subduction signature bearing granites and B: non-subduction signature bearing granites compared with terrane data (Creaser et al., 1997; Patchett & Gehrels, 1998; K.Fallas, pers. com.) All data calculated for $t=100\text{Ma}$. Shaded terrane fields indicate rocks of igneous origin, unshaded indicate sedimentary origin.

There are two terranes located in the Teslin area that contain rocks of

oceanic origin, the Cache Creek terrane in the Intermontane Belt, and the Slide Mountain Terrane in the Omineca Belt. All the data for non-subduction signature granites falls in an array between published values for igneous and sedimentary components of the Cache Creek terrane, $^{147}\text{Sm}/^{144}\text{Nd}$ ratios being far to low for a Slide Mountain source. A Cache Creek source is easy to justify for the Hayes Peak pluton, as it is hosted by that terrane, but both the Deadman Creek and the Quiet Lake batholiths lie on the east side of the TTZ, within Omineca Belt rocks. Our data therefore suggests that the Cache Creek terrane, or rocks with similar oceanic crustal affinity, extend some distance beneath the Yukon-Tanana, Slide Mountain and Cassiar terranes of the Omineca Belt

CONCLUSIONS

Geochemical and isotopic data from granites in the Teslin area can provide information about the rocks from which they were derived. Our data indicates at least two distinct sources for these granites, oceanic crustal rocks and moderately evolved continental crust. While granites west of the TTZ can be correlated with their host terranes, indicating that these terranes are deep seated, those east of the TTZ cannot. Indeed, the isotopic composition of granites east of the TTZ closely matches that from terranes within and west of the zone. This suggests that the Yukon-Tanana and Cassiar terranes that host the granites east of the TTZ are relatively thin and are underlain by more primitive material similar to, or indeed the same as that exposed west of the zone.

EOCENE MAGMATISM ALONG THE SLOKO VOLCANIC ARC

Jonah Resnick¹ and Don Francis²

Department of Earth and Planetary Sciences, McGill University; 3450 University Street,
Montreal, QC email 1: jresnick@eps.mcgill.ca , 2: donf@eps.mcgill.ca

Lower Tertiary volcanic complexes and coeval plutonic intrusions of the Sloko Volcanic Arc are exposed along the eastern margin of the Coast and Boundary Ranges of northwestern British Columbia and the southwestern Yukon Territory, representing the terminal event in the evolution of the Coast Plutonic Complex (CPC). The greatest preserved accumulations of Eocene volcanic rocks occurs in the Sloko Lake Volcanic Complex (SLVC) of northwestern British Columbia and at the Mt. Skukum (MSVC) and Bennett Lake (BLVC) Volcanic Complexes of the Southwestern Yukon Territory.

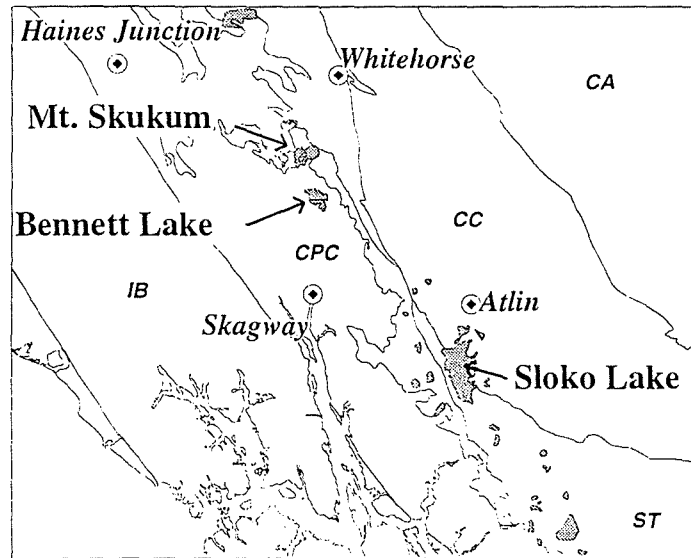


Figure 1. Location of the Sloko Lake, Bennett Lake, and Mt. Skukum Volcanic Complexes (Dark grey) in the northern Canadian Cordillera. Abbreviations denote Insular Belt (IB), Coast Plutonic Complex (CPC), Stikine Terrane (ST), Cache Creek Terrane (CC), and Cassiar Terrane (CA).

The SLVC is characterized by flat to gently dipping stratigraphy constituting the largest preserved volcanic complex in the northern Canadian Cordillera. Approximately 1500 m of stratigraphy are exposed in the SLVC that can be subdivided into three stratigraphic units; 1) a lower unit of pyroclastic and volcanoclastic breccia and ignimbrite flows overlain by 2) a thick middle unit of dominantly basaltic to andesitic lava flows with thin interbedded ash horizons, and 3) an uppermost unit consisting of a series of low-Mg basalt and basaltic andesite lava flows. The transition from the middle to the

upper stratigraphic unit represents a change from explosive volcanism to late stage effusive volcanism. Associated plutons and numerous late-stage dykes cross-cut the volcanic stratigraphy. The SLVC exhibits a transitional calc-alkaline and tholeiitic fractionation trend, characterized by depletions in LILE in comparison to typical continental calc-alkaline suites, but exhibiting no evidence of Fe enrichment characteristic of tholeiitic volcanic suites. Although the compositions of the volcanic rocks range from basalt through to rhyolite in composition, there is a paucity of samples within the dacite field. The mafic and intermediate rocks are dominated by low-Mg and high-Al (>18 wt% Al_2O_3) basalts and andesites but also include rare high-Mg basalts (8-9 wt% MgO) with enrichments in Cr and Ni.

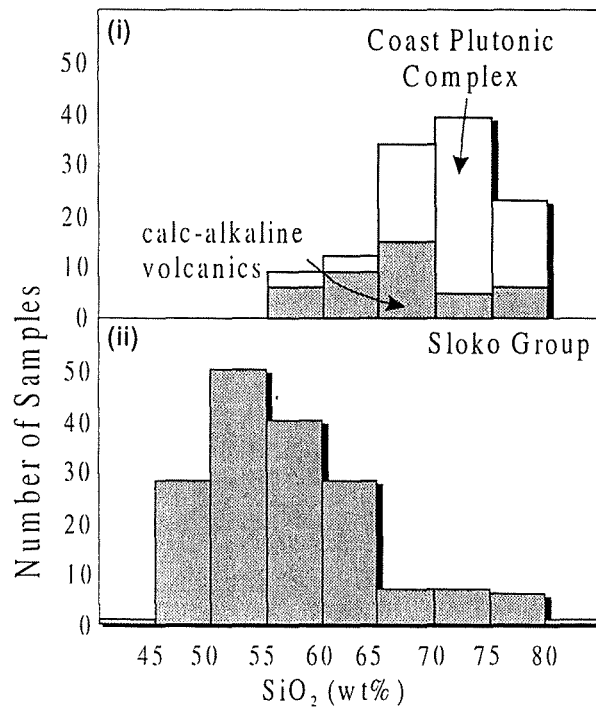


Figure 2. Histogram showing distribution of silica for various Eocene volcanic rock suites and granitoids of the Coast Plutonic Complex. Eocene volcanic rocks: (i) calc-alkaline series at Bennett Lake, Mt. Skukum, and Sifton Range, (ii) Sloko Group.

Lavas of the SLVC are dominantly basaltic to andesitic in composition characterized by low SiO₂, in contrast to the evolved (higher SiO₂) lavas of the MSVC and BLVC (Figure 2). Intermediate lavas of the SLVC also exhibit slight depletions in LILE (K, Rb) in comparison to lavas of similar composition in the MSVC and BLVC. The MSVC and BLVC lie within the CPC, while the SLVC lies on the eastern boundary of the CPC, within the Intermontane Belt. The geochemical differences between the SLVC and the MSVC and BLVC may be due to different degrees of contamination by

granitic magma of the CPC. The lower SiO_2 and slight LILE depletion of the SLVC is indicative that SLVC magmas are less contaminated than lavas of the MSVC and BLVC. The differences in degree of contamination may be explained by differences in the thermal state of the continental crust through which magmas ascended; the MSVC and BLVC magmas ascending through hotter crust and the SLVC magmas ascending through cooler crust.

Minimal geotectonic motion of the Yukon-Tanana terrane relative to North America: Preliminary paleomagnetic results from the Dawson Range Batholith.

P.J.A. McCausland¹, D.T.A. Symons², C.J.R. Hart³, and W.H. Blackburn⁴

¹Earth Sciences, University of Western Ontario, London, Ontario N6A 5B7 pjam@julian.uwo.ca

²Earth Sciences, University of Windsor, Windsor, Ontario N9B 3P4 dsymons@uwindsor.ca

³Yukon Geology Program, Government of Yukon, Box 2703 [F-3], Whitehorse, YT Y1A 2C6

⁴Royal Roads University, 2005 Sooke Rd., Victoria, BC V9B 5Y2

1. Introduction

The Yukon-Tanana terrane (YTT) is an extensive assemblage of continental North American rocks with uncertain past relations to other far-travelled terranes and to North America itself (Mortensen, 1992; Lowe et al., 1994). Its size, cratonic provenance and 'inboard' position makes the YTT a key tectonic element in the assembly of the northwest Cordillera (Figure 1). Did the YTT act as an in situ 'bumper' to halt the motions of other terranes (McClelland et al., 1992; Mihalynuk et al., 1994), or did it at least in part participate with other Intermontane terrane motions relative to North America (Irving et al., 1996; Johnston et al., 1996)?

Thus, understanding the geotectonic history of the YTT is fundamental for relating northwest Cordilleran allochthonous terranes to North America. Paleomagnetic studies of YTT Mesozoic and Cenozoic plutons are underway to ascertain the geotectonic motion history of the YTT, and to assess whether it has formed a coherent entity since the Early Jurassic. The approach is similar to that used with units of the Intermontane Belt terranes, a synthesis of which is reported by Harris et al., (this meeting).

This report presents a preliminary paleomagnetic analysis of the mid-Cretaceous Dawson Range batholith and summarizes results which suggest only minimal geotectonic motion of the YTT relative to North America. An appendix reports the status of other collections from this project.

2. Geological setting

The ~10 000 km² mid-Cretaceous Dawson Range batholith (Figure 2) intrudes YTT Paleozoic gneisses and schists, and the Early Jurassic Big Creek batholith (Johnston, 1995; 1999). Intrusive phases of the batholith range from diorite to quartz-monzonite granite, giving U-Pb (zircon) ages of 105 Ma for the diorite (Johnston, 1995) and K-Ar (hbl, bt) ages ranging from 105-95 Ma (Wanless et al., 1978).

The batholith is overlain by flat-lying mid-Cretaceous Mount Nansen Group volcanics and is intruded by Late Cretaceous latite-dacite dykes and plugs which acted as feeders for the overlying ~70 Ma Carmacks Group volcanics (Johnston, 1995).

3. Paleomagnetism

A collection of 273 specimens from 23 sites was obtained by helicopter from a portion of the Dawson Range batholith some 110 km northwest of Carmacks in the vicinity of the Selwyn River (Figure 2). The specimens underwent standard thermal and alternating field (AF) treatment at the University of Windsor Paleomagnetism Laboratory using a Sapphire Instruments SI-4 AF demagnetizer, a Magnetic Measurements MMTD80 thermal demagnetizer, and an automated CTF DRM-420 cryogenic magnetometer, all set inside a magnetically-shielded room which permits only 0.2% of the Earth's ambient magnetic field intensity.

Saturation isothermal remanent magnetization (SIRM) testing was performed on 18 specimens with a Sapphire Instruments SI-6 pulse magnetizer and AF demagnetization. SIRM acquisition and decay curves indicate that the dominant magnetic carrier is pseudosingle domain magnetite, while thermal step demagnetization curves show distributed unblocking punctuated by a sharp intensity drop in the 530°-580°C range, implying that the characteristic remanent magnetization (ChRM) is carried by titanomagnetite or magnetite. Specimens from the finer grained sites 17 and 18 (Figure 2) appear to bear single domain magnetite, consistent with a smaller magnetite grain size.

AF step demagnetization removes a viscous remanent magnetization (VRM) by ~20 mT, while thermal methods reveal distributed unblocking with more clearly defined ChRM directions above ~500°C. ChRM directions were identified using the least-squares method (Kirschvink, 1980).

The Dawson Range collection has a well-defined very steep down ChRM in 11 of the 23 sites (sites 8, 11-19 and 21; Figures 2,3), 10 of which are from the earliest, dioritic phase of the batholith. Site 20 and some specimens from site 19 carry, an additional SE and up magnetization which is likely a thermoremanent overprint due to a nearby Carmacks-related intrusion (Figures 2,3). Sites 1 and 10 from a granodioritic phase of the batholith yielded poorly-resolved ChRM directions that are grouped to the NW and down (Figure 3), which are similar to the normal site directions reported by Wynne et al. (1998) for the Carmacks volcanics. Other granodioritic sites (2-6,9) gave erratic or unclear demagnetizations.

The unit mean ChRM direction of the Dawson Range batholith is $D=131.7^\circ$, $I=88.8^\circ$; $a95=4.1^\circ$, $k=128$; $N=11$ sites (Figure 3). Granodiorite sites 1 and 10 may carry normal-polarity Carmacks overprints, antipodal to those more clearly recorded in specimens from site 20. However, conclusions based on ~18 contributing specimens from 3 sites cannot be anything but speculative; the remaining discussion will deal solely with the well-determined 11 steep down sites.

4. Geobarometry

Emplacement depths have been estimated to test for the need to make a tilt-correction to paleomagnetic data using the temperature-corrected Al-in-hornblende geobarometer (Anderson and Smith, 1995). After petrographic inspection of a thin section from each site, specimens from 8 sites were chosen to spatially represent the sampled area of the Dawson Range batholith. Electron microprobe analyses of hornblende and plagioclase pairs were performed using a JEOL JXA-8600 Superprobe at the University of Western Ontario (see Symons et al. (2000) for further details of the method).

Seven sites gave temperature-corrected pressure estimates for the batholith sampling area (Figure 4). Site 3 failed to provide useable plagioclase for temperature correction of the preliminary pressure estimate, which was similar to those at other sites.

Assuming a gradient of 0.036 km/MPa (density 2.8 g/cm³), the Dawson Range batholith crystallized at depths of 10.3 to 12.7 km, statistically indicating that the batholith has experienced no significant post-emplacement tilt.

5. Discussion

Paleomagnetism of the mid-Cretaceous Dawson Range batholith yields a paleopole of 61.1°N, 226.3°E ($dp=8^\circ$, $dm=8^\circ$), which is 1370 km +/- 860 km near-sided compared with the 100 Ma North American reference pole of Besse and Courtillot (1991). Unit rotation cannot be significantly assessed due to the steep inclination of the ChRM, which places the Dawson Range sampling location inside the uncertainty ellipse of its paleopole.

Previously reported YTT poles from the Early Jurassic Big Creek batholith (Symons et al., 2000) and the Late Cretaceous Seymour Creek stock (McCausland et al., 1998) are similarly near-sided (Figure 5). All three YTT poles indicate minimal transport away from their North American reference poles, markedly distinct from the poleward transport found for units in the Intermontane terranes (Figure 6) (Harris et al., 1999; Harris et al., this meeting).

The motion histories of the YTT and Intermontane terranes are clearly convergent towards their present locations during the interval 110 Ma -50 Ma (Figure 6). Thus paleomagnetic evidence does not place the Intermontane terranes near the pericratonic YTT until Eocene time, supporting accretionary models which postulate a 'bumper' role for the YTT, against which advancing Intermontane terranes impacted (McClelland et al., 1992; Mihalynuk et al., 1994; Symons et al., 2000). It should be noted that these three YTT results all come from units in the south-central Yukon west of Carmacks, and may not be applicable to the YTT lying to the northwest, or east of the Teslin fault (Figure 1).

Paleomagnetic results from the 70 Ma Carmacks volcanics (Wynne et al., 1998) are discordant from units of the Intermontane terranes (Harris et al., 1999), and strikingly

different from YTT units (Figure 6). This is puzzling since the extensive Carmacks volcanism intrudes and overlies the Dawson Range batholith and other YTT units (Figure 2) (Johnston, 1995; 1999).

Similar near-sided results for all three YTT plutonic units and geobarometric estimates of paleohorizontal rule out significant post-emplacement tilt. However, the Carmacks paleomagnetism, which overprinted porous Mesozoic redbeds and tuffs (Wynne et al., 1998) appears to be geologically, if not geotectonically, meaningful. This discrepancy in YTT plutonic and volcanic remanence directions remains an open question.

Appendix

Further investigation of YTT units is underway to broaden the YTT database, refine estimates of its motion history, and to test YTT coherency over Mesozoic time. During this past summer collections were obtained from units east of the Teslin fault and towards the northwest of the YTT (Figure 1). The ~100 Ma Quiet Lake batholith was sampled by helicopter to provide an eastern YTT complement to the Dawson Range batholith. To the northwest, the 68 Ma Swede Dome stock, 205 Ma Taylor Mountain batholith and the 92 Ma Fort Knox pluton were road sampled to extend the temporal and spatial coverage of the YTT paleomagnetic investigation. The four collections each average 317 specimens from 23 sites.

Results from the 190 Ma Big Creek batholith (Williams, 1998) are in press (Symons et al., in *Tectonophysics*). Other initial results are being presented (McCausland et al., 1999; Symons et al., 1999), or undergoing analysis (the 56 Ma Pattison Pluton).

References

- Anderson, J.L., and Smith, D.R. (1995) The effects of temperature and fO_2 on the Al-in-hornblende barometer. *American Min.*, V80: pp 549-559.
- Besse, J., and Courtillot, V. (1991) Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian plates, and true polar wander since 200 Ma. *Jour. Geophys. Resch.* V96 (B3): pp 4029-4050.
- Engelbreton, D.C., Cox, A., and Gordon, R. (1985) Relative motions between oceanic and continental plates in the Pacific basin. *GSA Special Paper* 206, 59p.
- Harris, M.J., Symons, D.T.A., Hart, C.J.R., Blackburn, W.H., and McCausland, P.J.A. (2000) Paleomagnetic evidence for the tectonic motions of the terranes underlying the northern Intermontane Belt, Canadian Cordillera. *SNoRCLE 2000 Workshop*, this meeting.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., and Hart, C.J.R. (1999) Paleomagnetic and geobarometric study of the Late Cretaceous Mount Lorne stock, southern Yukon Territory. *Can. Jour. Earth Sci.*, V36: pp 905-915.

Irving, E., Wynne, P.J., Thorkelson, D.J., and Schiarizza, P. (1996) Large (1000 to 4000 km) northward movements of tectonic domains in the northern Cordillera, 83 to 45 Ma. *Jour. Geophys. Rsch.*, V101 (B8): pp 17901-17916.

Johnston, S.T. (1995) Geological compilation with interpretation from geophysical surveys of the northern Dawson Range, central Yukon (115 J/9 & 10; 115 I/12); 1:100 000 map. Yukon Geology Program Open File 1995-2(G).

Johnston, S.T. (1999) Large-scale coast-parallel displacements in the Cordillera: a granitic resolution to a paleomagnetic dilemma. *Jour. Struct. Geol.* V21: pp 1103-1108.

Johnston, S.T., Wynne, P.J., Francis, D., Hart, C.J.R., Enkin, R.J., and Engebretson, D.C. (1996) Yellowstone in Yukon: The Late Cretaceous Carmacks Group. *Geology*, V24: pp 997-1000.

Kirschvink, J.L. (1980) The least squares line and plane and the analysis of paleomagnetic data. *Geophys. Jour. Roy. Astron. Soc.* V62: pp 699-718.

Lowe, C., Horner, R.B., Mortensen, J.K., Johnston, S.T., and Roots, C.F. (1994) New geophysical data from the northern Cordillera: preliminary interpretations and implications for the tectonics and deep geology. *Can. Jour. Earth Sci.*, V31: pp 891-904.

McCausland, P.J.A., Symons, D.T.A., Hart, C.J.R., and Blackburn, W.H. (1999) Further paleomagnetic evidence for minimal motion of the pericratonic Yukon-Tanana terrane relative to North America. AGU Fall 1999 Meeting, EOS, V76: p F279.

McCausland, P.J.A., Symons, D.T.A., and Hart, C.J.R. (1998) Post-Cretaceous geotectonic motion of the Yukon-Tanana terrane from paleomagnetism of the Seymour Creek stock, Yukon Territory. EOS V75: pp F219-F220.

McClelland, W.C., Gehrels, G.H., and Saleeby, J.B. (1992) Upper Jurassic-Lower Cretaceous basinal strata along the Cordilleran margin: Implications for the accretionary history of the Alexander-Wrangellia-Peninsular terrane. *Tectonics*, V11: pp 823-835.

Mihalynuk, M.G., Nelson, J.L., and Diakow, L.J. (1994) Cache Creek terrane entrapment: Oroclinal paradox within the Canadian Cordillera. *Tectonics*, V13: pp 575-595.

Mortensen, J.K. (1992) Pre-mid-Mesozoic evolution of the Yukon-Tanana terrane, Yukon and Alaska. *Tectonics*, v11: pp 836-853.

Symons, D.T.A., Williams, P.R., McCausland, P.J.A., Harris, M.J., Hart, C.J.R., and Blackburn, W.H. (2000) Paleomagnetism and geobarometry of the Big Creek batholith suggests that the Yukon-Tanana terrane has been a parautochthon since Early Jurassic. *Tectonophysics*.

Symons, D.T.A., McCausland, P.J.A., Hart, C.J.R., and Blackburn, W.H. (1999) Yukon-Tanana terrane: Backstop for the accreted North American Cordilleran terranes. IUGG Abstracts 'A,' p 315.

Wanless, R.K., Stevens, R.D., and LaChance, G.R. (1978) Age determinations and geological studies, K-Ar isotopic ages, Report 13. GSC Paper 77-2, 60p.

Williams, P.R. (1998). Measuring the geotectonic motion of the Yukon-Tanana terrane. Unpublished B.Sc. Thesis, Univ. of Windsor, 38p.

Wynne, P.J., Enkin, R.J., Baker, J., Johnston, S.T., and Hart, C.J.R. (1998) The big flush: paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera. *Can. Jour. Earth Sci.*, V35: pp 657-671.

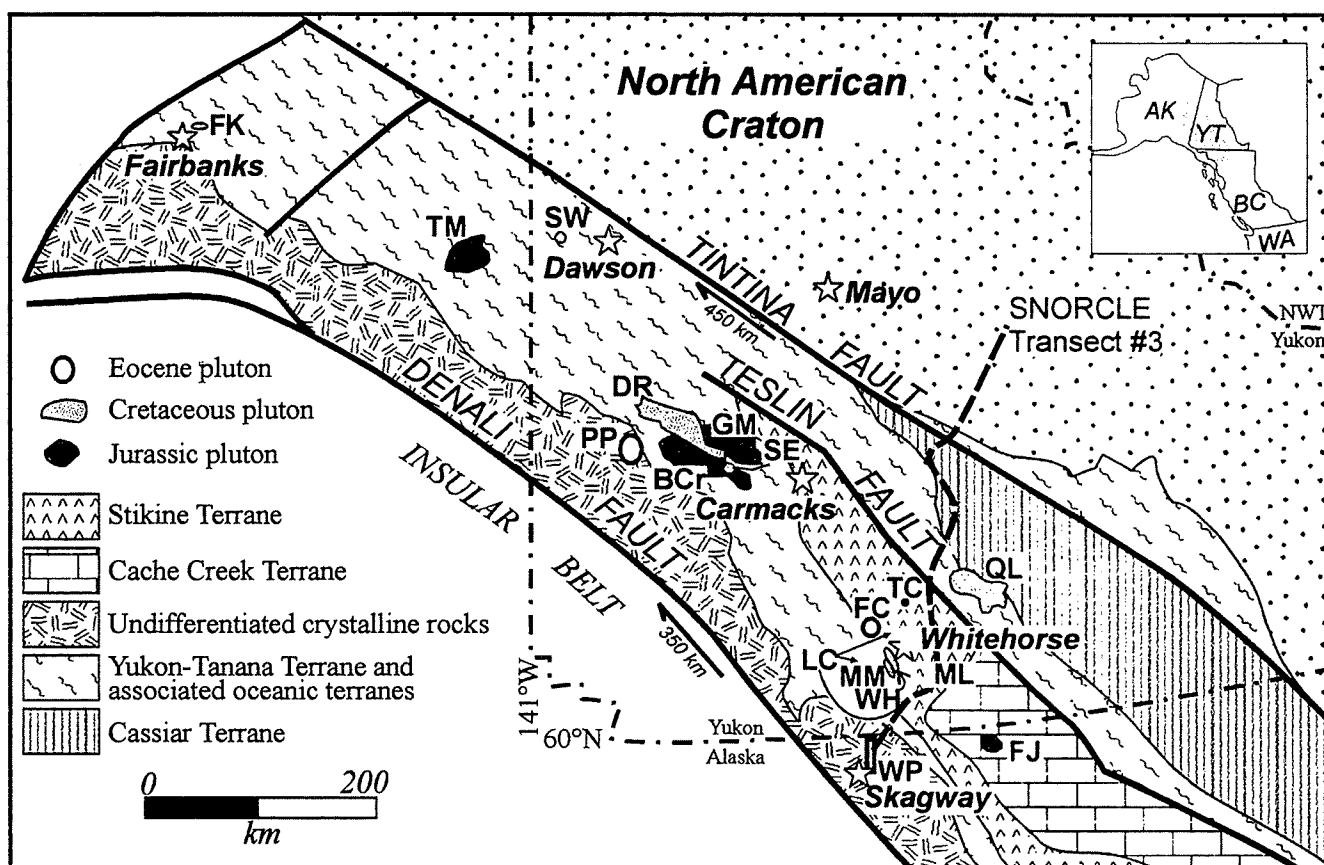
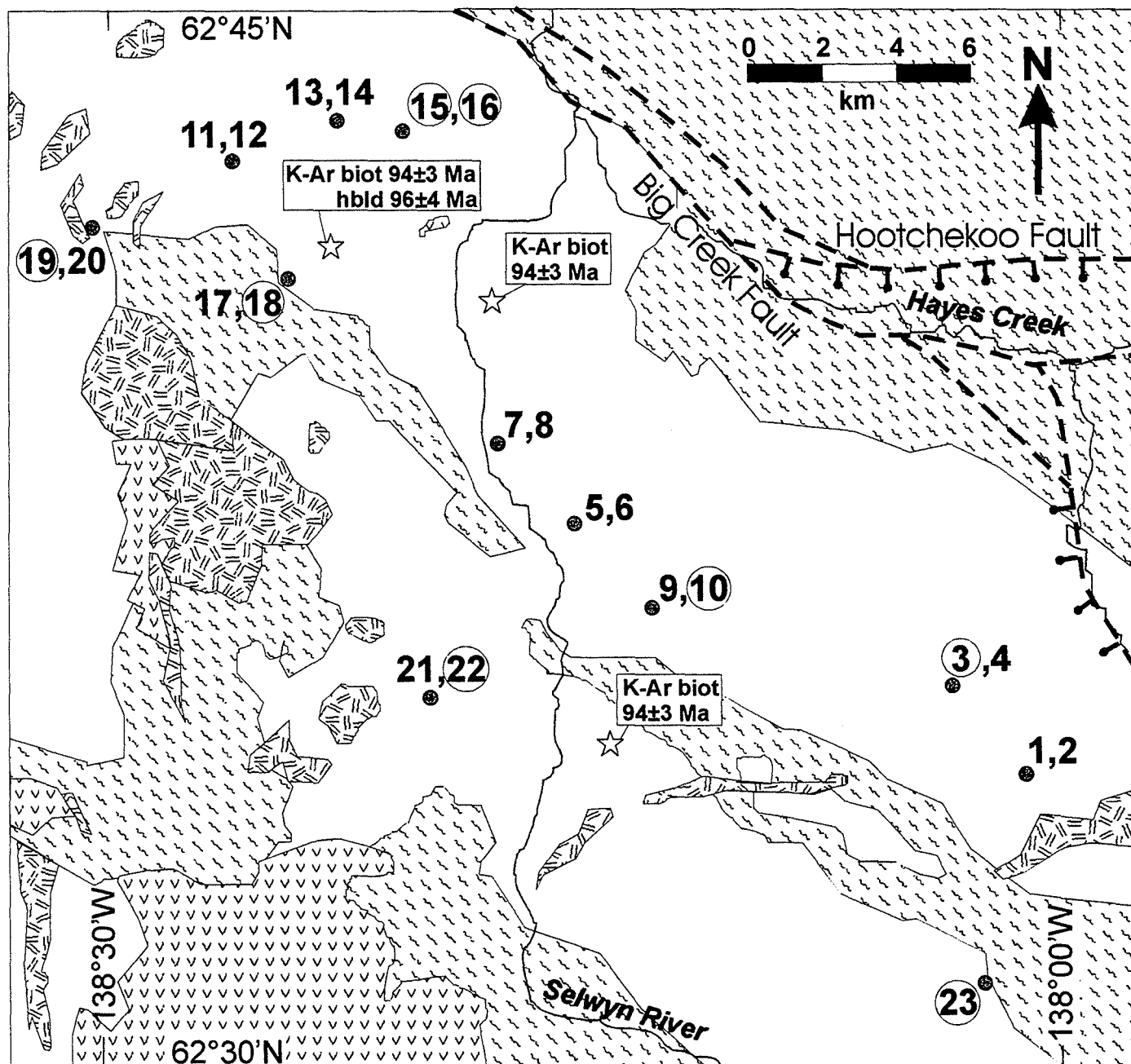


Figure 1. YTT context and collection locations. **AK** - Alaska; **BC** - British Columbia; **BCr** - Big Creek Batholith; **DR** - Dawson Range Batholith; **FC** - Flat Creek Stock; **FJ** - Fourth of July Batholith; **FK** - Fort Knox Stock; **GM** - Granite Mountain Batholith; **LC** - Laberge Conglomerate sites; **ML** - Mount Lorne Stock; **MM** - Mount McIntyre Pluton; **PP** - Pattison Pluton; **QL** - Quiet Lake Batholith; **SE** - Seymour Creek Stock; **SW** - Swede Dome Stock; **TC** - Teslin Crossing Stock; **TM** - Taylor Mountain Batholith; **WA** - Washington; **WH** - Whitehorse Batholith; **WP** - White Pass dikes; **YT** - Yukon Territory.

Figure 2: Dawson Range sampling sites and general geology.



Late Cretaceous

Carmacks Group Volcanics (~70 Ma)

shallow intrusions; Carmacks feeders

Cretaceous

Dawson Range Batholith (~100 Ma)

1, 2 Paleomagnetic sites
(○ = geobarometry)

Paleozoic

Yukon-Tanana terrane host schist and gneiss

contact fault, -drop side

Age data, location



Figure 3: Dawson Range batholith site and unit mean directions.

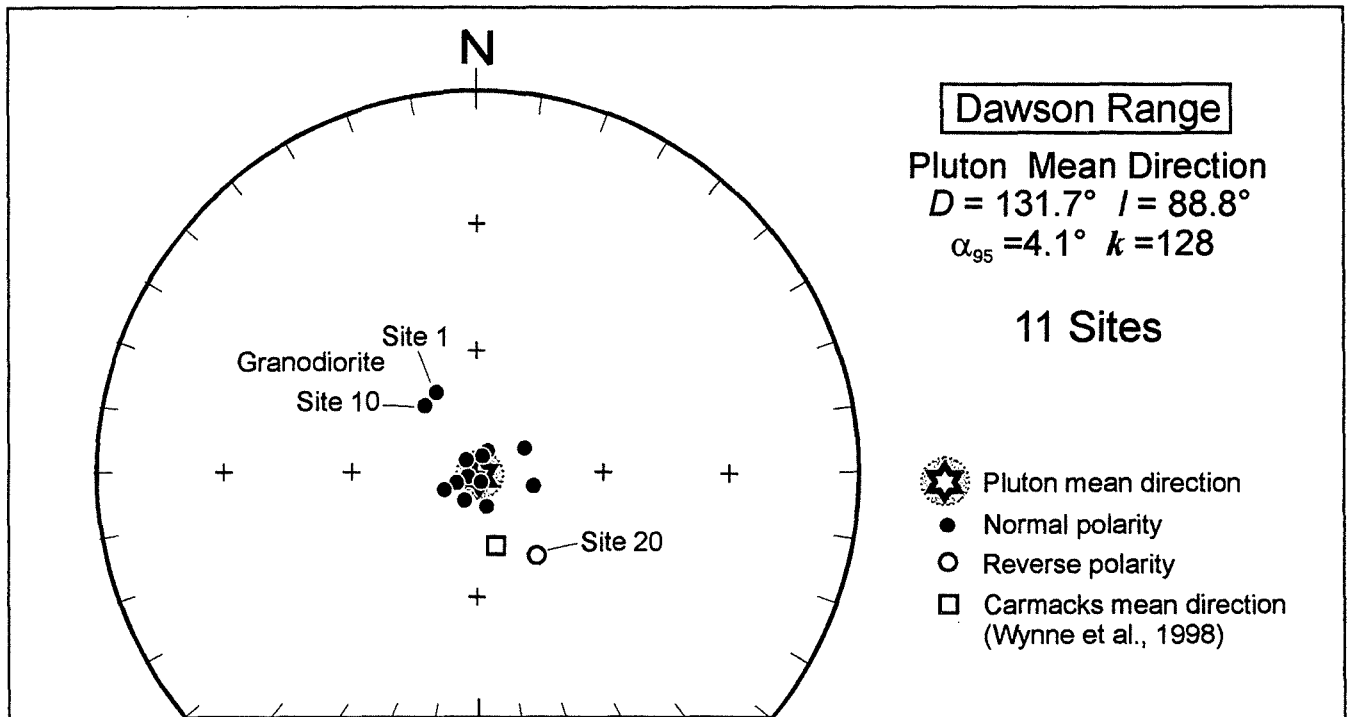


Figure 4: Paleodepths from Al-in-hornblende geobarometry.

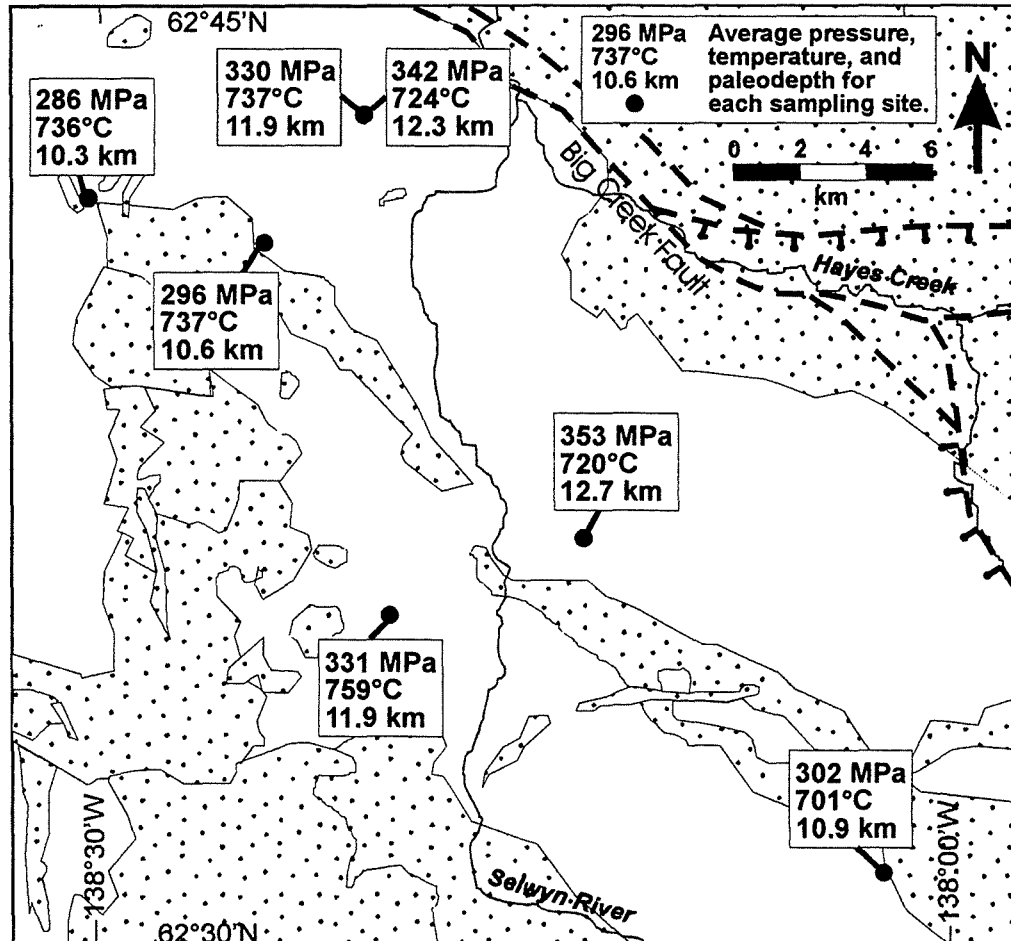


Figure 5: Yukon-Tanana terrane -paleopoles relative to NA path.

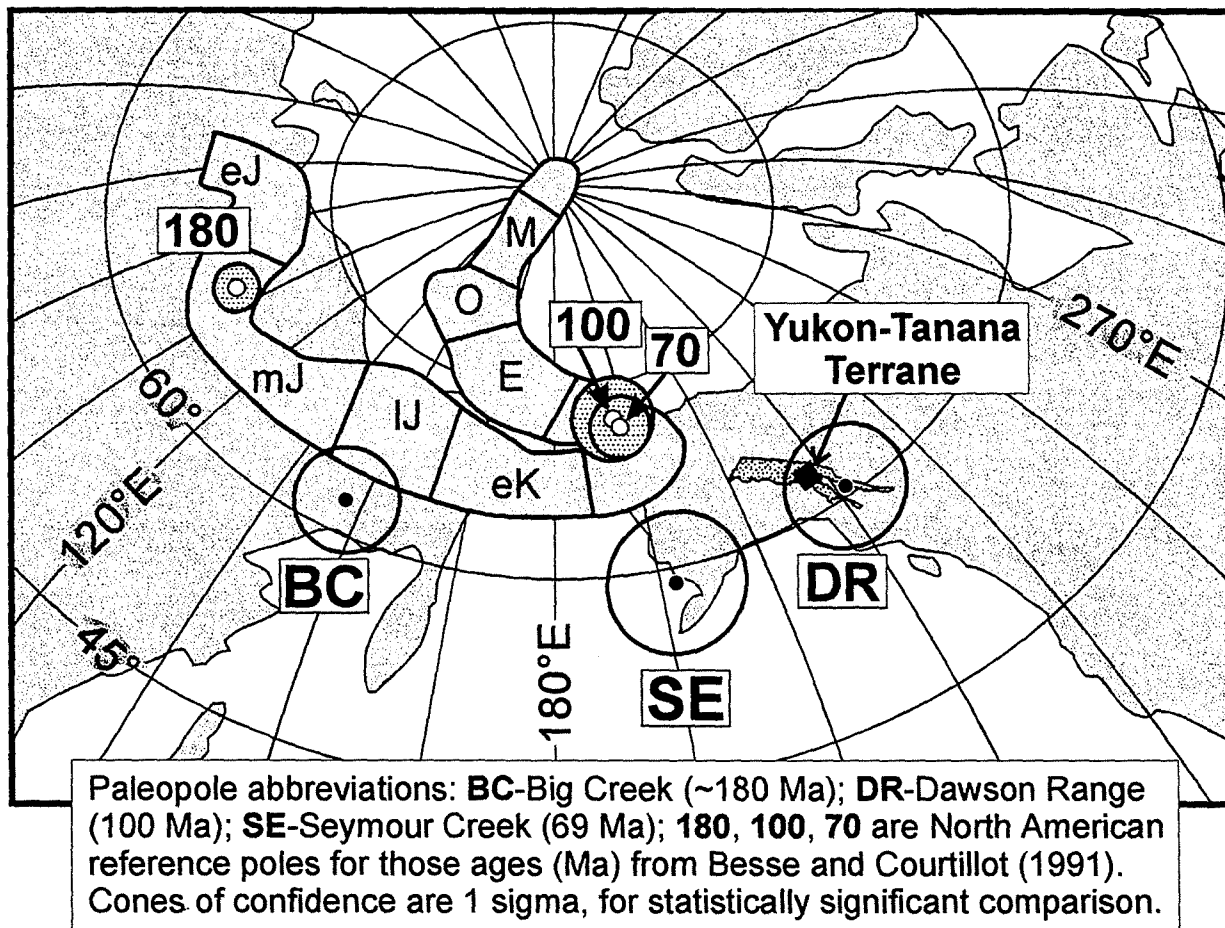
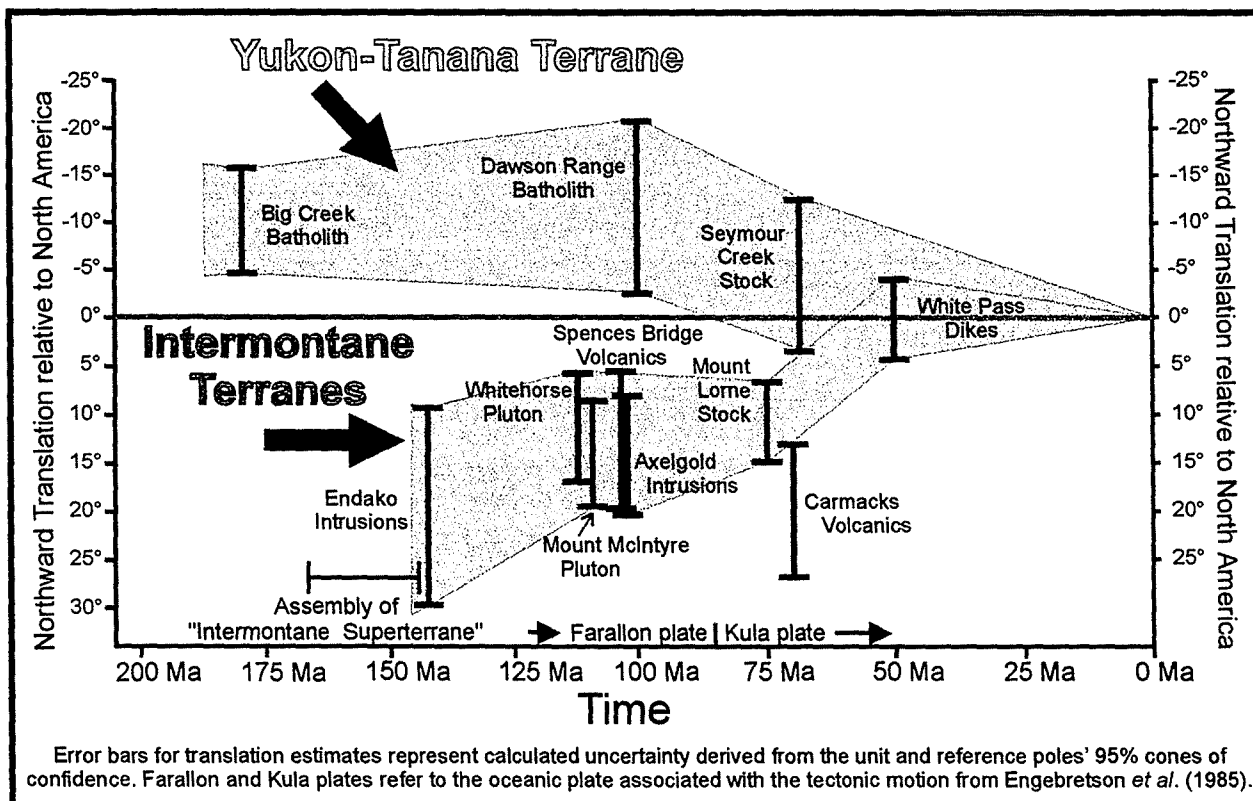


Figure 6: YTT, Intermontane unit translations relative to North America.



Paleomagnetic evidence for the tectonic motions of the terranes underlying the northern Intermontane Belt, Canadian Cordillera: A Summary

M.J. Harris, D.T.A. Symons (Univ. Windsor, mjh@uwindsor.ca)

C.J.R. Hart (Yukon Geology Program)

W.H. Blackburn (Royal Roads Univ.)

P.J.A. McCausland (Univ. Western Ontario)

INTRODUCTION

Previous to the LITHOPROBE-SNORCLE project, few tectonic motion estimates were available from paleomagnetic studies for the southern Yukon/northern British Columbia part of the Canadian Cordillera. Presently, 14 of 18 rock units have been paleomagnetically measured at the University of Windsor.

Seven of the rock units studied lie in two of the several terranes comprising the Intermontane Belt: the Stikine Terrane (six) and the Cache Creek Terrane. Six of these seven studies were the basis of a Ph.D. thesis (Harris 1998) that has provided a clear understanding of the tectonic motions of the terranes underlying the Intermontane Belt since the Jurassic. The following is a synthesis of the motions of these terranes and how they compare with previous studies from the Intermontane Belt within central to southern British Columbia.

CRETACEOUS UNITS

Mount Lorne Stock

The 75 Ma Mount Lorne Stock lies south of Whitehorse (Fig. 1) and intrudes sediments and volcanics within the Whitehorse Trough, which overlies the Stikine Terrane. The stock is a circular intrusion and is exposed over $\sim 30 \text{ km}^2$. It was sampled at 20 sites for paleomagnetic analysis, with eight of those sites also used to collect Al-in-hornblende geobarometric data (Fig. 2a). The latter results yielded a bimodal geographical distribution of pressures with the eastern locations having an average emplacement pressure (depth) of $\sim 200 \text{ MPa}$ ($\sim 7 \text{ km}$) and the western sites having an average pressure of $\sim 165 \text{ MPa}$ ($\sim 6 \text{ km}$) (Harris *et al.* 1999a). This result indicates that a fault extends through the stock, and its magnitude is consistent with that of the fault that is mapped to the south between the volcanic rocks and the Laberge Group rocks (Fig. 2a) (Hart, unpublished data). Geobarometric data do not otherwise indicate any post-magmatic movement or tilting of the stock, and this is further supported by the circular shape of the pluton and its parallel, circular aeromagnetic signature (GSC 1962).

The paleomagnetic sites comprised 19 granitoids and one mafic dike. Thermal demagnetization and saturation isothermal remanent magnetization (SIRM) testing indicated that the magnetizations were mostly carried by pseudosingle domain magnetite. Characteristic remanent magnetization (ChRM) directions were successfully calculated for 18 of the granitoid sites and also for the mafic dike, with all sites having their cones of 95% confidence (α_{95}) $\leq 10^\circ$. The mafic dike and its baked zone failed the paleomagnetic contact test, suggesting that the dike is coeval with the stock with both acquiring their magnetizations at about the same time. Six of the granitoid sites have their mean ChRM directions to the north-northeast and steeply down and the other 12 sites are anti-parallel with their mean ChRM directions to the south-southwest and steeply up. The site directions were averaged after reversing the up-directed site means to calculate the unit mean ChRM direction and associated paleopole (Table 1). Comparison of the paleopole with its interpolated 75 Ma reference pole from the North American craton (Besse and

Courtillot 1991) indicates that the Mount Lorne Stock records $10.5 \pm 3.5^\circ$ northwards translation (1170 ± 390 km) and $57 \pm 11^\circ$ clockwise rotation (Harris *et al.* 1999a).

Table 1 Summary of paleomagnetic data for the Intermontane Belt.

Collection	# sites N / n ^a	Unit mean direction			Paleopole		Reference
		D(°)	I(°)	α_{95} (°)	(°W)	(°N)	
Mount Lorne Stock	19 / 18	24.2	75.9	2.4	69.1	78.3	Harris <i>et al.</i> 1999a
Mount McIntyre Stock	21 / 11	39.8	73.8	3.4	60.1	70.5	Harris <i>et al.</i> 1996
Whitehorse Batholith	22 / 22	16.7	76.2	3.1	74.5	81.7	Harris <i>et al.</i> 1997
Fourth of July Batholith	31 / 31	49.5	70.5	3.0	54.9	63.4	Harris <i>et al.</i> 2000
Teslin Crossing Stock	19 / 15	5.9	77.7	8.8	110.6	84.3	Harris <i>et al.</i> 1999b

^a # sites: number of sites used (n) in the unit mean direction of the number of sites collected (N).

Mount McIntyre Pluton

The 109 Ma Mount McIntyre Pluton is a slightly elongated body that is exposed over 30 km² just west of the city of Whitehorse (Fig. 1). The pluton has intruded Triassic and Jurassic sediments of the Whitehorse Trough within the Stikine Terrane. It was sampled at 21 sites for paleomagnetic measurements and specimens from seven of those sites were further used for geobarometric analyses (Fig. 2b). Two of these sites yielded negative pressures and two other sites were later determined not to be part of the pluton. Further, results from the last three sites were not in agreement with each other nor with accepted results from the neighbouring Whitehorse Batholith (see next section), and thus the geobarometry study on the Mount McIntyre Pluton was deemed inconclusive (Harris *et al.* 1996).

From the 21 paleomagnetic sites, sites 1 and 2 (Fig. 2b) were later determined to have been collected from a belt of unassigned igneous rocks that do not belong to the pluton; they will not be further discussed. One of the other 19 sites sampled a mafic dike to use as a paleomagnetic contact test. Thermal demagnetization and SIRM testing showed that the magnetization is mostly carried by multidomain to pseudosingle domain magnetite (Harris *et al.* 1996). Site mean ChRM directions were successfully calculated for all 19 sites with 18 of them having α_{95} values $\leq 10^\circ$. Their mean directions yielded a loose cluster that was better fitted as two smaller populations, which had a geographical distribution. The northern sites (3-10, 19-21) yield a northeast and steeply down mean ChRM direction, while the southern sites (11, 12, 14-18) yield a northwest and steeply down mean ChRM direction (Harris *et al.* 1996). The contact test between the mafic dike and its baked zone was located in the southern part of the pluton and failed, suggesting that the dike is coeval with the pluton. The two populations were found to be statistically significantly different at the 95% confidence level using the McFadden and Lowes (1981) test (*i.e.*, $F_{\text{calc}} = 4.57 / F_{\text{tab}} = 3.32$) and, therefore, paleopoles were calculated for the northern sites, southern sites and for all sites combined. The latter result had no geological or tectonic significance. The paleopole for the southern sites records a northward translation of 35° and no rotation, while the paleopole for the northern sites records a northward translation of $14.3 \pm 5.0^\circ$ (1590 ± 550 km) and a clockwise rotation of $79 \pm 16^\circ$.

Whitehorse Batholith

The ~112 Ma Whitehorse Batholith is exposed over 160 km², on the west side of the city of Whitehorse (Fig. 1), and it intruded into sediments of the Whitehorse Trough which overlie the Stikine Terrane. It was sampled at 27 sites for paleomagnetic analysis, of which nine sites were used to obtain Al-in-hornblende geobarometric data. Emplacement pressures and related depths ranged from 203 MPa (7.3 km) to 155 MPa (5.6 km) from the north-northwest to the south-southeast, excluding one value from a nearby fault-skarn zone that was deemed to be altered (Harris *et al.* 1997). These values correspond to a south-southeast downward tilt of ~2.3°. Compared to the errors on the geobarometric and tectonic results, this tilt angle is statistically insignificant and hence the batholith was deemed not to have been tilted since emplacement (Harris *et al.* 1997). At most, correction for this ~2.3° tilt would increase the northward translation estimate by only ~250 km.

Twenty-two of the sites sampled granitoids of the batholith, three sites sampled host rocks for contact tests, and the remaining two sites provided another contact test between a mafic dike and its baked zone within the batholith. Two of the contact tests with the host rocks failed, likely because they were collected too close to the batholith, being remagnetized during the batholith's intrusion. The third host rock site yields different magnetic remanence directions both before and after tectonic correction, yielding a positive contact test, indicating that the batholith retains a primary remanence. The contact test with the mafic dike was deemed inconclusive (Harris *et al.* 1997). Thermal demagnetization and SIRM testing indicates that the magnetic carriers are pseudosingle to multidomain magnetite. Site mean ChRM directions were successfully calculated in 22 sites with all having α_{95} values $\leq 7^\circ$. The unit mean ChRM direction and associated paleopole were calculated (Table 1) and the latter was compared to its 112 Ma reference pole (Besse and Courtillot 1991). This yielded a northward translation of $11.0 \pm 4.8^\circ$ (1220 ± 530 km) for the pluton and a clockwise rotation of $59 \pm 17^\circ$ (Harris *et al.* 1997).

JURASSIC UNITS

Fourth of July Batholith

The 172 Ma Fourth of July Batholith intrudes rocks of the Cache Creek Terrane in northern British Columbia, northeast of the town of Atlin (Fig. 1). Thirty-three sites were sampled for the collection, with 20 of the sites from granitoids of the batholith, 11 sites were from coeval associated mafic dikes that cross-cut the southern half of the batholith, and two sites were from the neighbouring ~84 Ma Surprise Lake Batholith (Fig. 2c). Three of the sites were used to obtain argon geochronological data and ten of the sites were used to obtain geobarometric data.

Argon geochronological determinations were done on three samples: a granodiorite from the Fourth of July Batholith, and two mafic dikes. The granodiorite yielded a hornblende ⁴⁰Ar/³⁹Ar age of 172.7 ± 1.7 Ma (Harris *et al.* 2000), identical to the 171.7 ± 3 Ma U-Pb zircon age (Mihalynuk *et al.* 1992). Biotite from the same granodiorite yielded a slightly younger age of 165 Ma. Only biotite ages were possible from the mafic dikes, yielding ages of 165 and 162 Ma.

Al-in-hornblende geobarometry yielded several interesting results. Firstly, two sites on the west side of Atlin Lake (Fig. 2c) have an average emplacement depth of 3.0 km, while six sites on the eastern side have an average depth of ~9 km, thus showing about six kilometres of differential uplift across the lake and delineating what is now referred to as the "Atlin Lake Fault Zone". Secondly, there is no geobarometric evidence of tilting for the western side of the

batholith. Thirdly, results from the eastern portion do have a systematic variation in depths that suggest that this portion of the batholith has been tilted $\sim 8.5^\circ$ down towards $\sim 170^\circ$.

Thermal demagnetization and SIRM testing shows that most of the specimens have pseudosingle to multidomain magnetite as their magnetic carrier, however, a few specimens do show pyrrhotite-type decay characteristics. All 20 granitoid sites gave acceptable mean ChRM directions with α_{95} values $\leq 12^\circ$, with 14 sites directed northeast and steeply down, and 6 sites are anti-parallel directed to the southwest and steeply up. All 11 dikes also gave acceptable mean ChRM directions with α_{95} values $\leq 10^\circ$, with 9 sites directed northeast and steeply down, and 2 sites directed southwest and steeply up.

The similarity in biotite argon ages between the batholith and the mafic dikes, plus petrologic similarities, suggest that the intrusion of the batholith and the dikes are nearly coeval and, therefore, likely retain a similar magnetization direction. Therefore, reversing all up-directed site mean directions, the unit mean ChRM direction and associated paleopole were calculated (Table 1). This *in situ* paleopole yields a $9.0 \pm 3.7^\circ$ “southward” translation and a clockwise rotation of $79 \pm 6^\circ$. If the tilt is taken into account, the tectonic motions change to $12.1 \pm 3.8^\circ$ “southward” translation and $106 \pm 6^\circ$ clockwise rotation.

Teslin Crossing Stock

The 177 Ma Teslin Crossing Stock intrudes flat-lying sedimentary strata in the Whitehorse Trough on the Stikine Terrane north of Whitehorse (Fig. 1). The stock was sampled at 19 sites for paleomagnetic measurements, and five of these sites were utilized for geothermometry. The lack of hornblende in the stock prevented the use of the Al-in-hornblende geobarometer. Therefore, the relatively unknown Ti-in-biotite geothermometer (LeBel 1979) was utilized to determine crystallization temperatures to correct for any post-emplacement tilting. Three of the five samples produced reliable results that are not significantly different at the 95% confidence level, suggesting that the stock has not been tilted. This is supported by the horizontal bedding planes of the nearby host rocks (Fig. 2d) (Harris *et al.* 1999b).

Thirteen of the 19 sites sampled monzonite and syenite of the stock, and the other six sites sampled associated monzodioritic sills that outcrop south of the stock (Fig. 2d). Thermal demagnetization and SIRM testing showed the magnetic carriers of the specimens from the stock to be single-, pseudosingle- and multi-domain magnetite, while for the sills they are single-, pseudosingle- and multi-domain magnetite and pseudosingle- to multi-domain pyrrhotite. The site mean ChRM directions were successfully calculated for 12 of the 13 sites from the stock ($\alpha_{95} < 24^\circ$) and for all six sites within the sills ($\alpha_{95} < 24^\circ$). However, two of the directions from the stock are divergent from the population, as is one from the sills. On the basis of similar mineralogy, ages and mean ChRM directions, the site mean directions for the stock and the sills have been combined to form one population, from which the paleopole has been calculated (Table 1). Comparison of the paleopole with the 177 Ma reference pole for North America (Besse and Courtillot 1991) suggests a “southward” translation of $21.1 \pm 7.4^\circ$ (2320 ± 810 km) and a clockwise rotation of $33 \pm 18^\circ$ (Harris *et al.* 1999b).

Laberge Conglomerate

The Early Jurassic Laberge Group Conglomerate was collected with the intention of providing a regional conglomerate test to examine hypotheses that pre-Cretaceous plutons in the Canadian Cordillera were remagnetized by regional metamorphism or by fluid flow during the Late Cretaceous – Paleocene Laramide Orogeny (*e.g.*, Irving *et al.* 1995; Johnston *et al.* 1996;

Wynne *et al.* 1998). The conglomerate test (Graham 1949) examines two alternatives. If the clasts of a conglomerate have random ChRM orientations, it implies that their pre-existing ChRM directions have not been remagnetized since deposition of the conglomerate. Alternatively, if the conglomerate has been exposed to hydrothermal fluids, metamorphic heating or deformation events later in its geological history, then the clasts may have become remagnetized, and their ChRM directions would then be aligned. Three approaches were made to test if the clast directions were randomly oriented: (1) subjectively, using the precision parameter, k , of Fisher (1953), where $k \leq 3$ is arbitrarily taken to suggest that the population of directions is random; (2) statistically, using the Watson (1956) test for randomness that compares the length of the resultant vector R , to calculated significance points of R_0 at the 95% confidence level; and, (3) also statistically using the test of Shipunov *et al.* (1998) that compares the directions of the clasts with a secondary component, that is commonly taken from the matrix of the host rocks, to determine if the host rock magnetization is found within the clasts.

The conglomerate unit constitutes about half of the fill in the Whitehorse Trough, which overlies most of the northern Stikine Terrane (Fig. 1). The unit was collected at three different localities, which are situated 5, 20 and 40 km east of the western margin of the Trough with the Coast Plutonic Complex. Further, four of the studies described above were done on plutons that lie east of these locations. With the suggested direction of fluid flow during the Laramide Orogeny being westerly, the results of the conglomerate tests have implications for the suggested timing of magnetization of these other studies. The 96 clasts sampled vary in composition with 54% from felsic plutonic rocks, 38% from mafic igneous rocks and 8% from metasedimentary and porphyritic rocks. The matrix is dominantly a fine-grained well-sorted greywacke.

Between the three localities there were 26 groups of specimens on which to perform the conglomerate test. These included groups of similar lithologies, all the specimens of a locality, all the clasts of a locality, all specimens that were AF demagnetized, all specimens which had pyrrhotite decay curves and all specimens that had magnetite decay curves. Using the k values, 17 groups pass the conglomerate test ($k \leq 3$), and 6 other sites have k values of 4 or 5. This is a strong indication that the ChRM directions of the clasts are randomly oriented. The Watson (1956) test implies a different result, with only three tests passing. However, this test was deemed inappropriate for this study because it does not factor in the potential effects of dual polarities. Using the Shipunov *et al.* (1998) test, 18 of the 22 tests passed at the specimen level, and 16 of the 18 tests passed at the clast level. This indicates that the magnetic direction found within the matrix is not present within the clasts. Although this study cannot constrain the age of magnetization on the matrix, other studies have suggested that extensive fluid flow occurred during the Late Cretaceous – Paleocene Laramide Orogeny (*e.g.*, Hart 1995; Smuk *et al.* 1997; Wynne *et al.* 1998). The fact that the clasts do not carry the matrix magnetization direction, but rather are statistically random, suggests that they have not been significantly remagnetized since deposition. Thus, given that small granitic clasts have not been remagnetized despite their host matrix being remagnetized, it is not likely that large, comparatively impermeable intrusions could be remagnetized by these Laramide-fluids. This result supports the finding of primary remanences in the Mount Lorne, Mount McIntyre, Whitehorse and Teslin Crossing intrusions.

DISCUSSION

The locations of the paleopoles from the five intrusions are all discordant with the North American apparent polar wander path (Fig. 3). However, the Cretaceous units are in accord with

other results found from Cretaceous units in the central and southern Stikine Terrane of British Columbia, in that they are situated in the North Atlantic region (Irving and Wynne 1991).

A plot of the translation distance over time shows several interesting features (Fig. 4). Firstly, northward motion is now confidently suggested to have ceased by 50 Ma (Symons *et al.* 1999 and references therein). From the above studies, a northward motion of the terranes of the Intermontane Belt is suggested from ~110 Ma to 50 Ma (Fig. 4), and other studies have suggested that this northward motion existed as far back as 140 Ma (Symons 1983; Harris 1998). The relatively slow rate of 0.7 cm/a from 110 to 75 Ma followed by a rapid rate of 4.0 cm/a can be associated with oceanic plate movement in the Pacific. The Farallon plate had a dominantly easterly motion before 130 Ma, and a northerly motion following 100 Ma. Thus in the 30 m.y. interval, the Farallon plate was slowing down and changing direction, and not likely having any significant translation with respect to the North American craton. At 83 Ma, the Kula Plate broke from the Farallon Plate and had a rapid northerly translation rate (8.0 cm/a) with respect to the craton (Kelley 1993). The rate implied by the Mount Lorne result suggests 50% coupling of the Intermontane Belt with Kula Plate. Jurassic results from these studies imply that the Stikine and Cache Creek terranes were located somewhat “north” of their present day locations. The only other two acceptable Jurassic results are both from the Quesnel Terrane, and suggest that the three terranes were not together during the Jurassic. Rather, it appears that the paleomagnetic data support geological data that suggest that the terranes of the Intermontane Belt amalgamated during the Middle to Late Jurassic (Gabrielse and Yorath 1991). Pacific basin plate models indicate that the Stikine and Cache Creek terranes would have to have an easterly motion during the Jurassic, relative to North America because of the movement of the Farallon Plate. This then provides a model of why the Cache Creek Terrane contains Permian-aged fossils related to the ancient Tethyan Ocean that are only correlated to fossils found in eastern Asia (Monger 1977) and nowhere else in the Canadian Cordillera.

One last feature noted in Fig. 4, is the location of the Carmacks Group result. Although not statistically distinct from the Mount Lorne result, it implies that some “southward” translation is necessary from ~110 to 70 Ma, if it is to be accepted. This motion contradicts all oceanic plate models, which all state the Farallon and then the Kula plates only had northward motions relative to the North American craton. Further, the Carmacks result alone requires 100% coupling with the Kula plate, or if averaged with the Mount Lorne result, they still require at least 80% coupling, which seems extreme taking into account the frictional effects found in transpressive tectonic regimes. The Carmacks result also conflicts with data now being analysed from the Yukon – Tanana Terrane (see McCausland *et al.* this meeting).

In summary, results from paleomagnetic work in the northern Intermontane Belt indicate that the Stikine and Cache Creek Terranes and likely Quesnellia have behaved as a single entity since the Early Cretaceous, as has been shown for the southern Intermontane Belt. Studies of Jurassic units are suggesting much different tectonic histories for the terranes, however, a clear understanding of these motions can not be stated yet.

References

- Besse, J., Courtillot, V., 1991. Revised and synthetic apparent polar wander paths of the African, Eurasian, North American and Indian Plates, and true polar wander since 200 Ma. *J. Geophys. Res.* **96**, B3: 4029-4050.
- Engelbreton, D.C., Cox, A., Gordon, R., 1985. Relative motions between oceanic and continental plates in the Pacific Basin. *Geol. Soc. Am. Spec. Pap.* **206**: 59 p.
- Fisher, R.A., 1953. Dispersion on a sphere. *Proc. Roy. Soc. London*, **A217**: 295-305.
- Gabrielse, H., Yorath, C.J., 1991. Tectonic Synthesis, Chapter 18. *In: Geology of the Cordilleran Orogen in Canada*. H. Gabrielse, C.J. Yorath (eds.), *Geol. Surv. Can.*, no. 4: 677-705.

- Graham, J.W., 1949. The stability and significance of magnetism in sedimentary rocks. *J. Geophys. Res.*, **54**: 131-167.
- GSC, 1962. Aeromagnetic maps 1341G, 1314G, MacRae (105D/10) and Robinson (105D/7) areas, Yukon. *Geol. Surv. Can.*
- Harris, M.J., 1998. Geotectonic motions of northern Cordilleran terranes from paleomagnetic measurements with geothermobarometric corrections. Unpub. Ph.D. thesis, Univ. Western Ontario, London, ON, CAN, 205p.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., Hart, C.J.R., 1996. Paleomagnetic study of the Mount McIntyre pluton, Whitehorse map area (105D), southern Yukon Territory. *Yukon Explor. Geol.* 1996: 122-130.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., Hart, C.J.R., 1997. Paleomagnetic and geobarometric study of the mid Cretaceous Whitehorse pluton, Yukon Territory. *Can. J. Earth Sci.* **34**: 1379-1391.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., Hart, C.J.R., 1999a. Paleomagnetic and geobarometric study of the Late Cretaceous Mount Lorne stock, southern Yukon Territory. *Can. J. Earth Sci.* **36**: 905-915.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., Hart, C.J.R., 1999b. Jurassic plate motions of the Stikine Terrane, southern Yukon: A paleomagnetic and geothermometric study of the Teslin Crossing Pluton (105E/7). *In: Yukon Explor. Geol.* 1998, C.F. Roots, D.S. Edmond (eds.), *Explor. Geol. Serv. Div., Yukon, Indian and Northern Affairs Canada*: 155-166.
- Harris, M.J., Symons, D.T.A., Blackburn, W.H., Hart, C.J.R., Villeneuve, M.J., 2000. Travels of the Cache Creek Terrane: A paleomagnetic, geobarometric and $^{40}\text{Ar}/^{39}\text{Ar}$ study of the Jurassic Fourth of July Batholith, northernmost British Columbia, Canada. *Tectonics*, submitted.
- Hart, C.J.R., 1995. Magmatic and tectonic evolution of the Intermontane Superterrane and Coast Plutonic Complex in southern Yukon Territory. M.Sc. thesis, Univ. British Columbia, Vancouver, BC, CAN, 196p.
- Irving, E., Wynne, P.J. 1991. Paleomagnetism: Review and tectonic implications, Chapter 3. *In: Geology of the Cordilleran Orogen in Canada*. H. Gabrielse, C.J. Yorath (eds.), *Geol. Surv. Can.*, no. 4: 61-86.
- Irving, E., Thorkelson, D.J., Wheadon, P.M., Enkin, R.J., 1995. Paleomagnetism of the Spences Bridge Group and northward displacement of the Intermontane Belt, British Columbia: A second look. *J. Geophys. Res.*, **100**: 6057-6071.
- Johnston, S.T., Wynne, P.J., Francis, D., Hart, C.J.R., Enkin, R.J., Engebretson, D.C., 1996. Yellowstone in Yukon: The Late Cretaceous Carmacks Group. *Geology*, **24**: 997-1000.
- Kelley, K., 1993. Relative motions between North America and oceanic plates of the Pacific basin during the past 130 million years. M.Sc. thesis, Western Washington Univ., Bellingham, WA.
- LeBel, L., 1979. Micas magmatiques et hydrothermaux dans l'environnement du porphyre cuprifère de Cerro Verde-Santa Rosa, Pérou. *Bulletin de Mineralogie*, **102**: 35-41.
- McCausland, P.J.A., Symons, D.T.A., Hart, C.J.R., Blackburn, W.H., this meeting. Minimal geotectonic motion of the Yukon – Tanana terrane relative to North America: Preliminary paleomagnetic results from the Dawson Range Batholith. LITHOPROBE – SNORCLE 2000 Workshop.
- McFadden, P.L., Lowes, F.J., 1981. The discrimination of mean directions drawn from Fisher distributions. *Geophys. J. Roy. Astron. Soc.*, **67**: 19-33.
- Mihalynuk, M.G., Smith, M.T., Gabites, J.E., Runkle, D., Lefebure, D., 1992. Age of emplacement and basement character of the Cache Creek terrane as constrained by new isotopic and geochemical data. *Can. J. Earth Sci.*, **29**: 2463-2477.
- Monger, J.W.H., 1977. Upper Paleozoic rocks of the western Canadian Cordillera and their bearing on Cordilleran evolution. *Can. J. Earth Sci.*, **14**: 1832-1859.
- Shipunov, S.V., Muraviev, A.A., Bazhenov, M.L., 1998. A new conglomerate test in palaeomagnetism. *Geophys. J. Intern.*, **133**: 721-725.
- Smuk, K.A., William-Jones, A.E., Francis, D., 1997. The Carmacks hydrothermal event: an alteration study of the southern Dawson Range, Yukon. *In: Yukon Explor. Geol.* 1996: 92-106.
- Symons, D.T.A., 1983. Further paleomagnetic results from the Jurassic Topley intrusions in the Stikinia subterrane of British Columbia. *Geophys. Res. Lett.*, **10**: 1065-1068.
- Symons, D.T.A., Harris, M.J., Gabites, J.E., Hart, C.J.R., 1999. Eocene (51 Ma) end to northward translation of the Coast Plutonic Complex: Paleomagnetism and K-Ar age dating of the White Pass dikes. *Tectonophysics*, in press.
- Watson, G.S., 1956. A test for randomness of directions. *M.N. Roy. Astron. Soc. Geophys. Suppl.*, **7**: 160-161.
- Wynne, P.J., Enkin, R.J., Baker, J., Johnston, S.T., Hart, C.J.R., 1998. The big flush: Paleomagnetic signature of a 70 Ma regional hydrothermal event in displaced rocks of the northern Canadian Cordillera. *Can. J. Earth Sci.*, **35**: 657-671.

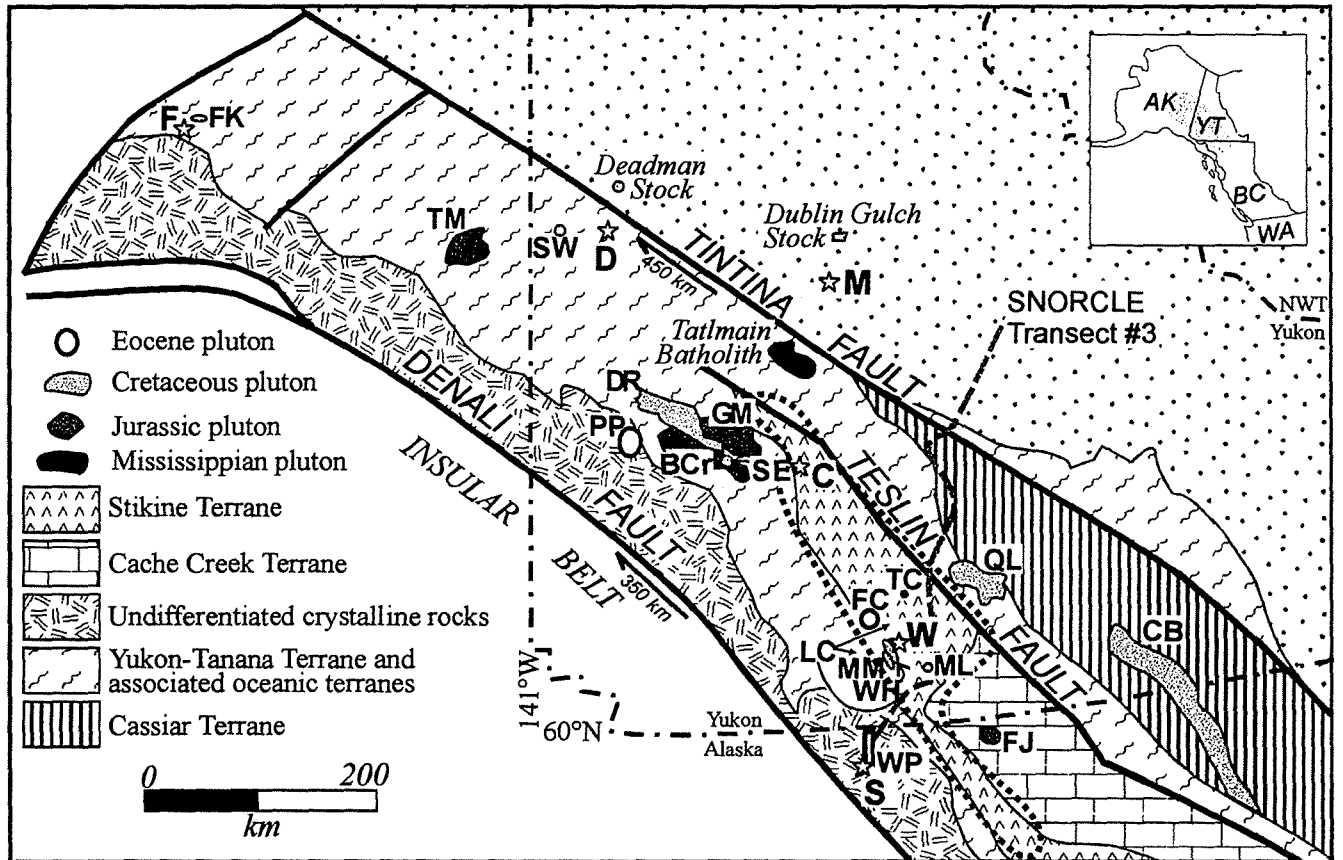


Figure 1. Collection locations. Dotted line encloses the Whitehorse Trough. AK - Alaska; BC - British Columbia; BCr - Big Creek Batholith; C - town of Carmacks; CB - Cassiar Batholith; D - Dawson City; DR - Dawson Range Batholith; F - city of Fairbanks; FC - Flat Creek Stock; FJ - Fourth of July Batholith; FK - Fort Knox Stock; GM - Granite Mountain Pluton; LC - Laberge Conglomerate sites; M - village of Mayo; ML - Mount Lorne Stock; MM - Mount McIntyre Pluton; PP - Pattison Pluton; QL - Quiet Lake Batholith; S - Skagway; SE - Seymour Creek Stock; SW - Swede Dome Stock; TC - Teslin Crossing Stock; TM - Taylor Mountain Batholith; W - city of Whitehorse; WA - Washington; WH - Whitehorse Batholith; WP - White Pass dikes; YT - Yukon Territory.

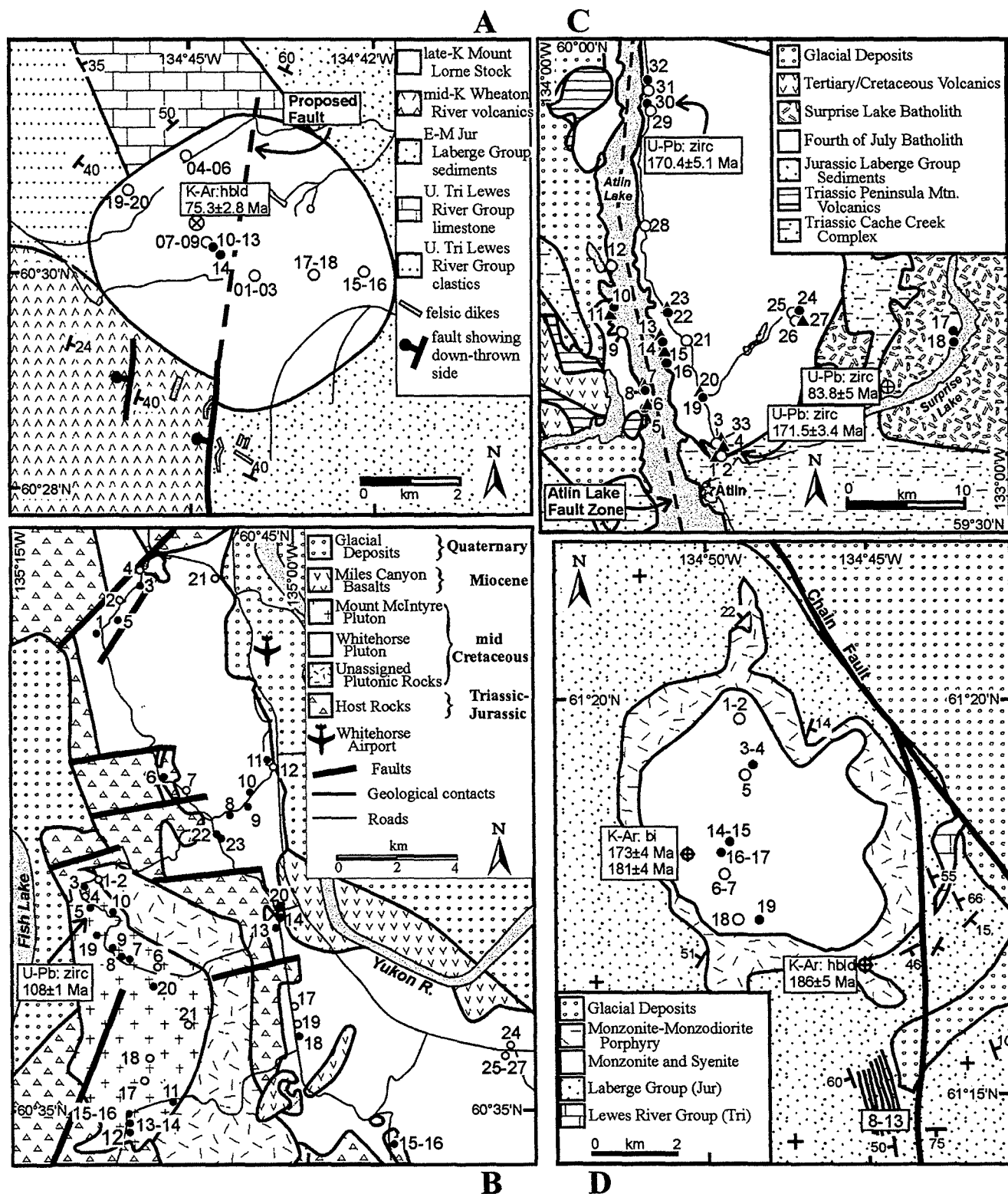


Figure 2 Geology and sampling sites of the: (A) Mount Lorne Stock (after Harris *et al.* 1999a); (B) the Whitehorse Batholith (after Harris *et al.* 1997) and Mount Lorne Stock (after Harris *et al.* 1996); (C) the Fourth of July Batholith (after Harris 1998); and, (D) the Teslin Crossing Stock (after Harris *et al.* 1999b). Open circles are sites where both paleomagnetic and geothermobarometric measurements were made, while closed circles represent sites where only paleomagnetic data was collected.

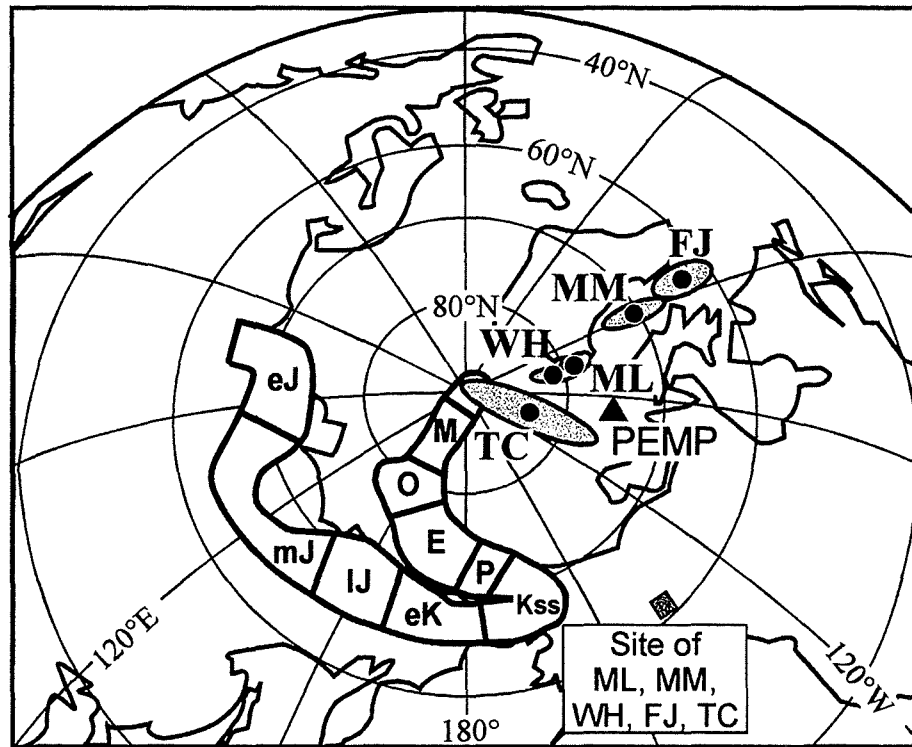


Figure 3. Location of the paleopoles for the studies of the northern Intermontane Belt from Table 1, and the APWP of Besse and Courtillot (1991). Abbreviations as in Figure 1, with PEMP being the location of the present Earth's magnetic pole.

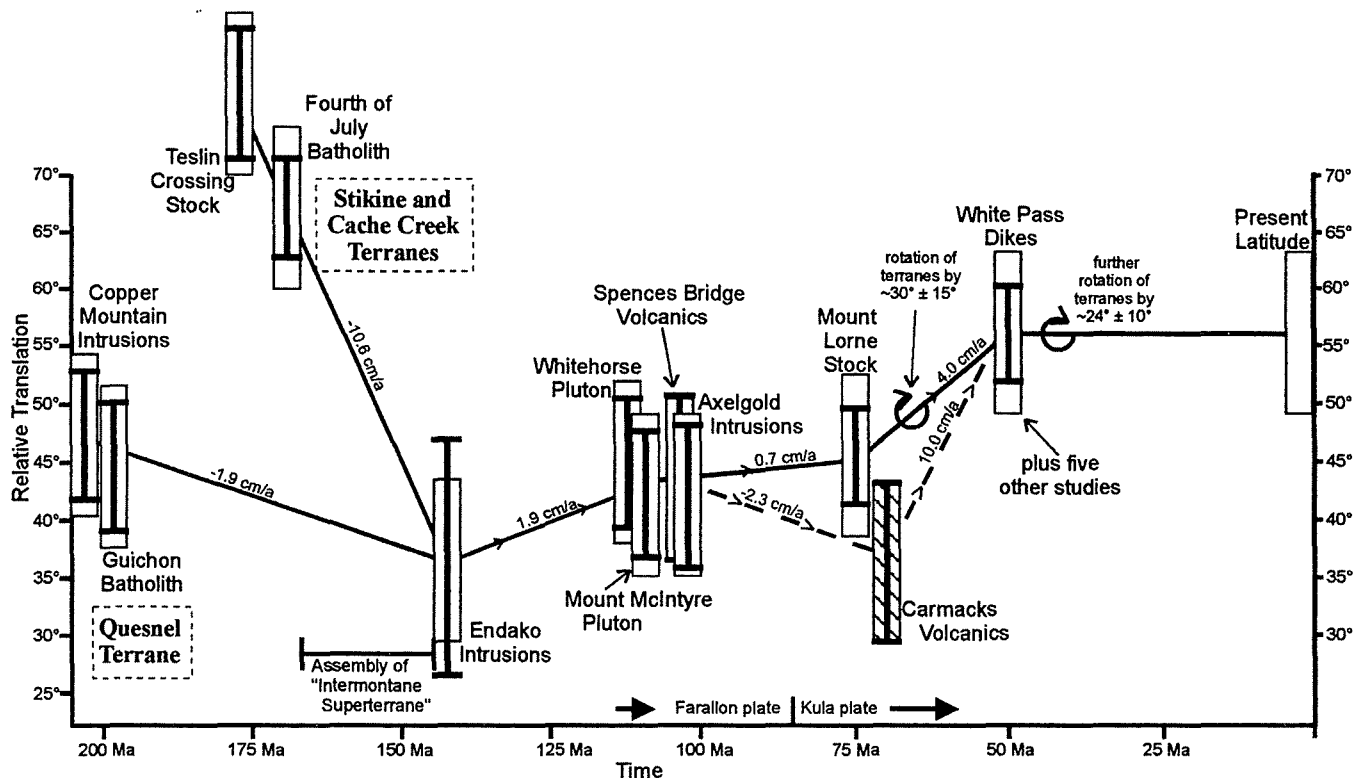


Figure 4. Plot of relative translation distances for Intermontane terranes with respect to the present day latitude (after Harris 1998). Blocks represent scaled dimensions of the present day Intermontane Belt. Error bars on the blocks represent the 95% confidence errors on the translation estimates. Farallon and Kula plates refer to the oceanic plate associated with the tectonic motion from Engebretson *et al.* (1985).

Multiple Deformations, Multiple Intrusions, Multiple Tectonic Levels and the Dating of Fabrics: A Cautionary Tale From Valhalla

P.S. Simony, Department of Geology and Geophysics University of Calgary, Calgary, AB. T2N 1N4; S.D. Carr, Department of Earth Sciences, Carleton University Ottawa, ON. K1S 5B6

The Valhalla complex of southeastern British Columbia is one of a number of Cordilleran core complexes formed as a consequence of Eocene extension. The complex is 80 km long and 20 km wide and consists of an upper plate of Jurassic arc volcanics and their Paleozoic basement at low metamorphic grade and a lower plate of high grade paragneisses and orthogneisses. The Eocene, ductile extensional east-directed Valkyr shear zone (Carr *et al* 1987) separates the upper plate from the lower plate. Mid-Jurassic laccolithic tonalite-granodiorite bodies, interconnected by a series of feeder sills, all at approximately one structural level, are in the upper plate. Granitoid sheet-like bodies of Cretaceous, Paleocene and Eocene age form a part of the layered sequence of the lower plate. The Eocene leucogranitic sheets of the Ladybird suite are the highest layer of the lower plate and the Valkyr shear zone (VSZ) propagated near their upper limit. The Valhalla complex has three domal culminations along its length; the northern Valhalla dome, the central Passmore dome and the southern complex culminating at China Creek south of Castlegar. The broad, Late Cretaceous, compressional east-directed ductile Gwillim Creek shear zone (GCSZ) is exposed in the cores of the three culminations (Schaubs and Carr 1998) and it has been imaged on Lithoprobe seismic profiles as the Valhalla Reflector (VR) (Eaton and Cook 1990).

In the southern complex, displacement on the VSZ is small and geological boundaries, including the contacts of Jurassic, Cretaceous and Eocene intrusions can be walked from the upper plate into the lower plate (Simony and Carr 1997). This geological setting, in conjunction with geochronology, makes it possible to establish the following sequence of events for the southern complex.

- (1) Folding and thrust faulting as well as garnet, muscovite, sillimanite metamorphism in the Mid-Jurassic. This is largely preserved in the upper plate only.
- (2) Intrusion of tonalite-granodiorite laccoliths at ~165 Ma (Armstrong *in* Fyles, 1984) mainly in the upper plate but the basal feeder sill complex extends into the lower plate.
- (3) Emplacement of grey biotite granodiorite sheets, largely below the Jurassic laccoliths and therefore in the lower plate. These were injected and foliated, and leucosome layers formed within them and in mica schist layers between them in the Early Cretaceous prior to 110 Ma intrusions.
- (4) Intrusion of the sheet-like porphyritic hornblende, biotite Kinnaird monzogranite largely, but not entirely, below the level of the Jurassic laccoliths at ~110 Ma (Parrish *et al* 1988). It cross-cuts the grey gneisses of (3).
- (5) Activation of the Gwillim Creek shear zone (GCSZ) at some time after 110 Ma (because the Kinnaird sheet is foliated in its lower part). GCSZ is a broad ductile shear zone with a central zone (some 2 km thick) of intense shear with transposition foliation and mylonitic gneiss layers. The top of the central zone of intense shear is some 2 km below the base of the Jurassic laccoliths in the southern complex but it is ~ 5 km below that level in Passmore and Valhalla domes. A sequence of pegmatites were emplaced near China Ck. into the GCSZ at ~78 Ma (U/Pb zircon ages by S.D. Carr, this study) and also strongly foliated. The melt + potassium feldspar + sillimanite metamorphism of pelite in Passmore dome occurred at ~76-67 Ma (Spear and Parrish, 1996). The transposition

foliation of the GCSZ is associated with that metamorphism (Schaubs and Carr, 1998). These data constrain GCSZ motion to be Late Cretaceous.

- (6) Emplacement of garnet, muscovite, biotite leucogranite sheets of the Ladybird suite with related aplite and pegmatite in the interval 59-54 Ma (Carr *et al* 1987), in a zone extending 1 to 3 km downward from the base of the Jurassic laccoliths. Emplacement of the Ladybird suite overlaps in time with the activation of the Valkyr shear zone. VSZ shearing is most intense in the upper levels of Ladybird granite but in the southwestern flank of the southern Valhalla complex VSZ foliation is overprinted on GCSZ foliation.

Foliation surfaces in the Paleozoic schists of the upper plate at the southwest margin of the Valhalla complex are axial-planar to Mid-Jurassic folds that are truncated obliquely by the basal tonalite feeder sill complex of the Jurassic laccoliths. These tonalite sills are highly foliated and lineated and that strain increases downward toward the GCSZ. It is most probably related, therefore, to the Late Cretaceous GCSZ. Set within the foliated tonalite and schists are sheets of Ladybird leucogranite with strong foliation and lineation. That Eocene foliation in the leucogranite can be “walked out” into the Late Cretaceous foliation in tonalite and into the Mid-Jurassic foliation in the schists.

In any given structural domain the foliations are all statistically parallel and the Mid-Jurassic foliation in the Paleozoic schist is in fact also Late Cretaceous and Eocene.

Implications

The analysis of S_1 , S_2 , S_3 , etc. in conjunction with geochronological methods is a very powerful tool where the geometry of strain is such as to produce refolding of the old S-surfaces. Where the geometry of superposed strains is such as to lead to reactivation and rotation into parallelism rather than refolding, the tectonic interpretations must be made with caution and seemingly conflicting sequences of tectonic events are to be expected at first.

Where emplacement of magma or the flow of hot fluids occurs at particular crustal levels, as we see in the Valhalla complex, deformation may be strongly thermally controlled and confined to particular levels. The Mid-Jurassic laccoliths are clearly post-tectonic with respect to Jurassic deformation at their upper levels and there they show no hints of the intense Late Cretaceous and Eocene deformation at their base, 4 km deeper in the structural edifice.

We see here a form of the notion of tectonic levels “stockwerktectonik” somewhat different from that originally envisaged by Wegmann and applied to the Cordillera in the seventies.

References

- Carr, S.D., Parrish, R. and Brown, R.L. 1987. Eocene structural development of the Valhalla complex, southeastern British Columbia. *Tectonics*: 6, 175-196.
- Eaton, D.W.S. and Cook, F.A. 1990. Crustal structure of the Valhalla complex, British Columbia from Lithoprobe seismic reflection and potential field data. *Canadian Journal of Earth Sciences* 27, 1048-1060.
- Fyles, J.T. 1984. Geologic setting of the Rossland Mining Camp British Columbia Energy, Mines and Petroleum Resources Bulletin 74.
- Parrish, R.R., Carr, S.D. and Parkinson, D.L. 1988. Eocene extensional tectonics and geochronology in the southern Omineca belt, British Columbia and Washington. *Tectonics* 7:181-212.

- Schaubs, P.M. and Carr, S.D. 1998. Geology of metasedimentary rocks and Late Cretaceous deformation history in the northern Valhalla complex, British Columbia, Canadian Journal of Earth Sciences, 35:1018-1036.
- Simony, P.S. and Carr, S.D. 1997. Large lateral ramps in the Eocene Valkyr shear zone: extensional ductile faulting controlled by plutonism in southern British Columbia. Journal of Structural Geology, 19:769-784.
- Spear, F.S. and Parrish, R.R. 1996. Petrology and cooling rates of the Valhalla complex, British Columbia, Canada. Journal of Petrology, 37:733-765.

Age constraints on penetrative structures at Joss Mountain, in the Selkirk Allochthon, southern Canadian Cordillera.

Kuiper, Yvette D¹., Carr, Sharon D²., and Williams, Paul F¹.

1. Department of Geology, University of New Brunswick, Fredericton, N.B., E3B 5A3

2. Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, Ontario, K1S 5B6.

The basement-cored Monashee Complex of the southern Omineca Belt comprises two structural culminations: Frenchman Cap in the north and Thor-Odin in the south. The Selkirk Allochthon structurally overlies the Monashee Complex. U-Pb studies have been carried out in order to constrain the ages of structures on the western flank of Thor-Odin (Johnston et al., in press; this study).

Early folds (F_1 and F_2) in the Monashee Complex and the Selkirk Allochthon, are transposed by penetrative shear towards the east-northeast (Williams and Jiang, 1999). The transposition foliation (S_T) is folded by open to tight F_3 folds. Upright F_4 folds are gentle to close, and trend north-south. Extensional shear bands and boudins (D_5) are manifest in the Greenbush shear zone (Johnston et al., in press) and to a lesser extent at lower structural levels.

An orthogneiss occurs in two sheets at Joss Mountain, in the Selkirk Allochthon. They are broadly warped, but lack isoclinal F_1 and F_2 folds. However, they are foliated and the foliation is interpreted as being related to the development of regional transposition foliation (S_T). Therefore S_T must be younger than 359 ± 4 Ma, the age of the orthogneiss (this study), and F_1 and F_2 older. The age of F_3 at Joss Mountain is constrained between ~ 73 and ~ 70 Ma by a leucogranitic dyke folded by F_3 (Johnston et al., in press), and a crosscutting pegmatite (this study). The crosscutting pegmatite is undeformed, and therefore marks the end of all penetrative deformation and probably metamorphism.

Within the Monashee Complex deformation occurred at younger ages. S_T in southern Thor-Odin was ongoing at 62-59 Ma and had ceased by 58 ± 0.5 Ma (Carr, 1992). At Grizzly Flats, just east of Joss Mountain in the Monashee Complex, S_T formed after 56.5 ± 1.0 Ma according to Johnston et al. (1999). F_3 in the Monashee Complex is only dated in the core of Frenchman Cap, between 52 and 49 Ma (Crowley, 1997). Penetrative deformation had ended by 49.5 ± 0.5 Ma in that area, but earlier (55.5 ± 1.0 Ma) at higher structural level in western Frenchman Cap.

These data, show an apparent decrease in age of deformation from the Selkirk Allochthon to the Monashee Complex. This can be explained by: 1) transport of the (earlier deformed) Selkirk Allochthon to the east, 2) progressive deformation of Selkirk Allochthon and Monashee Complex towards the east, or 3) a combination.

Carr, S.D. 1992. Tectonic setting and U-Pb geochronology of the early Tertiary Ladybird leucogranite suite, Thor-Odin - Pinnacles area, southern Omineca Belt British Columbia. *Tectonics*, 11: 258-278.

Crowley, J.L. 1997. U-Pb geochronology in Frenchman Cap dome of the Monashee complex, southern Canadian Cordillera: early Tertiary tectonic overprint of a Proterozoic history. Unpublished PhD Thesis, Carleton University, Ottawa, Ontario.

Johnston, D.H., Williams, P.F., Brown, R.L., Crowley, J.L. and Carr, S.D. in press. Northeastward and extensional exhumation of crystalline rocks of the Monashee Complex, southeastern Canadian Cordillera. *Journal of Structural Geology*

Williams, P.F., and Jiang, D. 1999. The Omineca Belt: a crustal scale shear zone or a zone of thrusting? *Lithoprobe Report* 69: p. 179.

VOLCANIC STRATIGRAPHY: ENDERBY CLIFFS AND TRINITY HILLS OUTLIERS OF THE EOCENE KAMLOOPS GROUP, SOUTHERN BRITISH COLUMBIA

Katrin Breitsprecher¹, Derek J. Thorkelson¹, Robert I. Thompson²

¹ Earth Sciences Department, Simon Fraser University, Burnaby, BC

² Geological Survey of Canada, Pacific Division (Sydney)

Introduction

Eocene magmatism of the Canadian Cordillera can be divided geochemically into the two categories of calc-alkaline (arc, or subduction generated) and alkaline (typically rift or intraplate magmatism). In southern British Columbia, volcanic rocks of these two categories are represented by the Kamloops Group (Ewing, 1981b) and Pentiction Group (Church, 1985) respectively. In addition to chemical differences, the groups display variations in lithology and morphology. Kamloops Group consists primarily of laterally extensive sheet lavas of basaltic to andesitic composition, with sporadic localized felsic bodies (Ewing, 1981a; Read, 1996). Pentiction Group comprises a number of discrete graben-fill successions, with andesites forming the base sequence and dacites to phonolites dominating upper lithologies. (Church, 1985).

Based on these characteristics, Kamloops Group has been reported to be the product of continental arc volcanism (Ewing, 1981b) while Pentiction Group and correlative rocks in Washington have been ascribed to asthenospheric upwelling (Morris & Hooper, 1997) or to extension (Church, 1985). Published K-Ar dates for the two groups range from 54-42 Ma for Kamloops Group (Mathews, 1981; Ewing, 1981b) and 55-47 Ma for Pentiction Group (Church, 1982). More reliable dating methods are required to refine the temporal relationship between these two apparently coeval groups. In addition, the nature of the spatial boundary between the two groups is not well defined. At a regional scale, successions of the two groups form a continuum. The nature of the contact with respect to magma sources may be gradational (mixing of reservoirs), interfingering (punctuated magmatism from two reservoirs feeding a common surface area) or abrupt (either temporally or spatially). In all of these cases, the spatial separation of the two magma sources is remarkably small if they are considered to be the products of vastly different and mutually exclusive, coeval tectonic processes. Some workers have presented models with the objective of accounting for the two types of magmatism under a single tectonic umbrella. Slab window magmatism, which results from ridge-trench intersection (such as the Kula-Farallon-North American plates) is one such model (Thorkelson and Taylor, 1989). Alternative models include intraplate magmatism, with variations in chemistry resulting from magmatic mixing of lithospheric and crustal sources (Morris & Hooper, 1997) and magmatism as a result of asthenospheric upwelling (Dudás, 1991).

This report examines some of the unmapped outliers on the eastern margin of the Kamloops Group. One objective is to refine the relationship of the contact between these two groups with respect to the above-noted tectonic models. For example, the possible presence of Pentiction Group-like rocks at any of the outliers may provide age information which may show temporal migration of that magmatism. Another objective is to address the volcanology of the outliers: are they remnants of the volcanic cover, which is well preserved to the west of the Okanagan Valley Fault, or are they the products of synvolcanic graben formation? These tasks will be accomplished through defining the stratigraphy at the Enderby Cliffs and Trinity Hills outliers and through detailed chemical analysis and modelling of samples collected throughout southern BC.

Previous work

Of particular relevance to this project is the work performed on the Kamloops and Pentiction Groups. Stratigraphic, petrologic and geochemical characterization of the former was reported by Ewing (1981a, 1981b). This was followed by various localized mapping projects by Read from 1987-1996, including recent mapping of the transition zone between the two groups (Read, 1996). A number of Kamloops Group outliers remain unmapped. Church (1973, 1982, 1985 and others) has provided detailed stratigraphic and lithological characterization of the Pentiction Group which, with the exception of the Torado Creek Graben, has now been mapped in detail. Regional geological mapping by Jones (1959) and by Okulitch (1979) provide the essential geological background without which this more detailed work could not follow.

Results

The first season of mapping of the Enderby Cliffs and Trinity Hills/Bobbie Burns outliers was conducted during the summer of 1999. Preliminary stratigraphic and structural interpretations follow:

Enderby Cliffs The Enderby Cliffs outlier has been divided into two basal sedimentary units, four non-clastic volcanic (lava flow) units, and two upper volcanoclastic units. Two basal conglomerates are distinguished: *EKmc* is a monomict unit comprised of tonalitic clasts; *EKc* contains clasts which reflect the various adjacent basement lithologies including phyllite, granitoids and hornblende schist. *EKc* has high matrix content and ranges from clast to matrix supported. Both units are poorly sorted and show no imbrication or

preferred clast orientation. These units are interpreted to be talus cone and debris flow/alluvial fan deposits respectively.

The first lava flow unit *EKja* is a 25-30 m thick sequence of at least three flows of columnar jointed aphyric basalt to andesite. Thin sections are dominated by plagioclase with minor amounts of augite. The second lava flow unit *EKma* is an 80 m thick flowfolded, massive, aphyric andesitic typified by small (under 2 mm) calcite or zeolite amygdules. The massive nature of the unit and its flowfolded morphology suggest extrusion as a dome or a thick, contorted flow. The third unit *EKfa* is a 200 m thick succession of aphyric to plagioclase-olivine-augite phyric basaltic to andesitic flows which display lateral continuity. The unit is typified by flow top breccia containing larger (2 - 10 cm) deformed quartz or chalcedony amygdules. The uppermost lava flow unit *EKmb*, a discontinuous unit of maximum 40 m thickness, is a massive nonvesicular aphyric basalt. Thin sections display felted texture. The morphology of the unit differs from those below and is suggestive of channelized flows which have locally ponded. These four lava flow units, comprising approximately 350 m of stratigraphy, represent the extrusive stage of deposition. It is expected that variations in morphology and lithology result from fractionation, assimilation, and changes in volatile content. Geochemical modelling will be conducted to verify this assumption.

Two volcanoclastic units succeed the lava flows. The first *EKvx* is approximately 40 m thick, and consists of varied interbedded lithologies, including non-volcanic sandstone and conglomeratic beds, tuff beds, minor volcanoclastic (lahar) beds and thin lava flows. The last unit *EKvd*, the highest unit in the Eocene sequence, is a 200 m thick massive volcanoclastic diamictite consisting of vitric lava clasts in a mudrock to sandy-mudrock matrix. This uppermost unit is interpreted to be one or more lahar deposits; however this interpretation will require further evidence, particularly with respect to locating a source which could supply the large volume of clast material contained in the unit. If the unit is locally derived, a source may be found in the northern portion of the outlier which has not yet been mapped. The main body of Kamloops Group strata to the west is an other source candidate.

Major structural elements of the outlier consist of normal fault sets. The first is a set of WNW oriented, north-side-down high angle faults at approximately 2 km spacing. Strata on the "down" (north) side of two of these faults form monoclines, suggesting that they are north-shallowing listric normal faults. The second set is a NE-SW oriented, northwest-side-down high angle faults. This set juxtaposes Eocene rocks against Paleozoic gneiss and parallels elongation of the outlier. South of the Shuswap River, N-S oriented west-side-down faulting is evident.

Stratigraphic columns for small outliers to the south of the main Enderby succession lack all of the lava flow units. This break in stratigraphy occurs across a NW-SE trending fault at the southern tip of the outlier. The absence of strata which should appear in the *middle* of the column suggests that the succession was deposited in a synvolcanic graben and is not a "remnant" of the main sheet to the west (Breitsprecher *et al*, 2000).

Trinity Hills/Bobbie Burns The units defined for Enderby are all present at Trinity Hills with the exception of units *EKmb* and *EKvx*, and additional units *EKss*, *EKpi* and *EKp* are defined. The basal sedimentary unit *EKss* consists of up to 100 m of interbedded concretionary sandstones and shales. The unit thins eastward and is capped by a thin sequence of *EKc* with a gradational contact. The unit is interpreted to be a distal or lacustrine facies of *EKc*. This unit is likely not unique to Trinity Hills; historical accounts of coal mined from near the Lambert Creek fault at Enderby Cliffs report shales and sandstones hosting the coal beds.

The other units are more relevant, and consists of porphyritic felsic flows *EKp* and related stocks and dykes *EKpi*. Field observations show the unit to be more similar to Penticton Group rocks than to Kamloops Group, and further show the unit to postdate those more mafic volcanics. One dyke in particular contains potassic feldspar megacrysts, similar to sanidine megacrystic volcanics found near Beaverdell. Comparative geochemistry will be used to determine if the unit may represent Penticton Group-type magmatism.

Post-depositional deformation is more complex at Trinity Hills than at Enderby; however, the main fault sets are similar. A set of NE-SW oriented northwest-side-down faults, a set of N-S oriented west-side-down faults and a set of WNW-oriented north-side-down faults mimic the style and orientations at Enderby. Preliminary reconstructions result in an elongate succession of similar size and orientation to the Enderby outlier.

Summary

Lithologies and stratigraphy defined at Enderby Cliffs and Trinity Hills outliers are typical of Kamloops Group bodies. Trinity Hills also hosts a slightly younger igneous body which may represent Penticton Group-like magmatism. Though deformation at Trinity Hills is more complex than at Enderby, the structures (fault sets) are very similar at both outliers. The outliers may represent en-echelon pull-apart basins formed as a result of north-south dextral strike slip faulting though no such motion has been previously reported for major faults adjacent to this region. Further fieldwork is required to verify the interpretations contained herein. Geochronological $^{40}\text{Ar}/^{39}\text{Ar}$ dating of the porphyritic unit *EKpi* will be performed to enable comparison of the two magmatic events in the context of the inter-group boundary. Geochemical trends for

samples collected from throughout the southern BC portion of the volcanic belt will be modelled, along with published data for the rest of the belt, to determine regional patterns, and to evaluate the suitability of proposed tectonic models.

References

- Breitsprecher, K., Thorkelson, D.J., Schwab, D.L., and Thompson, R.I. (2000), *Volcanic stratigraphy and petrology of the eastern margin of the Kamloops Group near Enderby, British Columbia*, in Current Research 2000-A16: Geological Survey of Canada, 7p. (online) <http://www.rodus.com/shop/>
- Church, B.N. (1973), *Geology of the White Lake Basin, B.C.*; Ministry of Energy, Mines and Petroleum Resources, Bulletin 61, 120 p.
- Church, B.N. (1982), *Notes on the Penticton Group: A progress report on a new stratigraphic subdivision of the Tertiary, south-central British Columbia*, in B.C. Ministry of Energy, Mines, and Petroleum Resources, Geological Fieldwork, 1981, Paper 1982-1, pp.12-16.
- Church, B.N. (1985), *Volcanology and structure of Tertiary outliers in South-Central British Columbia, Trip 5 in Field guides to geology and mineral deposits in the southern Canadian Cordillera*, D. Tempelman-Kluit (Ed), Geological Survey of Canada, pp.5.1-5.46.
- Dudás, F.Ö. (1991), *Geochemistry of igneous rocks from the Crazy Mountains, Montana, and tectonic models for the Montana Alkaline Province* in Journal of Geophysical Research, Vol.96, No.B8, pp.13,261-13,277
- Ewing, T.E. (1981a), *Regional stratigraphy and structural setting of the Kamloops Group, south-central British Columbia*, in Canadian Journal of Earth Sciences, v.18, pp.1464-1477.
- Ewing, T.E. (1981b), *Petrology and geochemistry of the Kamloops Group volcanics, British Columbia*, in Canadian Journal of Earth Sciences, v.18, pp.1478-1491.
- Jones, A.G. (1959), *Vernon map-area, British Columbia*; Geological Survey of Canada, Memoir 296, 186 p.
- Mathews, W.H. (1981), *Early Cenozoic resetting of potassium-argon dates and geothermal history of north Okanagan area, British Columbia*, in Canadian Journal of Earth Sciences v.18, pp.1310-1319.
- Morris, G.A. and Hooper, P.R. (1997), *Petrogenesis of the Colville Igneous Complex, northeast Washington: Implications for Eocene tectonics in the northern U.S. Cordillera*, in Geology, Vol.24, No.9, pp.831-834
- Okulitch, A.O. (1979), *Lithology, stratigraphy, structure and mineral occurrences of the Thompson-Shuswap-Okanagan area, British Columbia*, Geological Survey of Canada, Open File 637, scale 1:250000.
- Read, P.B. (1996), *Kamloops to Vernon: Tertiary stratigraphy and structure, industrial mineral and precious metal potentials, Kamloops, Nicola and Vernon Mining Divisions*, in Geological Survey Branch Assessment Report 25,361
- Thorkelson, D.J. and Taylor, R.P. (1989), *Cordilleran slab windows*, in Geology, Vol.17, pp.833-836

Structural, Metamorphic, and Plutonic History of Rocks Adjacent to Shuswap Lake, British Columbia: Evidence of Early to Middle Paleozoic Deformation

N. Slemko, University of Alberta
nslemko@ualberta.ca

INTRODUCTION

This study focuses on five aspects of the rocks near Shuswap Lake, British Columbia: the internal stratigraphy of the Mount Ida Group (the Silver Creek, Sicamous, and Eagle Bay formations) of Jones (1959); the nature and regional affinity of the Queest Mountain assemblage, a unit which does not fit within the Eagle Bay Formation as previously mapped; the nature of the contact relationship between a granitoid pluton, correlated with the Late Devonian Mount Fowler Batholith by Okulitch *et al.* (1975), and the country rock; confirmation of the age of the pluton; and the tectonic history of the study area. This study aims to better explain what is currently known about Cordilleran margin evolution in the region.

STRATIGRAPHY AND STRUCTURAL GEOLOGY

The Neoproterozoic Silver Creek Formation is composed mainly of biotite-muscovite-quartz schist and minor calcareous mica schist, and is intruded by numerous aplite and pegmatite sills and dykes.

The Silver Creek Formation is overlain by the early (?) Paleozoic Sicamous Formation, a carbonaceous marble with distinctive black and white layering.

The Eagle Bay Formation overlies the Sicamous Formation, and is comprised of greenstones (chlorite schist, chlorite-sericite schist, and amphibolite), biotite-muscovite schist, quartzite, and marble. Regionally, rocks mapped as the Eagle Bay Formation should be subdivided into at least two units, one which is Cambrian and the other which is Devonian and Mississippian. The type section of the Eagle Bay Formation (Jones, 1959) consists of Cambrian rocks, so the younger rocks should be assigned to another unit.

Contacts between the Silver Creek, Sicamous, and Eagle Bay formations are interpreted to be stratigraphic.

An assemblage of biotite-muscovite schist $\pm$ staurolite $\pm$ garnet $\pm$ sillimanite and grossular-diposide-tremolite calcsilicate and marble, termed the Queest Mountain assemblage (Slemko and Thompson, 1998), occurs in the northeastern part of the study area. These rocks were previously mapped as part of the Eagle Bay Formation but are separated based on lithology, structural history, and metamorphic grade. Based on lithological similarities, the Queest Mountain assemblage may be correlative with the Lichen assemblage of Johnson (1994).

The contact between the Eagle Bay Formation and the Queest Mountain assemblage is interpreted as a fault, termed the Queest Mountain fault, which strikes approximately east-west and dips to the north at between 16 and 30 degrees.

GEO THERMOBAROMETRY

Quantitative pressure-temperature estimates were made to evaluate possible differences in metamorphic grade between the Eagle Bay Formation and the Queest Mountain assemblage, and thereby establish the sense of motion and amount of displacement on the Queest Mountain fault. Five samples each from the Eagle Bay Formation and the Queest Mountain assemblage were analysed (Figure 1). The minerals used for this analysis include garnet, biotite, plagioclase, muscovite (where present), and sillimanite (where present). The Eagle Bay Formation had an average peak metamorphic temperature of 682.5 °C and a pressure of 6.9 kbar. The Queest Mountain assemblage had an average of 560 °C and 4.8 kbar. These pressure and temperature differences between the Eagle Bay Formation and the Queest Mountain assemblage suggest that it is a normal fault with between 14 and 25 km displacement.

GEOCHRONOLOGY

A granitoid pluton intrudes the Eagle Bay Formation and the Queest Mountain assemblage, cutting foliation in the host rocks and the Queest Mountain fault. The pluton also contains inclusions of Eagle Bay Formation schist. Zircon fractions were analysed using U-Pb geochronology from three samples from the pluton on the east side of Shuswap Lake (Figure 1). These samples were chosen from two different phases, Dg, a medium-grained biotite-hornblende granite that comprises most of the pluton, and Dgm, a fine-grained mafic biotite-hornblende granite to granodiorite, in order to determine if different phases of the pluton are the same age. Also, samples were chosen from either side of the Queest Mountain fault to test the hypothesis that the pluton is the same unit across the fault.

Sample NS97-14 is from the medium-grained granite (Dg) phase of the pluton, south of the Queest Mountain fault. Three zircon populations were obtained from this sample; none were abraded. These three analyses plot on a discordia line with an upper intercept of 365.4 ± 3.7 Ma (Figure 2), interpreted to be the age of crystallization of Unit Dg.

Sample NS97-83 is from the Dgm (fine-grained mafic) phase of the pluton north of the Queest Mountain fault. Four populations of zircon were analysed from this sample; the last two were abraded. These four fractions plot on a discordia line with an upper intercept of 366.2 ± 10 Ma (Figure 3), considered to be the crystallization age of the Dgm phase of the pluton.

Sample NS97-13B is from an outcrop north of the Queest Mountain fault where a contact between the pluton and calcsilicate rocks of the Queest Mountain assemblage is exposed. This rock was taken from the Dgm (fine-grained mafic) phase of the intrusion. Only one zircon fraction from this sample was analysed, which yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ date of 365.6 ± 1.9 Ma.

The two phases of the pluton that were dated represent most of the pluton. The dates obtained for Samples NS97-14 and NS97-83 are identical within error. The analysis from NS97-13B would plot on a discordia line with the other analyses, implying that the pluton also has the same age at that outcrop. If all fractions from the three samples are plotted on a single diagram, an age of 365.9 ± 2.7 Ma is obtained, which is interpreted to be the crystallization age of the pluton. The results show that at least two phases (Dg and Dgm) of the pluton are the same age, and that the pluton is the same age on both sides of the fault. The pluton appears to cut the Queest Mountain fault and some foliation in the host rocks, implying a pre- 366 Ma age for these structures.

The results of this study are identical within error to the 372 ± 6 Ma date of Okulitch *et al.* (1975), confirming the postulate that the pluton within the study area is part of the Late Devonian Mount Fowler suite.

CONCLUSION

This study provides evidence of Early to Middle Paleozoic compression and extension. Extension on the Queest Mountain fault would have occurred parallel to the margin of Ancestral North America. This tectonic activity may be related to the Devonian-Mississippian Antler orogeny or to an earlier event.

REFERENCES

- Johnson, B.J. (1994) Structure and tectonic setting of the Okanagan Valley fault system in the Shuswap Lake area, southern British Columbia; Ph.D. thesis, Carleton University, Ottawa, Ontario.
- Jones, A.G. (1959) Vernon Map-Area, British Columbia; Geological Survey of Canada, Memoir 296, 186p.
- Okulitch, A.V., Wanless, R.K., and Loveridge, W.D. (1975) Devonian plutonism in south-central British Columbia; *in* Canadian Journal of Earth Sciences, vol. 12, p. 1760-1769.
- Slemko, N.M. and Thompson, R.I. (1998) A re-evaluation of the geology adjacent to Shuswap Lake, Vernon map area, British Columbia; *in* Current Research 1998-A, Geological Survey of Canada, p. 175-179.

366 Ma

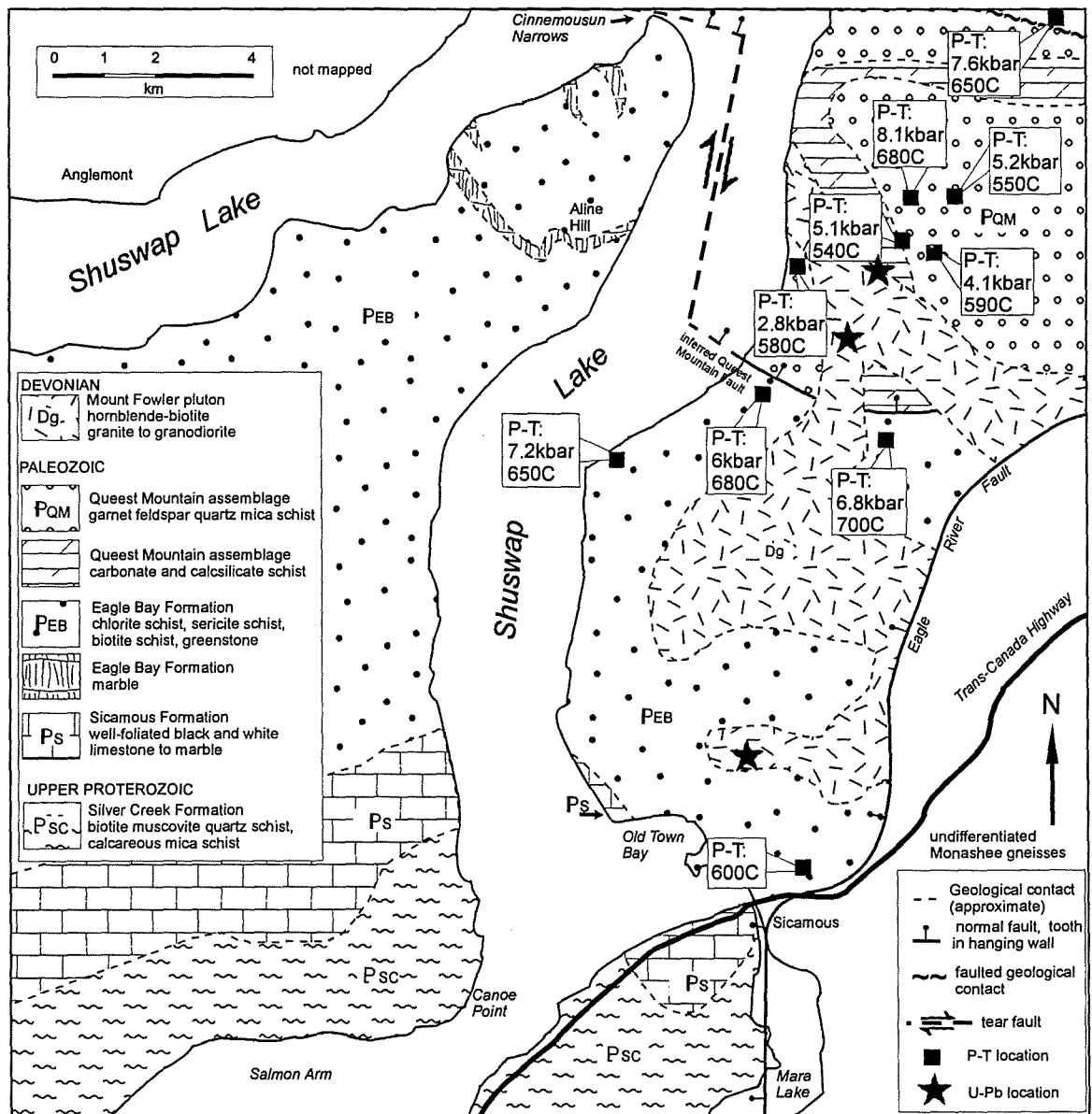


Figure 1: Generalized geological map of the Shuswap Lake area showing locations and data from geothermobarometry.

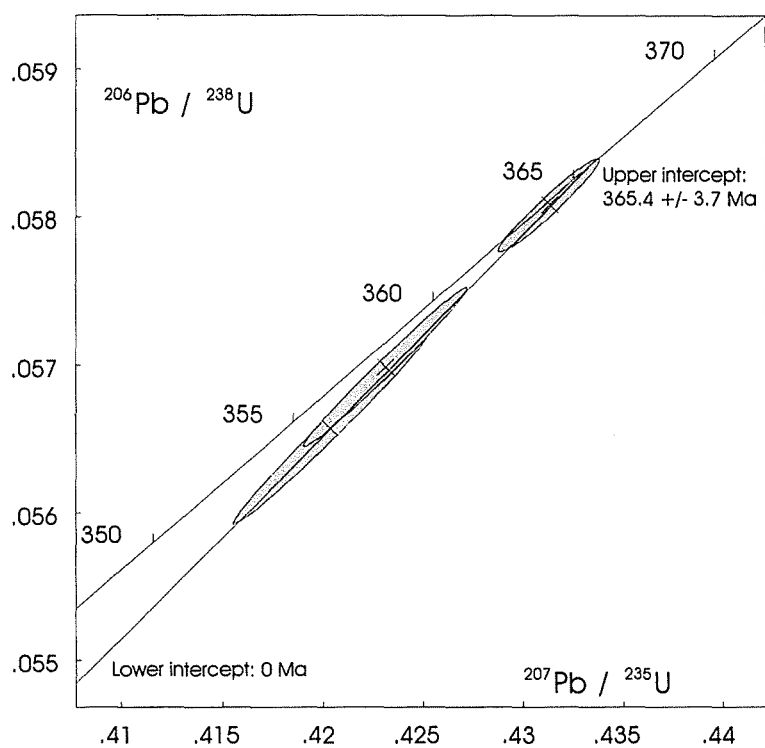


Figure 2:
Concordia diagram for Sample NS97-14.

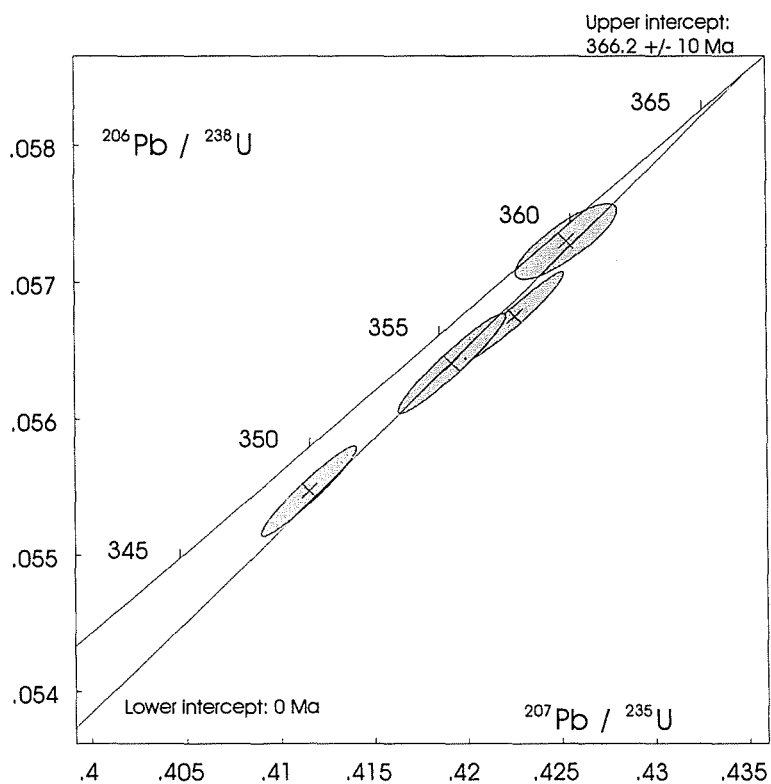


Figure 3:
Concordia diagram for Sample NS97-83.

Nicola Horst: Toward a Geochronology and Cooling History¹

John M. Moore², Janet E. Gabites³ and Richard M. Friedman³

Introduction:

The Nicola Horst (Fig. 1, 2) is a Tertiary fault-bounded uplifted block in the western part of the Intermontane Belt, in the southeast quadrant of Ashcroft map area (92I). It is surrounded by volcanic and volcanoclastic rocks of the Late Triassic Nicola Group that are predominantly metamorphosed to lower greenschist facies and lack penetrative strain except near some shear zones. Within the Nicola Horst, supracrustal rocks are highly deformed and intruded by a variety of plutonic units (Fig. 2). Subhorizontal basalt flows of Oligocene and Miocene age (14-32 Ma by whole rock K-Ar dating; Monger, 1989) overlap the northeastern part of the Horst and also appear as outliers within it. The Ashcroft sheet was most recently mapped by Monger and McMillan, 1989; more detailed studies in and immediately around the Nicola Horst were reported by Moore and Pettipas (1990). More recent information is given in Moore (2000).

Deformed supracrustal assemblages in the Horst include:

- a) Probable pre-Late Triassic chert-clast metaconglomerates and associated graphitic mica schists that contain andalusite, staurolite and garnet;
- b) Amphibolite and biotite-amphibole schists derived from augite porphyries and finer volcanoclastics that are probably correlative with units of the surrounding Late Triassic Nicola Group; and
- c) Andesitic meta-volcanoclastic rocks, probably ignimbritic, that are not common in nearby Nicola rocks; two of these have yielded Middle Jurassic U-Pb ages (Table 1).

Plutonic rocks include weakly to strongly foliated metagabbro/diorite and metatonalite bodies that are cut by three foliated and non-foliated granodioritic intrusive units. Characteristics and ages of these rocks are summarized in Table 1.

U-Pb Dating:

Table 1 lists our new U-Pb zircon and titanite ages for rocks from the Nicola Horst and vicinity, together with published and unpublished U-Pb dates from other laboratories. Sample localities are shown on Figure 2. Interpreted magmatic ages broadly group in three intervals; Late Triassic, Middle Jurassic to earliest Cretaceous and latest Cretaceous to earliest Tertiary. Titanite U-Pb systematics for Late Triassic to earliest Cretaceous rocks are complicated, suggesting Pb-loss and possible repeated crystallization largely synchronous with the Cretaceous-Tertiary magmatic episode.

¹ Contribution to the ancient Pacific Margin NATMAP Project

² Department of Earth Sciences, Simon Fraser University, Burnaby, BC V5A 1S6

³ Geochronology Laboratory, Department of Earth and Ocean Sciences, University of British Columbia, 6339 Stores Road, Vancouver, BC V6T 1Z4

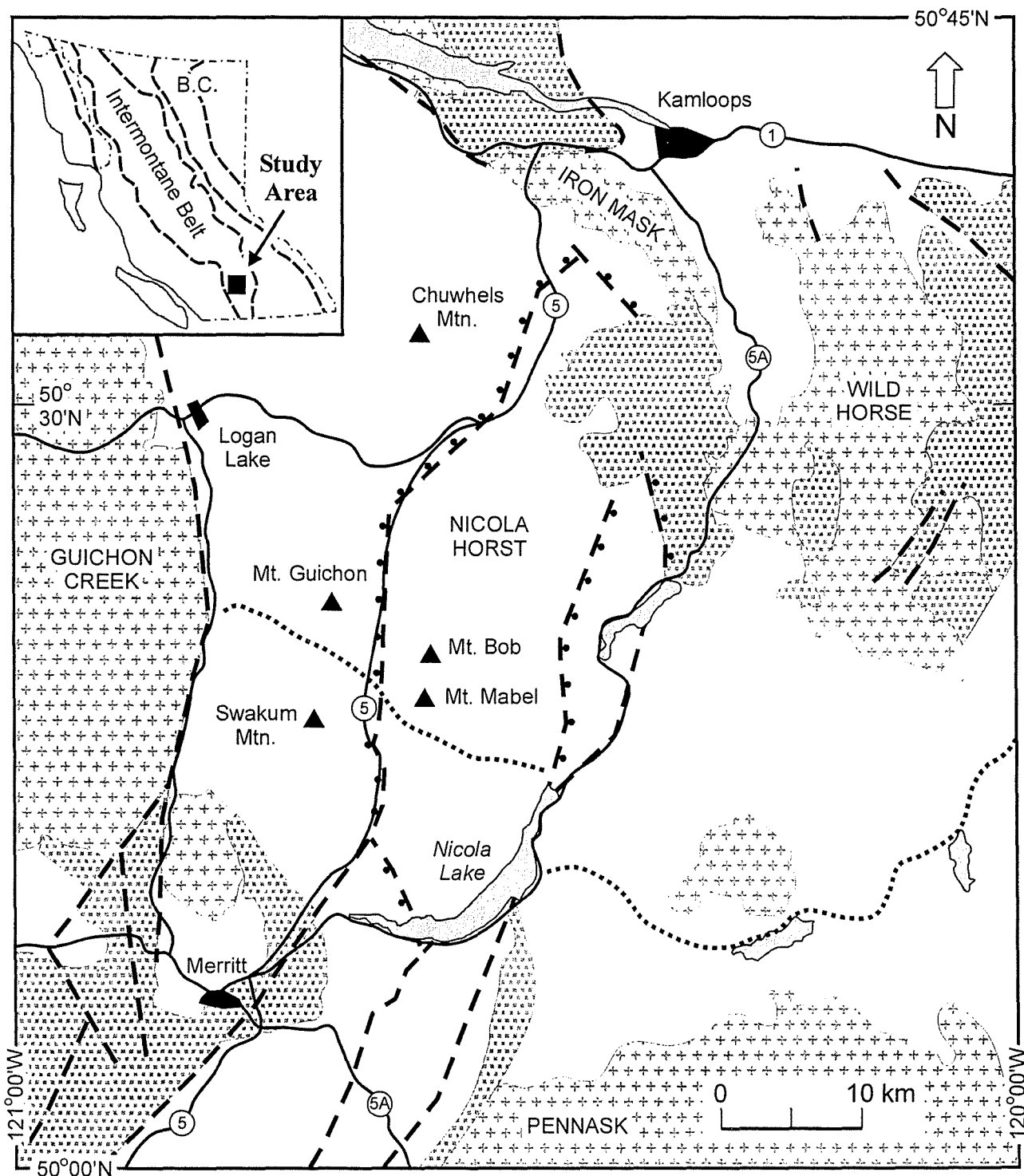


Figure 1: Location of the Nicola Horst and its environs, with main road access. Crosses with names: Triassic-Jurassic plutons; fine pattern: Cenozoic volcanic rocks. Heavy dashed lines are Tertiary faults; downdropped side of known normal faults is shown by ornament. Heavy dotted line is 1989 Lithoprobe transect.

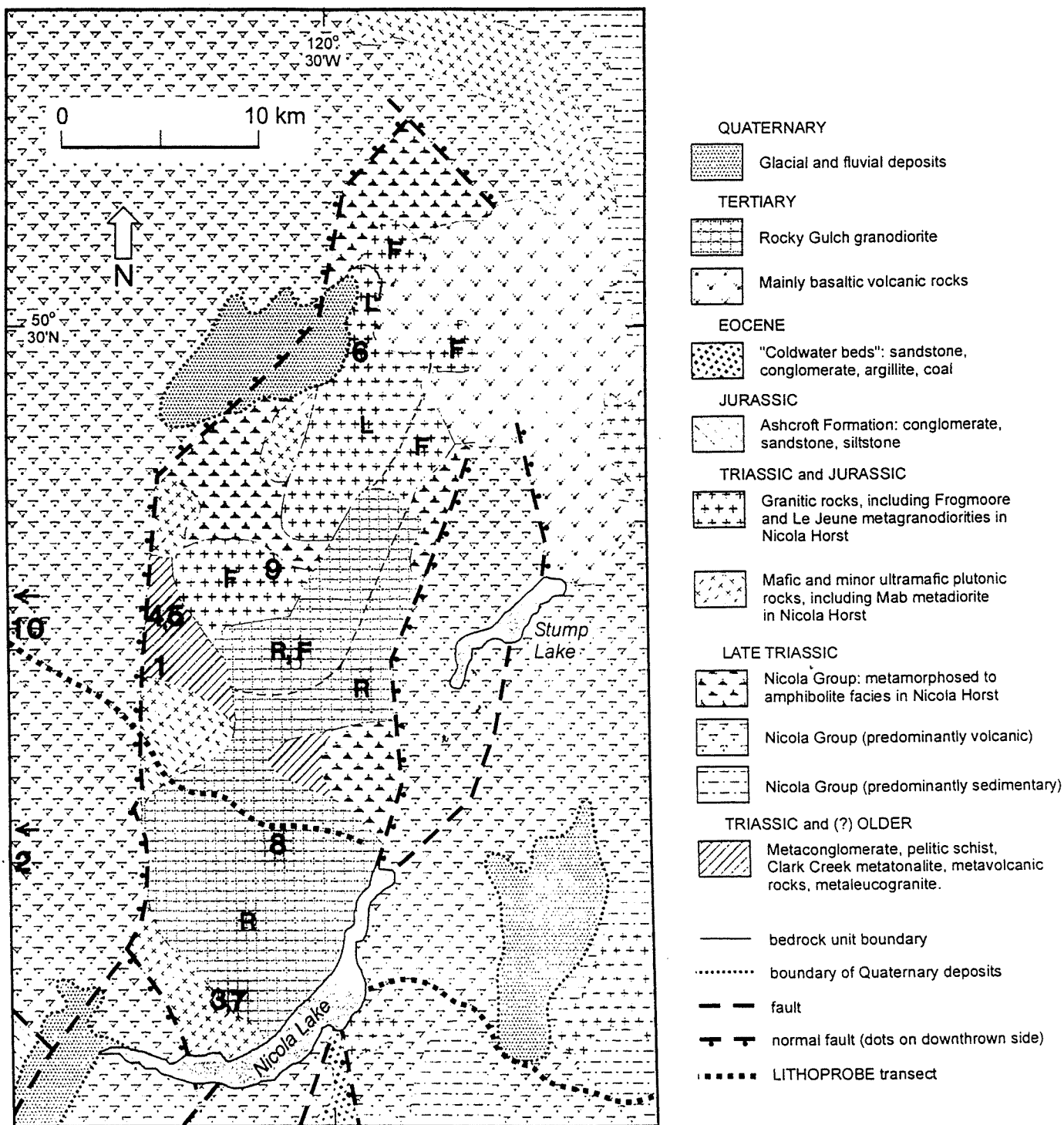


Figure 2: Generalized geology of the Nicola Horst, with numerals showing sample localities referred to in Table 1. Granodioritic plutonic units are designated: R: Rocky Gulch; F: Frogmoore; L: LeJeune. Note the large zone of admixed R and F.

TABLE 1: NICOLA HORST AND ENVIRONS: CHRONOLOGY OF IGNEOUS ROCKS

LOC	UNIT	DESCRIPTION	SAMPLE NUMBER	U-Pb AGE	INTERPRETATION
1	Clark Creek	strongly lineated and foliated bi metatonalite	88-136B	228.0 ± 0.6 ¹ 77.9 ± 1.1 ² 56.0 ± 1.4 ²	¹ oldest concordant zr ²⁰⁶ Pb/ ²³⁸ U age ² ti age, mean of 2 fractions
2	Nicola Group W. facies	dacitic welded tuff	89-356C	222.5 ± 1.4	mean ²⁰⁶ Pb/ ²³⁸ U age of 2 zr fractions
3	Mab	massive blasto-ophitic to strongly foliated bi-hb metadiorite/ gabbro	88-182B	210.0 ± 0.5 ¹ 206, 202, 195 ²	¹ oldest concordant zr ²⁰⁶ Pb/ ²³⁸ U age ² 3 concordant ti ²⁰⁶ Pb/ ²³⁸ U ages
4,5	meta-andesite porphyry	strongly lineated and foliated, pc-augen bi metatonalite/ andesite, in part fragmental	4: 88-081A 5: PE90-27A (UA)	4: 158.3 ± 0.6 ¹ 70.9 ± 1.3 ² 63.6 ± 0.9 ² 5: ca 160	¹ mean ²⁰⁶ Pb/ ²³⁸ U age of 3 zr fractions ² ti age, mean of 2 fractions
6	Le Jeune	foliated Kf augen hb-bi granodiorite	Nic 2 (coll. R.L. Armstrong)	144.3 ± 1.6 ¹ 119.6 ± 1.4 ²	¹ oldest ti ²⁰⁶ Pb/ ²³⁸ U age, consistent with 1 zr fraction. Possible inheritance in 2 zr fractions ² ti age, 1 fraction
7,8	Rocky Gulch	massive Kf-qz-phyric hb-bi granodiorite	7: 88-182D 8: Egd7-2 (GSC)	7: 65.1 ± 0.9 ¹ 8: 64.6 ± 0.4	¹ mean ²⁰⁶ Pb/ ²³⁸ U age of 3 ti fractions, overlaps 1 zr fraction
9	Frogmoore	weakly foliated equigran. to Kf-qz-phyric hb-bi granodiorite	89-433C	64.5 ± 0.1	mean ²⁰⁶ Pb/ ²³⁸ U age of 3 zr and 1 ti fractions
10	Rey Lake	similar lithology to Rocky Gulch; assoc. Cu-Mo	89-322A	64.3 ± 0.4	mean ²⁰⁶ Pb/ ²³⁸ U age of 2 zr fractions

Notes: except where indicated, samples collected by J. Moore and dated at UBC Geochronology Lab by J. Gabites and R. Friedman.

Loc 5: P. Erdmer and L.M. Heaman (pers. comm. 1999), Loc 8: Parrish and Monger, 1992.

zr = zircon, ti = titanite.

Dated Late Triassic rocks include the Clark Creek metatonalite (228 Ma), a dacitic ignimbrite from the western facies of the Nicola Group, (sampled 10 km west of the Horst; 224 Ma), and the Mab metadiorite (210 Ma). Each of these ages is based on one or more concordant zircon analyses. The relative ages of the two Triassic intrusive rocks are inconsistent with observed contact relationships. However, Late Triassic intrusions within the Horst are broadly associated in time with Nicola arc magmatism.

Jurassic-Cretaceous dated rocks are the meta-andesite porphyry (158, 160 Ma; supracrustal unit (c)) and the LeJeune metagranodiorite (144 Ma). The porphyry is, at least in part, a fragmental extrusive rock that shows approximately the same degree of strain as the metaconglomerate, with which it is in tectonic(?) contact. There are at least two distinct bodies of this rock, separated by metaconglomerate. We have dated one and the other has been dated by L.M. Heaman at University of Alberta, with a closely similar result (personal communication, 1999). They are distinctly younger than the other supracrustal units and more comparable in age to the LeJeune intrusion, that occurs in the northern part of the Horst and also exhibits a pronounced foliation. These rocks are broadly coeval with Jura-Cretaceous plutonic rocks in the Eagle Complex to the southwest (Greig et al., 1992).

The youngest dated units are the latest Cretaceous to Paleocene Frogmoore, Rocky Gulch and Rey Lake granodiorites (64-65 Ma). Our date for the Rocky Gulch unit (65.1 ± 0.9 Ma) agrees within error with that published by Parrish and Monger (1992, stated as 64.3 ± 0.3 Ma but re-interpreted by us from their data as 64.6 ± 0.4 Ma). The Frogmoore body typically exhibits a foliation expressed by biotite lenticles and the preferred orientation of tabular foliated xenoliths, but locally is impossible to distinguish from the unfoliated Rocky Gulch unit. There is a large area of admixture of the two types (Fig.2), in which the unfoliated granodiorite is seen locally to intrude similar but foliated granodiorite. The Rey Lake pluton is a small, poorly-exposed body, megascopically identical to the Rocky Gulch granodiorite, that lies 5 km west of the Horst.

Titanite fractions from the Mab metadiorite and the Cretaceous-Paleocene granodiorites (Table 1) are close in age to their associated zircons. Those in the Clark Creek metatonalite and the Jurassic meta-andesite porphyry, however, are much younger than the coexisting zircons, with ages approaching those of the Paleocene intrusive rocks. A titanite from the LeJeune metagranodiorite is intermediate in age between the associated zircon and the younger titanite dates.

Comparison with Previous Geochronology in the Region:

The oldest dated igneous rocks in Ashcroft map area are Late Permian to earliest Triassic: Mt. Lytton pluton (250 ± 5 Ma; Friedman and van der Heyden, 1992) and a diorite-tonalite body that cuts felsic volcanic rocks in the Venables Valley-Red Hill area (242 ± 2 Ma; Childe et al., 1998). Both of these intrusions are west of the Nicola Horst and adjacent to the Fraser Fault system; they predate any igneous activity identified in the Horst.

Horst and adjacent to the Fraser Fault system; they predate any igneous activity identified in the Horst.

The late Triassic age of 222 Ma determined for the ignimbrite in the western volcanic facies of the Nicola Group is the only zircon dating of this unit known to us. It compares well with Carnian-Norian fossil ages determined for these rocks. The 228 Ma date on the Clark Creek metatonalite is slightly older but falls within the probable period of Nicola arc magmatism. The age of the Mab metadiorite is identical within error to that of the Guichon Creek Batholith (Fig.1), that has been dated by U-Pb zircon as having been emplaced at 210 ± 3 Ma. In combination with K-Ar and Rb-Sr dating, a history of intrusion, mineralization, cooling and uplift spanning 20 Ma is indicated for the Guichon body (Mortimer et al., 1990).

Most of the other isotopic dating before the present study is summarized in Monger (1989) and Parrish and Monger (1992). The Iron Mask Batholith (Fig.1) is of similar age to the Guichon Creek Batholith, and plutonic rocks of similar age are also found in the Mt. Lytton Complex (Monger, 1992). The Wild Horse Batholith is younger, with a U-Pb zircon date of 196 ± 1 Ma. The Pennask Batholith yielded U-Pb zircon ages of 194 ± 1 Ma, inferred by Parrish and Monger (1992) as the age of emplacement. The Douglas Lake Stock, between the Wild Horse and Pennask bodies, with a K-Ar biotite date of ca. 183 Ma, may have been emplaced at the same time. The Bromley pluton, to the south of the Pennask Batholith in the Hope map area (92H), is also of similar age, with a U-Pb zircon age of 193 ± 1 Ma, although the intervening Osprey Lake Batholith is distinctly younger at 166 ± 1 Ma (Parrish and Monger, 1992).

The Jura-Cretaceous igneous activity in the Nicola Horst represented by metavolcanic rocks and LeJeune metagranodiorite also has counterparts in the surrounding region. These ages are similar to U-Pb zircon dates recorded for tonalite and tonalite orthogneiss of the Eagle Plutonic Complex, south of the Mt. Lytton Complex in the Hope map area (92H), of 148-157 Ma (Greig, 1992). The undeformed Mount Martley and Tiffin Creek stocks, that intrude the Cache Creek terrane adjacent to the Fraser Fault to the north of the Mt. Lytton complex, have similar Late Jurassic ages of 155 ± 2 and 152 ± 5 Ma, respectively. Concordant titanite U-Pb ages from the Early Jurassic Pennask Batholith are ca. 145-148 Ma. No geological significance was ascribed to this age by Parrish and Monger, but we note that K-Ar dates of biotite from the same body are ca. 144 and 160 Ma (Monger, 1989), suggesting a thermal event around that time.

The Late Cretaceous to Early Paleocene granitic rocks that predominate in Nicola Horst are not well represented in the surrounding region. Dykes of ca. 62 Ma U-Pb zircon age cut the Pennask and Osprey Lake batholiths (Parrish and Monger, 1992). Intrusive rocks approximately 64 Ma old occur in the southeastern part of the Coast belt (Bendor tonalite; Friedman and Armstrong, 1995).

Discussion:

The Nicola Horst exposes a mid-crustal section in the western part of the Nicola Group, and thus may provide clues about basement rocks in the area. Undated metaconglomerate and mica schist, different from any known facies of the Nicola Group in the region, could represent pre-Nicola basement; their contact relations to the Nicola Group are not as yet established. Lithologically similar sedimentary units to the east, in Vernon (82L) map area, lie unconformably beneath Nicola Group strata and are interpreted to have North American continental affinity (Erdmer et al., 1999).

The present dating has revealed that the history of igneous activity seen in the Nicola Horst is more complex than had been believed. In addition to intrusive rocks that are contemporaneous with (and probably comagmatic with) the volcanic rocks of the Nicola Group (Clark Creek metatonalite; Mab metadiorite), there are Mid- to Late Jurassic extrusive and intrusive (LeJeune granodiorite) rocks. These have possible counterparts in the Eagle Complex, another deeply-eroded block to the west, as well as in several stocks intrusive into the Cache Creek Group farther north. Late Cretaceous-Early Tertiary granodiorite is mainly restricted to the Horst, but does appear locally outside its boundaries.

Middle-grade metasedimentary and metavolcanic rocks within Nicola Horst, including Nicola Group equivalents and Jurassic meta-andesite, as well as the Clark Creek metatonalite, all contain consistent northwesterly-striking foliation and westerly-plunging stretching lineation. These features occur in rocks that range in age from possibly pre-Upper Triassic to late Mid-Jurassic and thus were subjected to high strain that occurred after this time interval. Mab metadiorite is less penetratively deformed but one body of it is cut by dykes of strongly-deformed Clark Creek metatonalite, suggesting that the explanation lies in the lower ductility of the metadiorite. Why the metadiorite yields an older age than the metatonalite is not certain, given these intrusive relationships. However, the dated sample of metadiorite is from a different body than that which is unequivocally intruded by the metatonalite, thus there may be metadiorite (and/or metatonalite) of more than one age.

The LeJeune granodiorite is typically foliated, but the planar structure is not as strong or consistent as in the older units and is typically north-trending. We thus conclude that there is evidence in the Horst of at least one metamorphism and deformation between ca. 158 and 144 Ma. This event is also evident in the Eagle Plutonic Complex and probably the Mt. Lytton Complex, both to the west of the Horst. Porphyroblasts have overgrown the foliation of the metasediments, thus there may also be a later metamorphic event, which could be related to the emplacement of the Cretaceous-Tertiary granodiorite. It is not known whether the weaker foliation that is developed in the Frogmoore granodiorite represents magmatic flow or imposed syn-emplacement deformation at ca. 65 Ma.

Titanite ages (Table 1) are close to those of zircon in the Cretaceous-Tertiary granodiorite, indicating rapid cooling through uplift at ca. 65 Ma. Some of the older units (Clark Creek metatonalite, meta-andesite porphyry and LeJeune granodiorite) display

titanite that is younger than associated zircon by varying amounts. Most of these ages could result from either new crystallization or resetting of titanite during the thermal event accompanying the emplacement of the younger granodiorite. The 56 Ma titanite from the Clark Creek body consists of clear grains, petrographically distinct from the 78 Ma titanite in the same sample, and thus appears to represent a yet younger event. Surprisingly, there is close correspondence between titanite and zircon in the 210 Ma Mab metadiorite, despite the fact that it was collected within a few metres of the Rocky Gulch granodiorite contact. The preservation of the original titanite age may result from low fluid content in the already deformed and metamorphosed diorite.

References:

- Childe, F.C., Thompson, J.F.H., Mortensen, J.K., Friedman, R.M., Schiarizza, P., Bellefontaine, K. and Marr, J.M., 1998: Primitive Permo-Triassic volcanism in the Canadian Cordillera: tectonic and metallogenic implications; *Economic Geology*, v.93.
- Erdmer, P., Thompson, R.I. and Daughtry, K.L., 1999: Pericratonic Paleozoic succession in Vernon and Ashcroft map areas, British Columbia; *in* Current Research, 1999-A; Geological Survey of Canada, p. 205-213.
- Friedman, R.M. and Armstrong, R.L., 1995: Jurassic and Cretaceous geochronology of the southern Coast Belt, British Columbia, 49° to 51° N; *in* Miller, D.M. and Busby, C., Jurassic Magmatism and Tectonics of the North American Cordillera; Geological Society of America Special Paper 299, p. 95-139.
- Friedman, R.M. and van der Heyden, P., 1992: Late Permian dates for the Farwell and Northern Mt. Lytton plutonic bodies, Intermontane Belt, British Columbia; *in* Current Research, Part A; Geological Survey of Canada, Paper 92-1A, p. 137-144.
- Greig, C.J., Armstrong, R.L., Harakal, J.E., Runkle, D., and van der Heyden, P., 1992: Geochronometry of the Eagle Plutonic Complex and the Coquihalla area, southwestern British Columbia; *Canadian Journal of Earth Sciences*, v. 29, p. 812-829.
- Monger, J.W.H., 1989: Isotopic date locations, Ashcroft, British Columbia; Geological Survey of Canada, Map 42-1989, sheet 3, scale 1:250,000.
- Monger, J.W.H. and McMillan, W.J., 1989: Geology, Ashcroft, British Columbia; Geological Survey of Canada, Map 42-1989, scale 1:250,000.
- Moore, J.M., 2000: Nicola Horst: window into the pre-Triassic margin of North America?; *in* Current Research, 2000-A; Geological Survey of Canada.

Moore, J.M. and Pettipas, A.R., 1990: Geological studies in the Nicola Lake region (92I/SE); Part A *in* Nicola Lake Region Geology and Mineral Deposits; British Columbia Geological Survey Branch, Ministry of Energy, Mines and Petroleum Resources, Victoria; Open File 1990-29, p. 3-11 and 1:100,000 map.

Mortimer, N., van der Heyden, P., Armstrong, R.L., and Harakal, J., 1990: U-Pb and K-Ar dates related to the timing of magmatism and deformation in the Cache Creek terrane and Quesnellia, southern British Columbia; Canadian Journal of Earth Sciences, v. 27, p. 117-123.

Parrish, R.R. and Monger, J.W.H., 1992: New U-Pb dates from southwestern British Columbia; *in* Radiogenic Age and Isotopic Studies: Report 5; Geological Survey of Canada, Paper 91-2, p. 87-108.

Geological Setting of the Rea and Samatosum sulphide deposits, Eagle Bay Assemblage south central British Columbia.

S.L. Bailey¹, S. Paradis², S.T. Johnston¹, and T. Höy³

¹ School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3055, STN CSC Victoria, British Columbia V8W 3P6 (slbailey@uvic.ca)

² Geological Survey of Canada, Mineral Resources Division, Pacific Geoscience Center

³ B.C. Geological Survey Branch, Ministry of Energy and Mines, Victoria

Geological mapping was completed in the Johnson lake -Adams lake area during the summer of 1999, as part of the first authors M.Sc project, and the Natmap initiative. The project was initiated to address the complex stratigraphic and structural relationships of this area, and how these relate to the distribution of sulphide deposits. Petrological, geochronological and geochemical methods will be employed to attempt to constrain these relationships.

Highly deformed, low-grade metasedimentary and metavolcanic rocks of the Eagle Bay Assemblage host the Rea volcanogenic massive sulphide deposit and the Samatosum vein deposit. The Rea deposit (Au, Pb, Zn, Ag, Cu, Ba) consists of at least two massive sulphide lenses. The Samatosum deposit (Ag, Pb, Zn, Cu) is a stratabound sulphide-rich quartz vein system that is interpreted as a stockwork zone.

The Rea and Samatosum deposits occur within metasedimentary sequences of sericitized and silicified argillites structurally overlain by mafic volcanoclastic rocks and flows. Bedding-cleavage relationships and way up indicators demonstrate that the east-dipping host rocks to these deposits are overturned and westward-younging. The stratigraphic sequences at Rea and Samatosum are similar. We interpret the deposits as being formerly contiguous, infer that structural repetition by west-verging thrust faults has occurred, and deduce that the sedimentary and volcanic succession is of Devonian-Mississippian age.

Lateral Asthenospheric Flow Through Slab Windows

Derek J. Thorkelson¹, Stephen T. Johnston², Raymond M. Russo³, and Ruth E. Murdie⁴

¹Simon Fraser University, Burnaby, Canada

²University of Victoria, Victoria, Canada

³Northwestern University, Evanston, U.S.A.

⁴University of Keele, Staffordshire, U.K.

Subducting slabs divide the upper mantle into regional sub-slab and supra-slab reservoirs which may remain distinct for tens of millions of years. However, the slab barrier between the reservoirs can be breached by slab windows at ridge-trench intersections, permitting mantle to flow from one reservoir to another (Dickinson and Snyder, 1979; Thorkelson and Taylor, 1989; Thorkelson, 1996). The direction of mantle flow through a slab window may have both vertical and horizontal components. Mantle upwelling (vertical flow) is probably common to most slab window environments, but lateral flow may be equally important. Lateral mantle flow has been documented in two cases along the Americas. Westward flow through the Patagonian slab window (Forsythe and Nelson, 1985) is evident from the volcanic arc (supra-slab) geochemical character in proximal parts of the Chile Rise (Klein and Karsten, 1995). Eastward flow through the Central American slab window (Johnston and Thorkelson, 1997) is evident from the ocean-island-like (sub-slab) geochemistry in the Panama-Costa Rica regions of the Central American volcanic arc (Herrstrom et al., 1995). Asthenospheric flow directions deduced from shear-wave splitting (Russo and Silver, 1994) indicate that the flow paths through the slab windows belong to a larger circuit. In this circuit, asthenosphere flows west from the supra-slab reservoir beneath Chile through the Patagonian slab window, and into the sub-slab (Pacific basin) reservoir. It then moves northward alongside South America to the Central American slab window where it flows eastward beneath Panama, and back into the supra-slab reservoir of the Caribbean. Lateral currents in the mantle, as illustrated by this flow circuit, are akin to ocean currents such as the Gulf Stream which transport thermal and chemical anomalies for thousands of kilometres. Mantle flow of this sort may have affected the North American Cordillera from Mexico to Alaska.

W.R. Dickinson, and W.S. Snyder, Geometry of subducted slabs related to San Andreas transform, *J. Geol.* 87, 609-627, 1979.

R.D. Forsythe and E.P. Nelson, Geological manifestations of ridge collision: evidence from the Golfo de Penas-Taitao Basin, southern Chile, *Tectonics* 4, 477-495, 1985.

E.A. Herrstrom, M.K. Reagan and J.D. Morris, Variations in lava composition associated with flow of asthenosphere beneath southern Central America, *Geology* 23, 617-620, 1995.

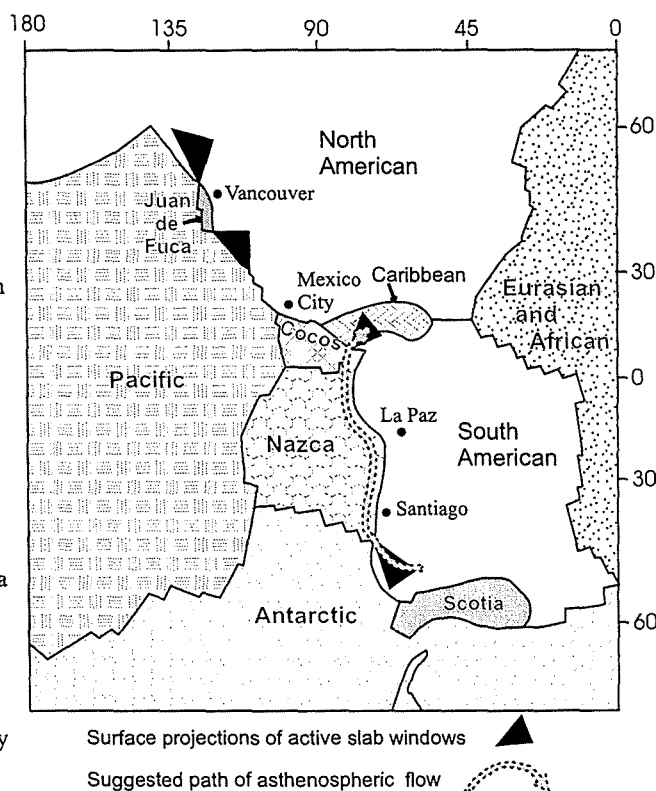
S.T. Johnston and D.J. Thorkelson, Cocos-Nazca slab window beneath Central America, *Earth and Planetary Science Letters*, 146, 465-474, 1997.

E.M. Klein and J. Karsten, Ocean-ridge basalts with convergent margin geochemical affinities from the Chile Ridge, *Nature*, 374, 52-57, 1995.

R.M. Russo, and P.G. Silver, Trench-parallel flow beneath the Nazca Plate from seismic anisotropy, *Science*, 263, 1105-1111, 1994.

D.J. Thorkelson, Subduction of diverging plates and the principles of slab window formation, *Tectonophysics* 255, 47-63, 1996.

D.J. Thorkelson and R.P. Taylor, Cordilleran slab windows, *Geology* 17, 833-836, 1989.



ABSTRACTS of
POSTER
PRESENTATIONS

COHERENT STRATIGRAPHIC SUCCESSION FROM LITTLE SALMON RANGE (YUKON-TANANA TERRANE), CENTRAL YUKON

Maurice Colpron¹ Yukon Geology Program
Whitehorse, Yukon Y1A 2C6

The portion of Yukon-Tanana Terrane exposed along Little Salmon Lake, in southeastern Glenlyon area, corresponds to the northern extension of the *Teslin suture zone* of Tempelman-Kluit (1979). Building on this model, and on the basis of micro-structural analysis, Oliver (1996) concluded that Yukon-Tanana rocks along Little Salmon Lake are the product of deformation in a subduction zone (*trench melange*) and that the stratigraphic succession in the eastern part of the area (Oliver and Mortensen, 1998) represents a crustal fragment incorporated in the *melange*. A key argument for this model was that regionally mappable units had not been identified in this portion of Yukon-Tanana Terrane.

Recent studies to the south, in the core of the *Teslin suture zone*, show that, on the contrary, regionally mappable units can be outlined by careful, detailed mapping (e.g., Stevens et al., 1996; de Keijzer et al., 1999) and that much of the structural features that had been attributed to deformation in a subduction zone are in fact later, post-accretionary tectonic features.

With these opposing interpretations of Yukon-Tanana Terrane geology in mind, a 1:50 000-scale regional mapping program of Little Salmon Range was undertaken by the Yukon Geology Program in 1999. This study was also fueled by the recent discovery of massive sulphide mineralization along the Robert Campbell Highway (Colpron, 1999a) and the potential for correlations with massive sulphide-bearing strata of the Finlayson Lake district.

COHERENT STRATIGRAPHY

Detailed mapping in Little Salmon Range (Colpron, 1999b; Colpron and Reinecke, 2000) shows that Yukon-Tanana Terrane consists of coherent stratigraphic units that can be followed for tens of kilometres and that primary textures are commonly well-preserved. Four distinct rock assemblages have been identified: **Unit 1** - an arkosic grit sequence, intruded by a granodiorite gneiss dated at 353 ± 1.4 Ma (Oliver and Mortensen, 1998); **Unit 2** - a heterogeneous sequence of quartzite and psammitic schist, including several marble units and abundant orthogneiss sills; **Unit 3** - a volcanic sequence, which includes a fossiliferous marble unit and is inferred to unconformably overlie Units 1 and 2; and **Unit 4** - an allochthonous sheet of dark grey siliceous phyllite, graded sandstone, and minor serpentinite. At the eastern edge of the area, near d'Abbadie Fault, undeformed aphanitic basalt of presumed Tertiary age is inferred to be faulted against Yukon-Tanana rocks.

The Little Salmon volcanic sequence (Unit 3) occupies the core of a northwest-trending synclinorium in the centre of the map area. It is inferred to unconformably overlie Units 1 and 2. This interpretation is primarily based on the apparent hiatus between the pre-353 m.y.-old (early Mississippian) arkosic grits (Unit 1) and mid-Mississippian felsic volcanic rocks (preliminary U-Pb age; Mortensen, pers. comm., 1999) near the base of the volcanic sequence along the west flank of the synclinorium. In addition, the occurrence of a conglomerate at the base of the volcanic sequence, along the west flank of the synclinorium, also suggests an unconformity.

The marble marker horizon, which occurs within the Little Salmon volcanic sequence, locally contains echinoderm columnals and corals. Coral specimens collected along the west flank of the Little Salmon volcanic sequence indicate a probable late Mississippian to mid-Pennsylvanian age (late Viséan to Moscovian) for this marble (E.W. Bamber, GSC Paleontological Report 3-EWB-1999). Although, these specimens are too poorly preserved for further identification and provide only a tentative age, it must be noted that this determination is consistent with the mid-Mississippian age of underlying felsic volcanic rocks.

¹ Maurice.Colpron@gov.yk.ca

STRUCTURE AND METAMORPHISM

Oliver (1996) described Yukon-Tanana Terrane rocks along Little Salmon Lake as strongly foliated and lineated tectonites of mylonitic character with little or no preservation of primary features with which to interpret protolith or relationships. Although all Yukon-Tanana Terrane rocks are penetratively deformed, we have found little evidence of the degree of deformation implied by Oliver (1996). Primary sedimentary and volcanic features such as fossils, graded beds, pillows, vesicles, etc., are common throughout the sequence and marker beds permit the definition and tracing of a stratigraphic succession.

The structure of the area is dominated by a broad synclinorium which is cored by volcanic rocks of Unit 3 and a thrust sheet of Unit 4. Axial planes of tight to isoclinal folds are defined by either a pressure-solution cleavage (in the east and in Unit 4), a penetrative schistosity (most widespread), or a strong transposition foliation and metamorphic segregation (in the west). The attitude of the dominant foliation varies across the area defining a structural fan with an axis that coincides with the core of the synclinorium. Lineations are most commonly intersection and/or crenulation lineations. A mineral elongation lineation (quartz rodding, mica streaking) is locally developed, most typically at lower structural level in the western part of the area. Mylonitic rocks are restricted to the footwall of the thrust fault at the base of the allochthonous rocks of Unit 4.

Evidence for an older phase of deformation is developed locally. Along the east side of the area, isoclinal folds deformed by the dominant regional structures are locally outlined by pelitic horizons in grits of Unit 1. To the west, rocks of Unit 2 more typically contain an early schistosity folded by the dominant folds.

The dominant foliation is deformed by younger, gently plunging open folds with a northwest-striking axial planar crenulation cleavage. These structures appear to be related to the large antiform of the dominant foliation in the western part of the area, as previously suggested by Oliver (1996; his western antiform). However, Oliver's eastern synform (our synclinorium) doesn't appear to be of the same generation of structures; the dominant foliation fans across the synclinorium rather than being folded by it (as implied by Oliver). I prefer to interpret the synclinorium as being linked to the dominant phase of deformation.

Another younger set of folds is restricted to the eastern part of the area (in Unit 1 only). These have shallow north-striking axial planar crenulation cleavage and typically deform the dominant foliation in tight east-verging folds. The relationship between these folds and open folds found to the west is unknown.

All rocks of Yukon-Tanana Terranes in Little Salmon Range are characterized by stable metamorphic mineral assemblages typical of greenschist facies. In the northeastern and northern parts of the area, the rocks are at chlorite grade. Elsewhere, the rocks contain biotite grade mineral assemblages. In the southwestern part of the area, rocks of Unit 2 have evidently experienced a more complex metamorphic history than the rest of Yukon-Tanana rocks in Little Salmon Range. The psammitic schist of Unit 2 commonly contains partially to completely retrograded syn- to post-tectonic garnet porphyroblasts and, locally, rectangular aggregates of muscovite which are probably pseudomorphs after an aluminosilicate phase. The significance of this earlier, higher grade metamorphism in rocks of Unit 2 has yet to be resolved.

$^{40}\text{Ar}/^{39}\text{Ar}$ dating of white micas along Little Salmon Lake yielded consistent integrated ages in the range 180-193 Ma, with plateau ages tightly clustered at ca. 192 Ma (Oliver, 1996). This indicates that greenschist facies metamorphism most likely occurred in Early Jurassic time.

SUMMARY AND SPECULATIONS

Detailed mapping of Little Salmon Range has outlined a coherent stratigraphic succession from rocks which were previously described as strongly foliated and lineated (L-S) tectonites. The remarkable preservation of primary textures alone, in rocks of Units 1, 3 and 4, is inconsistent with the degree of deformation implied by previous studies.

The overall stratigraphic succession in the eastern part of the area is generally similar to that described by Oliver and Mortensen (1998; our Units 1 and 3). This succession has been mapped for ~20 km to the northwest and may well extend for another 20 km to the north-northwest (Campbell, 1967). A key element of this stratigraphic succession is the

Little Salmon volcanic sequence (Unit 3) which hosts a massive sulphide occurrence and probable exhalative horizons. If this sequence can indeed be mapped for more than 40 km, then it would greatly increase the area of prospective stratigraphy for hosting volcanogenic massive sulphide deposits.

As described by Oliver and Mortensen (1998), rocks in the western part of the area (our Unit 2) are more heterogeneous and marker beds are more difficult to define. These rocks have evidently experienced a metamorphic history which is distinct from other stratigraphic assemblages in the area. Further work is required in order to establish the origin and tectonic significance of this earlier amphibolite facies metamorphism.

We have suggested that both Units 1 and 2 are unconformably overlain by the Little Salmon volcanic sequence (Unit 3). If this is correct, then what is the relationship between Units 1 and 2? Unit 1 has apparently not experienced the higher grade metamorphic event recorded in Unit 2. One hypothesis would be that Units 1 and 2 were tectonically juxtaposed prior to deposition of the Little Salmon volcanic sequence (Unit 3). If that is the case, then perhaps the structure bounding Units 1 and 2 served as conduit for the emplacement of volcanic rocks of Unit 3.

Finally, the identification of an allochthonous sheet of distal turbidite (Unit 4) raises another problem of regional significance: what is the origin of this allochthon? The presence of serpentinized ultramafic rocks along the basal thrust suggests that an ocean basin separated the turbidite sequence from rocks of the Little Salmon sequence. Additional work is required in order to resolve the depositional and kinematic history of this enigmatic sequence.

REFERENCES

- Campbell, R. B., 1967. Geology of Glenlyon map-area, Yukon Territory (105 L). Geological Survey of Canada, Memoir 352.
- Colpron, M., 1999a. A new mineral occurrence in Yukon-Tanana terrane near Little Salmon Lake, central Yukon (NTS 105L/2). *In: Yukon Exploration and Geology 1998*, Roots, C. F. and Emond, D. S. (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 255-258.
- Colpron, M., 1999b. Preliminary geological map of Little Salmon Range (parts of NTS 105L/1, 2 & 7), central Yukon. Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, Open File 1999-2, 1:50 000 1:50 000.
- Colpron, M. and Reinecke, M., 2000. Glenlyon Project: Coherent stratigraphic succession from Little Salmon Range (Yukon-Tanana Terrane), and its potential for volcanic-hosted massive sulphide deposits. *In: Yukon Exploration and Geology 1999*, Emond, D. S. and Weston, L. H. (eds.), Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, (*in press*).
- de Keijzer, M., Williams, P. F. and Brown, R. L., 1999. Kilometre-scale folding in the Teslin zone, northern Canadian Cordillera, and its tectonic implications for the accretion of the Yukon-Tanana terrane to North America. *Canadian Journal of Earth Sciences*, v. 39, p. 479-494.
- Oliver, D. H., 1996. Structural, kinematic, and thermochronologic studies of the Teslin suture zone, south-central Yukon Territory. Unpublished Ph.D. thesis. Southern Methodist University, 231 p.
- Oliver, D. H. and Mortensen, J. K., 1998. Stratigraphic succession and U-Pb geochronology from the Teslin suture zone, south central Yukon. *In: Yukon Exploration and Geology 1997*, Exploration and Geological Services Division, Yukon, Indian and Northern Affairs Canada, p. 69-75.
- Stevens, R. A., Erdmer, P., Creaser, R. A. and Grant, S. L., 1996. Mississippian assembly of the Nisutlin assemblage: Evidence from primary contact relationships and Mississippian magmatism in the Teslin tectonic zone, part of the Yukon-Tanana terrane of south-central Yukon. *Canadian Journal of Earth Sciences*, v. 33, p. 103-116.
- Tempelman-Kluit, D. J., 1979. Transported cataclastite, ophiolite and granodiorite in Yukon: evidence of arc-continent collision. Geological Survey of Canada, Paper 79-14.

The Role of Provenance, Chemical Weathering, and Sorting in the Evolution of Late-Stage Orogenic Basins in the Slave Craton: a combined geochemical, petrographic and facies analysis approach

P.L. Corcoran Dept. of Earth Sciences, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5

W.U. Mueller Sciences de la terre, Université du Québec à Chicoutimi, Québec, Canada, G7H 2B1

J. Dostal Geology Dept., Saint Mary's University, Nova Scotia, Canada B3H 3C3

Geochemistry and point and clast counts, combined with facies analysis and stratigraphy, reflect the major processes controlling the composition of sedimentary rocks. The controlling factors include 1) tectonic setting, 2) source rock composition, 3) relief, 4) climate, and 5) sorting during transport and at the site of deposition. These parameters change with respect to atmospheric conditions at different periods throughout geologic time, and sedimentary processes associated with specific depositional settings. The Archean Keskarrah, Beaulieu Rapids, and Jackson Lake formations in the Slave Province, Northwest Territories, are ca. 2.6 Ga, tectonically-controlled sedimentary basins characterized by intra- and inter-basinal unconformities and bounding, crustal-scale faults (Fig. 1). The north-trending, crustal-scale Beniah Lake Fault, located approximately 2 km west of the Keskarrah Formation and bordering the Beaulieu Rapids Formation on the east, in addition to the ancestral Jackson Lake fault marking the eastern margin of the Jackson Lake Formation, may have played crucial roles in the formation of the tectonically-influenced sedimentary basins. The sedimentary formations contain similar lithofacies, rapid lateral and vertical lithofacies changes, and fining-upward or coarsening- then fining-upward sequences, consistent with tectonic influence. All three basins were primarily governed at varying degrees by climate, provenance, and sorting, resulting in distinct geochemical and petrographical characteristics.

Local Geology and Depositional Setting

The Keskarrah Formation, in the north-central Slave Province (Fig. 1) unconformably overlies the 3.15-3.22 Ga (Henderson et al., 1982; Northrup et al., 1999) Augustus Granite, the pillowed and massive mafic volcanic flows of the 2.67-2.69 (Northrup et al., 1999)

Peltier Formation, and the turbiditic Contwoyto Formation. The Keskarrah Formation was deposited as coalescing alluvial fans and fan deltas that prograded into a shallow-water, shelf setting influence by tide and wave action (Corcoran et al., 1998).

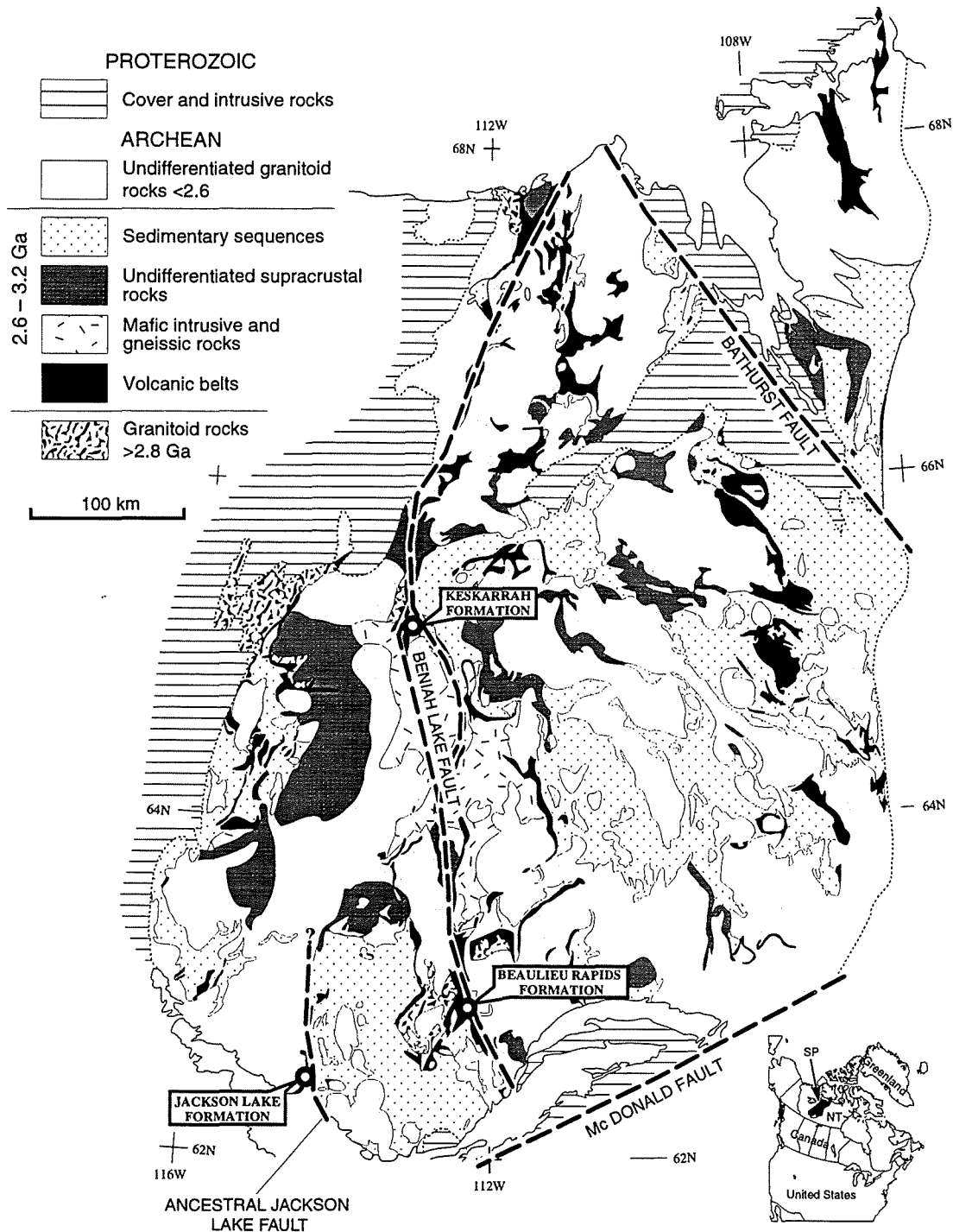


Figure 1: Lithological map of the Slave Province (SP) in the Northwest Territories (NT), illustrating the location of the Keskarrah and Beaulieu Rapids formations adjacent to the Beniah Lake fault and the Jackson Lake Formation adjacent to the ancestral Jackson Lake fault.

The Beaulieu Rapids Formation, located in the south-central Slave Province (Fig. 1), unconformably overlies the Beaulieu River volcanic belt, which is inferred to be time-equivalent with the 2663 Ma Cameron River belt (Henderson et al., 1987; Lambert et al., 1992). Quartz-feldspar porphyry stocks are associated with the Beniah Lake fault along the eastern margin of the remnant sedimentary basin. The Beaulieu River belt overlies the granodioritic-tonalitic Sleepy Dragon Complex in the west. The Beaulieu Rapids lithofacies are consistent with deposition during two episodes of tectonism, 1) alluvial fan/fan deltas prograding into a braided stream setting with local ponds, and 2) alluvial fan/fan deltas passing onto a high-energy sandy braidplain setting (Corcoran et al., 1999).

The Jackson Lake Formation, located in the southern Slave Province (Fig. 1) overlies the 2658-2722 Ma (Isachsen et al., 1991; van Breemen et al., 1992; Isachsen and Bowring, 1994) Kam, Banting, and Duncan Lake Groups of the Yellowknife volcanic belt unconformably. The turbiditic Burwash Formation of the Duncan Lake Group is interstratified with Banting Group-age felsic volcanic centres. Older granitic rocks of the Anton Complex represent basement to the Yellowknife volcanic belt (Isachsen and Bowring, 1997). The Jackson Lake Formation was deposited as alluvial fan/fan deltas along a rugged coastline that prograded into a macrotidal, shallow water, shelf setting.

Compositional characteristics-Keskarrah Formation

The extent to which specific source rocks in each of the three study areas contributed detritus to the sedimentary sequences is determined through point and clast counts as well as geochemistry. Sandstones and siltstones in the Keskarrah Formation are sublitharenites and feldspathic litharenites, respectively. The sandstones are notably quartz-rich as indicated by >90% quartz in seven samples, and >95% in four samples. Rock fragments are predominantly plutonic, but contain minor sedimentary and volcanic varieties (Fig. 2a). Conglomerates in the Keskarrah Formation contain plutonic (46%), mafic volcanic (36%), felsic and intermediate volcanic (14.5%), quartz (3%), and sedimentary (0.5%) clasts. Most of the Keskarrah clast count localities plot as plutonic-rich on a PVS (plutonic-volcanic-sedimentary) diagram (Fig. 2b).

Geochemical data from four selected Keskarrah samples demonstrate 77-91 wt% SiO₂, 0.18-1.03% MgO, and lower Ti, Sc, and Ni, and higher Th values than samples from the Beaulieu Rapids and Jackson Lake formations. CIA (chemical index of alteration) values range from 74-95, indicating substantial levels of chemical alteration. In terms of tectonic setting, the Keskarrah samples plot in the active continental margin (ACM)/passive margin (PM) field on a La-Th-Sc diagram, and are concentrated around the active continental margin field on a Th-Sc-Zr/10 plot (Fig. 3).

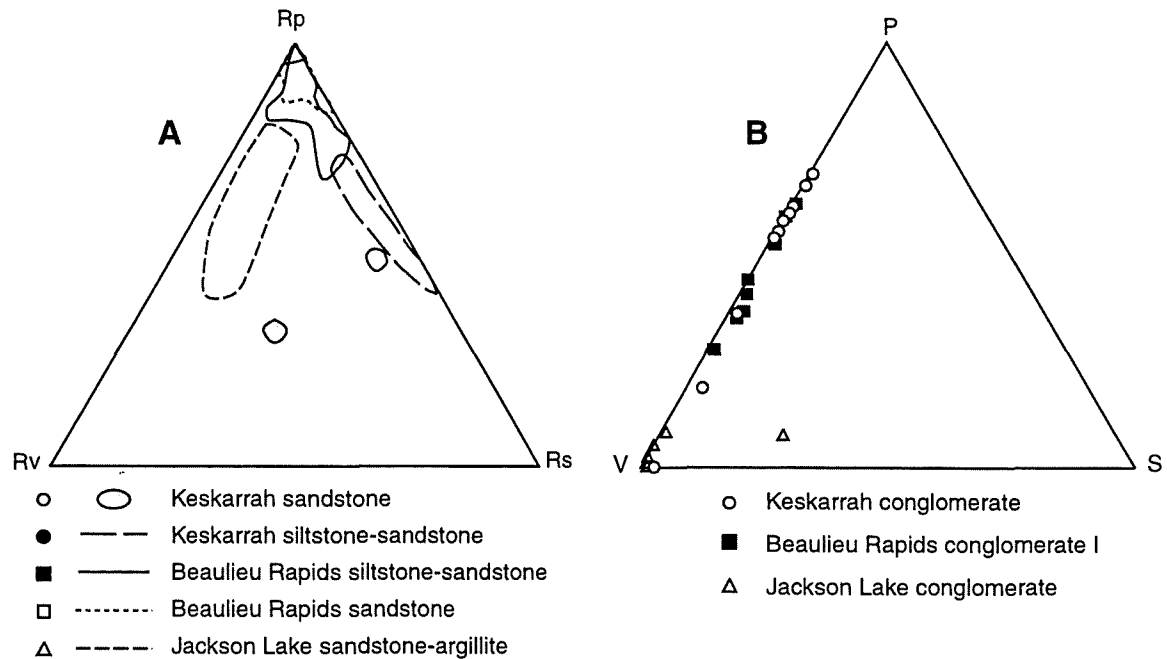


Figure 2: (A) RpRvRs diagram illustrating the fields of rock fragment compositions. Rp, plutonic fragments; Rv, volcanic fragments; Rs, sedimentary fragments. (B) PVS diagram illustrating the composition of clasts from 10 stations in the Keskarrah Formation, 8 stations in the Beaulieu Rapids Formation, and 5 stations in the Jackson Lake Formation. P, plutonic clasts; V, volcanic (mafic and felsic) clasts; S, sedimentary clasts.

The ACM field is associated with plate convergence, strike-slip margins, and thick continental crust (Bhatia and Crook, 1986). The sedimentary sequence formed in a tectonically-active setting and not along a stable shelf which is normally associated with quartz arenites (Eriksson and Fedo, 1994). Elevated proportions of Th and La generally reflect a high quartz component, suggestive of a granitic source. The Keskarrah samples are HREE depleted with $La_n/Yb_n = 23-37$, $Sm_n/Yb_n = 4-6$, and small negative Eu anomalies (Fig. 4a). La_n/Yb_n ratios of 27 and 28 for the Augustus granite, and an intermediate volcanic rock interstratified with the Peltier Formation basalts, respectively, are comparable to the values produced by the sedimentary rocks. Negative Eu anomalies are reported from a

dacitic rock sample (Easton, 1985), thus indicating a probable contribution of source material to the sedimentary succession.

Compositional characteristics-Beaulieu Rapids Formation

Beaulieu Rapids Formation sandstones and siltstone-sandstones are subarkoses and lithic arkoses, respectively. The rocks are rich in polycrystalline quartz, as indicated by an average Qp/Q ratio of .83, which is consistent with rapid deposition, a prominent plutonic source, and a first-cycle origin because monocrystalline quartz becomes predominant with multi-cycle sedimentation (Blatt and Christie, 1963). Rock fragments are mainly plutonic, with minor sedimentary and volcanic components (Fig. 2a). Clasts comprising the Beaulieu Rapids Formation are mainly mafic volcanic (41.5%) and plutonic (35%) with subordinate felsic volcanic (10.5%), porphyry (7.5%), quartz (5%), and sedimentary (.5%) components. The clast count localities demonstrate a mixed plutonic-mafic volcanic source (Fig. 2b).

Five samples selected from the Beaulieu Rapids Formation for geochemical analysis demonstrate 72-84 SiO₂ wt% and MgO contents between 0.95-2.14%. CIA values range from 69-78, indicating a high chemical weathering component. Ti, Sc, and Ni values are higher, and Th values are lower compared with those of the Keskarrah Formation. The samples lie in the ACM/PM and continental island arc fields on the La-Th-Sc diagram, and are closely clustered in the continental island arc field on the Th-Sc-Zr/10 plot (Fig. 4). Beaulieu Rapids samples produce $La_n/Yb_n = 11-27$ and $Sm_n/Yb_n = 3-5$ with two samples demonstrating very slight Eu anomalies (Fig. 4b). Relatively high La_n/Yb_n ratios with only slight negative Eu anomalies in some samples are consistent with a mixed mafic/felsic extrusive or intrusive source.

Compositional characteristics-Jackson Lake Formation

Jackson Lake sandstone-argillites are lithic arkoses with a relatively low polycrystalline component as indicated by a Qp/Q ratio of .35. Higher monocrystalline quartz percentages favour a volcanic rather than plutonic source, in contrast to the Keskarrah and Beaulieu

Rapids formations. Rock fragments are predominantly volcanic with subordinate

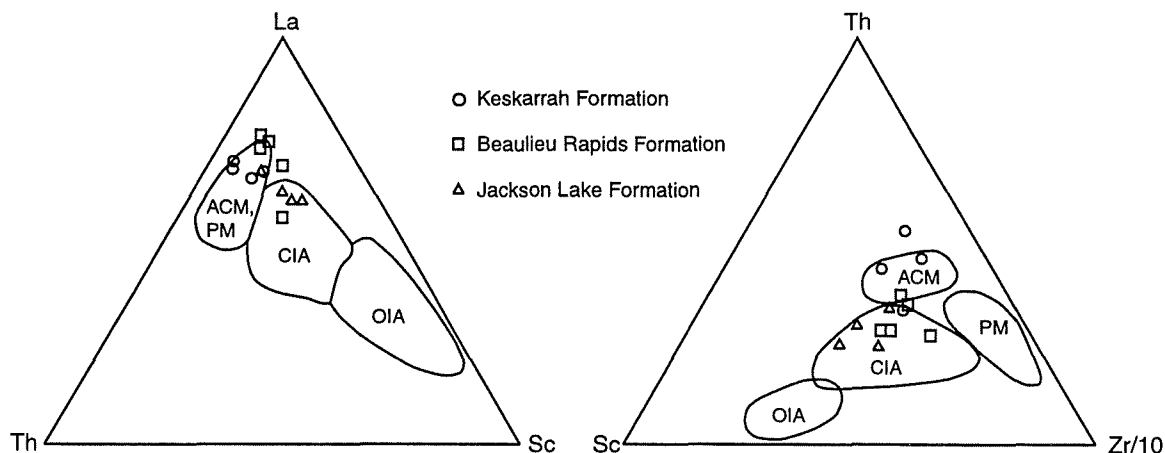


Figure 3: La-Th-Sc and Th-Sc-Zr/10 plots (Bhatia and Crook, 1986) for discriminating tectonic settings of the Keskarrah, Beaulieu Rapids, and Jackson Lake formations. ACM, active continental margin; PM, passive margin; CIA, continental island arc; OIA, oceanic island arc. Note how the Keskarrah samples plot consistently in the ACM field; the Beaulieu Rapids samples in the CIA and ACM fields; and the Jackson Lake samples in the CIA field.

sedimentary and plutonic components, indicating a prominent volcanic hinterland (Fig. 2a). Clasts in the Jackson Lake conglomerate are mainly mafic volcanic (72%) with subordinate felsic volcanic (including pyroclastic; 18%), sedimentary (5.5%), plutonic (4.5%) and quartz-feldspar porphyry (<.1%) components. All clast count stations lie in the lower 25% plutonic and sedimentary portions on the PVS diagram, emphasizing a significant volcanic input (Fig. 2b).

Four samples selected from the Jackson Lake Formation for geochemical analysis contain 62-75% SiO₂ and higher MgO contents (1.15-3.56%) than those of the Keskarrah and Beaulieu Rapids formations. CIA values vary from 67-83, suggestive of substantial chemical alteration. Ti, Sc, and Ni values are higher than in the Keskarrah and Beaulieu Rapids formations, and Th is lower compared with the Keskarrah Formation. The Jackson Lake samples plot in the continental island arc field on both the La-Th-Sc and Th-Sc-Zr/10 discrimination diagrams (Fig. 3). The continental island arc field is representative of plate convergence, inferring a strong tie with volcanic source rocks as indicated by lower Th and La and higher Sc values (Bhatia and Crook, 1986). REE patterns with La_n/Yb_n = 13-21 and Sm_n/Yb_n = 3-4 are flatter than those of the other formations, inferring a greater mafic volcanic contribution, which is further supported by the absence of negative Eu anomalies (Fig. 4c).

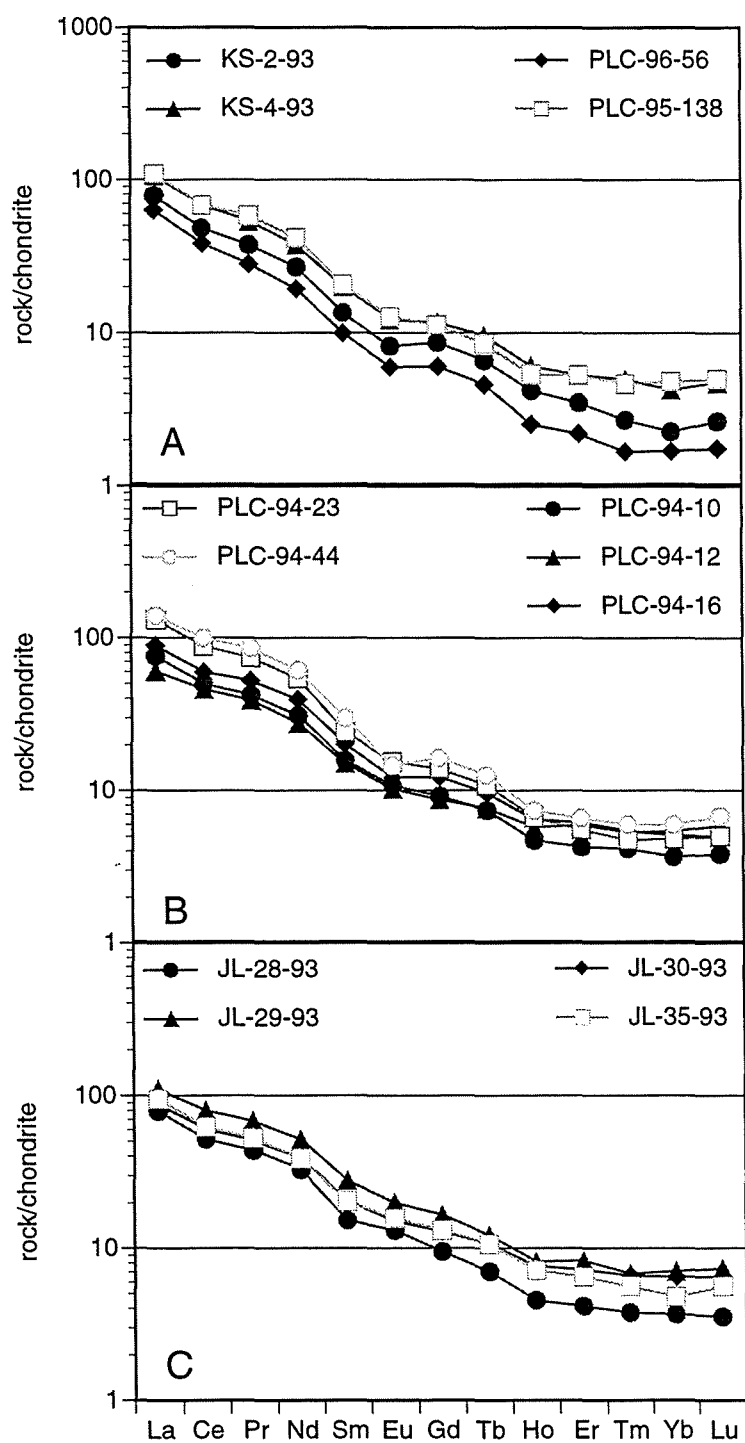


Figure 4: Chondrite-normalized REE abundances for samples from the (A) Keskarrah Formation, (B) Beaulieu Rapids Formation, and (C) Jackson Lake Formation. Normalizing values after Sun (1982).

Factors controlling composition

High CIA values for the Keskarrah, Beaulieu Rapids, and Jackson Lake samples indicate that chemical weathering during the Archean was significant. Inferred higher atmospheric CO₂ levels (Young, 1991; Kasting, 1993), elevated temperatures (Kasting, 1993), and humid conditions (Des Marais, 1994) in the Archean would have destroyed feldspars and clay minerals, but enhanced quartz percentage. Although chemical weathering played a significant role in the composition of the sedimentary sequences, it was not the overriding factor governing the quartz-rich nature of the sedimentary rocks. Other factors include source rock type and sorting. The latter process was more prominent in the Keskarrah and Jackson Lake formations where feldspars were preferentially sorted and removed along ancient shorelines where tide and wave influence was prominent. The shoreface to proximal offshore setting of the Keskarrah Formation would have been a favourable site for the diminution of feldspar (Fig. 5). A predominantly granitic source, high levels of chemical weathering, and preferential breakdown of feldspar through tidal currents, wave activity, longshore drift, and storm transport was sufficient to increase the proportion of quartz in a high-relief, tectonically active setting (Fig. 5). Macrotidal conditions facilitated sorting in the Jackson Lake depositional setting. Geochemistry and clast counts indicate a predominant mafic volcanic source, but high silica in the sandstone-argillite lithofacies indicates that the tide-dominated shoreline was extremely conducive to breakdown and removal of labile minerals, such as feldspars associated with volcanic source rocks. The fluvial-dominated depositional setting of the Beaulieu Rapids Formation promoted less sorting than the coastal marine conditions of the other sequences. The combination of chemical weathering and source rock composition were the major controls on composition in the Beaulieu Rapids basin.

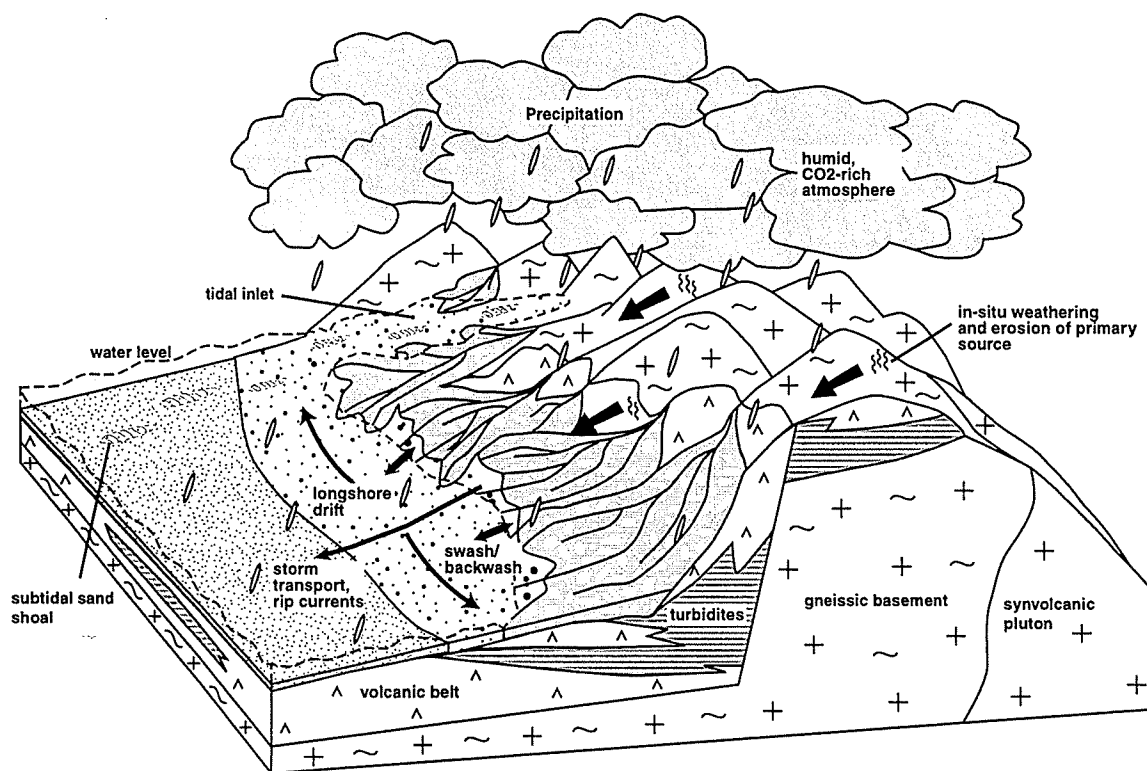


Figure 5: Paleogeographic model illustrating various factors controlling the composition of the Keskarrah Formation sediments at the time of deposition. Plutonic and volcanic source rocks were weathered in-situ under humid, warm, CO₂-rich Archean atmospheric conditions. The material was eroded while constantly being subjected to chemical weathering during transport. Coalescing alluvial fans and fan-deltas developed in the tectonically-active, high relief setting. Fan-deltas prograded directly onto a marine shelf and into a tidal inlet where the sediments were subjected to longshore drift, swash/backwash processes, storm transport, and subtidal waves.

Conclusions

Sedimentary rock composition in the tectonically-active, high-relief, late-orogenic Keskarrah, Beaulieu Rapids and Jackson Lake formations, was highly dependent on source rock type. Geochemical, petrographical, and clast counting results demonstrate that the major source rocks for the sedimentary sequences include: 1) primarily plutonic and subordinate mafic volcanic for the Keskarrah Formation, 2) mixed plutonic-mafic volcanic for the Beaulieu Rapids Formation, and 3) primarily mafic volcanic for the Jackson Lake Formation. The lack of quartz-rich sandstones and quartz arenites in the Jackson Lake Formation is attributed to the lack of a significant plutonic source, regardless of the shoreline setting that would have promoted diminution of feldspar. The paucity of quartz

arenites in the Beaulieu Rapids Formation is a function of the alluvial-fluvial depositional setting which did not favour significant sorting. The combination of a plutonic-dominated source, high levels of chemical weathering, and extensive sorting, conditions occurring during deposition of the Keskarrah Formation, are necessary for extreme quartz enrichment in high-relief, tectonically active settings.

REFERENCES

- Bhatia, M.R., Crook, K.A.W., 1986.** Trace element characteristics of graywackes and tectonic setting discrimination of sedimentary basins. *Contrib. Mineral. Petrol.*, 92: 181-193.
- Blatt, H., Christie, J.M., 1963.** Undulatory extinction in quartz of igneous and metamorphic rocks and its significance in provenance studies of sedimentary rocks. *J. Sed. Petrol.* 33, 559-579.
- Corcoran, P.L., Mueller, W.U., Chown, E.H., 1998.** Climatic and tectonic influences on fan deltas and wave- to tide-controlled shoreface deposits: evidence from the Archean Keskarrah Formation, Slave Province, Canada. *Sed. Geol.*, 120: 125-152.
- Corcoran, P.L., Mueller, W.U., Padgham, W.A., 1999.** Influence of tectonism and climate on lithofacies distribution and sandstone and conglomerate composition in the Archean Beaulieu Rapids formation, Northwest Territories, Canada. *Precamb. Res.*, 94:175-204.
- Des Marais, D.J., 1994.** The Archean atmosphere: its composition and fate. In: K.C. Condie (Editor), *Archean Crustal Evolution: Developments in Precambrian Geology 11*. Elsevier, Amsterdam, 528pp.
- Easton, R.M., 1985.** The nature and significance of pre-Yellowknife Supergroup rocks in the Point Lake area, Slave Structural Province, Canada. In: L.D. Ayres, P.C. Thurston, K.D. Card, W. Weber (Eds.), *Evolution of Archean Supracrustal Sequences*, *Geol. Assoc. Can. Spec. Pap.* 28, 153-167.
- Eriksson, K.A., Fedo, C.M., 1994.** Archean synrift and stable-shelf sedimentary successions. In: K.C. Condie (Ed.) *Archean Crustal Evolution*. Elsevier, Amsterdam, 171-204.
- Henderson, J.B., Loveridge, W.D. and Sullivan, R.W., 1982.** A U-Pb study of zircon from granitic basement beneath the Yellowknife Supergroup, Point Lake, District of Mackenzie. In: *Current Research, Part C. Geol. Surv. Can., Pap.* 82-1C: 173-177.
- Henderson, J.B., van Breemen, O., Loveridge, W.D., 1987.** Some U-Pb zircon ages from Archean basement, supracrustal and intrusive rocks, Yellowknife-Hearne Lake area, District of Mackenzie. In: *Radiogenic Age and Isotopic Studies Report 1*. *Geol. Surv. Can. Pap.* 87-2, 111-121.
- Isachsen, C.E., Bowring, S.A., 1994.** Evolution of the Slave Craton. *Geology* 22, 917-920.
- Isachsen, C.E., Bowring, S.A., 1997.** The Bell Lake group and Anton Complex: a basement - cover sequence beneath the Archean Yellowknife greenstone belt revealed and implicated in greenstone belt formation. *Can. J. Earth Sci.* 34, 169-189.
- Isachsen, C.E., Bowring, S.A., Padgham, W.A., 1991.** U-Pb zircon geochronology of the Yellowknife volcanic belt, NWT, Canada: New constraints on the timing and duration of greenstone belt magmatism. *J. Geol.* 99, 55-67.
- Kasting, J.F., 1993.** Earth's early atmosphere. *Science* 259, 920-926.
- Lambert, M.B., Ernst, R.E., Dudas, F.O.L., 1992.** Archean mafic dyke swarms near the Cameron River and Beaulieu River volcanic belts and their implications for tectonic modelling of the Slave Province, Northwest Territories. *Can. J. Earth Sci.* 29: 2226-2248.
- Northrup, C.J., Isachsen, C., Bowring, S.A., 1999.** Field relations, U-Pb geochronology, and Sm-Nd isotope geochemistry of the Point Lake greenstone belt and adjacent gneisses, central Slave craton, N.W.T., Canada. *Can. J. Earth Sci.* 36: 1043-1059.
- Sun, S.S., 1982.** Chemical composition and origin of the Earth's primitive mantle. *Geochim. Cosmochim. Acta* 46, 179-192.
- van Breemen, O., Davis, W.J., King, J.E., 1992.** Temporal distribution of granitoid plutonic rocks in the Archean Slave Province, northwest Canadian Shield. *Can. J. Earth Sci.* 20, 2186-2199.
- Young, G.M., 1991.** The geologic record of glaciation: relevance to the climatic history of the Earth. *Geosci. Canada* 18, 100-108.

PHYSICAL MODELLING DOCUMENTS MECHANICAL COUPLING BETWEEN THE THRUST-SHEET AND FOOTWALL PANELS NEAR LATERAL RAMPS AND TEAR-FAULTS

John M. Dixon, Birgit Dietrich and David Deline
Dept. of Geological Sciences and Geological Engineering,
Queen's University, Kingston, Ontario K7L 3N6

We use scaled physical (centrifuge) models to investigate patterns of deformation associated with displacement of a thrust sheet over ramp systems consisting of two frontal-ramp segments linked by either a vertical tear fault or a gently dipping lateral ramp. The models include four stratigraphic units of alternating competency, composed of laminae of plasticine and silicone putty. A ramp system is cut in the lowest stratigraphic unit during assembly. Matched models are serial-sectioned transversely or longitudinally to constrain the structures in 3-D.

A GOCAD computer-graphics visualization of structures associated with the tear fault demonstrates that the thrust sheet is draped over the tear-fault and has been internally deformed into an overturned fault-propagation fold that has grown by along-strike propagation of the trailing frontal ramp.

A GOCAD visualization of the lateral-ramp model shows that both the trailing and leading frontal ramps have propagated along strike. The trailing ramp nucleated a fault-propagation fold in the thrust sheet. The leading frontal ramp nucleated a similar structure involving the footwall of the lateral ramp.

Models of the tear-fault configuration deformed to different amounts of total shortening document evolution of structures and strain in the vicinity of the tear fault. The models confirm our previous conclusions: there is rotation of the tear fault out of the transport direction, and the two frontal ramps tend to propagate along strike to change the system from a tear-fault linkage to a lap-joint displacement transfer zone. We have additional evidence of significant mechanical coupling between the hanging wall and the footwall across the tear fault. Material in the immediate footwall of the trailing frontal ramp and along the top edge of the tear fault tends to be transferred to the thrust sheet. Linear strain markers embedded within the lowest stratigraphic unit document local shear-strain in the thrust sheet and the adjacent footwall as a result of drag across the tear fault.

The main thrust sheet is offset vertically (by faulting or ductile strain) along the trace of the tear-fault as one part of the sheet is lifted on the trailing frontal ramp. The offset is subsequently restored as the adjacent part of the thrust sheet is lifted to the same structural level on the leading frontal ramp. However, owing to 3-D strain of the panel that was lifted first, the panels can overlap along the trace of the tear fault.

Acknowledgements: We are grateful for financial support from the Petroleum Industry sponsors of the Foothills Research Project and from the Natural Sciences and Engineering Research Council of Canada (NSERC). Robin Harrap maintains our SGI workstation, provides technical advice in the use of GOCAD, and has contributed to our ongoing discussions about the topology of the models.

Coherent Blueschist Terrane, French Range, British Columbia

P. Erdmer¹, E. D. Ghent², M. Mihalynuk³, F. Cordey⁴

¹Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, AB, T6G 2E3

²Department of Geology and Geophysics, University of Calgary, Calgary, AB, T2N 1N4

³British Columbia Geological Survey Branch, P.O. Box 9320 Stn. Prov. Govt., Victoria, BC, V8W 9N3

⁴Sciences de la terre, Université Claude-Bernard Lyon 1, 69622 Villeurbanne Cedex, France

The French Range lies 40 km west of Dease Lake in northwestern British Columbia, and exposes rocks of the Cache Creek terrane. Blueschist facies mineral assemblages characterize the French Range Formation, which comprises Permian agglomeratic basalt breccia grading into pillow basalt, interbedded limestone, chert and tuff. Rock units are stratigraphically and structurally coherent over an area of more than one hundred square kilometres. Field work in 1999 resulted in the following discoveries, which are being followed up with petrological, paleontological and isotopic age studies.

A range of bulk rock compositions have developed blueschist-facies assemblages. In particular, glaucophane is considerably more widespread than reported from earlier studies, and is present essentially in all outcrops of favorable bulk composition. The blueschist mineral assemblages are not entirely fine grained; glaucophane crystals are locally more than 5 mm long.

On the basis of the presence of the assemblage glaucophane + lawsonite, metamorphism appears to have been in the aragonite stability field. However, the occurrence of calcite only in fusulinid-bearing limestone units suggests either that aragonite was not produced because of unfavorable P-T conditions or reaction kinetics, or that all aragonite was converted

back to calcite following peak metamorphism. Late epidote-bearing veins show that the P-T- P_{H_2O} - f_{CO_2} conditions were not in the lawsonite field at the time of veining.

There is a striking lack of strong internal deformation of the primary stratigraphy. Depositional textures in volcanic and interlayered sedimentary rocks are commonly preserved. Pervasive, metre- to mountain-scale folds that are overturned to the northeast and have a subhorizontal crenulation cleavage are interpreted to have developed on the lower limb of a nappe.

Recently obtained $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic age data from samples of blueschist indicate that fabric-defining minerals formed at about 173 Ma (Middle Jurassic), the youngest known time of high-pressure metamorphism in the Cache Creek terrane. As tectonic fabrics are cut by plutons as old as 172 Ma, the age of blueschist metamorphism also constrains precisely the time of emplacement of the Cache Creek terrane.

The penetrative fabrics are interpreted to have formed during low-temperature nappe extrusion. Early exhumation of parts of the Cache Creek terrane is recorded by chert granules deposited in Early Bajocian strata of the adjacent Whitehorse Trough before ~ 170 Ma.

Geology along the southern 250 km of SNORCLE line 2 - Iskut to Stewart

Carol A. Evenchick

*Geological Survey of Canada, 101-605 Robson St., Vancouver, B.C., V6B 5J3
email: cevenchi@nrcan.gc.ca*

The southern quarter of SNORCLE line 2 crosses major structural and tectonic features in NTS map sheets 104A,B,H, and 104G. Recent regional mapping in these regions (Greig and Evenchick, 1992; Evenchick and Thorkelson, 1993; Lewis, 1996; Evenchick et al., 2000a; unpublished data of the author), as well as regional structural interpretations (Evenchick, 1991a, b; Evenchick, 1995, 1997, 1998; Evenchick et al., 1999) provide a geological framework for interpretation of new seismic data.

The primary regional stratigraphic/tectonic elements in this part of the SNORCLE transect are an allochthonous terrane (Stikinia), overlain by an overlap assemblage (Bowser Lake Group); both are intruded by plutons of the Coast Belt. Stikinia is composed of Paleozoic volcanic arc and platform carbonate rocks, and Triassic and Early Jurassic volcanic arc rocks. These are overlain by strata of the Bowser Basin (Bowser Lake Group), an upper Middle Jurassic to mid-Cretaceous marine and nonmarine clastic succession. Bowser Basin strata are an overlap assemblage because chert clasts in the Bowser Lake Group are derived from the Cache Creek Terrane, and therefore provide a Jurassic stratigraphic link between Cache Creek Terrane and Stikinia. Stikinia and Bowser Basin strata are intruded by plutons of the Coast Belt in the southernmost part of SNORCLE Line 2. Volumetrically minor strata are Pliocene and younger volcanic rocks.

The folded contact between Stikinia and Bowser Basin strata also separates two units of significantly different structural character. Stikinia is host to a range of styles of deformation, and metamorphism from subgreenschist to greenschist grade (Read et al., 1991). Units vary from thick and competent to thinly layered and incompetent. Several episodes of deformation occurred before Middle Jurassic overlap of the Bowser Lake Group; these imparted a complex structural geometry which was further complicated by involvement in the Skeena Fold Belt in Cretaceous time. Although the tectonic evolution of this part of Stikinia is known in a general sense from the stratigraphic succession, few structures in the vicinity of southern Line 2 have been studied in enough detail to determine kinematics. Where the geometry is well known, it is unclear how widespread or significant that particular feature is. Although pre-Middle Jurassic contractional, extensional, and strike slip structures are known, the timing of specific features is in most cases not narrowly constrained.

In contrast to Stikinia, strata of the Bowser Basin display one primary style of deformation. Strata are sub-greenschist facies, and structures define a regional fold and thrust belt known as the Skeena Fold Belt (Fig. 2; Evenchick, 1991a,b). The Skeena Fold Belt is best expressed in the thinly layered Bowser Lake Group, but also clearly involves Stikinia, as shown by folded contacts, structural culminations of Stikinian rocks within the fold belt, and klippen of early Mesozoic volcanic rocks on Cretaceous strata (Evenchick, 1991a,b). Upper Cretaceous strata of the Sustut Basin, on the east side of the fold belt, were derived from, and subsequently cannibalized by the fold belt. The fold belt accommodated a minimum of 44% (160 km)

northeasterly shortening, and terminates to the northeast in a classic triangle zone within the Sustut Basin (Evenchick, 1991a,b). It is inferred to root to the west in the Coast Belt. Age of the fold belt is generally contemporaneous with contractional deformation in the Coast, Omineca, and Rocky Mountain Fold and Thrust belts, a relationship which led Evenchick (1991a) to suggest that a detachment at some depth below the Skeena Fold Belt and either within Stikinia, or separating Stikinia from other terranes or cratonic North American basement, was required to feed displacement from the active plate margin (west of the Skeena Fold Belt) eastward.

Age of the fold belt is known generally from regional stratigraphic relationships, but the age of few specific structures has been resolved. The age of the youngest folded *marine* Bowser Basin strata is at the Jurassic/Cretaceous boundary. Sustut Basin strata (Albian to latest Maastrichtian age) unconformably overlie contractional structures in Bowser Basin strata, and are the youngest deformed rocks in the Skeena Fold Belt. From these relationships, the fold belt could have initiated as early as earliest Cretaceous time; at least some deformation was pre-Albian, and it lasted into latest Cretaceous or earliest Tertiary time. Synorogenic clastic rocks include a mid-Cretaceous piggy-back basin in the north-central part of the fold belt which records mid-Cretaceous subaerial erosion of topographic highs in the central and eastern fold belt. Farther northeast, more than 1500 m of synorogenic clastic deposits in the Sustut Basin record a western source of clastic material from Albian or Cenomanian through Maastrichtian time.

Structural geometry at the surface is in many places well defined, but extrapolation to depth in most of the fold belt has been hampered by the lack of laterally continuous markers. Folds in the Skeena Fold Belt have two dominant orientations (Fig. 2). Northwest-trending folds occupy the eastern two-thirds of the fold belt and parts of the western fold belt. Most are northeast verging, and vary from upright to overturned, on scales of several hundred metres to a kilometre or more wavelength. Larger folds occur near culminations that expose Stikinian volcanic rocks, and the scale of folding in these places is inferred to be controlled by the relatively competent and thick units of Stikinia. Larger scale folds also occur in the piggy-back basin, where thick competent sheets of conglomerate dominate the succession; there folds are one to several kilometres wavelength. Mesoscopic folds are rare. Larger order culminations are difficult to recognize because of the lack of laterally continuous markers within the Bowser Basin. Domains of southwest-verging folds are uncommon, and may reflect (i) parts of larger order culminations, or (ii) may be folds in the hanging walls of back thrusts. Folds have broad rounded to narrow angular hinges, and interlimb angles ranging from 140° to 30°, although the majority are 90° to 60° (see Figs. 4 to 9 of Evenchick, 1991a).

The second group of folds, occupying domains along the west side of the fold belt, trend northeast and north-northeast. They are of similar geometry and scale as northwest-trending folds, and verge both southeast and northwest. Fold interference occurs locally at the boundary between domains of northeast and northwest trending folds, and within the western domains. Origin of the high angle between these folds and northwest-trending ones is under investigation; current interpretation is that they are a result of sinistral convergence early in the history of the fold belt (Evenchick, 1997,1998,2000). Both orientations of folds affect the contact between Stikinia and the Bowser Basin on a scale large enough to be expressed on regional maps, and therefore both have the potential to be imaged in SNORCLE Line 2.

Thrust faults are recognized at the northeast margin of the fold belt where different map units are present, but they are difficult to identify within Bowser Basin strata unless hanging wall

or footwall cutoffs are exposed. They are required by the style of folding, and are inferred to be largely bedding-parallel blind thrusts.

The youngest period of significant deformation is late Tertiary (to Quaternary?) extensional faulting which affected the southwest-most part of SNORCLE Line 2 (Evenchick et al., 1999), and possibly portions farther north.

REFERENCES CITED AND SELECTED BIBLIOGRAPHY

Anderson, R.G.

1989: A stratigraphic, plutonic, and structural framework for the Iskut River map area, northwestern British Columbia; *in* Current Research, Part E; Geological Survey of Canada, Paper 89-1E, p. 145-154.

1993: A Mesozoic stratigraphic and plutonic framework for northwestern Stikinia (Iskut River area), northwestern British Columbia, Canada; *in* Mesozoic Paleogeography of the Western United States--II, Dunne, G. And McDougall, K (ed.); Pacific Section, Society of Economic Paleontologists and Mineralogists, v. 71, p. 477-494.

Evenchick, C.A.

1991a: Geometry, evolution, and tectonic framework of the Skeena fold belt, north central British Columbia. *Tectonics* v.10, 527-546.

1991b: Structural relationships of the Skeena fold belt west of the Bowser Basin, Northwest British Columbia. *Canadian Journal of Earth Sciences* 28, 973-983.

1995: Structural evidence of Early Cretaceous sinistral displacement in the northern Canadian Cordillera. *Geological Association of Canada Program with Abstracts* 20, A-30.

1997: Contractional structures in the western Skeena fold belt; an indication of Cretaceous sinistral convergence within the Coast Belt. *Geological Society of America Abstracts with programs* 29; A-82.

1998: Evolution of sinistral to dextral transpressional structures in the Skeena Fold Belt; *in* Evolution of Structures in Deforming Rocks, Abstracts of Canadian Tectonic Group Annual Meeting and Geological Association of Canada NUNA conference, Sept. 26-28, September 1998, Canmore, Alberta.

2000: Cretaceous sinistral convergence expressed as folds in the Skeena Fold Belt, northwest Canadian Cordillera, In review

Evenchick, C.A., Mustard, P.S., Porter, J.S. and Greig, C.J.

1992: Regional Jurassic and Cretaceous facies assemblages, and structural geology in Bowser Lake map area (104A), British Columbia; Geological Survey of Canada, Open File 2582, 17p.

Evenchick, C.A., Thorkelson, D.J.

1993: Geology, Spatsizi River, British Columbia (104H); Geological Survey of Canada, Open File 2719, scale 1:250,000. (NOTE: 1:50 000 maps of 104H also available)

Evenchick, C.A. and McNicoll, V.J.

1993: U-Pb ages for Late Cretaceous and early Tertiary plutons in the Skeena Fold Belt, north-central British Columbia; *in* Radiogenic Age and Isotopic Studies: Report 7; Geological Survey of Canada, Paper 93-2, p. 99-106.

Evenchick, C.A., Crawford, M.L., McNicoll, V.J., Currie, L.D., and O'Sullivan, P.B.

1999: Early Miocene or younger normal faults and other Tertiary structures in west Nass River (103P) map area, northwest British Columbia, and adjacent parts of Alaska; *in* Current Research 1999-A; Geological Survey of Canada, p. 1-11.

Evenchick, C.A., Mustard, P.S., Greig, C.J., Porter, J.S., and McNeill, P.D.

2000a: Geology, Bowser Lake (104A), British Columbia; Geological Survey of Canada, Open File xxxx, scale 1:250 000 (in review).

Evenchick, C.A., Poulton, T.P., Tipper, H.W.

2000b: Fossils and facies of the northern two-thirds of the Bowser Basin, British Columbia; Geological Survey of Canada, Open File xxxx, scale 1:250 000 (in revision).

Green, D., Greig, C.J., and Friedman, R.M.

1995: Portland Canal dyke swarm, Stewart area, northwestern British Columbia: geological setting,

- geochronology, and thermal modelling; in Current Research 1995-E; Geological Survey of Canada, p. 47-57.
- Greig, C.J.
 1992: Fieldwork in the Oweegee and Snowslide ranges and Kinskuch Lake area, northwestern British Columbia; in Current Research, Part A; Geological Survey of Canada, Paper 92-1A, p. 145-155.
- Greig, C.J. And Gehrels, G.E.
 1992: Latest Triassic - earliest Jurassic orogenesis, Stikine Terrane, northwestern British Columbia; Geological Society of America, Abstracts with Program, v.24, no.5, p.28.
- Greig, C.J. and Evenchick, C.A.
 1993: Geology with cross-sections of Oweegee Dome-Delta Peak and Taft Creek map areas (104A/11W,12), northwestern British Columbia; Geological Survey of Canada, Open File map 2688, scale 1:50 000.
- Greig, C.J., Anderson, R.G., Daubeney, P.H., and Bull, K.F.
 1994a: Geology of the Cambria Icefield area: Stewart (103P/13) Bear River (104/4) and parts of Meziadin Lake (104A/3) and Paw Lake (103P/14) map areas, northwestern British Columbia; Geological Survey of Canada, Open File 2931, scale 1:50 000.
- Greig, C.J., Anderson, R.G., Daubeney, P.H., Bull, K.F., and Hinderman, T.K.
 1994b: Geology of the Cambria Icefield: regional setting for Red Mountain gold deposit, northwestern British Columbia; in Current Research, 1994-A; Geological Survey of Canada, p. 45-56.
- Greig, C.J., McNicoll, V.J., Anderson, R.G., Daubeney, P.H., Harakal, J.E., and Runkle, D.
 1995: New K-Ar and U-Pb dates for the Cambria Icefield area, northwestern British Columbia; in Current Research 1995-A; Geological Survey of Canada, p. 97-103.
- Gunning, M.H.
 1996: Definition and interpretation of Paleozoic volcanic domains in northwestern Stikinia, Iskut River area, British Columbia; unpublished Phd thesis, Department of Earth Sciences, University of Western Ontario, London, Ontario, 531 p.
- Lewis, P.D.
 1996: Metallogenesis of the Iskut River Area, Northwestern B.C., Final Report and Geological Data Sets; unpublished report of Mineral Deposits Research Unit, Department of Geosciences, University of British Columbia.
- Read, P.B., Woodsworth, G.J., Greenwood, H.J., Ghent, E.D., and Evenchick, C.A.
 1991: Metamorphic Map of the Canadian Cordillera, Geological Survey of Canada, Map 1714A, scale 1:2 000 000.
- Souther, J.G.
 1972: Geology, Telegraph Creek, British Columbia; Geological Survey of Canada, Map 11-1971, scale 1:250 000 (see also GSC Paper 71-44).
- Thomson, R.C., Smith, P.L., and Tipper, H.W.
 1986: Lower to Middle Jurassic (Pliensbachian to Bajocian) stratigraphy of the northern Spatsizi area, north-central British Columbia; Canadian Journal of Earth Sciences, v. 23, p. 1963-1973.

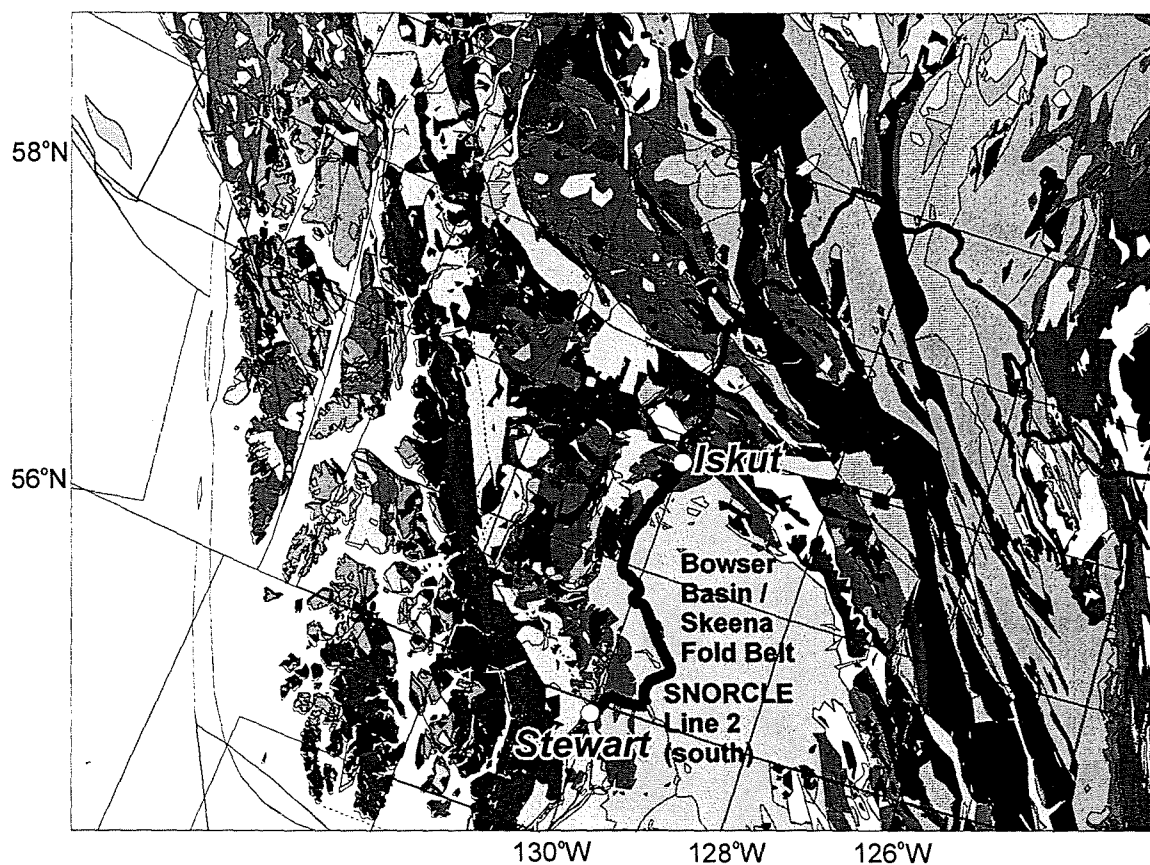


Figure 1. Location of SNORCLE Line 2, Bowser Basin, and Skeena Fold Belt (map is a portion of Wheeler and McFeely, 1991). The part of Line 2 highlighted is discussed.

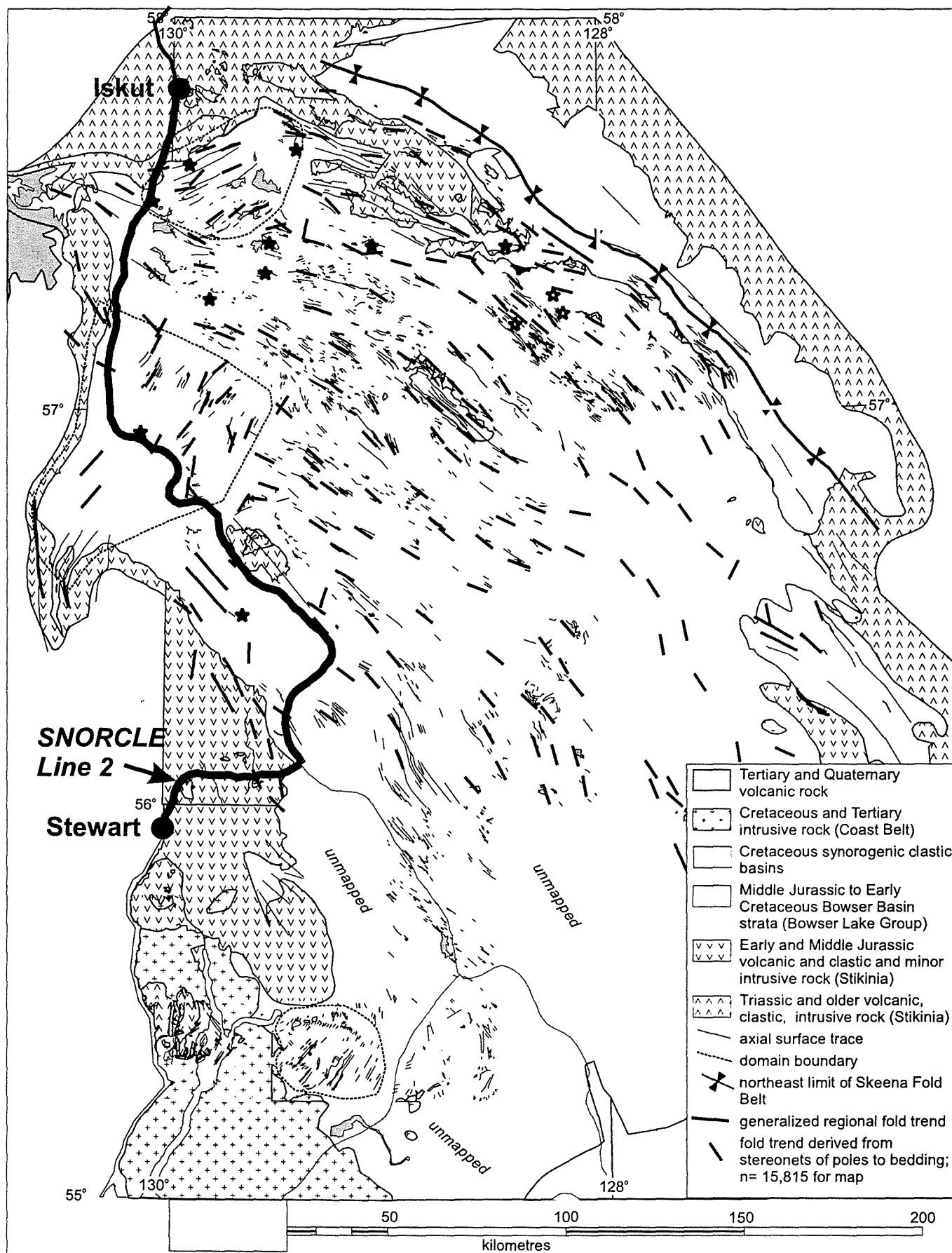


Figure 2. Structures in the Skeena Fold Belt, showing 1) structures which deform the contact between Bowser Basin strata and Stikinia; 2) northeast trend of the majority of folds in the eastern two-thirds of the fold belt; and 3) domains of northeast trending folds along the west side of the fold belt.

Sedimentology and tectonic setting of the Late Archean Burwash Formation, Southern Slave Province, Northwest Territories

Mark Ferguson, Dept. of Earth Sciences, Dalhousie University, Halifax N.S. B3H 4J1
John Waldron, Geology Department, Saint Mary's University, Halifax N.S. B3H 3C3
Wouter Bleeker, Continental Geoscience Division, Geological Survey of Canada, Ottawa,
Ont. K1A 0E8

The Late Archean Burwash Formation is a supracrustal package that overlies volcanics of the Yellowknife Supergroup in the southern Slave Province (Figure 1). The Formation has been deformed by three generations of folds, and has been metamorphosed at greenschist to amphibolite facies. The base of the formation is exposed along contacts with underlying volcanics and at the contact with a coarse clastic unit along the southern margin of the Sleepy Dragon basement massif. The Formation comprises predominantly turbidites, with minor sandy debris flows that are typically associated with felsic volcanic tuff layers. The sedimentological features and stratigraphy are best exposed and preserved farthest from granitic plutons. Within these areas, where the structural history is relatively well understood, the presence of distinctive volcanic tuff layers allows excellent lateral correlation.

Along the southern margin of the Sleepy Dragon basement massif, the coarse clastic Raquette Formation overlies regolith of the basement massif. The unit comprises a basal, volcanic-derived conglomerate overlain by carbonate-rich, locally matrix dominated conglomerate. These are locally interbedded with felsic volcanics. Large (>1m) fissures filled with carbonate-rich conglomerate have been observed that extend into the basal clastic conglomerate, and more rarely into the underlying regolith. This suggests that the conglomerates were deposited during extensional tectonism. Overlying the conglomerates are black, siliceous shales, interbedded with fine grained felsic tuffs (Figure 2). These are in turn overlain by the basal turbiditic sandstones of the Burwash Formation. This deeper water, fine-grained package likely records a transgression.

Farther from the basement and higher in the stratigraphy, medium to coarse grained, sand-filled channels are partially exposed. The channel-filling sands represent deposition by high concentration turbidity currents. Thinner bedded, mud-dominated intervals, that are compacted and often poorly exposed, represent levees to these channels. In one location, laterally continuous sandstone beds adjacent to and overlying a mud-dominated interval probably represent sheet sandstones and a levee system. This is analogous to high amplitude reflection packages (HARPS) seen in some modern fan systems, where avulsion of a channel results in sheet sandstone deposition on levee flanks and interchannel areas (Figure 3).

The coarse-grained sandstone turbidites comprise wackes that correspond compositionally to arkoses and lithic arkoses. Plutonic fragments and quartz grains

dominate the grain population. Lithic fragments form only a minor component although the abundant matrix of fine-grained material may include additional unrecognized lithic fragments. They include quartzites, iron rich cherts, metamorphic fragments, and volcanics. Potential sources for all the different rock fragments are presently exposed in the southern Slave Province.

The early evolution of the Burwash Formation basin took place in an extensional tectonic setting. Regolith development during exposure of basement rocks was followed by deposition of the coarse clastic sediments and volcanics. Subsequently, a transition into a deeper water environment resulted in deposition of a fine-grained package. The following development of a turbidite system was fed by multiple sediment sources including plagioclase-rich granitoids, metamorphic rocks, quartzites and volcanics. This system involved a mid-fan setting where channel-levee systems developed with sheet sandstones deposited on levee flanks and interchannel areas.

References

- Bleeker, W.B., and Ketchum, J., 1998. The Central Slave Basement Complex: its autochthonous cover, decollement, and structural topology. In Current Research 1998-C, Geological Survey of Canada, 9-19.
- Piper, D.J.W., and Normark, W. R., In Press. Sandy Fans – From Hueneme to Amazon.

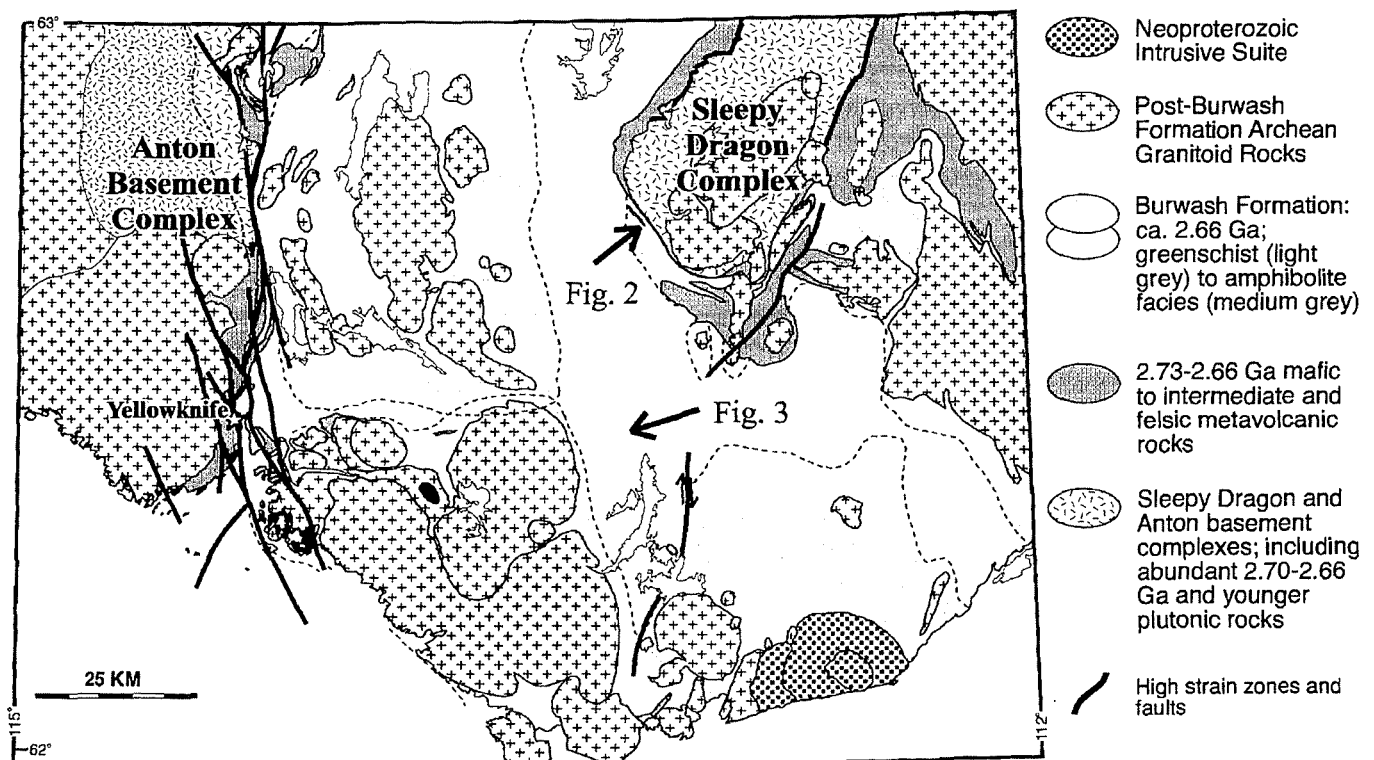


Figure 1: Geology of the Yellowknife Domain. (modified from Ketchum and Bleeker, 1998).

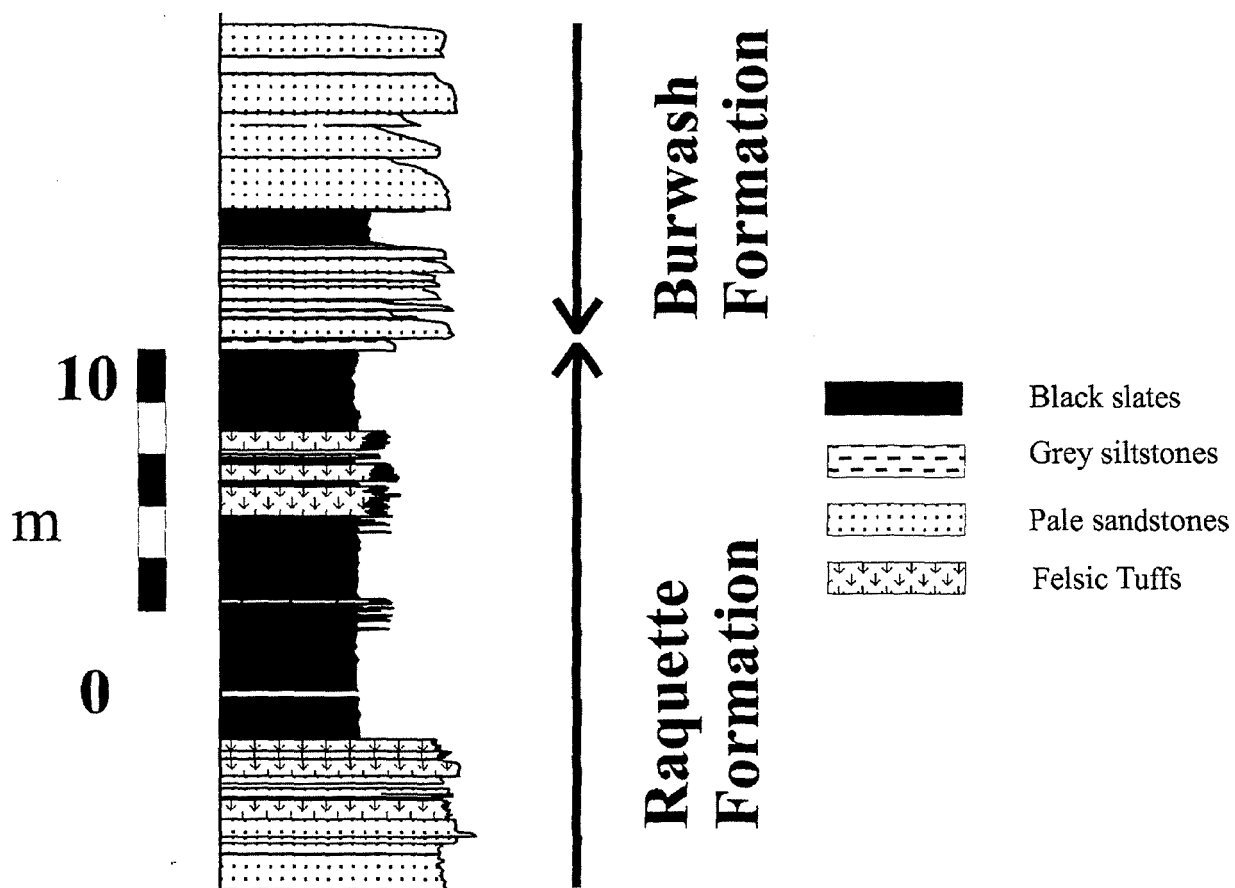


Figure 2: Stratigraphic column illustrating the top of the Raquette Formation and the base of the Burwash Formation.

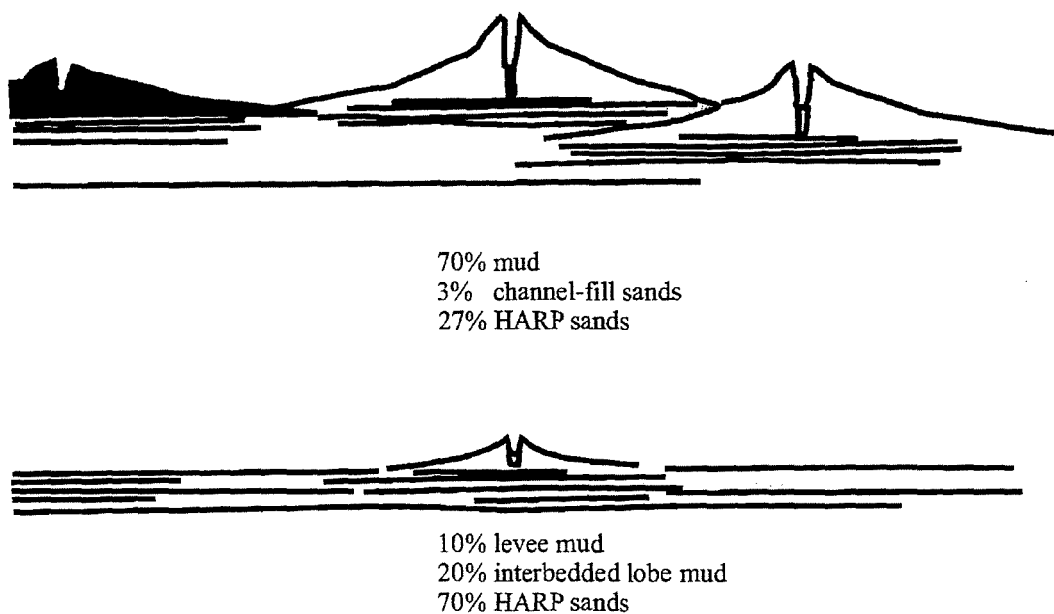


Figure 3: Schematic cross-sections from part of the Amazon Fan (Piper and Normark, 1999) to illustrate relationship of sheet sandstones (E.g. HARP sands) to channel-levees.

U-Pb geochronologic constraints on metamorphism and deformation within the northern Selkirk Mountains, southeastern Canadian Cordillera

H. Daniel Gibson, Sharon D. Carr, and Richard L. Brown

Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University,
Ottawa, ON, K1S 5B6, Canada

Email: dhgibson@ccs.carleton.ca

The northern Selkirk Mountains are situated within the metamorphic hinterland of the southeastern Canadian Cordillera, where there is excellent exposure of exhumed middle-crustal, polydeformed and metamorphosed rocks. Three generations of structures have been recognized. Of particular interest are the second (F_2) and third (F_3) generation folds that verge to the SW and NE, respectively, across a mappable structural fan axis. F_2 folds dominate the west side of the fan structure where they are tight to isoclinal, and are strongly overturned toward the SW. F_3 folds are primarily concentrated in the NE, with steep to vertical NE verging axial surfaces. This zone of structural divergence, termed the Selkirk Fan Structure (SFS), is orogen parallel and extends on a SE-NW trend for more than 120 km across the northern Selkirk Mountains. A similar zone of divergence extends southward into the US Cordillera and northward to Alaska. In southeastern British Columbia, the northern part of the fan axis is coincident with a zone of sillimanite-grade rocks, which trends from the northern Selkirk Mountains in the east, across the Columbia River, and into the Monashee Mountains to the west, with no known structural break. Metamorphic assemblages flanking both sides of the sillimanite zone become progressively lower grade (kyanite through chlorite) with distance away from the fan axis. Knowledge of the thermotectonic evolution of this region is necessary for understanding the orogenic processes responsible for the formation of the Canadian Cordillera. This study provides geochronologic data that are used to constrain timing of metamorphism and deformation, which demonstrate that the thermotectonic history of the region was protracted and complex.

Detailed U-Pb geochronology and SEM images of samples collected in the northern Selkirk Mountains have been completed. Data provided by monazite and zircon separated from pelitic schists, pre- to syn- and post-tectonic pegmatite, granodioritic dykes, and a metavolcanoclastic horizon support the following first order conclusions: 1) U-Pb monazite ages suggest that the sillimanite metamorphism was diachronous, from Early to Late Cretaceous, 2) the second generation of folding occurred between ~165 Ma to 155 Ma, and 3) formation of third generation folds is tentatively interpreted to have occurred between ~100 Ma and 81 Ma. These conclusions suggest that the formation of the SW-verging folds, F_2 , occurred during a distinctly separate orogenic event relative to the much younger NE-verging F_3 structures. Furthermore, the Cretaceous sillimanite metamorphism appears to have been coeval with F_3 .

The timing of F_3 and its relationship to the sillimanite metamorphism remains equivocal. Past studies have demonstrated that F_3 deforms the sillimanite isograd, indicating that F_3 , in part, post-dates the sillimanite metamorphism. However, recent thin section analyses of the dated sillimanite pelitic schists demonstrate that the growth of the sillimanite-muscovite assemblage post-dated most of the strain associated with F_3 . Thus, it appears as though, at least in the areas that were dated, some of the sillimanite metamorphism outlasted or post-dated the development of F_3 folds. Additionally, caution must be exercised when interpreting the U-Pb ages of monazite from the sillimanite pelitic schists because of the complexities associated with them. For

instance, SEM images display variable zoning, which results from significant differences in concentrations of thorium and uranium from one zone to another. As such, these zones may represent micron-scale age domains that are undetectable using conventional U-Pb dissolution techniques. Consequently, the following questions must be asked: 1) Did F_3 outlast sillimanite metamorphism or vice versa? 2) Is the apparent temporal link between sillimanite metamorphism and F_3 fortuitous? 3) Could the monazites dated represent growth related to a late overprinting fluid event rather than regional metamorphism associated with burial during F_3 ? These questions need to be addressed before solid conclusions can be made and applied to the formulation of a tectonic model for the region, and thus are the focus of ongoing research.

A NEW LOOK AT EASTERN NASS RIVER MAP-AREA (103P), BRITISH COLUMBIA

Haggart¹, James W., **Mahoney**², J. Brian, **Justason**³, Angelique J., **Rowe**², Carrie, and **Schmidt**², Mike. ¹Geological Survey of Canada, Vancouver, BC V6B 5J3; ²Department of Geology, University of Wisconsin, Eau Claire, WI 54702; ³Earth & Ocean Sciences, University of Victoria, Victoria, BC V8W 3P6.

A 1:250K-scale geologic map has never been prepared for the entirety of Nass River map-area (103P). Rocks in the western and central part of the map-area are of generally higher metamorphic grade and have been the subject of recent ongoing GSC and University collaboration (work of Evenchick and colleagues); we have initiated a study of low-grade rocks in the eastern part of the sheet. Our 1999 field program examined the four 1:50K map-areas along the eastern margin of the map-area (103P/1, 8, 9, and 16), and adjoining the Hazelton sheet, as well as 103P/2, adjacent to the Terrace sheet. The entire region is underlain by Mesozoic strata, with associated minor (?)Pleistocene volcanic flows and (?)Tertiary plutonic bodies. The Mesozoic strata have experienced minimal levels of diagenetic alteration and are of hornfelse grade over a large extent of their outcrop. Mesozoic strata are essentially monolithologic and marker beds and age control are scarce, making correlation difficult.

Two principal stratigraphic packages are noted within the Mesozoic sequence of eastern Nass River map-area. The first package crops out extensively in the northern part of the study area (103P/9, 16) and consists of fine- to coarse-clastic deposits correlated with the Bowser Lake Group; limited fossil control (buchiid bivalves) indicates that these strata are of Late Jurassic age. The strata aggregate at least several hundred meters in thickness and consist of interstratified shale and turbiditic sandstone. Turbidite deposits reflect deposition in submarine-fan channel systems (coarse sandstones) to distal fan environments (Bouma T_{ce} and T_{cde} sequences). At least four coarsening-upward sequences can be recognized in the Bowser Lake Group at a single locality, but age control is insufficient to determine if these cycles are of basinwide extent. Bowser Lake Group turbidite facies are widespread in the north-central portion of Nass River map-area west of our study area (Evenchick and Mustard, 1996; Haggart et al., 1998).

The second stratigraphic package is dominated by coarse sandstone and interstratified siltstone and mudstone, locally rich in organic detritus. This package trends in a ENE-WSW belt across the southern part of the map-area (103P/1, 2, 8). The bulk of these strata reflect deposition in marginal marine to deltaic settings. Limited marine macrofossil control (ammonites, bivalves) indicate these strata are of Early Cretaceous age (Hauterivian in part) and thus correlative with the Skeena Group. Skeena Group coarse-clastics grade upwards into black, organic-rich shales of uncertain age. Organic detritus includes abundant wood and plant fragments up to 35 cm diameter, and significant coal deposits are noted locally.

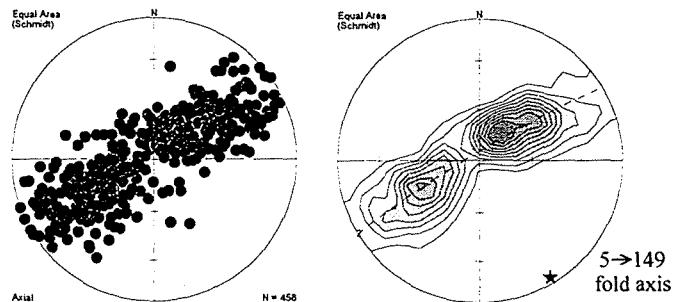
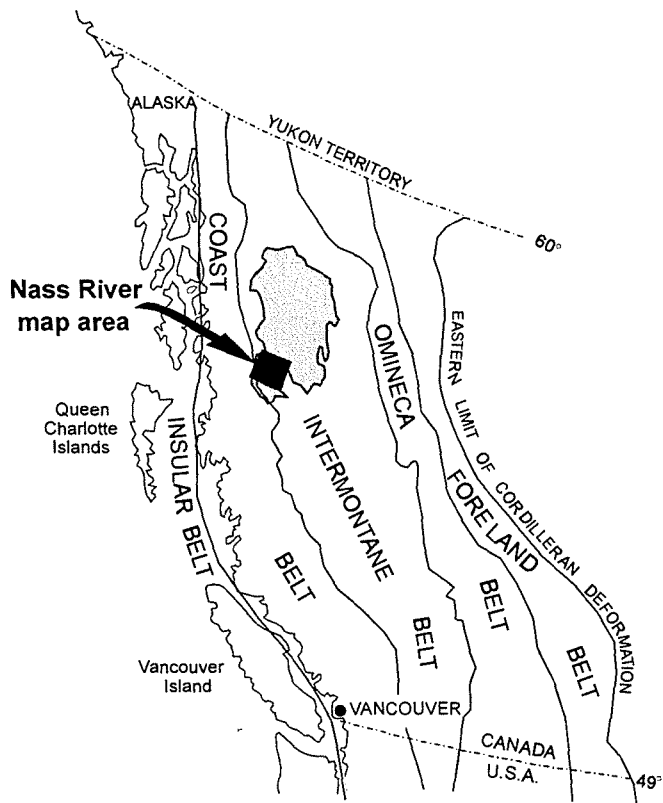
The provenance of both Bowser Lake Group and Skeena Group sediments in the study area is presently unknown, although ongoing petrographic studies may provide data on this question. Limited paleocurrent data from across the study area suggest E-W transport directions for strata of both Bowser Lake Group and Skeena Group. Detrital muscovite, often coarse-grained, is

common in Skeena Group but is also known in Bowser Lake Group, although rare. Chert pebbles are found in both Bowser Lake Group, where they are rare, and in Skeena Group, where they are common. Upper and lower stratigraphic limits of both Bowser Lake Group and Skeena Group have not been identified and the relationship between the two packages is poorly understood at present; it is presumed to be a disconformity.

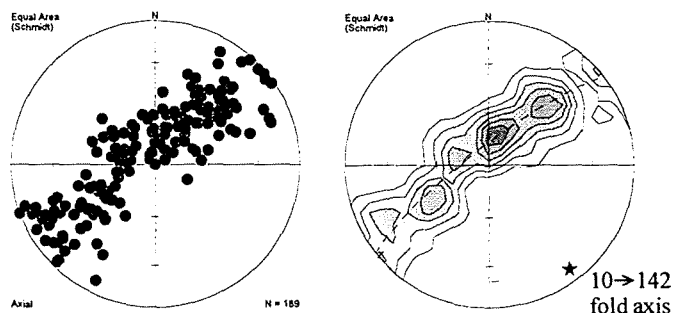
The structural grain of eastern Nass River map-area forms a large-scale arcuate pattern and present-day topographic trends parallel this pattern. Contractional structures predominate across the region, and include thrusts and steeply-dipping to overturned folds, often traceable laterally for tens of kilometers. NNE-vergent structures dominate in the northeast part of the map-area, and change gradually to E-vergent structures in the east-central part of the area, and then to SSE-vergent structures in the southeast part of the map-area. These trends mirror patterns seen farther to westward in the central part of Nass River map-area (103P/15, P/10, P/7, and P/6; Evenchick and Mustard, 1996; Haggart et al., 1998). Contractional features affect both Upper Jurassic and Lower Cretaceous strata. Extensional features include rare (?) Late Cretaceous to Tertiary dikes and localized small-scale normal faulting, generally oriented around N-S trends; limited evidence suggests that the extensional features may post-date the contractional regime.

Skeena Group strata are widespread and laterally continuous across the southeastern part of the map-area, transecting both alpine and valley bottom regions. No evidence is seen for the large, valley-bounding graben structures which have been previously mapped in the region. The structural style of eastern Nass River map-area is that of a fold-and-thrust belt system, and is presumably related to the Skeena Fold Belt of Evenchick (1991). The fold-and-thrust regime likely trends eastward and southward from Nass River map-area into the adjoining Hazelton (93M) and Terrace (103I) sheets, respectively.

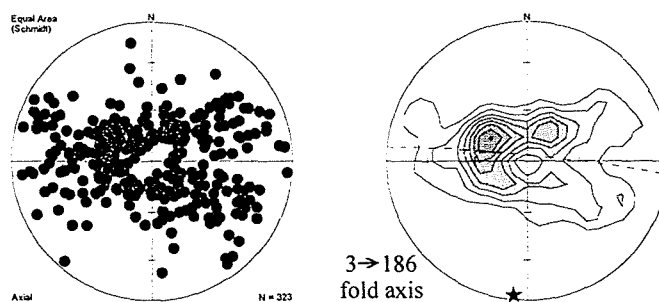
The presence of abundant organic detritus in finer clastic facies of the region may constitute a source rock of sufficient quality to produce hydrocarbons. The structural style of eastern Nass River map-area consists of tightly-folded anticline/syncline pairs, of significant lateral extent and generally of minimal plunge, thus serving as possible hydrocarbon traps.



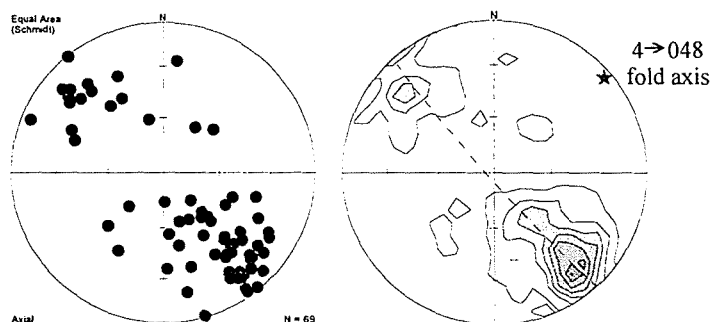
Stereographic projection of poles to bedding
103P/16



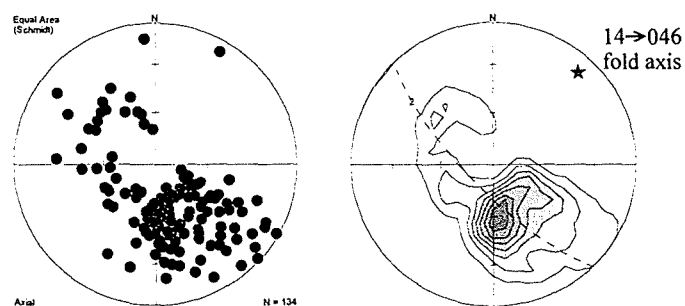
Stereographic projection of poles to bedding
103P/9



Stereographic projection of poles to bedding
103P/8



Stereographic projection of poles to bedding
103P/2



Stereographic projection of poles to bedding
103P/1

Lithospheric structure across the Coast orogen of NW British Columbia and SE Alaska from seismic wide-angle studies: Lithoprobe SNORE Line 22 and ACCRETE profiles

Philip T. C. Hammer and Ron M. Clowes
University of British Columbia, Dept. of Earth and Ocean Sciences
2219 Main Mall, Vancouver, BC, V6T 1Z4
hammer@eos.ubc.ca

Introduction

Crustal structure beneath the Coast orogen of the northwestern Canadian Cordillera is interpreted from the inversion of refraction and wide-angle reflection (R/WAR) seismic data. The profile (Fig. 1) traverses an accretionary suture zone (Coast Plutonic Complex) resulting from the mid-Cretaceous collision between the exotic Insular superterrane (Alexander and Wrangellia terranes) and the previously accreted Intermontane superterrane (Stikinia, Taku and Yukon terranes). Using data acquired by the ACCRETE onshore/offshore experiment and by a partially overlapping Lithoprobe onshore experiment (SNORE), *P* and *S* wave travel time inversion and forward amplitude modeling are employed to determine crustal velocity structure. Poisson's ratio analysis, physical properties and gravity inversion are also incorporated in the study.

The North American Cordillera experienced its last major phase of continental growth during the Mesozoic and early Cenozoic. During that period, the Cordillera grew by the accretion of the Insular superterrane through a complex and still controversial process of transpressional deformation and magmatic intrusion. The resulting collisional suture zone, or Coast belt (CB), now divides the Insular and Intermontane superterrane and extends from the Yukon Territory to northern Washington State (Fig. 1). The orogen-parallel complex cuts across terrane boundaries and is defined by voluminous plutons and north trending contractional and strike-slip fault systems. Accretion collapsed Stikinia by more than 160 km as is evidenced by the thin-skinned Skeena thrust and fold belt [Evenchick, 1991]. The Insular and Coast belts were further influenced by subsequent mid-late Cenozoic extension [e.g., Morozov *et al.*, 1998; Evenchick *et al.*, 1999].

Determining the current structure of the Coast orogen is necessary in order to refine current hypotheses of the western Cordilleran accretionary and extensional history. In addition, these studies are linked to more fundamental questions concerning continental evolution and dynamics during transpressive accretion and subsequent extension. Through analysis of the merged seismic data sets, we present the first crustal velocity model across the eastern transition from the Coast orogen plutonic core to Stikinia. In addition, we compare our velocity structural model across the northern Cordilleran Coast belt (54.5-56.5°) with a model for the southern Cordillera (49-52°), previously the focus of detailed study [e.g., Cook, 1995].

Experiments: ACCRETE and SNORE Line 22

The 1994 ACCRETE seismic refraction/wide-angle reflection (R/WAR) experiment and the 1997 SNORCLE R/WAR Experiment (SNORE) provide a continuous profile across the transition between the Coast Plutonic Complex (CPC) and the Skeena fold and thrust belt of the Stikinia terrane (Fig. 1). Using coastal fjords for access, ACCRETE profiled with a towed 132 L airgun array. Data were recorded by 40 Reftek 3-component seismographs deployed along the 180 km-long Portland Canal. 17 additional seismographs were deployed in-line with the shiptrack, extending the profile 105 km northeast from the head of the fjord through the CPC and into Stikinia. Seismic coverage across the transition was significantly improved by the overlapping SNORE Line 22 dataset. Extending south from the Tintina fault across the Intermontane terranes and into the CPC, the profile reaches 50 km down Portland Canal, providing 150 km of overlap with ACCRETE. Nine explosive shots (1000 - 3000 kg) were detonated along the 600 km profile. Two of these shots (2 and 3) are inline with ACCRETE and are included in the combined analysis (Fig. 1). Data were recorded by 450 1-component (PRS and SGR) and 3-component (Reftek) seismographs. The two R/WAR datasets provide a densely sampled, 2-D profile. Data quality is excellent; numerous reflected and refracted *P* and *S* phases are

identifiable and are observed to large offsets.

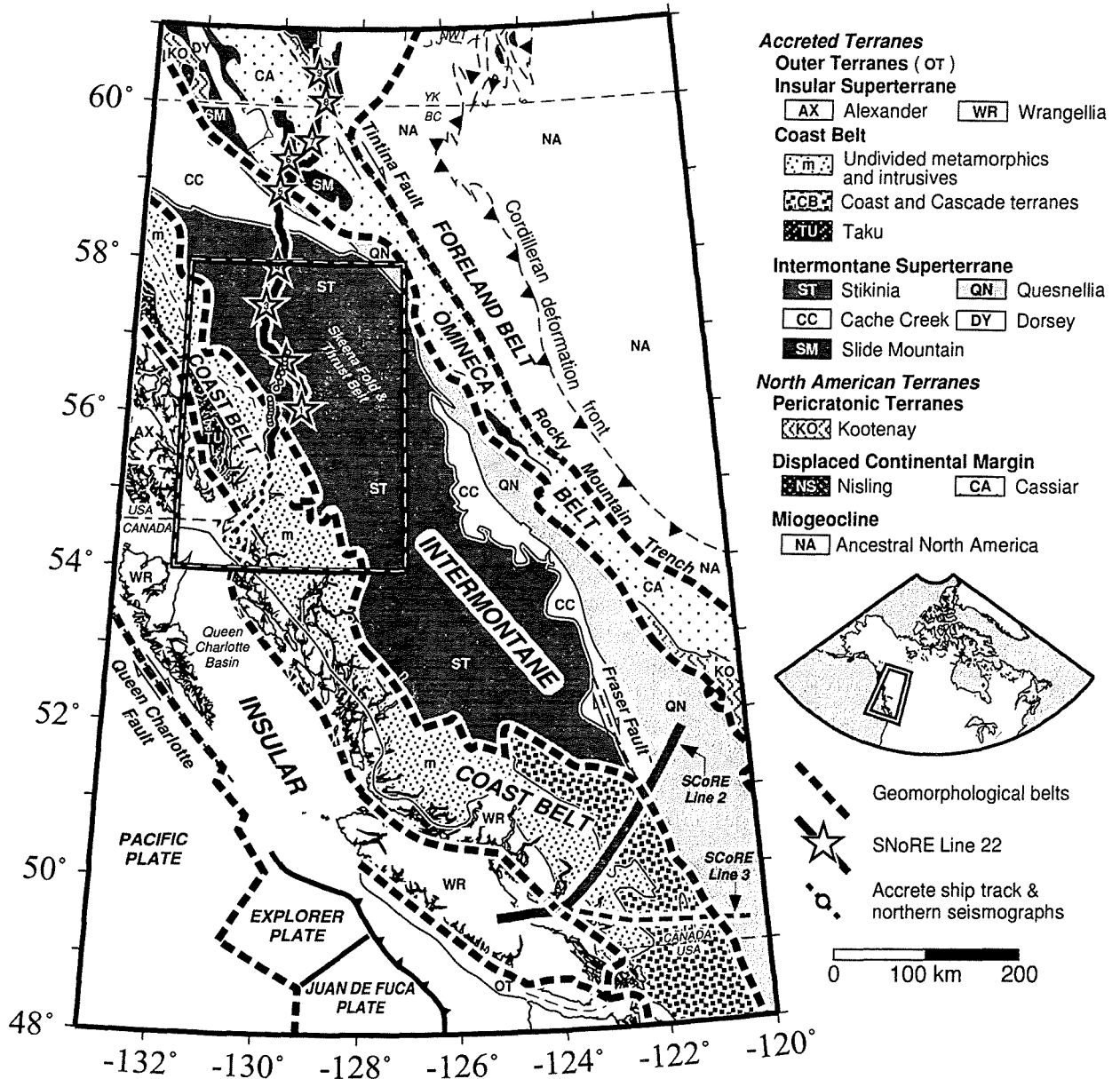


Figure 1: Terranes and geomorphological belts of the northwestern Canadian Cordillera (modified from Wheeler *et al.* [1988]). SNORE line 22 energy was generated by explosive shots (stars) and recorded by receiver arrays (thick solid lines). ACCRETE air gun shots (thin dashed lines) along Portland Inlet were recorded by inline seismographs (circles). Dashed box demarcates the ACCRETE/SNORE profile region. Related refraction/wide-angle reflection transects crossing the southern Coast belt are located by shaded lines.

Data and Modeling

Data quality from both experiments is generally excellent and a rich suite of P and S wave arrivals are observed. The ACCRETE dataset, in particular, includes strong S -wave arrivals. These are indicative of efficient P -to- S conversion along the fjord sediment/basement interface. Refracted arrivals include upper crustal refractions (P_g , S_g) and upper mantle refractions (P_n). Intracrustal reflections are observed in the upper crust (PcP_S , PcP_F , PcP_1), at the base of the upper crust (PcP_2 , ScS_2) and within the mid-lower crust (PcP_3) (see Fig. 2a). Strong Moho reflections are also observed (PmP , SmS). In addition, the ACCRETE dataset

includes converted Moho reflections (*SmP*); this unusual phase is observed on several adjacent receivers at ~80 km offset.

P and *S* wave arrivals were analyzed using a combination of 1-d tau-p velocity modeling [Gorman and Clowes, 1999] and subsequent 2-d traveltimes inversion and forward amplitude modeling [Zelt and Smith, 1992]. Velocity and reflector depth resolution varies throughout the model. In general, upper crustal *P* velocities have uncertainties of 0.1-0.2 km/s and lateral resolution of 3-35 km. Lower crustal *P* velocities exhibit 0.2-0.3 km/s uncertainty and lateral resolution of 20-75 km. Moho depth is constrained to 1.5-3 km and upper mantle *P* velocities to 0.1 km/s. For a detailed discussion of the modeling procedure and uncertainty analysis, please see Hammer *et al.* [2000].

Velocity and Density Modeling Results

The northern Cordilleran Coast belt and Intermontane superterrane are clearly distinguished within the ACCRETE/SNORE velocity structure model (Fig. 2; Hammer *et al.* [2000]).

- (1) Throughout the crust, Coast belt *P* and *S* velocities are faster than those observed in the Intermontane. Average crustal *P* velocities are 6.45 km/s for the Coast belt and 6.25 km/s for the Intermontane. The Coast belt upper crust is markedly faster than the Bowser Lake assemblage and the Stikinia upper crust. Similarly, the lower crustal velocities beneath the western and central Coast belt are higher than those beneath Stikinia.
- (2) Crustal thickness beneath the Coast Plutonic Complex (30-32 km) is significantly thinner than beneath Stikinia (35-37 km).

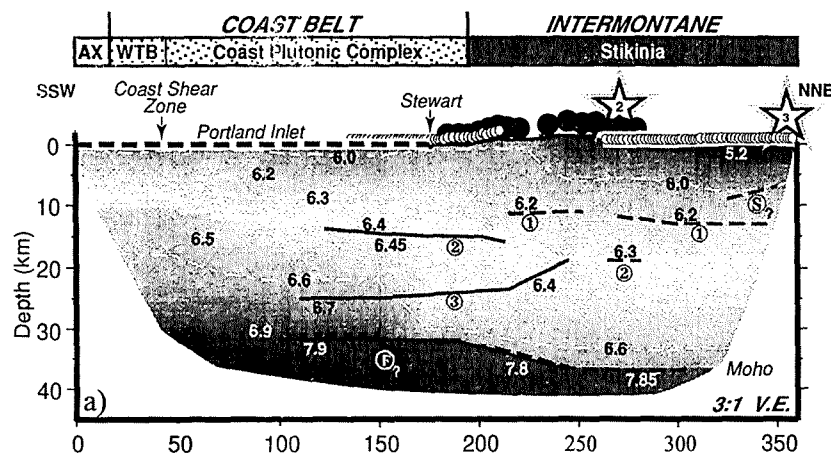
The *S* velocity model was combined with the *P* velocity model to generate a Poisson's ratio model for the ACCRETE/SNORE profile. Poisson's ratio (σ) is proportional to V_p/V_s and improves constraints on crustal composition. These results are compared with average velocities of appropriate rock types derived by laboratory measurements [Christensen, 1995 and personal communication]. A number of these measurements were made on rocks sampled within the ACCRETE corridor in regions where lower crustal sections were exposed. The upper crust of the CPC ($\sigma = 0.250 \pm 0.005$) is felsic and corresponds closely to the laboratory measurements of granite-granodiorite. Shallow *S* arrivals within the Stikinia crust give a Poisson's ratio of $\sigma = 0.265 \pm 0.005$, significantly higher than that observed within the upper CPC. Poisson's ratio in the lower crust is averaged over the lower 15 km as only *SmS* arrivals were recorded. However, the ratio yields $\sigma = 0.26 \pm 0.01$, consistent with a mafic composition of high metamorphic grade.

Using the major structural features and general compositional constraints determined by the seismic experiments, the density structure beneath the Insular/Coast belt and Coast belt/Intermontane boundaries was evaluated using 2.5-D forward modeling (Fig. 3). Density structure was also modeled using 3-D inversion of the Bouguer gravity field. Studies of regional isostasy are ongoing.

Discussion

The observations are consistent with the Coast belt being strongly influenced by uplift and extension. The thin crust and velocity structure are similar to that observed in the Basin and Range and correspond closely to average extensional structure [Christensen and Mooney, 1995]. Although the Coast belt average *P* velocity is higher than the global average for extended crust (6.21 ± 0.22 km/s), this results from the absence of slow velocities in the upper few kilometers and from mid-lower crustal velocities reaching relatively shallow depths. Both of these characteristics can be attributed to the 10-20 km of uplift that has exhumed the CPC [e.g., Evenchick *et al.*, 1999].

NORTHERN CORDILLERA: ACCRETE-SNoRE Line 22



SOUTHERN CORDILLERA: SCoRE Line 2

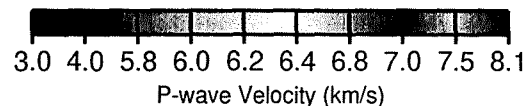
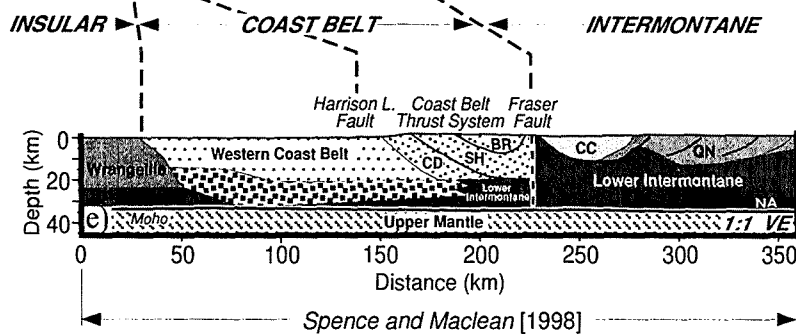
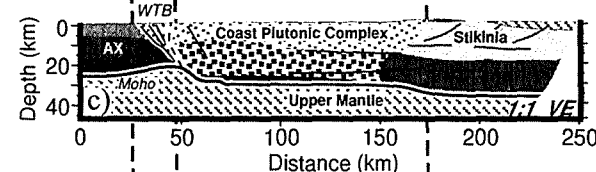
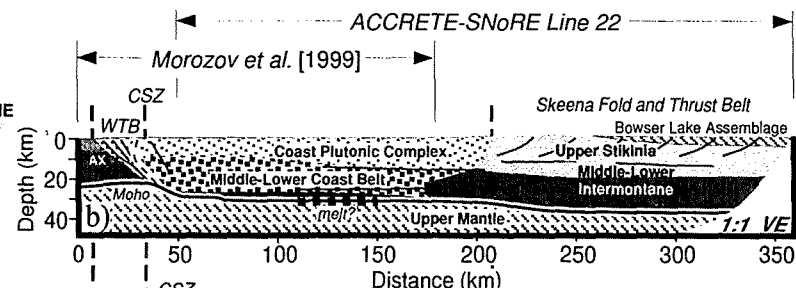
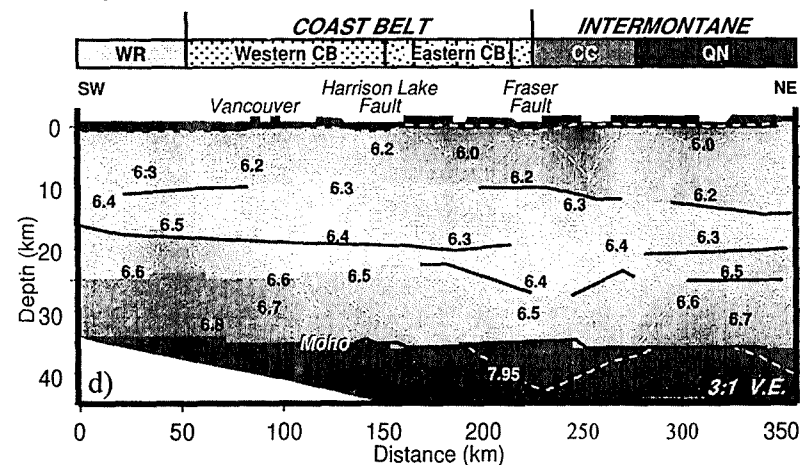


Figure 2: (a) *P* velocity structure model for the crust and upper mantle. Velocities are shaded and noted by numbers (km/s). The unconstrained model region is masked out. Crustal reflectors are numbered corresponding to the associated phase (e.g., ② for PcP2). Reflectors modeled from the ACCRETE (—) and the SNoRE (---) datasets are indicated. See text for discussion of PcPs. The location of the converted Moho reflector (SmP; ■■■) is also noted. Accrete airgun shots (---) along Portland Inlet were recorded by the northern seismograph array (●). SNoRE Line 22 energy generated by explosive shots (☆) was recorded by an overlapping receiver array (○○○). White dashed lines represent velocity contours. (b) Interpretive section based on our velocity model and the overlapping model of Morozov et al. [1999]. (c) Projection of (b) to a perpendicular crossing of the northern Coast belt. (d) *P* velocity structure model from the Southern Cordillera Refraction Experiment Line 2 [Spence and McLean, 1998]. Profile location shown on Figure 1. (e) Interpretive section of Line 2 based on multidisciplinary studies [Spence and McLean, 1998]. Abbreviations: AX (Alexander), BR (Bridge River), CB (Coast belt), CC (Cache Creek), CD (Cadwallader), CSZ (Coast Shear Zone), NA (North American craton), QN (Quesnel), SH (Shuksan), VE (Vertical Exaggeration), WR (Wrangel), WTB (Western Thrust Belt).

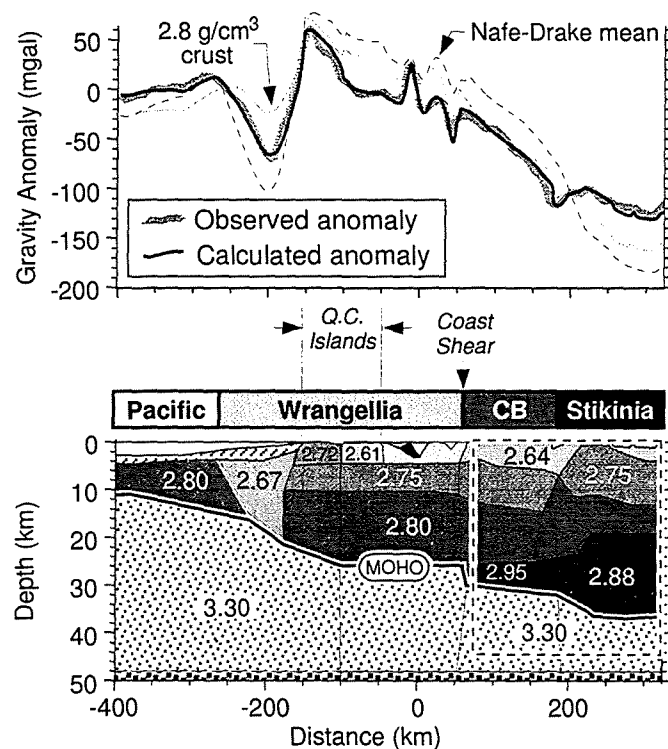


Figure 2: Density models based on 2-D forward modeling. Bouguer and free-air gravity anomaly along the SNORE/ACCRETE corridor and across the Queen Charlotte Islands was projected onto a line perpendicular to the orogen strike. Moho depth and crustal framework in density model based on seismic interpretations. Dashed box represents area modeled by the ACCRETE/SNORE study.

A number of observations provide additional support for extensional influence on current Coast belt structure: (a) an offline reflector ($PcPs$) west of Portland Canal likely represents a shallow, steeply dipping fault within the CPC [Hammer *et al.*, 2000]. The modeled strike is subparallel to that of a Neogene fault suite attributed to east-west extension within the Coast belt [Evenchick *et al.*, 1999], (b) converted Moho reflections (S -to- P) were observed beneath the central Coast belt. This unusual observation is indicative of locally sharp impedance contrasts that perhaps represent melt lenses, and (c) active magmatism is consistent with the high upper mantle temperatures required by the slow observed velocities (7.8-7.9 km/s) and high regional heat flow.

Although evidence of Neogene extension is concentrated within the Insular and Coast belts, the low mantle velocities determined along SNORE line 22, supported by consistently high heat flow across the region, indicate that no thermal boundary divides these belts from the Intermontane superterrane. This is consistent with the isotope studies of Francis *et al.* [1999] that indicate the radiogenic source region of the recent (0-15 Ma) Coast belt alkaline basalts extends beneath the western margin of the Intermontane. This supports the hypothesis that Neogene extension within the Coast belt is linked with processes generating Neogene-Quaternary volcanism to the north across the Intermontane and Omineca belts [e.g., Edwards and Russell, 1999].

Structure modeled within the Coast Plutonic Complex is not clearly linked to the transpressional processes that dominated the formation of the Coast belt. The most convincing shear-related feature lies to the southwest of our study region where Morozov *et al.* [1998] showed that the Coast Shear Zone is a crustal-scale feature separating the Insular belt and the westernmost Coast belt (Fig. 2b). In contrast, velocities within the CPC exhibit little complexity, gradually decreasing toward the eastern boundary with the Intermontane belt (Fig. 1a). The high-velocity lower crust below the western CPC (6.9 km/s at 31 km depth) could be

associated with restites derived from the extensive period of orogenic magmatism, as suggested by *Clowes et al.* [1997] to explain high-density lower crust in the southern Cordilleran Coast belt. However, the strong evidence for extension suggests that structure related to the Coast orogeny may be overprinted by recent tectonics. Our velocity model cannot date or determine the primary mechanism controlling Coast belt crustal structure; indeed, more than one process may play an important role. The location of the transition between the Coast and Intermontane belts is well defined but varies somewhat with depth. Lateral changes in upper crustal velocity and crustal thickness correspond closely with the mapped boundary (model distance 210 km (MD210), Fig. 2a). In the mid-lower crust the velocity transition shifts slightly westward, beneath the Coast belt (MD175). This provides weak support for Intermontane crust underlying the Coast belt. Alternatively, the location of the mid-lower crustal transition could be related to the eastern extent of orogenic deformation or to more recent extensional processes.

Comparison of velocity models crossing the northern and southern Coast belts reveals similar velocity structure within the massive plutonic complexes (i.e., the Coast Plutonic Complex in the north and the western Coast belt in the south). Differences between the velocity models emphasize along-strike variation in the western Cordillera. Not only are the terranes involved in the collision different, but the patterns of deformation and plutonic intrusion within the Coast belt vary considerably. The influences of postorogenic extension in the northern Cordillera and Cascadia subduction in the southern Cordillera are distinguished by clear differences in crustal thickness [*Hammer et al.*, 2000]. However, upper mantle velocities in both regions are slow (7.8-7.9 km/s), consistent with high heat flow values.

References

- Christensen, N. I. [1996]: Poisson's ratio and crustal seismology. *J. Geophys. Res.*, vol.101, 3139-3156.
- Christensen, N. I., and W. D. Mooney [1995]: Seismic structure and composition of the continental crust. *J. Geophys. Res.*, vol.100, 9761-9788.
- Cook, F. A. (Ed.) [1995]: The southern Canadian Cordillera Transect of Lithoprobe, *Can. J. Earth Sci.*, vol.32, 1483-1824.
- Edwards, B. R., and J. K. Russell [1999]: The northern Cordilleran volcanic province: A northern Basin and Range? *Geology*, vol.27, 243-246.
- Evenchick, C. A. [1991]: Geometry, evolution and tectonic framework of the Skeena Fold Belt, North Central British Columbia. *Tectonics*, vol.10, 537-546.
- Evenchick, C. A., M. L. Crawford, V. J. McNicoll, L. D. Currie, and P. B. O'Sullivan [1999]: Early Miocene or younger normal faults and other Tertiary structures in west Nass River map area, northwest British Columbia, and adjacent parts of Alaska. in *Current Research, Pap. Geol. Surv. Can.*, vol.99-1A, 1-11.
- Francis, D., A. C. Abraham and M. Poive [1999]: Volcanic probes of the craton's edge beneath the northern Canadian Cordillera. in *SNORCLE Transect and Cordilleran Tectonics Workshop Meeting*, Lithoprobe Report No. 69, compiled by F. Cook and P. Erdmer, pp. 142-145.
- Gorman, A. R., and R. M. Clowes [1999]: Wavefield tau-p analysis for 2-D velocity models: Application to western North American lithosphere. *Geophys. Res. Lett.*, vol.26, 2323-2326.
- Hammer, P. T. C., R. M. Clowes, and R. M. Ellis [2000]: Crustal structure of NW British Columbia and SE Alaska from seismic wide-angle studies: Coast Plutonic Complex to Stikinia. *J. Geophys. Res.*, in press. **For a preprint, see:** <http://www.geop.ubc.ca/~hammer/pubtext/ACCRETE/ACC1.html>
- Morozov, I. B., S. B. Smithson, L. Hollister, and J. B. Diebold [1998]: Wide-angle seismic imaging across accreted terranes, southeastern Alaska and western British Columbia. *Tectonophysics*, vol.299, 281-296.
- Spence, G. D., and N. A. McLean [1998]: Crustal seismic velocity and density structure of the Intermontane and Coast belts, southwestern Cordillera. *Can. J. Earth Sci.*, vol.35, 1362-1379.
- Zelt, C. A., and R. B. Smith [1992]: Seismic traveltime inversion for 2-d crustal velocity structure. *Geophys. J. Int.*, vol.108: 16-34.

A Summary of Jurassic Paleomagnetic Data Describing the Tectonic Motions of the Terranes Underlying the Intermontane Belt, Canadian Cordillera

M.J. Harris, D.T.A. Symons (Univ. Windsor, mjh@uwindsor.ca)

W.H. Blackburn (Royal Roads Univ.)

C.J.R. Hart (Yukon Geology Program)

A clear understanding of the Late Cretaceous and younger tectonic motions for terranes underlying the Intermontane Belt of the Canadian Cordillera are well documented. However, paleomagnetic results for rock units older than ~110 Ma are not as abundant, often have problems with age control and/or tectonic corrections, and have been viewed with skepticism by some. Despite these short-comings, there are several results from Jurassic intrusions that imply very different tectonic histories for the accreted terranes. Tilt-corrected paleomagnetic data for two intrusions in the northern Cordillera – the 177 Ma Teslin Crossing Stock, Stikine Terrane, and the 172 Ma Fourth of July Batholith, Cache Creek Terrane – suggest a trans-Pacific path during the Jurassic prior to contact with the North American craton in the Early Cretaceous. These paleomagnetic results are supported by Pacific Basin plate motion models which describe the Farallon plate as having an easterly motion through the Jurassic to ~130 Ma. This implied motion also addresses the enigmatic origin of verbeekiniid faunas of Permian age that are found in the northern Cache Creek Terrane, and are correlated with similar faunas found in eastern Asia, but not anywhere else in the Canadian Cordillera. Results from two Jurassic intrusions from the southern Canadian Cordillera suggest a different tectonic history for the Quesnel Terrane. The 205 Ma Copper Mountain Intrusions and the 198 Ma Guichon Batholith yielded paleomagnetic results indicating that they were situated near-to the North American craton, but about 13° south of their present position. This implies that the terranes of the Intermontane Belt did not amalgamate until the Middle to Late Jurassic, in accord with other geologic evidence. After amalgamation, the Intermontane Belt, substantially as a single entity, began its northward transpressive trek along the North American margin until final accretion at ~50 Ma.

Regional electrical conductivity of the Southern Canadian Cordillera
Juanjo Ledo and Alan G. Jones
Geological Survey of Ottawa, 615 Booth St., Ottawa, On K1A 0E9

Abstract

The regional crustal structure of the southern Canadian Cordillera of western Canada is interpreted from the inversion of magnetotelluric data. Decomposition of the data shows that the regional structure can be interpreted along five profiles as a 2D structure. The combination of the five models allows us to obtain a first image of the 3D electrical crustal structure. The strikes directions obtained imply a local clockwise rotation of southern Intermontane and Omineca Belts. The models shown an upper resistive crust in contrast with a more conductive lower crust, although a variation along strike in the lower crust resistivity is observed in the Omineca Belt. The joint interpretation of the magnetotelluric models and other geophysical data suggest that the presence of fluids in the lower crust can explain the observed data.

Introduction

The southern Canadian Cordillera of western Canada lies in a region of oceanic and island-arc lithosphere accreted to North America over the last 200 Ma. This area had been subject to close geological and geophysical studies as part of the Canadian multidisciplinary Lithoprobe program of study of the Canadian Cordillera in southern British Columbia (Gabrielse and Yorath, 1991; Clowes et al., 1992; Cook et al., 1995 and references herein). The region is divided into five major morphogeological belts (Figure 1) representing fault-bounded geological entities of regional extent, each characterized by its own geological history different from the neighbors terranes. From west to east are as follows: the Foreland Belt, the Omineca Belt, the Intermontane Belt, the Coast Belt and the Insular Belt, each of which (except for the Foreland Belt) consists of a multitude of terranes. The development of these belts reflects the Mesozoic and Cenozoic collision and deformation along the northwestern margin of North America. The Foreland Belt contains rocks mainly deposited from latest Proterozoic to Late Jurassic time along the rifted passive margin of western ancestral North America and late Mesozoic synorogenic clastics. The Omineca Belt is composed of extremely compressed crystalline rocks that may consist of the roots of Andean type mountains uplifted behind a subduction active in late Mesozoic time. The Intermontane Belt comprises upper Paleozoic to mid-Mesozoic marine volcano-sedimentary sequences overlain by Cretaceous and Tertiary non-marine sequences. The Coast Belt is made up of Late Jurassic to early Tertiary granitic rocks, and is considered to contain the suture resulting from the mid-Cretaceous collision between the Insular Belt and the previously accreted Intermontane Belt. The Insular Belt comprises locally latest Proterozoic, to Paleozoic, to Neogene volcanic and sedimentary rocks and subordinate granitic rocks added to the continent since 165 Ma.

The depth to the moho at the Foreland Belt is imaged about 42 km and decreases westwards, showing an abrupt change in the boundary between the Foreland and the Omineca belts. In the Omineca and Intermontane belts the seismic reflection data imaged three large crustal antiforms, the Monashee Complex, the Vernon antiform and the central Nicola horst (Cook, 1995). Below these structures the lower crust is interpreted to be a thin tongue of modified North American cratonic basement, to the Fraser fault. The crust – mantle boundary is imaged about 32 km depth along these belts, which contrast with the high structural relief observed in the crust. The limit between the Intermontane and the Coast Belts is marked by the Fraser fault that penetrates the entire crust. To the west, rocks of the Intermontane Belt are interpreted to have been wedged into the middle crust of the eastern and central Coastal Belt during contraction in the late Cretaceous. The west side of the Coast Belt exhibits deep east-dipping reflections which can be traced up dip to reflections on the sections from the Vancouver Island (Clowes et al., 1987).

Large amounts of electromagnetic data have been acquired in this area, and different authors, focussing on several geological targets, have interpreted these data (Kurtz et al., 1996; Jones

and Dumas, 1993; Gupta and Jones, 1995, Jones et al., 1992; Jones et al., 1993; Marquis et al., 1995). The previous results of the regional conductivity structure of the Southern Canadian Cordillera revealed a lower crust and upper mantle with anomalous high electrical conductivity. Here we will present a regional quantitative interpretation of the whole dataset continuing the qualitatively interpretation done by Jones and Gough (1995). The aim of this paper is to present the interpretation of the MT data using decomposition techniques and inversion procedures developed recently and its comparison with other geophysical and geological data.

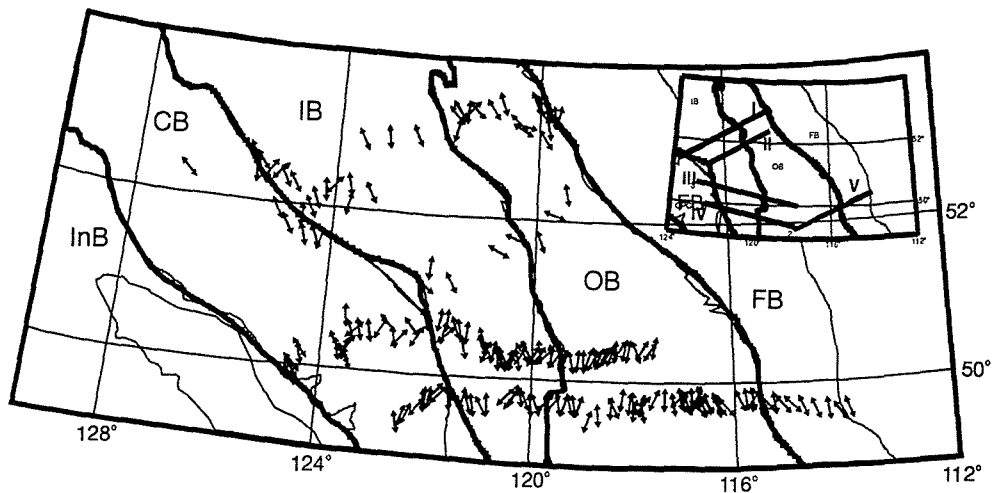


Figure 1. Location of the MT sites. Arrows indicates the tsrike determined by the GB method for the bulk of the crust and upper mantle.

Magnetotelluric Data

The magnetotelluric method (MT) involves measuring the fluctuations of the natural electromagnetic field at the Earth's surface to infer the lateral and vertical variation of electrical conductivity of the Earth's interior. Magnetotellurics has proved to be successful in detecting high electrical conductivity zones related to partial melting and/or fluids (ionic conduction) and conductive phases, i.e. graphite, sulphides (electronic conduction). The bulk electrical conductivity depends not only on the amount of ionic fluids and/or electronic conductors but also on their interconnection and geometric distribution within the host rock. Electrical conductivity is a physical parameter that is complementary of those measured by seismic and potential field methods, being a useful tracer of tectonic and geodynamic processes that are impossible to sense remotely by other techniques.

In the Southern Canadian Cordillera magnetotelluric data have been acquired in a number of surveys since 1980. The MT sounding sites used in this work are shown in relation to the surface geology in figure 1. The main subset was recorded as part of the Lithoprobe program (Clowes et al., 1992) along two east-west transects between latitudes 49° and 51° N. The period range of the data is 384 Hz – 1820 s, which allow us to image the conductive structure from near surface to upper mantle depths. The University of Alberta (Majorowicz and Gough, 1991) recorded a second subset of data with a smaller period range (130 Hz – 62.5 s) which limits penetration to crustal depths. A complete description of the available data and its characteristics can be found in Jones and Gough (1995).

To retrieve the regional response from the observed MT data the Groom and Bailey (GB) decomposition method (1989) was applied following the scheme of McNeice and Jones (1998), to detect the presence of local distortion and to determine the regional strike and dimensionality of the data. Geoelectric strike directions are shown in figure 1 for the periods higher than 0.01 s, which corresponds to the electromagnetic response of the bulk of the whole crust. These geoelectric strike directions are dominated by the response of the regional and deeper structures.

After the GB decomposition the data has been split into five sets showing a similar strike (figure 1) to obtain the regional electrical structure. The resistivity variations along strike for each one of the profiles are small enough to justify a two-dimensional interpretation at least as a first-order approximation. Profiles I, II and V have a strike angle of -30 degrees and profiles III and IV $+15$ degrees.

2D Inversion and Interpretation

For each profile simultaneous inversions of E and B polarizations apparent resistivity and phases data were undertaken using the RRI code of Smith and Booker (1991) fitting the data to within 10%. The levelling of the apparent resistivity was determined as part of the procedure. The inversion generates the smoothest resistivity model consistent with the data. The resulting models are shown in figure 2. The models from the five profiles are similar in most features, this indicates that although some data show a 3D behaviour the data can be still inverted robustly in a 2D manner to obtain a broad regional pattern of the conductivity structure.

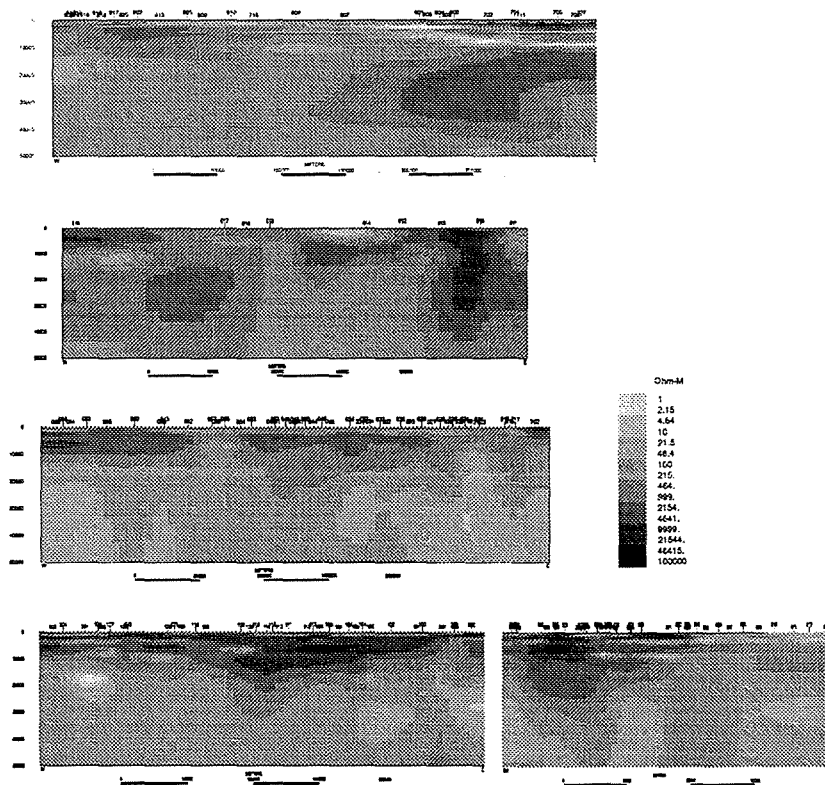


Figure 2. 2D MT models.

The main regional features from west to east are as follows: The Fraser River Fault (FF) that separates the Coast belt from the Intermontane Belt, is imaged by all the models as an abrupt increase of the resistivity from the Coast Belt to the Intermontane Belt up to lower crustal levels. The IB presents an upper resistive crust in all the models. Below, the lower crust has a resistivity value between 100-300 Ohm.m in all the models, having a small variation along strike. The boundary between the Intermontane and Omineca Belts is the Okanagan Valley Fault (OVF). This fault it is not imaged at upper-middle crustal depths by the models except for some shallow conductive structures in the Omineca Belt at profile I. These near surface conductive structures were also imaged by previous 1D inversions of the data (Gough and Majorowicz, 1991). Due to the screening effect of the shallow conductive structures in the western Omineca Belt at profile I it is no possible to resolve a significant change at lower crustal depths. In the lower crust a resistivity variation can be observed through the OVF. In the

southern models there is a smooth resistivity decrease from the IB to the OB, while in the northern models there is a resistivity increase. The boundary between the resistive upper crust and the more conductive lower crust is shallower in the OB in comparison with the IB. The OB is the one that shows a bigger variation along strike of the electrical properties, the causes and implications of this variation will be discussed below. The Slocan Fault (SLF) that separates the OB from the FB, is part of a series of extensional faults that accommodated crustal thinning in the Eocene. The MT model V imaged this fault up to lower crustal depths separating structures of different conductivities. This result agrees with the fault geometry imaged by the seismic reflection data (Cook et al., 1992) and the wide-angle velocity model of Zelt and White (1995). To summarise, the first order regional results from our MT models are: 1) the characterisation of the lower crust as a conductive structure in comparison with the upper crust, and 2) the variation of the electrical properties at lower crustal depths along strike in the OB.

To realize the interpretation of the MT models a synthesis figure showing the crustal conductive structure from the Coast belt to the North American Craton has been constructed taking into account the southern MT models (Figure 3). Moreover, to obtain an estimate of the temperature and strength distribution for the Intermontane, Omineca and Foreland belts, we used the data published by Marquis et al. (1995) and Lowe and Ranalli (1993). The one-dimensional rheological profiles (figure 3) have shown that the transition brittle-ductile occurs around 12, 9 and 22 km for the IB, OB and FB respectively.

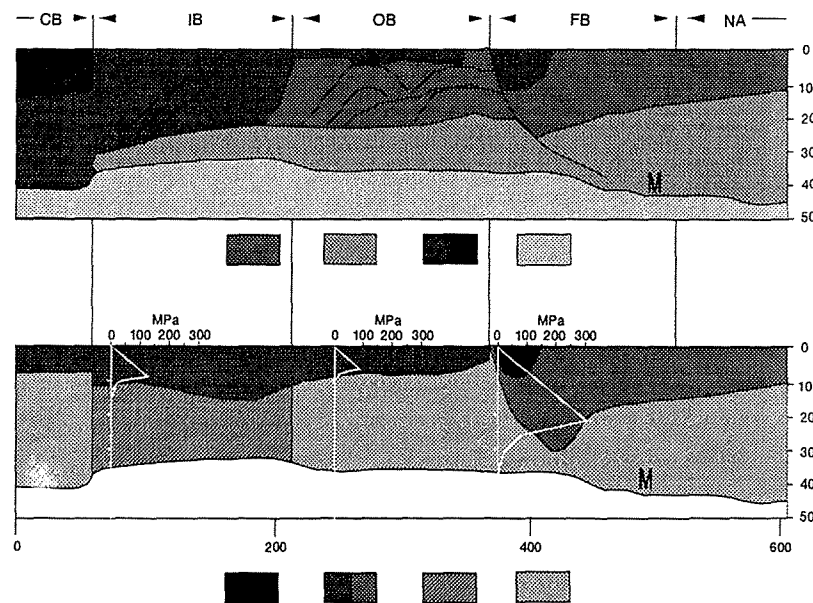


Figure 3. Seismic and MT sketch models.

These are minimum values for the transition zone given that we used steady state equations for the temperature distribution. These results roughly agree with the transition between the resistive upper crust and the conductive lower crust imaged by our models. Majorowicz et al. (1993) showed that the top of the lower crustal conductor found by 1D inversion of MT data in the Canadian Cordillera coexists with the 450°C isotherm, associated to the brittle-ductile transition. From the comparison between the interpreted seismic and MT results (Figure 3) it is clear that the enhanced conductivity is located mainly at lower crustal depths and cannot be associated with a particular geological unit. Based on their different geological origins it might be expected to observe different conductivity characteristic across the different terranes, yet our models don't manifest major differences. Something similar occurs with the crustal velocity model obtained by Burianik and Kanasevich (1995), where there is not a significant change in the lower crust across the different terranes. Marquis et al. (1995) had shown that the Southern

Canadian Cordillera lower crust is reflective, and that many of the observed reflectors are not primarily of structural origin. Lewis et al. (1992) suggest a correlation between the depth of the lower crustal reflectivity and heat flow for the eastern part of the Lithoprobe Southern Cordillera transect. All these observations may reflect the processes occurred after the accretion of the terranes. The agreement in the transition depth among these three different physical parameters is consistent with more local and detailed studies done in the Canadian Cordillera (Marquis et al. 1995) and with global compilations (Jones, 1987; Hyndman and Shearer, 1989; Marquis and Hyndman, 1992).

Discussion

Interplay among mechanical, chemical, hydrological and thermal processes in the lower crust makes an analytical approach to their study difficult. The simplest possible interpretation of the observed data correlation suggests that the change in electrical, elastic and rheological properties may have a common origin. The choice of a unique mechanism, which must be compatible with the physical and chemical state of the lower crust provides a very important constraint on the evolution of the geological structures. In this section we are going to discuss the simplest possible scenarios explaining the maximum of the observed data. From the MT models is clear that the electrical boundary between the upper and lower crust must be related to the rheological properties of the crust. Enhanced conductivity at lower crustal depth is proposed to result from [Jones, 1992]: graphite, free fluids and partial melting. On the other hand, the presence of mafic intrusions, horizontal mylonite shear zones or metamorphic layering has been suggested to explain the lower crustal reflectivity (Mooney and Meissner, 1992). The presence of mafic intrusions can be ruled out in this case, given the horizontal extension of the reflective pattern. Although the presence of graphite can explain the observed conductivity values, and have been observed at specific areas in the Southern Canadian Cordillera (Jones et al., 1992), it cannot significantly affect the elastic properties (Marquis and Hyndman, 1992). The presence of partial melting located at the boundary between the upper and lower crust it is not possible given that the temperature it is not enough to produce partial melting of lower crustal material, moreover, it would imply the existence of a very high temperature at shallow depths. The only explanation that meets the requirements of high conductivity and reflectivity is the presence of fluids in the porous ductile lower crust. The Canadian Cordillera forms a region of new crust recently accreted from predominantly oceanic and island-arc materials. In such a region ionically conductive fluids are to be expected, both by dehydration metamorphic reactions and by fluids presents in the accreted sediments. Moreover, the presence of fluids will reduce the strength of the lower crust and thus favour the presence of shear zones that can explain the observed reflection seismic pattern. The permanence of this fluid would be caused by the low permeability of the ductile lower crustal rocks (Thompson and Connolly, 1990). A similar mechanism to generate and maintain fluids at lower crustal depths may have been suggested to explain isotopic data from Alaska (Goldfarb et al., 1991).

Variation of properties along strike in the Omineca Belt

The presence of fluids in the lower crust also allows us to explain the conductivity variation along strike of the lower crust in the OB. The Southern Omineca Belt underwent an extensional phase in the Eocene; the extension will produce an increase of the temperature and the weakening of the crust at shallower depths. At the same time, it will produce the release of some of the fluids trapped in the lower crust. The migration of the fluids through the crust will produce the formation of mineral systems. This hypothesis agrees with the observed distribution of mineral occurrences in the Canadian Cordillera (Dawson et al., 1991), showing a maximum in the southern part of the Omineca Belt, which agrees with the model proposed by Goldfarb et al. (1991) for Alaska. The migration of the fluids produces a decrease of the amount of fluids, however the extension of the lower crust will increase the connectivity of the remaining fluids (O'Hara, 1994; Schmeling, 1986) and consequently the conductivity, explaining the variation along the strike in the OB. Moreover, the increase of temperature and consequently the possible existence of small amount of partial melting in the lower crust cannot be ruled out for the Southern OB, although the increase of the velocity from north to south in the OB (Burianik and Kanasevich, 1995) doesn't agree with this proposition.

Conclusions

The variation of the regional electromagnetic strike (-30 degrees, profiles I, II and V, and +15 degrees profiles III and IV) implies a local clockwise rotation of southern Omineca and Intermontane Belts. This result agrees with both, the estimates of rotation obtained from paleomagnetic data and with palinspatic reconstruction of Foreland Belt. Assuming a rigid block rotation and no internal deformation a ~25 degrees clockwise rotation had been estimated (Sears, 1994; Cook, 1995). The presence of water in the lower crust allow us to explain the first order results obtained from the regional MT models and the correlation among electrical, elastic and rheological properties of the Southern Canadian Cordillera lower crust.

REFERENCES

- Burianik, M. J. A., Kanasewich, E. R., 1995, Crustal velocity structure of the Omineca and Intermontane Belts, southeastern Canadian Cordillera: *Journal of Geophysical Research* v. 100, p. 15303-15316
- Clowes, R.M., Brandon, M.T., Green, A.G., Yorath, C.J., Sutherland Brown, A., Kanasewich, E.R. and Spencer, C., 1987, LITHOPROBE-southern Vancouver Island: Cenozoic subduction complex imaged by deep seismic reflections *Canadian Journal of Earth Sciences* v.24, p. 31-51.
- Clowes, R. M., Cook, F.A., Green, A.G., Keen, C.E., Ludden, J.N., Percival, J.A., Quinlan, G.M., West, G.F., 1992, Lithoprobe: New perspective on crustal evolution: *Canadian Journal of Earth Sciences* v. 29, p. 1813-1864.
- Cook, F.A., Varsek, J.L., Clowes, R.M., Kanasewich, E.R., Spencer, C.S., Parrish, R.R., Brown, R.L., Carr, S.D., Johnson, B.J. and Price, R.A., 1992, Lithoprobe crustal reflection cross section of the southern Canadian Cordillera, 1, Foreland thrust and fold belt to Fraser River fault: *Tectonics* v. 11, p. 12-35.
- Cook, F.A., 1995, Lithospheric processes and products in the southern Canadian Cordillera: a Lithoprobe perspective: *Canadian Journal of Earth Sciences* v.32, p. 1803-1824.
- Dawson, K.M., Panteleyev, A., Sutherland Brown, A. and Woodsworth, G.J., 1991, Regional Metallogeny p. 707-768, in eds Gabrielse, H and Yorath, C.J.: *Geology of Northamerica*, v. G-2, Geol. Soc. Am., Geol. Surv. Can., Ottawa.
- Gabrielse, H. and Yorath, C. J., 1991, Introduction, in *Geology of the Cordilleran Orogen in Canada*, p. 15-59, eds Gabrielse, H and Yorath, C.J.: *Geology of Northamerica*, v. G-2, Geol. Soc. Am., Geol. Surv. Can., Ottawa.
- Goldfarb, R. J., Snee, L.W., Miller, L. D. and Newberry, R. J., 1991, Rapid dewatering of the crust deduced from ages of mesothermal gold deposits: *Nature* v.354, p. 296-298.
- Gough, D.I., and Majorowicz, J.A., 1992, Magnetotelluric soundings, structure, and fluids in the southern Canadian Cordillera: *Canadian Journal of Earth Sciences* v.29, p. 609-620.
- Groom, R.W. and Bailey, R.C., 1989, Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion: *Journal of Geophysical Research* v. 94, p. 1913-1925.
- Gupta, J.C. and Jones, A.G., 1995, Electrical conductivity structure of the Purcell Anticlinorium in southeast British Columbia and northwest Montana: *Canadian Journal of Earth Sciences* v.32, p. 1563-1583.
- Hyndman, R.D. and Shearer, P.M., 1989, Water in the lower continental crust: modelling magnetotelluric and seismic reflection results: *Geophysical Journal International* v.98, p.343-365.
- Jones, A. G., 1992, Electrical conductivity of the continental lower crust, p. 81-143, in *Continental Lower Crust*, eds. Fountain, D.M., Arculus, R. and Kay, R.W., Elsevier, Amsterdam.
- Jones, A. G., Gough, D.I., Kurtz, R.D., DeLaurier, J.M., Boerner, D.E., Craven, J.A., Ellis, R.G. and McNeice, G.W., 1992, Electromagnetic images of regional structure in the southern Canadian Cordillera: *Geophysical Research Letters* v. 12, p. 2373-2376.

- Jones, A.G. and Dumas, I., 1993, Electromagnetic images of a volcanic zone: *Physics of the Earth and Planetary Interiors* v. 81, p. 289-314.
- Jones A.G., Groom, R.W. and Kurtz, R.D., 1993, Decomposition and modelling of the BC87 dataset: *Journal of geomagnetism and Geoelectricity* v. 45, p. 1127-1150.
- Jones, A.G. and Gough, D.I., 1995, Electromagnetic images of crustal structures in southern and central Canadian Cordillera: *Canadian Journal of Earth Sciences* v. 32, p.1541-1563.
- Kurtz, R.D., DeLaurier, J.M. and Gupta, J.C., 1990, The electrical conductivity distribution beneath Vancouver Island: a region of active plate subduction: *Journal of Geophysical Research* v. 95, p. 10929-10946.
- Lewis, T.J., Bentkowski, W.H. and Hyndman, R.D., 1992, Crustal temperatures near the LITHOPROBE Southern Canadian Cordillera Trancsect: *Canadian Journal of Earth Sciences* v. 29, p. 1197-1124.
- Lowe, C. and Ranalli, G., 1993, Density, temperature, and rheological models for the southeastern Canadian Cordillera: implications for its geodynamic evolution: *Canadian Journal of Earth Sciences* v. 30, p. 77-93.
- Majorowicz, J.A. and Gough, D.I., 1991, Crustal structures from MT soundings in the Canadian Cordillera: *Earth and Planetary Sciences Letters* v. 102, p. 444-454
- Majorowicz, J.A., Gough, D.I and Lewis, T.J., 1993, Correlation between the depth to the lower crustal high conductive layer and heat flow in the Canadian Cordillera: *Tectonophysics* v. 225, p. 49-56.
- Marquis, G. and Hyndman, R.D., 1992, Geophysical support for aqueous fluids in the deep crust: seismic and electrical relationships: *Geophysical Journal International*, v. 110, p. 91-105.
- Marquis, G., Jones, A. G. and Hyndman, R. D., 1995, Coincident conductive and reflective middle and lower crust in southern British Columbia: *Geophysical Journal International* v. 120, p. 111-131.
- Mooney, W.D. and Meissner, R. 1992, Multi-genetic origin of crustal reflectivity: a review of seismic reflection profiling of the continental lower crust and moho p.45-71, in *Continental Lower Crust*, eds. Fountain, D.M., Arculus, R. and Kay, R.W., Elsevier, Amsterdam.
- O'Hara, K. D., 1994, Fluid-rock interaction in crustal shear zones: A directed percolation approach: *Geology* v. 22, p. 843-846.
- Sears, J.W., 1994, Thrust rotation of the belt basin, Canada and United States: *Northwest Geology* v. 23, p. 81-92.
- Schmeling, H., 1986, Numerical models on the influence of partial melt on elastic, anelastic and electrical properties of rocks. Part II: electrical conductivity: *Physics of the Earth and Planetary Interiors* v. 43, p. 123-136.
- Smith, J.T. and Booker, J.R., 1991, Rapid inversion of two and three-dimensional magnetotelluric data: *Journal of Geophysical Research* v. 96, p. 3905-3922.
- Thompson, A.B. and Connolly, J.A.D, 1990, Metamorphic fluids and anomalous porosities in the lower crust: *Tectonophysics* v. 182, p. 47-55.
- Zelt, C.A. and White, D., 1995, Crustal structure of the southeastern Canadian Cordillera from wide-angle seismic data: *Journal of Geophysical Research* v. 100, p. 24255-24273.

ANCIENT CRYSTALLINE BASEMENT IN WESTERN CANADA: ITS INFLUENCE ON THE PLATFORMAL SEDIMENTARY COVER, AND BASEMENT REMNANTS ACROSS THE CORDILLERA

Henry Lyatsky

Lyatsky Geoscience Research & Consulting Ltd.
4827 Nipawin Cres. NW, Calgary, AB T2K 2H8
ph./fax (403) 282-5873 lyatskyh@cadvision.com www.cadvision.com/lyatskyh

Some basic tectonic definitions

Cratons are the continents' strong, ancient, rigid tectonic backbones. Stable cratons are traditionally defined in opposition to orogenically mobilized zones of continents: in the early-20th-century classical geology, the opposing German-language notions were *Kratogen* vs. *Orogen*. Boundaries of cratons on a continent shift with time. As former orogenic provinces become stable and cratonized, or, on the contrary, new orogenic provinces appear when parts of an old craton undergo tectonic mobilization, the craton changes its configuration. With each such event, a new generation of craton is produced. For example, North America's huge Proterozoic Laurentian craton was formed essentially with the conclusion of the Hudsonian (~1.9-1.8 Ga) and other Early Proterozoic orogenies. The modern North American craton took shape when the Laurentian craton was gradually reduced since ~1.1 Ga, by losing wide lithospheric zones on its flanks to the Grenville-Appalachian and Cordilleran orogenic reworking.

Cratons themselves comprise two principal types of subsidiary tectonic entity - shields and platforms. These lithospheric-scale constituent cratonic entities differ most visibly by the presence or absence of an unmetamorphosed, stratified volcano-sedimentary cover and, less clearly, in the deep seismic velocity structure of their continental lithosphere. The platformal volcano-sedimentary cover, though it conceals the cratonic crystalline basement from direct observation, nonetheless contains a valuable and decipherable rock record of the movements of basement tectonic blocks and warps.

Trending mostly NE-SW, huge ancient crustal weakness zones are well known to divide the North American craton into distinct large blocks. Some of these continental-scale weakness zones, from their rock-deformation record, predate even the Laurentian cratonization. Many more steep brittle faults, variously following and cutting across the ancient structures, were created in the upper crust after cratonization. The same ancient NE-SW grain is strongly expressed in the Phanerozoic structurally controlled igneous provinces, potential-field anomaly pattern and upper-mantle velocity structure across the U.S. Cordillera. Many NE-SW cratonic weakness zones are also seen from their geological and geophysical manifestations to continue all across the Canadian Cordillera, transecting the NNW-SSE Cordilleran tectonic grain and testifying to former continuity of North America's ancient craton(s) across what is now the Cordillera.

Self-development of continental lithosphere

Continents are sometimes incorrectly assumed to be tectonically passive and inert, merely responding to external influences from the mobile sublithospheric mantle below and the plate-boundary zones to the side. But on the contrary, continental lithosphere has its own sources of radiogenic heat, and hence a capacity to self-develop. External plate-boundary influences (subduction, terrane collisions etc.) and mantle plumes, though possible, are not necessarily required to explain all intracontinental tectonism.

No complete picture can be discerned, for this reason, by attempting to reconstruct the continents' evolution from an external vantage point of a presumed history of adjacent plate interactions. Cratons,

similarly, must be studied not from the external vantage points of neighboring orogenic zones but based on their own rock record. The influences on continents from other tectonic plates, and on cratons from neighboring orogenic provinces, are typically confined, respectively, only to fairly narrow continental-margin or pericratonic zones. The latter commonly contain non-indigenous, teleorogenically induced tectonic features such as foredeeps and rootless fold-and-thrust belts.

Indigenously driven tectonic self-development is the dominant influence in the evolution of continents and their constituent lithospheric provinces. Independently from examination of other tectonic regions, the cratons and orogenic provinces must be studied on their own terms, based on their own rock record. Any genetic or causal links between them must not be assumed *a priori*, but can only be inferred from these comparative independent factual studies. An interpreter must avoid the pseudo-science of tectonic determinism. Not assumption-based, speculative tectonic scenarios and “models”, but examination of real rocks in the continental provinces’ own crystalline basement and volcano-sedimentary cover can reliably help to decipher these regions’ geologic evolution and resource potential.

Place of geophysical methods in geological studies

The most reliable method to study rocks and rock bodies is by direct observation. Examination of rocks in exposures and drillholes, coupled with laboratory analysis of collected rock samples, is the only way to obtain unambiguous factual evidence about the composition and structure of the crust. Where no direct observations are possible, we are reduced to the less-reliable practice of studying the rock mass indirectly, by sensing it remotely, with geophysical techniques.

A geophysical anomaly, by itself, is unable to reveal the nature, genesis or age of its geologic, rock-made source. All an anomaly indicates, non-uniquely and with limited resolution, is some geometric perturbation in the distribution of this or that physical property of the rocks. This is very far from being a direct indication of the shape and relationship of rock bodies. Without direct geological observations, the inherent non-uniqueness in the interpretations of geophysical images precludes definitive conclusions about the composition and structure of the crust. Even in the well studied, exposed and drilled uppermost part of the crust, every dry oil or water well, and every failed mining or geotechnical project, represents a failure of prediction.

Geophysical considerations and modeling may usefully rule out certain rock-property geometries, if these geometries are shown to fail to account for the observed geophysical anomalies. But, due to the non-uniqueness, geophysical methods do not permit to rule solutions in. Interpretation of geophysical data, though constrained by some quantitative restrictions inherent to the physics of subsurface-sounding methods or the mathematics of data processing, is not a numerical but essentially a geological exercise.

Being very poor at detecting high-angle discontinuities in the rocks’ acoustic properties, deep seismic reflection profiles yield only a partial picture of the subsurface. To a geologically unwary interpreter, they may give an incomplete impression that only low-angle discontinuities exist in the continental crust. The rock nature, genesis and age of these deep, low-angle acoustic discontinuities deep in the crust are unknown. They may be related to a multitude of possible causes: original discontinuities in the protolith, subsequent superimposed metamorphic fabrics, present or former rheologic boundaries, changes in the patterns of rock fracturing, ductile and brittle shears, intrusive igneous bodies, and so on.

Most steep discontinuities are invisible in seismic reflection images, but they are better detected with potential-field data. Here, too, caution is in order. Potential-field data cheaply offer broad regional coverage, but generally with lower resolution than do seismic reflection profiles. As well, an excessive focus on this type of data to the exclusion of others may mislead one into thinking that high-angle discontinuities are the only ones present in the crust. In fact, crustal discontinuities occur in many types and geometries, and a wide variety of geophysical tools are required to obtain a realistic picture of the crust. Above all, the most indispensable for interpretation is geologic calibration provided by direct observation and analysis of real rocks.

Seismic experiments in crystalline continental provinces worldwide show the acoustic properties of strongly reworked rocks to be exceedingly complex, with countless, variously oriented, unpredictable

reflectors, refractors and diffractors. Superdeep wells drilled into the upper continental crust in Europe, Russia and North America have presented many sudden surprises quite unanticipated by prior geophysical predictions, including unexpected findings about sources of seismic reflections and potential-field anomalies, as well as position of the brittle-ductile boundary and thermal and hydrologic conditions. Not even such sparse factual geological constraints are available to help interpret geophysical images of the middle and lower crust. The arbitrary and model-driven assumption that low-angle seismic-reflection geometries deep in the continental crust mostly represent thrusting contradicts the existing geological observations and leads to an incorrect perception that continental crust is usually a stack of thrust sheets.

Practical regional geophysical studies of the continental crystalline basement have been reported widely in the western and central United States as well as overseas, particularly in Australia, Europe and parts of Asia. Aiming to delineate the basement blocks and faults that affected the sedimentary cover, potential-field methods have been used extensively in those advanced continental studies. But in western Canada, previous regional potential-field studies have not been as sophisticated or comprehensive or practical. Their major shortcomings have been to rely on incomplete old data sets; make no consistent effort to correlate basement-block-related anomalies with independently studied geologic variations in the sedimentary cover; underuse many modern anomaly-enhancement processing and display methods; cover only small areas; and/or fail to combine gravity and magnetic maps.

Another common error in continental-basement studies is to throw caution to the wind and cavalierly assume a specific geologic meaning for geologically uncalibrated potential-field and deep seismic anomalies. Unjustifiably, this has led to fanciful (and, for oil exploration, irrelevant) speculations about hidden ancient continent and terrane sutures, giant thrust zones and fossil orogens deep in the crystalline crust, while overlooking the existence of very real, basin-controlling Phanerozoic brittle high-angle faults. Few wells in the Alberta and Williston basins reach the basement. Our direct knowledge of the platform basement in regions far away from the Canadian Shield is thus very limited. Mistakenly, some regional studies in the western Canadian platforms simply assume a particular potential-field anomaly-amplitude contour (e.g., zero contour in IGRF-reduced total-field magnetic maps) to represent the boundaries of hypothesized but little-sampled cratonic-basement geologic domains, with attendant speculations about Archean and Proterozoic collisions, accretion and subduction between these supposed tectonic units. Being based on very little factual data, such speculations are idle, groundless and impractical.

Direct observation being the only way to obtain unambiguous factual information about the rock mass, the spearhead of regional geologic studies should be the methods of geology proper, based on direct examination of available rocks themselves. Geophysical methods play an important but auxiliary part, as they permit to extrapolate observational geological information into unobserved areas. To do this successfully, interpretations must never take on a life of their own, and they must unglamorously remain driven by geological considerations.

Practical studies of basement-cover relationships in the cratonic platforms in western Canada: the data-based approach

Two fundamentally different types of crystalline-crust structure, of different ages and tectonic origins, are recognized in the Canadian Shield and cratonic-platform basement in western Canada:

- (1) *Archean and Early Proterozoic ductile orogenic structures*, and
- (2) *Middle Proterozoic to Recent brittle cratonic ones*.

The latter are usually brittle, steep block-bounding faults, which partly follow the ancient orogenic structures (as in the large Snowbird-Virgin River and Great Slave Lake-MacDonald fault systems) but commonly cut across them. Phanerozoic block faulting with many kilometers of vertical offset is well recognized in the Cordilleran foreland and miogeosyncline in the U.S., where Precambrian crystalline basement rocks are exposed in the uplifted blocks' cores. In the craton in western Canada, however, the basement block structures are by comparison low-amplitude and subtle, and often overlooked.

Distribution of oil, gas and coal deposits in the Phanerozoic platform Alberta and Williston

basins has for decades been known to partly follow regional and local linear trends. High-angle faults from the crystalline basement, not always detectable with seismic data, are commonly suspected to be a reason for this linearity. But the exact ways in which basement fractures and faults can control the structures, lithofacies, unit thicknesses and hydrocarbon traps in the sedimentary cover are manifold and often unclear, and many steep fractures lacking big offsets are hard to delineate. For these reasons, the obvious predictive power of this causal basement-cover relationship has not been used in exploration to its full practical potential.

Boundaries of platformal basins

Large basement arches, such as Tathlina and Sweetgrass, form the boundaries of the Alberta Basin. The latter arch separates it from the Williston Basin, which is another constituent part of the Western Canada Sedimentary Province. But, based on its own sequence of reconstructible block movements and thus tectonic stages, the Williston Basin should tectonically be assigned to the Midcontinent Platform. The Alberta Basin, in contrast, lies in the Interior Platform, which has a different sequence of tectonic stages reflected in its sedimentary-cover rock record. The Alberta Basin's southern boundary is the Central Montana Trough (crustal weakness zone), which separates the tectonically relatively quiescent northern Interior Platform in Canada from this platform's tectonically more active southern part in the U.S.

Less clear, in Canada, is the western boundary of the northern Interior Platform and, with it, of the North American craton. The Laramide Rocky Mountain fold-and-thrust belt is by all indications rootless, as abundant drillhole and seismic evidence suggests its deformation fails to involve the cratonic crystalline basement. Metamorphic evidence of whole-crust orogenic tectonic reworking appears only near the Rocky Mountain Trench fault, which is conventionally regarded as the Rocky Mountain Belt's western boundary with the miogeosynclinal Omineca orogen of the Cordillera. The enormous Rocky Mountain Trench fault is remarkably straight over its entire length of many hundreds of kilometers. A huge straight fault such as this must be very high-angle. The entire crustal reflection pattern in deep seismic profiles changes across it dramatically.

Because the Cordillera-induced teleorogenic tectonic disturbance in most of the Rocky Mountain fold-and-thrust belt is only structural (lacking known metamorphic or magmatic manifestations), and because it is evidently confined to the above-basement level only, the unaltered deeper crust in most of the Rocky Mountain Belt must be regarded as cratonic. The edge of the craton therefore lies farther west, where evidence of whole-crust tectonic reworking first appears, near the Rocky Mountain Trench fault.

Diverse types of platformal-basement relief, and their influences on the sedimentary cover

Features of two dissimilar main types define the modern relief of the Alberta and Williston basins' cratonic crystalline basement (misleadingly referred to sometimes as "basement structure"). They are related to the two main types of geologic structure in the basement, ancient ductile and younger brittle, and their influences on the sedimentary cover were quite different. One is Precambrian erosional remnants, formed when the future platforms' basement was exposed at the surface. This part of the basement relief might bear some connection with the ancient ductile orogenic structures, linked to which is the distribution of variously resistant and recessive crystalline rocks. However, these old ductile structures were not reactivated subsequently, and the erosional basement relief passively affected only the lowest parts of the Phanerozoic platformal sedimentary cover. Studies of Early Proterozoic Hudsonian and older ductile orogenic basement structures are thus of limited utility for the practical needs of hydrocarbon exploration.

Of much more consequence for the Phanerozoic cover's evolution and hydrocarbon accumulation have been the post-orogenic, cratonic crustal warps and especially high-angle brittle faults, which have controlled the Phanerozoic movements of basement blocks. Some of these faults had formed in post-Hudsonian Precambrian time, and were already available for reactivation even at the onset of early Paleozoic platformal sedimentation. Others formed later, at various times in the Phanerozoic.

Geophysical detection of high-angle basement faults

Steep basement fractures tend to be expressed poorly in seismic reflection profiles. In the oil-industry data, many faults with <10 m offset in the sedimentary cover (especially at longer traveltimes) are invisible, as reflection-character changes due to small fault disruptions are easily confused with changes related to lithofacies variations or just noise. Details of basement-cover relationships in Alberta are hard to resolve seismically for another reason as well: the lower Paleozoic cover rocks commonly have seismic velocities similar to those of the uppermost part of the crystalline basement, so the basement-cover contact lacks a clear seismic signature.

The steep fractures' diagnostic but subtle gravity and magnetic anomalies are commonly masked by strong, undesirable anomalies related to the ancient ductile orogenic structures. Gravity and magnetic lineaments and anomaly-domain boundaries are identified not from twists and turns of any particular anomaly-amplitude contour, but based on a variety of anomaly criteria - linear breaks and discontinuities in the pattern of anomaly shapes, wavelengths, orientations and amplitudes; alignments of local anomalies; aligned disruptions in many amplitude contours; gradient zones; various subtle features that appear in derivative maps. The steep brittle faults in the Alberta and Williston basins are seen to be regionally and locally pervasive, and so are the linear lithofacies trends at many levels of the sedimentary cover. Detailed processing of gravity, magnetic and 3-D seismic data reveals their common presence even on a township (6x6 miles) and smaller prospect scales.

An essential part in the studies of basement-cover relationships therefore belongs to diverse processing of gravity and magnetic geophysical data, which helps to enhance and delineate the desirable subtle anomalies. Cheap public-domain aeromagnetic data in most of Alberta and southern Saskatchewan, available for only a few hundred dollars, offer a sufficiently detailed coverage to resolve all the anomalies originating in the basement. Exceptions occur near the edge of the Canadian Shield, where the platformal basement is shallow and detailed aeromagnetic coverage is needed to resolve all the basement-sourced anomalies. The sedimentary cover contains some magnetic-anomaly sources, of primary and secondary origin, but these intra-sedimentary sources are usually very minor and lack a general geologic correlation with hydrocarbon reservoirs. Exploration money can be saved if the public-domain data, both gravity and magnetic, are analyzed in detail before any resort to the costly "high-resolution" surveys.

Gravity anomalies, being controlled by lateral variations in the density of rocks, are particularly sensitive to fault offsets. The usual gravity coverage of one station per township in the Plains of western Canada is too sparse to resolve the smallest of the basement-sourced gravity anomalies, but it is sufficient to identify regional trends and anomalies from broad sources. The gravitational potential field is much simpler than its magnetic counterpart. Rock-density causation of anomalies simplifies the rock-anomaly relationships further, by reducing the dependence of anomalies on minute intra-formational variations that bedevil the magnetic surveys. Gravity data, coupled with other geophysical methods and geological information, have proved extremely valuable in our practical basement studies.

Experience shows that no single, universal "silver-bullet" data-processing trick brings to light all the desirable subtle potential-field anomalies in all parts of western Canada. Many complex mathematical data-processing methods are available with modern computers, but, like any mathematical exercise, they are abstract. Only those processing methods can yield geologically meaningful anomaly information that have a basis in the physics of potential fields (which is universal) or the rock-anomaly relationships (which are specific locally).

Good results are obtained in many parts of western Canada with horizontal gradients, vertical derivatives, and some convolution filters. The sharpest and most vivid displays of anomalies are often achieved by combined color-coding and contouring of anomalies on the same map sheet. Shadowgrams (shaded-relief maps) help to identify potential-field lineaments as well as boundaries of domains with a consistent anomaly pattern. The most vivid and intuitive shadowgrams are obtained with the vertical "sun" angle: they are direction-neutral and, by highlighting the steepest slope, are correlative with horizontal-gradient maps.

But the anomalies in each particular area are not identical to those in any other. Neither are the

rock-anomaly relationships. The experience gained in one locality is not directly transferable elsewhere. In each area, extensive local experimentation is required, with various methods and parameters of data processing and display, as it is not known ahead of time which methods will produce the most geologically meaningful results.

Many steep faults are recognizable from their subtle potential-field (especially gravity) and occasionally seismic signatures and topographic expressions, as well as from their effects on the distribution of lithofacies, depocenters and arches at various levels in the sedimentary cover. But no matter how well enhanced, geophysical images offer only an indirect picture of a basin. Geologic features are the most reliably identified from the real, observed rock record itself.

Distribution of depocenters and arches in relation to basement faults

Similar to the observed potential-field lineament patterns, the same orthogonal lineament families - NE-SW/NW-SE and weaker N-S/E-W - are widespread in the Plains and Canadian Shield topography. They are particularly clear in the patterns of prairie rivers and lakes. In detail, the collections of surface trends differ from area to area. The NNW-SSE topographic trends, for example, are common in northern Alberta, gradually changing to largely NW-SE in central Alberta and largely WNW-ESE in the south of the province. In the northern Williston Basin in Saskatchewan, the pattern of geological, geophysical and topographic lineaments is more complicated, with many observed trends being variously NNW-SSE/ENE-WSW and WNW-ESE/NNE-SSW, as well as N-S/E-W.

In various combinations, at 90° and 120° angles, these fractures combined into conjugate pairs that were newly created or available for reactivation at various times in the fluctuating regional stress field. Some steep fractures propagated not from the basement up but from the ground surface down, as some detailed coal-field studies suggest to be the case for fractures formed due to Laramide crustal flexure in the pericratonic areas. Which fractures were active during which tectonic intervals, and in what fashion, is inferred from their preserved effects in various rock horizons of the sedimentary cover.

Large and small lithofacies variations in the Phanerozoic sedimentary cover in the Alberta and Williston basins, including variations in the petroliferous Devonian carbonate units, commonly match the geophysically resolved basement fault networks or surface topographic lineaments. The famous Leduc reef chain, for example, runs at an angle to many magnetic anomalies but is seen to be better aligned with gravity gradient zones. Much later, by affecting the dissolution of Devonian salt beds, basement fractures were also able to influence the Cretaceous fluvio-deltaic sedimentation patterns in the swampy lowlands that occupied much of Alberta at that time, as well as the modern Plains drainage. This influence is suggested by the stark linearity of many salt-dissolution fronts and Cretaceous channel deposits, as well as modern rivers and lakes. Influence such as this could be exerted even by geophysically invisible fractures lacking any structural offset: all they had to be was open enough to conduct the salt-dissolving water.

Raised basement blocks and warps in the cratonic platforms produced the arches, while downdropped ones controlled the depocenters. The famous Peace River Arch in northern Alberta, for example, is well known to have manifested itself repeatedly during the Phanerozoic, variously as a composite positive or negative feature hundreds of meters in vertical amplitude, creating at different times either a depocenter or an arch. This area is extensively drilled, and many steep faults and blocks are clearly recognized in this active cratonic crustal zone. Despite their undeniable presence and large throws, these brittle faults have only subtle - but, with careful processing, discernible - gravity and magnetic signatures. Similar basement-block fluctuations and inversions, with smaller amplitudes, are also recognized throughout the Alberta and Williston basins.

Because all Phanerozoic basement faults were not active during every cratonic tectonic stage, and some faults that were active lack detectable geophysical signatures, the correlation between inferred basement fault networks and geologic variations in the cover should never be expected to be immaculately 1:1. Causal connections are nonetheless suggested by the evident partial basement-cover correlations. By direct propagation or control on salt dissolution, basement fractures are the probable influence behind the remarkable linear arrangement of oil-rich Paleozoic reef trends and polygonal shale basins, and of the

linear alignment of many prospective Mesozoic fluvial channel deposits. Many linear boundaries of geologically reconstructed, large and small depocenters and arches all over the Alberta and Williston basins are seen to coincide with strong and subtle, basement-sourced gravity and magnetic anomalies.

Thickness and lithofacies variations within some depocenters indicate block tilts. As the pattern of raised, lowered and tilted blocks changed during restructuring episodes, so did the pattern of depocenters and arches. Major marine regressions, due to continental epeirogenic or marine eustatic causes, might have produced prominent regional unconformities - but they do not mark tectonic-stage boundaries unless they were accompanied by regional rearrangement of raised, lowered and tilted crustal blocks and warps. Some of the block-related depocenters and arches persisted through several tectonic stages, others vanished temporarily or for good, and new ones occasionally appeared. Yet, many of these depocenters and arches followed the same, long-lived families of basement faults.

Indigenous tectonic stages of cratonic-platform evolution

In the Alberta and Williston basins, the Phanerozoic sedimentary record of shifting depocenters, arches and facies patterns indicates periods of relative tectonic stability, interrupted by episodic restructuring when the depocenter-arch configurations changed significantly. In the Peace River area and elsewhere, some depocenters were created by the inversion of former arches, and vice versa. On these principles, several Phanerozoic cratonic tectonic stages, represented by their characteristic rock assemblages, are distinguished in the Alberta Basin:

- (1) *Early/Middle Cambrian to Silurian*;
- (2) *Devonian to Early Mississippian*;
- (3) *Late Mississippian to Triassic*;
- (4) *Jurassic to Early Cretaceous*;
- (5) *late Neocomian to middle Late Cretaceous*;
- (6) *Late Cretaceous Campanian to ?Early Tertiary*;
- (7) *Pliocene to Recent*.

These indigenously cratonic platformal tectonic stages bear little correlation with the tectonic stages of the Cordilleran orogenic evolution (see next section). They also differ from the hypothetical cratonic stages of Sloss, for two main reasons:

- (1) *Sloss' unconformity-bounded Sequences are only provincial - determined for the U.S. Midcontinent Platform, not the northern Interior Platform in Canada*; and
- (2) *Sloss failed to distinguish between platform-scale unconformities of tectonic and non-tectonic (e.g. eustatic) origin, thus leaving the geologic nature of his Sequences ambiguous*.

These indigenous tectonic stages, more than any external influences, defined the Alberta Basin's geologic structure and natural resources.

Remnants of the ancient ex-cratonic basement across the Cordillera

Erroneously thinking the craton to be inert and only passively responding to external influences, attempts are sometimes made to interpret the Phanerozoic tectonic evolution of the western part of the North American craton by applying tectonic templates assumed for the evolution of the neighboring Cordillera. This approach is illogical at its core - to study a geologic province, one must first of all examine its own rock record. The craton and the Cordillera are very different tectonic provinces, with dissimilar rock records due to dissimilar tectonic stages.

The craton is the more ancient part of the continent, and a continent-wide study should begin with it. Besides, many model-driven scenarios of the Cordilleran evolution are themselves in error, as they assume the Cordillera's development was driven entirely from without, by plate-boundary influences. These scenarios fail to consider the Cordilleran rock assemblages on their own terms.

The Cordilleran orogenic province evolved on the fringes of the ancient Laurentian craton, and the inherited ancient ex-cratonic crustal structures had a significant part in its orogenic development. Review of diverse geological and geophysical evidence shows that, contrary to some common misconceptions,

- (1) *the Canadian Cordilleran miogeosynclinal region has never contained an Atlantic-type passive continental margin; and*
- (2) *the main differences between tectonic zones in the Cordilleran interior lie not in their assumed exotic-terrane composition but in the degree and history of in situ, multi-aspect, multi-cycle orogenic reworking of the indigenous, ex-cratonic North American lithosphere and crust.*

Evidence for former continuity of North America's ancient craton(s) across the Cordillera

On trend with the Proterozoic Athabasca Basin and the much-inverted latest Proterozoic-Phanerozoic Peace River Arch in the craton, the prominent NE-SW-trending Skeena Arch in the Cordilleran interior has manifested its activity since at least the Mesozoic. It divides the Intermontane Belt into distinct major crustal blocks and forms the southern boundary of the Bowser Basin. Faults on trend with the Skeena Arch are seen to continue farther southwest into the Coast and Insular belts, accounting for large Mesozoic and Cenozoic transverse structures and potential-field anomalies in the Queen Charlotte Basin and reaching the continental margin.

Another regional transcurrent structure in the Intermontane Belt, the Stikine Arch, bounds the Bowser Basin on the north. Mesozoic sedimentary basins in the Intermontane Belt - Bowser, Nechako, Whitehorse Trough - owe their existence to differential uplift, subsidence and tilting of crustal blocks separated by transverse and Cordillera-parallel crustal faults. Further indications of transcurrent crustal structures, seen though the dominant NNW-SSE trends, are NE-SW gravity and magnetic lineaments crossing much of the Cordillera, mapped faults, E-W-elongated Mesozoic igneous plutons, and NE-SW and E-W lakes and rivers. Big transcurrent arches, fault systems and related mineral-deposit zones (lode gold and others) crossing the Canadian and U.S. Cordillera follow the inherited ancient NE-SW cratonic tectonic trends, regardless of any assumed accreted terranes.

Many smaller NE-SW- and E-W-oriented faults and potential-field anomalies are also known in the orogenically semi-reworked Intermontane and Insular tectonic belts of the Cordillera, on trend with the ancient structures on the craton. The strongly and repeatedly orogenized Omineca and Coast belts are more dominated by the Cordillera's own NNW-SSE tectonic grain, as these very reworked belts retain less of their ancient tectonic inheritance.

Tectonically reworked ancient rock remnants of various Archean and Proterozoic ages are recognized in many parts of the Canadian Cordillera. Meanwhile, the three main lines of evidence for exoticism of assumed accreted terranes on which the entire terrane concept of the Cordillera was originally founded - paleontological, paleomagnetic and structural - are continually revised or eliminated.

The oldest known incidence of the "Cordilleran" NNW-SSE tectonic trend is the ~1,760-Ma thermally induced Kimiwan geochemical anomaly in the cratonic basement of the central and western Alberta Platform, but thereafter orogenic activity shifted to the west.

Geochemical evidence of reworked, ex-cratonic ancient basement rocks is well known from the domal but aligned metamorphic complexes in the southern Omineca Belt. Highly metamorphosed former Phanerozoic supracrustal rocks are known in these complexes as well. To achieve their high metamorphic grades, in the Mesozoic and early Cenozoic these rocks had to be first lowered to great crustal depths of ~20-30 km, and then rapidly returned to the surface. Mapped tectonic manifestations (magmatic, metamorphic, structural and sedimentary) have been reported to indicate that intense Nevadan and Columbian orogenic episodes occurred in that region in the Middle Jurassic and mid-Cretaceous, each ending with decompression and crustal extension. Other, more obscure orogenic pulses are also indicated for various times in the Paleozoic and Precambrian. The Late Cretaceous-Early Tertiary Laramide orogenic cycle, which created the dramatic Rocky Mountain fold-and-thrust belt and had its own well-recognized extensional pulse(s) in the end, was only one in this long series.

The repetitive, multi-cycle orogenic tectonic history negates the commonly assumed simplistic scenario with a passive continental margin in the eastern Cordillera before the mid-Mesozoic, exotic-terrane accretion and compressional stacking from then till the Early Tertiary, and extension thereafter.

Two-sided Middle Proterozoic (Belt-Purcell), Late Proterozoic (Windermere), late Paleozoic

(Prophet-Ishbel) and Mesozoic (Fernie) volcano-sedimentary basins in the eastern Cordilleran miogeosynclinal and adjacent pericratonic regions are known from geological field studies to have received sediments from uplifted continental regions to the east and west. Internal variations inside these basins are known to be related to numerous faults and blocks with various orientations. The Belt-Purcell Basin, though ~20 km deep, was evidently broad, intracratonic and non-orogenic, and the ancient cratonic area to the west of it is conventionally called the Western craton. The NNW-SSE Cordilleran tectonic trend was firmly established with the onset of Windermere rifting at ~780 Ma, when a ~10-km-deep, trough-like Neoproterozoic basin began to take shape. The much shallower Prophet-Ishbel trough was probably a foredeep to the middle and late Paleozoic Antler and Teslin orogens, which are known from their preserved metamorphic, deformational, magmatic and depositional rock manifestations to have lain in the Canadian Cordilleran regions to the west. Tectonic quiescence of the miogeosynclinal zone in early Paleozoic time permitted the platformal depositional environments to temporarily spread from the cratonic Alberta Basin all the way into the Cordilleran interior, producing there the Alberta-like carbonate platforms and basins (Cassiar and others) whose deformed and metamorphosed remnants are found in various areas.

Two-sided, not one-sided continental basins have existed in the eastern Cordilleran miogeosyncline ever since ancient Precambrian times. Faced with this determination as well as all the evidence for trans-Cordilleran continuity of ancient ex-cratonic crust, the often-assumed former Atlantic-type, one-sided passive continental margin in the eastern Cordillera is seen to have never actually existed.

Evolution of the cratonic Alberta Basin in relation to the Cordillera

The conventional division of the platformal Alberta Basin into a "passive-margin" stage before the mid-Jurassic and a "foreland" stage after is without meaning. The separately self-developing cratonic Alberta Basin, in relation to the evolving Cordillera, was in a foreland position even in Antler-Teslin time. In the mid-Jurassic, western-derived, Cordilleran detrital clasts first appeared in the basin, reflecting a rise of topographic highlands and mountains in the eastern Cordillera. This change, though sedimentologically and paleogeographically notable, was not accompanied within the Alberta Basin itself by any significant restructuring of depocenters and arches. It had little tectonic significance in the basin's evolution, which was essentially cratonic and platformal both before and after.

Another misleading consideration in some studies of the Alberta Basin and the eastern Cordillera is the Bond-Kominz theoretical model of basin subsidence. Wrongly, that model assumes the former existence in the eastern Cordillera of an Atlantic-type continental margin, and it counter-factually supposes that the formative tectonic evolution in that region commenced only at the onset of the Phanerozoic. Neither assumption is correct, and the early Cordilleran Windermere tectonism is known from field studies to date back to at least ~780 Ma. Some prior, if poorly understood, orogenesis in that region seems to have taken place even earlier, in the interval between Belt-Purcell and Windermere times, based on metamorphic and deformational dissimilarities between the Belt-Purcell and Windermere rocks.

Tectonic zonation of Cordilleran crust

In contrast to the recurrent, strong crustal tectonic reworking in the Omineca and Coast Belt orogenic zones, metamorphism and deformation were considerably less intense in the more-rigid crustal blocks of the Intermontane-Belt, Yukon-Tanana and Insular-Belt semi-orogenized ex-cratonic massifs. These massifs' volcano-sedimentary cover is preserved largely intact, its upper parts are metamorphosed only weakly or not at all, and block faults are common. Magmatism in these regions was largely teleorogenic, related to orogenesis in adjacent strongly mobilized zones (mostly, Coast Belt). So slight was the metamorphism of the upper parts of these massifs' volcano-sedimentary cover that several Mesozoic and Cenozoic sedimentary basins in them are known to contain economic deposits of coal and oil.

Preserved blocks of rigid, semi-reworked ex-cratonic Precambrian crystalline crust probably lie beneath the massifs' exposed Late Proterozoic and Phanerozoic volcano-sedimentary cover (the oldest known cover rocks are Devonian in the Intermontane Belt, Late Proterozoic in the Yukon-Tanana massif,

and middle or late Paleozoic in the Insular Belt). Presence of an ancient continental basement is suggested by radiometric inheritance (Early Proterozoic in the Yukon-Tanana massif), thickness and seismic-velocity structure of the crust, and long-time rigidity of these crustal blocks that preserved them from a more profound orogenic reworking. Indigenous, ex-cratonic crystalline basement, tectonically reworked at various times and to various degrees, seems to continue as far west as the Insular Belt.

Local rifts, Mediterranean- or Red-Sea-type deep marine basins and even ephemeral minor subduction zones might nonetheless have existed in the Canadian Cordillera at various times and localities. Inversion and closure of these marine basins is known from field evidence to have taken place largely in late Paleozoic Antler-Teslin time (although the southern Cache Creek inlier is known from fossil evidence to have existed as a marine basin into the Jurassic). During these pre-Mesozoic tectonic events, which involved the development and inversion of deep marine basins and may account for the split of the Intermontane Belt into the Stikine and Quesnel crustal blocks, the main active crustal weakness zones were the ones oriented NNW-SSE. Quite different was the subsequent, Mesozoic partition of the Intermontane Belt into blocks by the ancient, transcurrent, reactivated Stikine and Skeena arches.

Because crustal blocks with a shared ancient crustal ancestry in the Cordilleran interior developed throughout the Phanerozoic side by side, essentially *in situ*, the often-hypothesized multiple big former oceans (Cache Creek, Bridge River, Teslin, Anvil) inside the Cordillera did not exist. Some local deep marine basins might have existed in the Canadian Cordillera, but they were not oceans. The Omineca, Intermontane, Coast and Insular belts developed essentially *in situ*, but the Intermontane and Insular belts are better preserved and retain more of their ancient ex-cratonic crustal inheritance than do the Omineca and Coast Belt orogenic zones.

Thrusting in the Cordillera: the poverty of “orogen-scale detachment” hypotheses

Outward-verging, fan-like Mesozoic and Cenozoic fold-and-thrust zones in the Cordilleran interior are known from surface geology to bilaterally flank the Coast Belt, Teslin and Omineca orogens. Like the grand Laramide Rocky Mountain fold-and-thrust belt on the east side of the Omineca orogen, these thrust zones are probably rather shallow-rooted. They partly obscure the deep, steep crustal boundaries of the Coast and Omineca orogenic belts with the less-reworked Intermontane Belt, Yukon-Tanana and Insular Belt massifs. The pericratonic Rocky Mountain Belt was able to grow bigger than its structural counterparts in the Cordilleran interior in part because the thick, unmetamorphosed, un-plutonized, stratified sedimentary-cover succession of the Alberta Basin offered a layered mechanical medium easily delaminated into thrust sheets.

Wholly unconvincing is the supposed seismic evidence that almost the entire crust of the Cordillera is a stack of exotic-terrane thrust slices. Geophysical anomalies say nothing about the imaged rock-property discontinuities' geologic nature, genesis or age. Lithoprobe's current interpretation holds that this assumed crustal-scale thrust stack overlies a thin ex-cratonic sliver preserved in the lower crust, and it presumes the underlying continental Moho in the Cordillera to be a Proterozoic remnant. Yet, strong disagreements exist between the current seismic and electrical-resistivity interpretations about the depth where the assumed ex-cratonic bottom sliver ends and the overlying terrane thrust slices begin. These disagreements underline the inherent uncertainties of geophysical interpretation. They are also arbitrary and sterile, because they fail to consider numerous other possible interpretations. More informative are instances where the seismically interpreted low-angle faults (such as Fraser) have been shown by other geophysical methods to remain steep all through the crust.

Differential subsidence and uplift of big crustal zones and blocks by tens of kilometers in the Mesozoic and Cenozoic are required to account for the mapped metamorphic and structural patterns in the miogeosynclinal Omineca orogenic belt. Such an evolution, marked by multi-cycle, laterally variable crustal reworking, has included repeated, profound and variable tectonic mobilization of the entire crust and perhaps the deeper lithosphere. Surface rock record indicates the amplitude and timing of these movements and thermal events varied significantly from area to area, but all the Omineca Belt is in various ways reworked. The eugeosynclinal Coast Belt orogen's crust is reworked and regenerated even

more, as at present it comprises ~80% Phanerozoic (mostly Mesozoic) granitoids. In the face of repeated and profound tectonic reworking of various zones of the Cordilleran crust, the postulated preservation and direct trans-Cordilleran continuity of old deep-crustal features are impossible.

No geological or geophysical evidence exists for the assumed creation and preservation within the eastern Cordilleran crust since the Proterozoic of an ancient passive-margin ramp. From geological evidence, no such continental margin has ever existed there, and anyway ancient structures deep in the crust were destroyed by the extensive orogenic reworking. For the same reason, direct and unbroken continuity from the craton of an unaltered ancient basement sliver under the Cordilleran interior is also impossible. Neither is the Cordilleran Moho a Proterozoic relic: indeed, COCORP seismic interpretations just south of the Canada-U.S. border note the Cordilleran Moho truncates the probably-orogenic seismic reflection patterns in the crust, and regard the Moho as a product of Cenozoic regeneration.

High-angle crustal discontinuities are usually missed in deep seismic reflection images. Correlation of visible low-angle seismic events is complicated by their unknown nature, common lack of continuity, reflection-character variations, and gaps in the data. In a strongly deformed and magmatized province like the Cordillera, many off-line arrivals and other hard-to-identify forms of coherent noise contaminate the seismic images at short and long traveltimes. The technical need for road access during data acquisition in the mountains caused the Lithoprobe seismic reflection profiles to be shot largely along passable valleys, which tend to follow steep NNW-SSE-trending and transcurrent crustal faults. As a consequence, some of the seismic lines were shot not across but along the grain of major crustal structures. Following the available roads across the Cordillera, these reflection seismic lines vary sharply in their orientations, and suffer from data gaps and line offsets tens of kilometers wide. The ACCRETE reflection profile across the northern Coast Belt orogen was shot from a ship sailing down a long fiord, producing huge reverberations at all traveltimes from the fiord's sides - and the fiord itself probably follows some big, steep crustal fractures. In the resulting profiles, all these acquisition shortcomings degrade the signal-to-noise ratio and undermine the interpretations.

Comprehensive analysis of various geological and geophysical evidence has previously shown that, contrary to the conventional interpretations of deep seismic data, no ongoing subduction is currently taking place off Vancouver Island. The modern Cascadia subduction zone exists off Oregon and Washington, but it does not reach north into Canada. As with seismic reflection data along the western Canadian continental margin, postulations of trans-Cordilleran sub-horizontal crustal detachments in the Cordilleran interior also rely on assumption-based and arbitrary correlations of selected, disconnected low-angle seismic events, as well as their tenuous assignments to faults that at the surface are known to be variously curved or straight, low-angle or steep. Principal significance in these interpretations is conferred only on those reflections that seem to fit the assumed structural (thrust) crustal geometry, while the numerous other reflections are disregarded as unimportant.

Today's lower continental crust exists in ductile conditions at high grades of metamorphism. Such a rock mass contains many diverse sources of seismic reflectivity. Indeed, the ductile lower continental crust is known to be reflective worldwide, for reasons that have nothing to do with crustal-scale thrusting. Older deformational and metamorphic fabrics in the evolving crust are obliterated by subsequent metamorphism, anatexis and re-deformation. Preservation of ancient structures deep in the Cordilleran crust is ruled out by all the geological evidence for large-scale vertical crustal movements and extensive tectonic reworking in Late Proterozoic, Paleozoic, Mesozoic and Cenozoic time.

Notoriously unpredictable are fault geometries deep in the crust, especially below the brittle-ductile transition. Faults at deep crustal levels can assume unexpected geometries, or dissipate. Faults that are low-angle at the surface can steepen at depth, and steep faults can flatten out. Many steep crustal fault systems have low-angle splays at shallow depths, giving them a deceptively thrust-like surface appearance. But straight fault systems that are hundreds of kilometers long (e.g. Fraser, Rocky Mountain Trench, Westcoast, Queen Charlotte and others) represent large crustal weakness zones, and as such they are likely to remain subvertical deep in the crust. Subvertical faults tend to be seismically invisible. To correlate their surface traces with some deep low-angle seismic events tens of kilometers or more to the side, and

from that to maintain that these steep faults are low-angle, fails the test of common sense.

It is groundless, misleading and without practical value to make assumption-based projections of fault geometries deep in the crust. The presumption about trans-Cordilleran low-angle crustal detachments is not supported by plausible correlations of geologically calibrated primary seismic reflections.

Local low-angle structural fabrics, ductile and brittle, are hardly surprising in the vicinity of metamorphic domes that rose diapirically through the crust. Indeed, many low-angle faults, normal and reverse, are mapped at the surface near the Cordilleran metamorphic core complexes. However, based on the seismic data themselves, large-scale regional correlations and trans-crustal depth projections of these faults are unfounded. The much-criticized use of discontinuous “floating” mid-crustal seismic events of unknown origin to justify many surface faults’ (e.g., Slokan, Monashee) presumed trans-crustal continuity is indeed unfounded. Besides, it contradicts the results of refraction seismic surveys, which show the velocity structure of the Cordilleran crust to be rather different. The biggest, steep fault system in the southern Omineca Belt region seems to be the one along the Kootenay Lake, which forms the western boundary of the Kootenay Arc and is associated with big seismic-velocity changes even in the lower crust.

Tectonic summary

The ancient Laurentian and ?Western cratons in pre-Cordilleran time continued far into the modern-day Cordilleran interior. Their semi-reworked but discernible remnants are found in the comparatively stable Intermontane-Belt, Yukon-Tanana and Insular-Belt crustal massifs, which are flanked by orogenic zones where multi-cycle crustal tectonic reworking was very much stronger. The main differences between tectonic zones in the Cordilleran interior lie not in their assumed exotic-terrane composition, but rather in the degree of *in situ*, multi-aspect, multi-cycle orogenic reworking of the indigenous, ex-cratonic North American lithosphere and crust.

In an essentially separate tectonic development, the Alberta and Williston basins evolved far within the continental interior, in quiescent cratonic and platformal conditions. Their development consisted of indigenous tectonic stages, whose characteristic depocenter-arch configurations are preserved in the platformal sedimentary cover. In their timing and genesis, these cratonic stages had little connection with the orogenic tectonic stages of the Cordilleran evolution. The influence of the Cordillera on the craton was confined mainly to a narrow pericratonic zone, where foredeeps and rootless fold-and-thrust structures were induced.

Relevant recent publications

- Edwards, D.J., Lyatsky, H.V., and Brown, R.J., 1998. Regional interpretation of steep faults in the Alberta Basin from public-domain gravity and magnetic data: an update; Recorder (Canadian Society of Exploration Geophysicists), v. XXIII, no. 1, p. 15-24.
- Lyatsky, H.V., 2000. Cratonic basement structures and their influence on the development of sedimentary basins in western Canada; The Leading Edge, in press.
- Lyatsky, H.V., 1996. Continental-Crust Structures on the Continental Margin of Western North America; Lecture Notes in Earth Sciences 62, Springer-Verlag, 352 p.
- Lyatsky, H.V. and Dietrich, J.R., 1998. Mapping Precambrian basement structure beneath the Williston Basin in Canada: insights from horizontal-gradient vector processing of regional gravity and magnetic data; Canadian Journal of Exploration Geophysics, v. 34, p. 40-48.
- Lyatsky, H.V., Friedman, G.M., and Lyatsky, V.B., 1999. Principles of Practical Tectonic Analysis of Cratonic Regions with Particular Reference to Western North America; Lecture Notes in Earth Sciences 84, Springer-Verlag, 369 p.
- Lyatsky, H.V. and Lyatsky, V.B., 1999. The Cordilleran Miogeosyncline in North America - Geologic Evolution and Tectonic Nature; Lecture Notes in Earth Sciences 86, Springer-Verlag, 384 p.
- Lyatsky, H.V., Thurston, J.B., Brown, R.J., and Lyatsky, V.B., 1992. Hydrocarbon-exploration applications of potential-field horizontal-gradient vector maps; Recorder (Canadian Society of Exploration Geophysicists), v. XVII, no. 9, p. 10-15.

SNORCLE Digital Data Archive Website

C. Elissa Lynn (lynn@litho.ucalgary.ca)

I have created a website to start archiving SNORCLE digital data. You can find this website at:

http://www.litho.ucalgary.ca/transect_info/snorcle/archive/index.html

The layout of the page is as follows:

The LEFT frame has **clickable topics**, a **search tool**, a **form** for inputting data and **links** to other related Lithoprobe sites.

The **clickable topics** within geology/geophysics include, for example, geochronology. When clicked, a link will bring you to a webpage with Lithoprobe geochronology publications.

☉It would be useful to have clickable authors or topics (either to **send mail** or **link to more detailed work** including images and text or **link to a homepage**).

Other general **clickable topics**, including, igneous, sedimentary and metamorphic rocks are available for the user if they want all publications associated with any of these rock types.

The **search tool** option allows the user to search for keywords within all the .html files. A search can be performed selecting qualifying words such as 'and' or 'or'. For example, the user can search for 'Francis' *and* 'geochronology' or 'Francis' *or* 'geochronology' and get different results.

A submission **form** is available to send your publication details and abstracts to the digital data manager. The user is requested to fill out all the fields and select the disciplines that he/she wishes to be included in. The abstract can be either typed into the 'abstract' field box or copied and pasted from a previous application into the 'abstract' field. Paragraphs are preserved as individual identities in the latter process, but the sentences will continue as if they are typed in one line, without margin breaks. Either data entry choice is acceptable for submission.

☉Eventually it would be convenient to have these abstracts clickable within the SNORCLE publications lists.

The RIGHT frame consists of five different clickable images of North America. The user can click on any province in the SNORCLE transect on the political map and retrieve all research within that province. For example, the user can click on NWT and receive all research associated with NWT. The potential field maps are also clickable. For example, clicking the Bouguer gravity in the SNORCLE transect links the user to a zoomed-in version of the gravity. A further click on line 1 takes the user to a gravity map including reflection shot point locations.

☉It would be nice to have images created by geoscientists from other disciplines included in this section.

Comments and suggestions from those that will utilize this site are encouraged and welcome!

Magma Storage Depths Beneath Northern British Columbia: Inferences from Thermodynamic Modeling

J. Nicholls and M.Z. Stout, Department of Geology and Geophysics, University of Calgary, 2500 University Drive NW, Calgary, Alberta, T2N 1N4

Six bright spots discovered along the SNORCLE transect suggest the presence of active magma chambers beneath northern British Columbia and Yukon Territory. That active magma chambers should exist beneath the region is not surprising, given the large number of volcanic centres scattered across northern British Columbia and The Yukon Territory. Depths to magma chambers that fed lava flows at six centres or complexes were estimated. These are the Nisga'a lava flows, The Thumb, Mount Edziza, and, in the Atlin area, the Ruby Mountain and Llangorse Mountain centres. The rock types range between basanite-nephelinite and peralkaline rhyolite.

Petrographic inferences of depths to magma chambers are based on equilibria between melts and crystals. At any given pressure and temperature it is possible to calculate the compositions of crystals in equilibrium with a melt of known composition. The melt composition can be approximated by the rock or glass composition of igneous samples. The compositions of the minerals in the rocks are compared to the predicted compositions from the model to fix the temperature and pressure at which equilibration may have occurred. Specific mineral assemblages can crystallize from melts of fixed composition only within small ranges of pressure and temperature. By comparing phenocryst assemblages with predicted assemblages, pressure and temperature constraints can be placed on the conditions under which the phenocrysts formed.

Orthopyroxene saturation pressures constrain magma chamber pressures to less than approximately 0.82 GPa for the Atlin area basanites. The youngest basalts from the Mount Edziza complex saturated with olivine, plagioclase, and clinopyroxene at pressures between 0.75 and 0.85 GPa. The basanite that forms The Thumb would have equilibrated with olivine and clinopyroxene at pressures in excess of 1.5 GPa. A thermodynamic model calculated at 0.3 GPa predicts saturation with olivine ($\text{Fo}_{68.3}$) at 1155°C in a melt with the composition of the Nisga'a lava flows. If a fractional crystallization path was followed, olivine would be joined by plagioclase ($\text{An}_{52.5}$) at 1135°C. Olivine and plagioclase would fractionate together and change composition as temperature falls. The mineral compositions in the rock, determined by electron microprobe, are similar to the predicted mineral compositions, however the zoning profiles in the olivine phenocrysts do not match the compositional abundances predicted by the model. Petrologic inferences are consistent with basanites entraining mantle xenoliths near the crust-mantle boundary and with some basalts being stored at intermediate depths in the range of 10 to 25 km.

Modeling the Evolution of the Lower Lithosphere during Continental Collision

Russ Pysklywec, Christopher Beaumont, and Philippe Fullsack

Oceanography Department, University, Halifax NS B3H 4J1

(russ@adder.ocean.dal.ca, chris.beaumont@dal.ca, philippe@adder.ocean.dal.ca)

While increasingly improved near-surface geological and geophysical observations have provided details of crustal structure, the evolution and fate of the mantle lithosphere beneath the continents remains enigmatic. This problem is particularly relevant to Lithoprobe because mantle lithosphere behaviour may control orogenesis and most of the Canadian continent comprises vestiges of collision zones.

There are several fundamental questions. Under what circumstances does continental mantle lithosphere (possibly together lower crust) subduct in a plate-like manner, analogous to oceanic lithosphere? What are the other styles of deformation of continental lithosphere? How do these styles evolve during orogenesis and does the temperature distribution control this evolution?

In our recent research we have focussed on models of lithosphere-mantle interactions in which the lithosphere is a viscous-plastic multilayer with density stratification: plastic (Von Mises or frictional) crust; plastic (von Mises or frictional) strong upper mantle with strain softening; linear uniform viscosity lower mantle lithosphere; and linear uniform viscosity asthenosphere/upper mantle.

Although these models are not realistic equivalents of the Earth, they exhibit a suite of deep lithospheric consumption styles during continental convergence. These comprise various styles of subduction-like behaviour including asymmetric underthrusting, ablative plate consumption, and slab breakoff, as well as the well-studied Rayleigh-Taylor type lithospheric 'dripping'. Using the chemical ALE finite element models of this lithosphere-mantle system we can explore the rheological and mechanical parameters which determine the mode of lithospheric consumption. Two of the primary controlling factors are the convergence velocity and the density field.

In addition, our models suggest that strain-softening of the mantle lithosphere can provide an effective mechanism for strain localization that leads to a preference of the system towards the subduction styles of deformation. Inherited plate boundary weak zones may also have an important influence and we investigate their role in controlling the behaviour of the mantle lithosphere during convergence.

Initial results suggest that it may be too simplistic to focus on end-member behaviours, for example subduction vs dripping, because both styles can occur together-subducting strong upper mantle lithosphere and dripping viscous lower mantle lithosphere.

Finally, the implications of these deep lithospheric dynamics for the evolution of the overlying crust is studied in an attempt to reconcile the model predictions with available geological and geophysical observables.

Clastic Dykes as Paleoslope Indicators in the Nanaimo Group, Hornby Island, British Columbia.

Rowe C.E.¹, Katnick D.C.², Mustard P.S.², Mahoney J.B.¹

1. Department. of Geology, University of Wisconsin - Eau Claire, Eau Claire, WI, 54702-4004

2. Earth Sciences, Simon Fraser University, Burnaby, B.C. V5A 1S6

Upper Cretaceous (92-65? Ma) Nanaimo Group is composed of eleven stratigraphic units, deposited in single foreland basin, termed the Nanaimo Basin (Muller and Jeletzky 1970, Ward et al 1997 and Mustard et al 1999a). Hornby and Denman Islands are the northernmost of British Columbia's Gulf Islands and provide excellent exposure of the upper two-thirds of the Nanaimo Group. Comprising more than two kilometers of clastic sedimentary strata, the Nanaimo Group on these islands consists of thick bedded conglomerate and sandstone-dominated formations interbedded with mudstone and thin-bedded sandstone units. These are interpreted as a series of stacked submarine fan sequences, derived from eastern sources, as indicated by abundant paleocurrent and other provenance data.

The upper Campanian Northumberland Formation on Hornby Island is characterized by thick successions of mudstone intercalated with thin sand interbeds, interpreted as an outer submarine fan facies. Near the top of this unit are numerous clastic sandstone dykes, chaotic slump facies and synsedimentary folds within thin-bedded turbidite deposits. These features form when partially lithified strata gravitationally fail and slide downslope. Orientations of synsedimentary fold axes, axial planes, and, potentially, clastic dykes, may be important paleoslope direction indicators.

Synsedimentary fold axes dominantly trend shallowly to the northwest and the folds consistently verge to the southwest (19/336, n=27). Fold axial planes strike northwest-southeast and dip northeast (304/47, n=27). Both of these features indicate a northwest-striking, southwest-dipping paleoslope, which is also compatible with the regional paleocurrent trends and other provenance data for this and adjacent units.

An unusually abundant set of closely spaced, subvertical clastic dykes occurs in this part of the Northumberland Formation. These dykes are thin (generally <5cm thick) and generally crosscut less than 2 m of the interbedded mudstone-sandstone turbidites. Most occur within roughly the same stratigraphic interval and are striking subparallel in their orientation. They primarily strike northeast/southwest (avg. 209/86, n=60) which is roughly parallel to the down slope direction of the paleoslope, suggesting extension perpendicular to the strike of the paleoslope during soft-sediment deformation. This orientation is counterintuitive, as logic suggests that extension would be in downslope direction, causing extension fractures parallel to the strike of the paleoslope. The mechanism responsible for slope parallel extension on a low-gradient turbidite fan lobe is unclear. However, the consistent nature of dyke orientations and their geometric relationship to synsedimentary folds suggests a common genetic origin. Further work is needed to constrain stress vectors responsible for the observed deformational features.

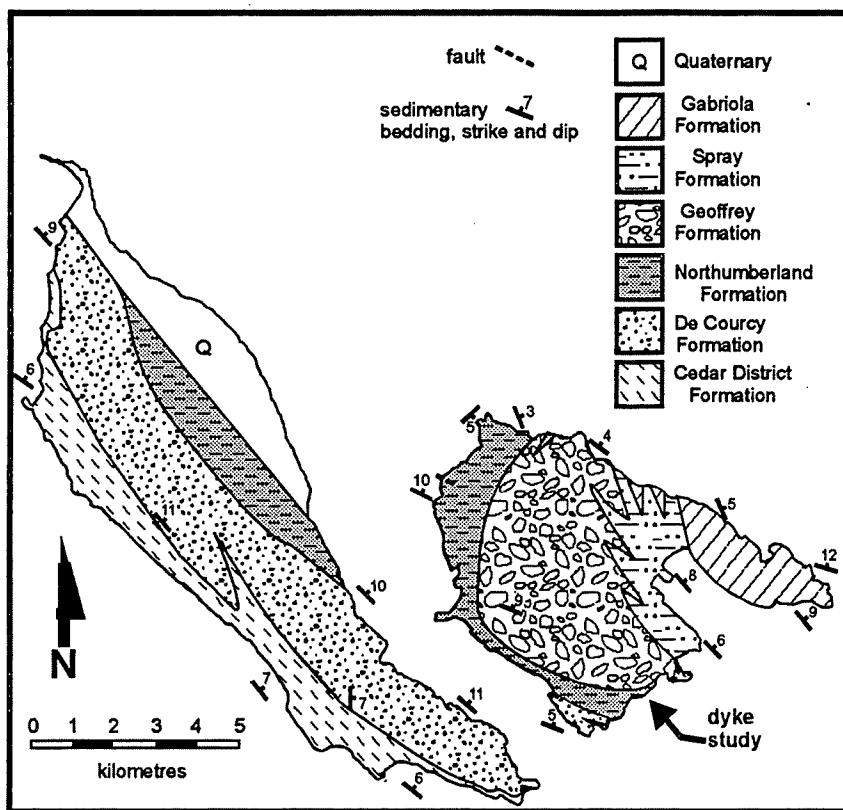


Figure 1
Geologic map of Honrby and Denman Islands,
showing distribution of Nanaimo strata.

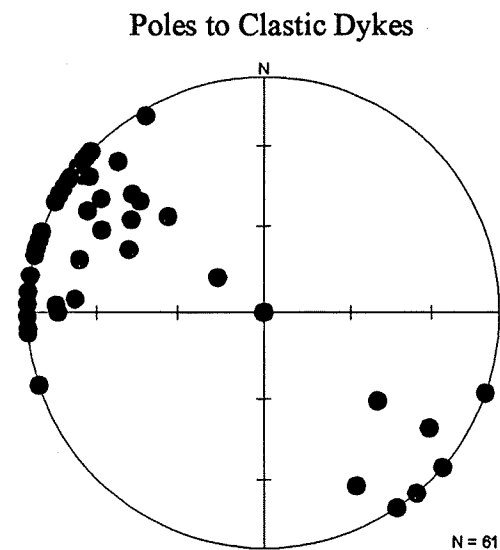
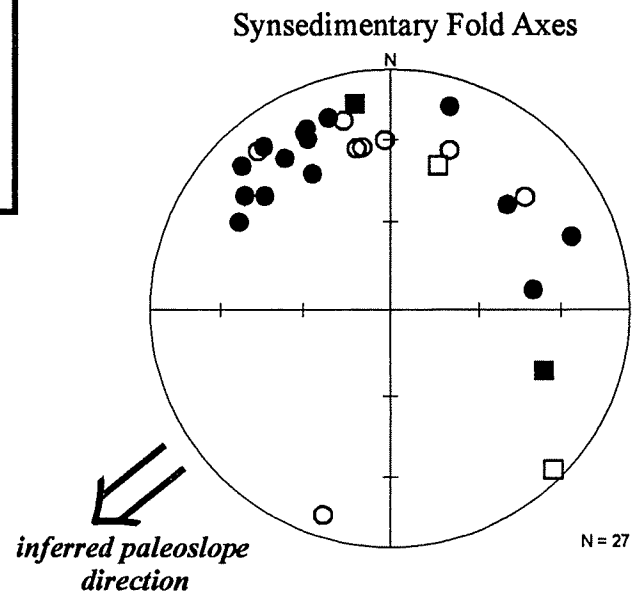
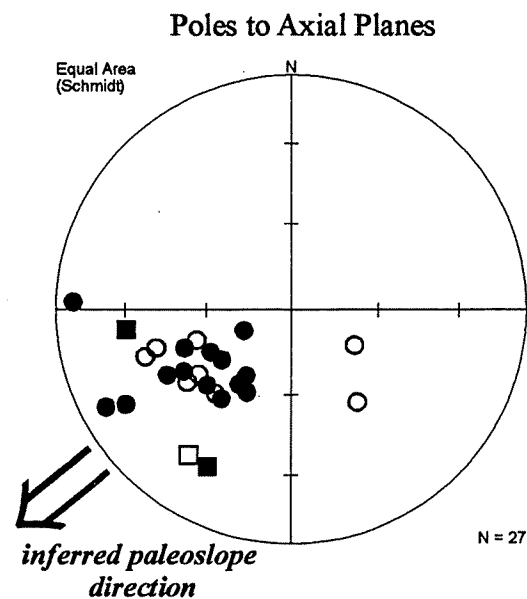


Figure 2
Equal area projections of synsedimentary
fold axes, axial planes and dykes

Explanation	
	High Folds Low Folds
Z Folds	■ □
S Folds	● ○

Comparative Geochemistry of the Spences Bridge Group and Coeval Volcanic Rocks: Potential Constraints on Large Scale Translation

Schmidt, M. J.¹, Haskin, M. L.², Mahoney, J. B.¹, Mustard, P. S.².

¹ Dept. of Geology, Univ. of Wisconsin, Eau Claire

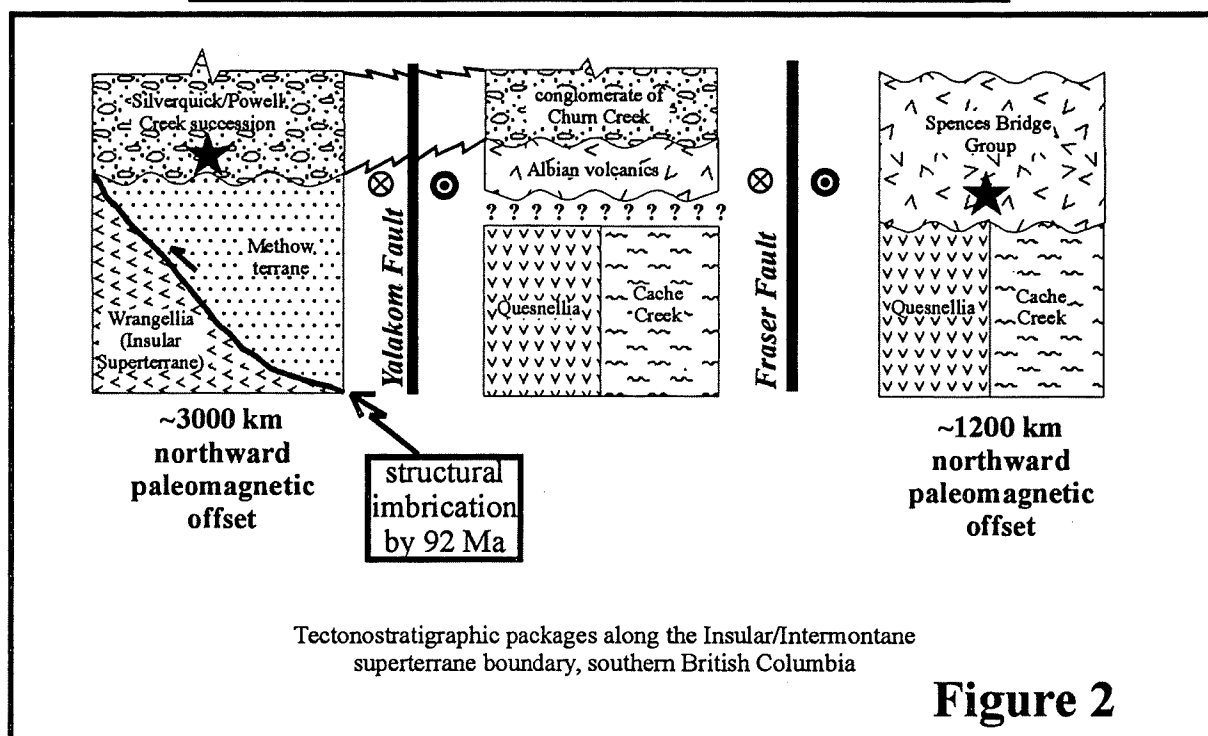
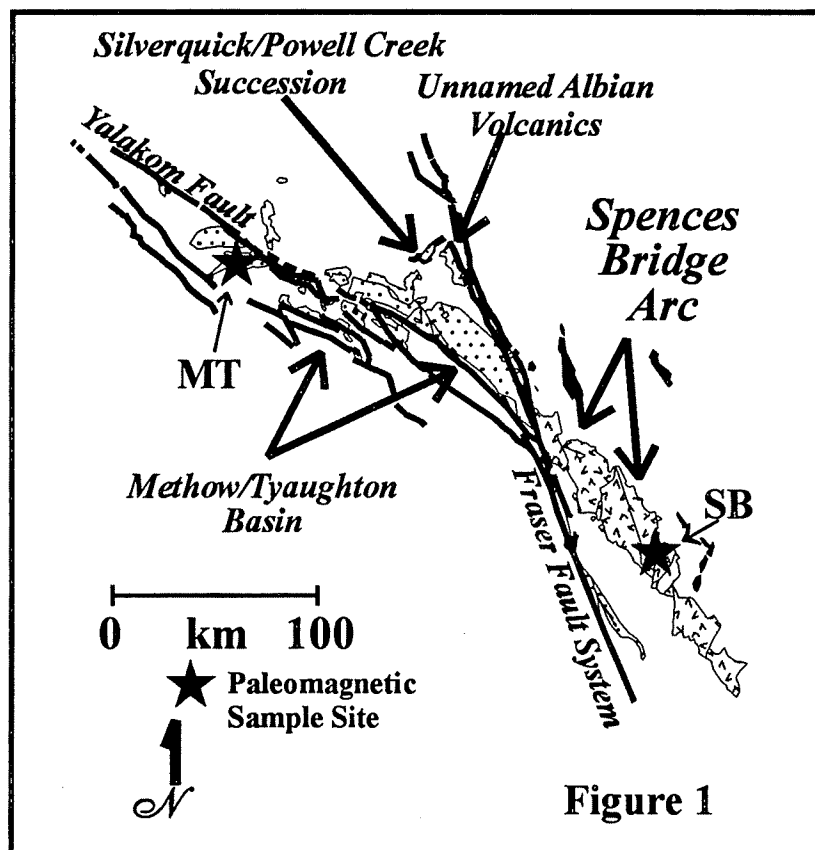
² Earth Sciences, Simon Fraser University, Burnaby, B.C.

The Canadian Cordillera is a complex melange of allochthonous terranes that are broadly grouped into the Insular and Intermontane superterrane. Controversy surrounds the timing and mechanism of superterrane juxtaposition. Paleomagnetic data indicates ~1100 +/- 500 km of northward translation of the Intermontane superterrane between 90-45 Ma and 3000 +/- 600 km northward translation of the Insular superterrane during the same period. These data require ~2000 km of relative displacement between the superterrane. Geologic constraints, including stratigraphic, structural and paleontologic data, suggest less than 500 km of relative displacement.

The Spences Bridge Group, an Albian (100 ± 4 Ma) volcanic arc on the western edge of the Intermontane Superterrane, is subdivided into two formations, including: 1) the Pimanus Formation, a sequence of andesitic to rhyolitic flows with abundant pyroclastic material, and, 2) the Spius Formation, dominated by amygdaloidal andesitic flows. The northwest edge of the Spences Bridge Group outcrop belt is truncated by the dextral Fraser fault system. On the west side of the fault, approximately 115 km to the northwest, an unnamed package of Albian volcanic rocks (101 ± 3 Ma) stratigraphically similar to the Spences Bridge Group is unconformably overlain by the late Albian-Santonian Silverquick/Powell Creek succession. These Late Cretaceous strata are structurally and paleomagnetically linked to the Insular superterrane. Paleomagnetic arguments therefore require the presence of a ~2000 km displacement transcurrent fault between the Spences Bridge Group and the unnamed Albian volcanic rocks.

The purpose of this investigation is to geochemically compare the unnamed Albian volcanic rocks with the Spences Bridge Group to test potential linkages between the two. Both volcanic successions display a subalkalic calc-alkaline geochemical signature, indicative of a destructive margin plate setting. Major element data define colinear trends in both successions, suggesting a similar magmatic evolution. Incompatible trace element data display a significant degree of overlap between the two units. Rare earth element data from both units display colinear trends with similar La/Yb ratios. Geochemical similarities between the Spences Bridge Group and the Albian volcanic rocks support a comagmatic relationship between the two.

Geochemical data alone are insufficient to definitively tie tectonostratigraphic packages together. However, several lines of evidence support a correlation between the Albian volcanic rocks and the Spences Bridge Group: 1) the volcanic successions are the same age (~104 Ma), 2) the successions are stratigraphically similar, with a lower heterogeneous andesitic to rhyolitic package unconformably overlain by an amygdaloidal andesite package, 3) fault restoration along the Fraser fault system place the Albian volcanic rocks directly west of the Spences Bridge Group. These constraints, coupled with the similar geochemical signature, strongly suggest the Albian volcanic rocks are the offset equivalent of the Spences Bridge Group. This correlation is problematic for currently proposed paleomagnetic terrane displacements.



Magnetotelluric Response and Geoelectric Structure of Great Slave Lake shear zone along SNORCLE Transect Corridor 1a

X. Wu, I.J. Ferguson

Department of Geological Sciences, University of Manitoba,
Winnipeg, Manitoba, R3T 2N2, Canada

Alan, G. Jones

Geological Survey of Canada
615 Booth St, Ottawa, Ontario, K1A 0E9, Canada

ABSTRACT

Magnetotelluric soundings were made at 15 sites crossing the Great Slave Lake shear zone (GSLsz) in the southwest portion of the Northwest Territories, Canada along Corridor 1a of the LITHOPROBE SNORCLE Transect. The magnetotelluric results indicate the resistivity structure is close to 1D at shallow depth (<1 km) and 2D with strike $\sim N30^{\circ}E$ in the upper crust which is sub-parallel to the GSLsz. The geoelectric strike changes in the middle and lower crust and is different on the two sides of the GSLsz. Two-dimensional inversions and modeling image a conductive zone from upper crust to mantle near the GSLsz. In the upper crust, this zone is west dipping with a relatively high resistivity, and is interpreted to the GSLsz. In the middle and lower crust, this zone maybe correspond to the extension of the GSLsz, maybe correspond to a conductor. These imply a complex deep structure of the GSLsz area. The structure boundary between Buffalo Head and Taltson magmatic arc shows a relatively conductive zone to the east of Corridor 1a.

Introduction

The LITHOPROBE SNORCLE (Slave-Northern Cordillera Lithospheric Evolution) Transect Corridor 1a, located in the Northwest Territories, crosses three geological structural elements: the Great Bear magmatic arc, the Great Slave Lake shear zone (GSLsz) and the Buffalo Head terrane. The Taltson magmatic arc is located to the east of Buffalo Head, just beyond the end of the corridor (Figure 1).

The magnetotelluric (MT) method has been used successfully to investigate other fault systems. Jones et al. (1992, 1995) imaged the Fraser Fault and the Slocan Lake Fault in British Columbia using the MT method and Ledo et al. (2000) have imaged the Tintina Fault on SNORCLE Corridor 3. Magnetotelluric and seismic reflection surveys at Parkfield, California, show that the San Andreas Fault zone is characterized by a vertical zone of low electrical resistivity. This zone is approximately 500 m wide and extends to a depth of ~ 4000 m. The low electrical resistivity is attributed to high porosity of saline fluids present in the highly fractured fault zone (Unsworth et al. 1997).

Geological Setting

The Great Slave Lake shear zone is a northeast-trending dextral continental transform fault (2.03-1.95 Ga). Where exposed, it consists of granulite to lower greenschist facies mylonite belts with a 25 km width (Hoffman, 1987). To the west of the fault in the area of study, the Proterozoic Wopmay Orogen (Hottah and Great Bear

magmatic arc terranes) consists of a metamorphic-plutonic complex, a volcano-plutonic depression, and a continental margin depositional prism (2.1-1.9 Ga) (Hoffman, 1989). To the east, the Buffalo Head terrane is a magmatic belt that comprises metaplutonic and subordinate felsic metavolcanic rocks (2.4-2.0 Ga) (Ross et al., 1991). The Taltson magmatic arc is located to the east of the Buffalo Head terrane. It is a belt of granitic to dioritic plutons (1.99-1.92 Ga) and contains magnetite- and ilmenite-series plutons. The western limit of Taltson magmatic arc is not exposed, but the continuity of magnetic anomalies suggests that they underlie much of northern Alberta (Huffman, 1987).

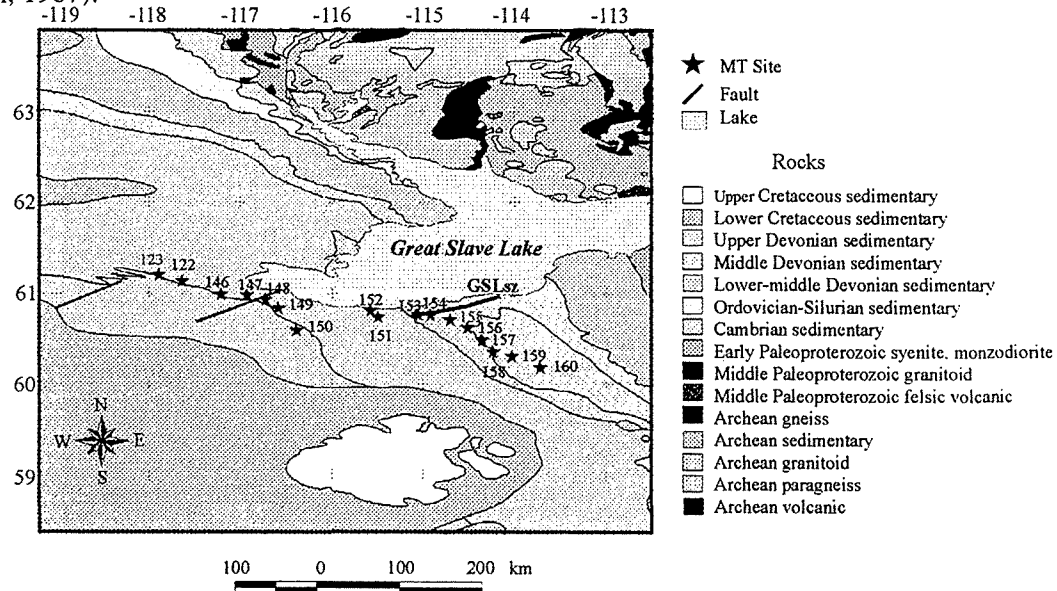


Figure 1. MT survey stations (symbol stars) along Corridor 1a. GSLsz: Great Slave Lake shear zone.

MT Survey and Data Processing

Soundings at 60 magnetotelluric (MT) sites were completed along SNORCLE transect Corridor 1 and Corridor 1a in the southwest Northwest Territories, Canada in the summer of 1996. There are 15 sites located in the Great Bear magmatic arc and the Buffalo Head terrane along Corridor 1a. Sites 153 and 154 are located on the GSLsz and sites 151 and 152 are close to the fault (Figure 1). At each site (except station 159 and 160) recordings include Phoenix V5 measurements (10^{-4} s - 100 s) and Geological Survey of Canada LiMS measurements (20 - 30,000 s) (Jones and Ferguson, 1997).

The Jones-Jodicke approach (Jones and Jodicke, 1984; Jones *et al.*, 1989) and the Chave approach (Chave *et al.*, 1987; 1989) were used to correct the long-period MT responses (LiMS data) for distortion due to non-uniform source fields associated with auroral geomagnetic activity. In order to obtain an eight-decade period range (10^{-4} - 10^4 s), we merged the V5 and LiMS data collected at each site. The V5 data is used to define the response at periods <20 s, and LiMS data is used at periods >20 s.

Goelectric Strike Directions

The goelectric strike in the survey area has been examined using induction vector, maximum phase split (MPD) and Groom-Bailey regional strike methods (see Wu et al, 2000). These parameters at periods of 0.01 s, 10 s, 100 s and 2500 s show:

- At short-periods (near-surface response), the real induction vectors and maximum phase split are small indicating the resistivity structure of the Phanerozoic sedimentary rocks is almost 1D. The strike direction is $\sim N60^{\circ}E$ around the GSLsz, and is irregular in the Great Bear magmatic arc.
- At a period of 10 s, corresponding to signal penetration deep into the middle crust, the induction vectors have an overall southwestern component. The maximum phase split directions and strike angles are $\sim N30^{\circ}E$ and sub-parallel to the direction of GSLsz.
- At period of 100 s, corresponding to signal penetration deep into the lower crust, the strike directions are $\sim N60^{\circ}E$ around the GSLsz. The maximum phase split direction shows differences between the Great Bear magmatic arc and the Buffalo Head terrane. Its direction is $\sim N60^{\circ}E$ in the Great Bear (which is similar to in Hottah terrane to the west) but is close to north-south in the Buffalo Head. The result implies a structural variation across the GSLsz in middle/lower crust. The induction vectors point southwest at sites in the south of GSLsz area. This direction implies a different strike direction from the other two strike indicators and requires additional modelling.
- At periods $>10^3$ s, corresponding to signal penetration into the lithospheric mantle, the strike and maximum phase split direction are close to north-south in the Great Bear, but change to $\sim N60^{\circ}E$ in the Buffalo Head. This result also indicates structural change across the GSLsz in the lower crust and the mantle.

MT Apparent Resistivity and Phase Responses

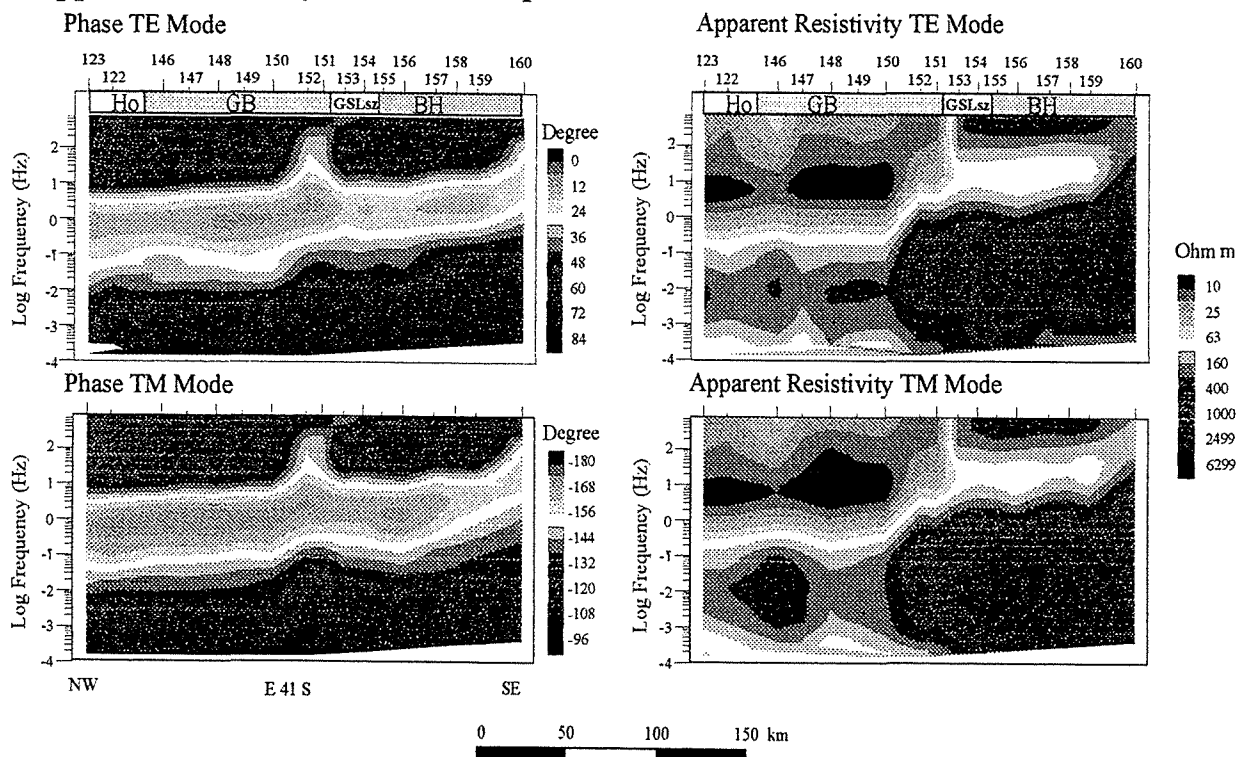


Figure 2. Apparent resistivity and phase pseudosections for TE and TM modes along Corridor 1a. The profile is perpendicular to regional geoelectric strike. E41S means the direction of profile is east 41 degree south. Ho: Hottah, GB: Great Bear, GSLsz: Great Slave Lake shear zone, BH: Buffalo Head.

From the analysis of the results for Corridor 1a, the average strike angle for the period range 0.01 - 200 s, $N41^{\circ}E$, was adopted as the geoelectric strike for subsequent model. The MT responses were rotated to this

direction. Figure 2 shows the TE mode (currents parallel to electrical strike) and TM mode (currents perpendicular to electrical strike) pseudosections of the apparent resistivity and phase along the profiles which are perpendicular to the geoelectric strike direction. These profiles indicate:

- At short periods (<1 s), both the TE and TM response show an abrupt change in resistivity at station 153: the resistivity is higher (>60 Ωm) to the east than to the west (<20 Ωm). There is also an anomaly in the short-period TE and TM phase response at stations 151 and 152. The response to the west is similar to that in the Hottah terrain and is explained by conductive Phanerozoic cover. The response to the east suggests the presence of less conductive sedimentary cover.
- At intermediate periods (1-1000 s), corresponding to signal penetration into the upper crust to penetration into the mantle, the resistivity is relatively high. The resistivity of the Buffalo Head terrane (> 400 Ωm) is higher than for the Great Bear (<400 Ωm). The lateral transition in apparent resistivity occurs around stations 150 and 152 and shifts to the west with increasing period. The phase plots also show a change near station 152. The results suggest the presence of a west-dipping structure beneath the Phanerozoic cover.
- At long period (>1000 s), the response is more conductive beneath the Great Bear magmatic arc than beneath Buffalo Head terrane.

2D Inversions

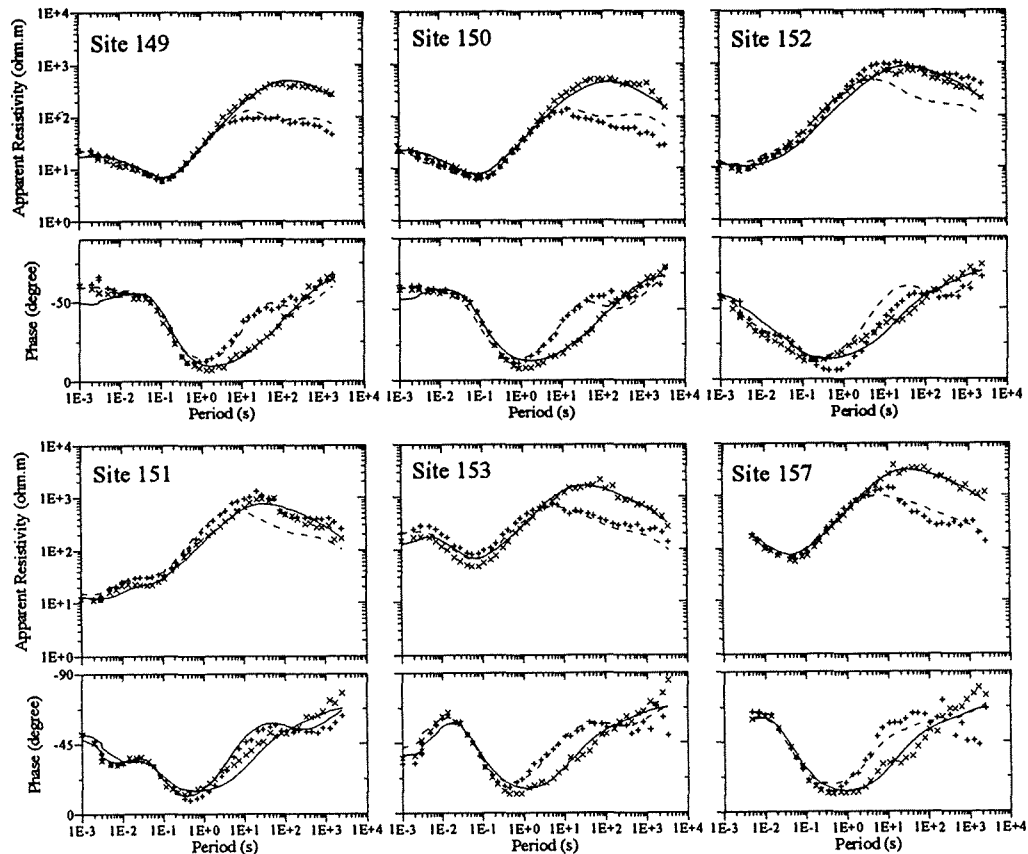


Figure 3. Comparing the apparent resistivity and phase from inversion model responses with the observed data at some stations. Solid line: TM response, dash line: TE response, x: TM observed data, +: TE mode observed data.

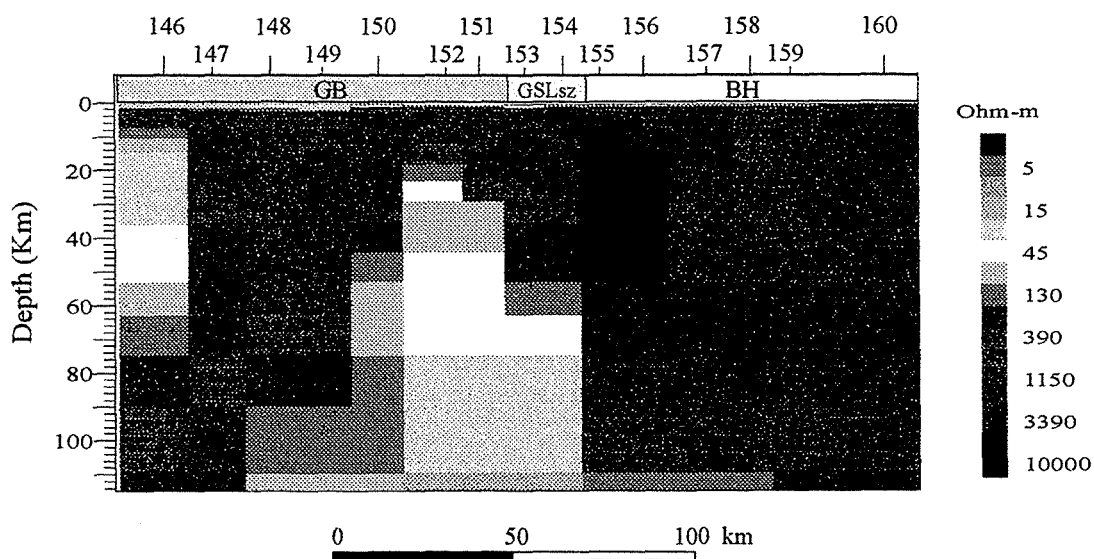


Figure 4. 2D Occam inversion model along Corridor 1a.

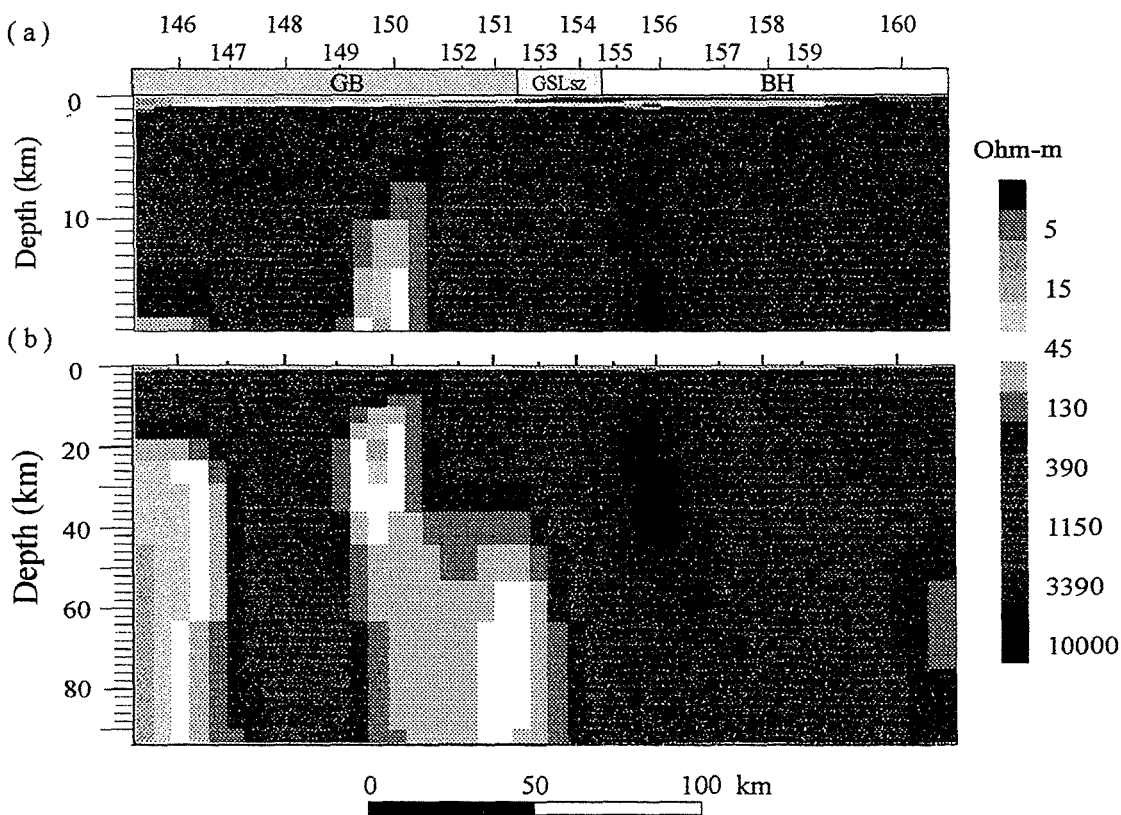


Figure 5. 2D Mackie inversion model along Corridor 1a. (a) shallow structure, (b) deeper structure.

The 2D inversion methods used included the Occam inversion (deGroot-Hedlin and Constable, 1990) and Randall Mackie inversion (Mackie, et al., 1993, 1997). The implementation of these programs in this study is discussed in Wu et. al (2000).

Figure 3 compares the responses of the Mackie inversion model with the observed data at representative sites. The TE data shows the poorest fits, particularly at periods of >10 s at some sites near the shear zone. It is difficult to get the 2D model to fit both the TE and TM data well. This result suggests a more complex crustal structure (maybe 3D) around the GSLsz area.

Figure 4 and 5 show the 2D inversion models from Occam and Mackie methods. The relatively good agreement between models suggests the structures are quite well resolved. The models indicate:

- At the surface (above 800 m), there is a resistivity change at sites 153 and 154, near the location of the fault (Figure 1). This change reflects a difference in the Phanerozoic sedimentary rocks to the east and west of this location. In the Phanerozoic units to the west of the GSLsz, there are two layers: a relatively resistive upper layer (~500 Ωm) with ~400 m thickness, which is a carbonate dominated unit, and a conductive second layer (~50 Ωm) with ~300 m thickness.
- Between the Phanerozoic cover and 7 km depth, there is a relatively conductive west-dipping zone (~250 Ωm) beneath sites 151, 152 and 150 above 7 km. This structure is visible on Figure 5a but it is somewhat difficult to make out with the colour scheme used. Its presence is supported by the observations in the apparent resistivity and phase pseudosections. The coincidence of the top of this structure with the surface position of the GSLsz suggests that the structure is associated with the shear zone. There is also a sharp change in resistivity to the east, beneath site 154.
- There are a number of deeper crustal structures visible on both Mackie and Occam inversion models. There is an anomalous conductive zone (<100 Ωm) beneath sites 152 and 150 in the middle to lower crust, which extends eastwards in the mantle (Figure 4 and 5b). The eastern margin of this structure, between sites 154 and 155, consists of a sharp transition to more resistive zone. There is also a mid to lower crustal conductor at the western end of Corridor 1a, discussed in Wu et al (2000). The Buffalo Head terrane is characterized by east-dipping structures. Finally, there is an indication of a more conductive zone in the crust and upper mantle near the boundary with the Taltson magmatic arc (located just east of the corridor). However, this feature is not well resolved because it is at the end of the profile and V5 data only is available at sites 159 and 160.

Conclusions

Analyses of the MT data from the GSLsz area of the SNORCLE Transect have shown:

1. The geoelectric strike is ~N30°E in the upper crust and sub-parallel to the GSLsz, and changes the direction in the middle and lower crust. There are changes in strike across the GSLsz.
2. The Phanerozoic sedimentary rocks have different conductivity on either side of the GSLsz.
3. There is a west-dipping conductive zone extending downwards from the western edge of the surface position of the GSLsz.
4. The exact relationship of the large-scale geometry of the GSLsz to the observed resistivity structure is still being interpreted. However, there are clear structures extending from the upper crust into the upper mantle: a conductive body beneath sites 150-153 and a transition from these conductive rocks to more resistive rocks beneath site 154. The GSLsz is imaged as a lithospheric-scale feature.

5. There is a conductive zone extending downwards from mid-crustal depths at the boundary of the Great Bear magmatic arc and Hottah terrane and a possible conductive zone extending downwards from a similar depth beneath the boundary of the Buffalo Head terrane and Taltson magmatic arc.

References

- Chave, A.D., Thomson, D.J. and Ander M.E., 1987. On the robust estimation of power spectra, coherences, and transfer functions. *J. Geophys. Res.*, 92, 633-648.
- Chave, A.D. and Thomson, D.J., 1989. Some comments on magnetotelluric response function estimation. *J. Geophys. Res.*, 94, 14215-14225.
- deGroot-Hedlin, C. and Constable, S., 1990. Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophys.*, 55, 1613-1624.
- Groom R.W. and Bailey, R.C., 1989. Decomposition of magnetotelluric impedance tensors in the presence of local three-dimensional galvanic distortion. *J. Geophys. Res.*, vol. 94, 1913-1925.
- Hoffman, P.F., 1987. Continental transform tectonics; Great Slave Lake Shear zone (1.9 Ga), northwest Canada, *Geology* 15, 785-788.
- Hoffman, P.F., 1989. Precambrian geology and tectonic history of North American, in *The Geology of North American*, Vol. A, The Geology of North American - An overview, The Geological Society of American.
- Jones, A.G. and Jödicke, 1984. Magnetotelluric transfer function estimation improvement by a coherence-based rejection technique. Contributed paper at *54th Annual International Meeting, Society of Exploration Geophysics*, Atlanta, Georgia, U.S.A., Dec. 2-6. Expanded abstracts 51-55.
- Jones, A.G., Chave, A.D., Egbert, G., Auld, D. and Bahr, K., 1989. A comparison of techniques for Magnetotelluric response function estimation. *J. Geophys. Res.*, 94, 14201-14213.
- Jones A.G. and Ferguson, I.J. 1997. Results from 1996 MT studies along SNORCLE profiles 1 and 1A. In *Lithoprobe 1997 Report*, pp. 6.
- Jones, A.G., Kurtz, R.D., Craven, J.A., McNeice, G.W., Gough, D.I., DeLaurier, J.M. & Ellis, R.G., 1992. Electromagnetic constraints on strike-slip geometry - The Fraser River fault system, *Geology*, 20, 561-564.
- Jones, A.G. and Gough D. I., 1995. Electromagnetic images of crustal structures in southern and central Canadian Cordillera. *Can. J. Earth Sci.*, 32, 1541-1563.
- Ledo, J. et al. 2000. Electromagnetic images of the northern Canadian Cordillera, In *LITHOPROBE Report, 2000 SNORCLE Workshop meeting (this volume)*.
- Mackie, R.L. and Madden, T.R., 1993. Three-dimensional magnetotelluric inversion using conjugate gradients. *Geophys. J. Int.*, 115, 215-229.
- Mackie, R., Rieven, S. and Rodi, W., 1997. Users Manual and software Documentation for Two-Dimensional Inversion of Magnetotelluric Data.
- Ross, G.M., Parrish, R.R., Villeneuve, M.E. and Bowring, S.A., 1991. Geophysical and geochronology of the crystalline basement of the Alberta Basin, western Canada. *Can. J. Earth Sci.*, 28, 512-522.
- Unsworth, M. J., Malin, P. E., Egbert, G. D., Booker, J. R., 1997. Internal structure of the San Andreas Fault at Parkfield, California. *Geology*, 25 (4), 359-362.
- Wu, X, Ferguson, I.J. and Jones, A., 2000. Magnetotelluric response and geoelectric structure of the southwestern Northwest Territories, Canada. In *LITHOPROBE Report, 2000 SNORCLE Workshop meeting (this volume)*.

