

LITHOPROBE

SOUTHERN CORDILLERA TRANSECT WORKSHOP

and

CORDILLERAN

TECTONICS WORKSHOP

UNIVERSITY OF ALBERTA

MARCH 6-8, 1992

LITHOPROBE SOUTHERN CANADIAN CORDILLERA WORKSHOP
and
CORDILLERAN TECTONICS WORKSHOP

held at the University of Alberta, March 6-8, 1992

FRIDAY, March 6, 1992

2000-???? REGISTRATION AND GET TOGETHER

SATURDAY, March 7, 1992

ORAL PRESENTATIONS - ROOM 3-27 EARTH SCIENCE

		<u>PAGE</u>
0800-1500	<u>SESSION 1</u> - INTRODUCTION AND RESULTS FROM THE SOUTHERN CANADIAN CORDILLERA Chairman: F. A. Cook	
0800-0810	INTRODUCTION AND WELCOME Philippe Erdmer and Fred Cook	
0810-0820	1) GEOLOGICAL SURVEY UPDATE D.. Templeman-Kluit	
0820-0840	2) LITHOPROBE UPDATE R. M. Clowes, Project Director	
0840-0900	3) BALANCING FOOTHILLS CROSS SECTIONS WITH SEISMIC DATA W. Langenberg and D. Halwas	2
0900-0920	4) STRUCTURAL AND STRATIGRAPHIC EVIDENCE FOR LOWER CAMBRIAN RIFTING IN THE MCNAUGHTON FORMATION, ROCKY MOUNTAIN MAIN RANGES, BRITISH COLUMBIA AND ALBERTA H. Lickorish	3
0920-0940	5) REINTERPRETATION OF THE CLACHNACUDAINN TERRANE AND STANDFAST CREEK FAULT, SOUTHERN OMINECA BELT, BRITISH COLUMBIA J. L. Crowley	4
0940-1020	COFFEE and POSTERS	

1020-1040	6) COMPOSITE DEFORMATION, INTRADEFORAMTIONAL LEUCOGRANITE MAGMATISM AND THERMAL HISTORY, NORTHERN MONASHEE MOUNTAINS, OMINECA BELT, B. C.	5
	R. Scammell	
1040-1100	7) STRUCTURE OF THE OKANAGAN VALLEY FAULT SYSTEM NEAR SHUSWAP LAKE, S. E. BRITISH COLUMBIA	12
	B. J. Johnson	
1100-1120	8) SUMMARY AND IMPLICATIONS OF RESULTS FROM SUPPORTING GEOSCIENCE FIELD MAPPING AND GEOCHRONOLOGY PROJECTS IN THE SOUTHERN CORDILLERA ADJACENT TO LITHOPROBE LINES 4-10 AND 19	13
	S. D. Carr, J. L. Crowley, B. J. Johnson, R. L. Brown and V. J. Coleman	
1120-1140	9) REGIONAL THREE DIMENSIONAL CRUSTAL STRUCTURE OF THE EASTERN CORDILLERA, SOUTHERN CANADA AND NORTHWESTERN UNITED STATES	19
	J. L. Varsek and F. A. Cook	
1140-1200	10) EARLY AND MIDDLE EOCENE CRUSTAL STRETCHING IN THE SOUTH-CENTRAL CANADIAN CORDILLERA: PASSIVE UPPER CRUSTAL RESPONSE TO DUCTILE BOUDINAGE OF THE LOWER CRUST ABOVE A FLUID UPPER MANTLE	34
	R. A. Price	
1200-1320	LUNCH.....	
1320-1340	11) BASEMENT AGES IN SOUTHERN B. C. AND THE NEARBY PARTS OF THE U.S.A, REVIEWED	37
	R. St. J. Lambert and V. E. Chamberlain.	
1340-1400	12) ORIGIN OF THE PACIFIC OCEAN: PRE-PANTHALASSA PLATE RECONSTRUCTIONS CONSTRAINED BY PROVENANCE STUDIES	38
	G. M. Ross	
1400-1420	13) GEOCHEMICAL STUDIES OF SYNTECTONIC FLUIDS ALONG THE SOUTHERN CORDILLERAN LITHOPROBE TRANSECT	39
	B. E. Nesbitt and K. Muehlenbachs	
1420-1440	14) MAGNETOTELLURIC SOUNDINGS, STRUCTURE AND FLUIDS IN THE CANADIAN CORDILLERA	43
	D. I. Gough and J. A. Majorowicz	

1440-1500	15) CORRELATION BETWEEN DEPTH TO THE LOWER CRUSTAL HIGH CONDUCTIVITY LAYER AND HEAT FLOW IN THE CANADIAN CORDILLERA	51
	J. A. Majorowicz, D. I. Gough, and T. J. Lewis	
1500-????	POSTERS AND COFFEE	
<u>SUNDAY, March 8, 1992</u>		
0800-1500	<u>SESSION 2</u> - RESULTS FROM THE NORTHERN CORDILLERA AND THE U. S.	
	Chairman: P. Erdmer	
0800-0820	16) ACCRETE: A PROPOSED PLAN TO STUDY THE DEEP CRUST UNDER THE ACCRETED TERRANES OF SOUTHEAST ALASKA	61
	L. S. Hollister, M. L. Crawford, and S. McGeary	
0820-0840	17) TECTONIC FRAMEWORK OF THE EASTERN COAST BELT	76
	J. M. Journeay	
0840-0900	18) ELECTRIC NOTEBOOK AND GIS, PINE PASS (930) S. W., B. C.	77
	L. C. Struik, A. Atrens, and A. Haynes	
0900-0920	19) REGIONAL GEOLOGY, STRUCTURE AND TECTONICS OF THE TESLIN SUTURE ZONE IN NORTHWEST TESLIN MAP AREA, YUKON	78
	R. A. Stevens and P. Erdmer	
0920-0940	20) PRESSURE-TEMPERATURE EVOLUTION OF BLUESCHISTS AND ECLOGITES FROM PINCHI LAKE, B. C.	79
	E. D. Ghent, M. Z. Stout, and P. Erdmer	
0940-1020	COFFEE AND POSTERS	
1020-1040	21) THE LAY RANGE ASSEMBLAGE: WHERE, WHAT AND WHEN ?	80
	F. Ferri, S. Dudka, and C. Rees	
1040-1100	22) EMPLACEMENT OF THE CACHE CREEK TERRANE AS CONSTRAINED BY NEW ISOTOPIC AND ELEMENTAL GEOCHEMISTRY FROM NORTHWESTERN BRITISH COLUMBIA	81
	M. G. Mihalynuk, M. T. Smith, and J. E. Gabites	

1100-1120	23) THE CACHE CREEK OCEAN: CLOSURE OR ENCLOSURE?	83
	J. Nelson and M. Mihalynuk	
1120-1140	24) NEW PALEONTOLOGIC AND LITHOGEOCHEMICAL DATA FROM THE NATION LAKES AREA AND ITS IMPLICATION FOR THE QUESNEL AND STIKINE ARCS	84
	K. Bellefontaine and J. Nelson	
1140-1200	25) EARLY CARBONIFEROUS PLUTONISM IN STIKINIA, STIKINE AND ISKUT RIVER AREA, NORTHWESTERN BRITISH COLUMBIA	85
	J. Drobe	
1200-1320	LUNCH	
1320-1340	26) THE LLEWELLYN-TALLY HO FAULT SYSTEM: CONTROLS ON TIMING AND TYPES OF INTERACTION BETWEEN NISLING AND STIKINE TERRANES, NORTHERN B. C. AND SOUTHERN YUKON TERRITORY	87
	C. Hart and M. Mihalynuk	
1340-1400	27) JURASSIC ACCRETION OF NISLING TERRANE ALONG THE WESTERN MARGIN OF STIKINIA, COAST MOUNTAINS, NORTHWESTERN BRITISH COLUMBIA	89
	L. Currie	
1400-1420	28) EVIDENCE AGAINST MAJOR STRIKE SLIP DISPLACEMENT ON THE KALTAG FAULT, NORTHERN YUKON	90
	L. S. Lane	
1420-1440	29) DETRITAL ZIRCON CONSTRAINTS ON THE PROVENANCE OF THE HARMONY AND VALMY FORMATIONS, NEVADA AND BEARING ON CORDILLERAN EVOLUTION	91
	M. T. Smith and G. E. Gehrels	
1440-1500	DISCUSSION	

POSTER PRESENTATIONS - ROOM 4-09 (Listed Alphabetically)

- 1) GEOCHRONOLGY OF MESOZOIC GRANITOIDS IN THE SOUTHERN
CANADIAN CORDILLERA 95

A. D. Brandon and R. St. J. Lambert
- 2) STRUCTURAL ELEMENTS IN WESTERN TELEGRAPH CREEK
MAP AREA (104G) AND THEIR WESTERN EXTENSIONS INTO
CHUTINE MAP AREA (104F) 105

D. Brown
- 3) LOW VELOCITY LAYERS IN THE CORDILLERAN CRUST:
EVIDENCE FROM WIDE ANGLE STUDIES 108

M. J. A. Burianyk, E. R. Kanasewich, and N. Udey
- 4) SUMMARY AND IMPLICATIONS OF RESULTS FROM SUPPORTING
GEOSCIENCE FIELD MAPPING AND GEOCHRONOLOGY PROJECTS
IN THE SOUTHERN CORDILLERA ADJACENT TO LITHOPROBE
LINES 4-10 AND 19 (See abstract for talk no. 8)

S. D. Carr, J. L. Crowley, B. J. Johnson, and R. L.
Brown and V. J. Coleman
- 5) STRUCTURAL GEOLOGY OF THE MISTY THRUST, KANANASKIS
COUNTRY, ALBERTA: STUDY OF RELATIONS BETWEEN
THRUSTING, FOLDING AND TRANSVERSE FAULTING USING
PALEOSTRESS AND KINEMATIC ANALYSIS 110

S. Castonguay
- 6) RELATIONSHIP BETWEEN LARAMIDE AND PROTEROZOIC AGE
STRUCTURES IN THE COLVILLE HILLS, NWT 111

E. A. Clark and F. A. Cook
- 7) THE 60⁰ NORTH TRANSECT (Title only)

P. Erdmer, A. Jones, E. Kanasewich, and F. Cook
- 8) SKEENA FOLD BELT (Title only)

C. Evenchick
- 9) STRUCTURE OF THE CARIBOO MOUNTAINS NEAR McBRIDE,
B.C. 112

C. Ferguson

10) PROBLEMS IN REGIONAL CORRELATION OF HADRYNIAN STRATA - SOUTHCENTRAL BRITISH COLUMBIA AND ADJACENT ALBERTA	113
S. E. Grasby	
11) DEFORMATION STYLES NEAR THE LEADING EDGE OF THE FOLD - THRUST BELT, PINCHER CREEK, ALBERTA	114
S. N. Hiebert and D. A. Spratt	
12) THE LOWER JURASSIC ROSSLAND GROUP IN SOUTHEASTERN BRITISH COLUMBIA - TECTONIC EVOLUTION AND PRECIOUS METAL DEPOSITS	115
T. Hoy and K Dunne	
13) COMPUTER AIDED GEOLOGICAL MAPPING IN THE ROCKY MOUNTAIN FOOTHILLS OF NORTHEASTERN B.C.	116
P. Jahans	
14) ANATOMY OF THE LARAMIDE FOREDEEP IN ALBERTA	117
T. Jerzykiewicz	
15) EVIDENCE AGAINST MAJOR STRIKE SLIP DISPLACEMENT ON THE KALTAG FAULT, NORTHERN YUKON (See abstract for talk no. 28)	
L. S. Lane	
16) BALANCING FOOTHILLS CROSS SECTIONS WITH SEISMIC DATA (See abstract for talk no. 3)	
W. Langenberg and D. Halwas	
17) MIDDLE JURASSIC STRATIGRAPHY OF THE SOUTH-CENTRAL CANADIAN CORDILLERA	118
J. B. Mahoney	
18) VELOCITY STRUCTURE FROM SEISMIC REFRACTION ACROSS THE COAST PLUTONIC COMPLEX AND INTERMONTANE BELT	119
N. McLean and G. D. Spence	
19) EXPLORATION AND DEVELOPMENT HIGHLIGHTS IN SOUTH-CENTRAL B. C. (Title only)	
R. Meyers	

- 20) MAIN RANGES GEOLOGY AND TECTONICS OF THE ATHABASCA PASS (83 D 8) AREA, ALBERTA AND BRITISH COLUMBIA (Title only)
- E. Mountjoy
- 21) ALASKAN - TYPE COMPLEXES: U-PB GEOCHRONOMETRY AND TECTONIC SIGNIFICANCE 120
- G. Nixon and L. Heaman
- 22) MIDDLE DEVONIAN THRUST BELT DEVELOPMENT IN THE SOUTHERN CANADIAN CORDILLERA - EVIDENCE FROM THE PURCELL MOUNTAINS, SOUTHEASTERN B. C. 121
- K. Root
- 23) STRUCTURAL RELATIONSHIPS BETWEEN CADWALLADER AND BRIDGE RIVER TERRANES AND TYAUGHTON AND METHOW BASINS, TASEKO-BRIDGE RIVER AREA, SOUTHWESTERN B.C. 122
- P. Schiarizza
- 24) LARGE LATERAL, SOUTH-FACING RAMPS WITH SOUTHWARD DECREASE IN DISPLACEMENT: EOCENE EXTENSIONAL VALKYR SHEAR ZONE, SOUTHERN BRITISH COLUMBIA CANADA 123
- P. S. Simony, S. D. Carr and C. R. Corbett
- 25) THE TRIANGLE ZONE AND FOOTHILLS STRUCTURE IN THE GREASE CREEK AREA OF ALBERTA 126
- G. Soule
- 26) GEOLOGY OF THE PILTZ PEAK PLUTONIC COMPLEX, B.C. 127
- P. Van der Heyden and S. Metcalf
- 27) REGIONAL THREE DIMENSIONAL CRUSTAL STRUCTURE OF THE EASTERN CORDILLERA, SOUTHERN CANADA AND NORTHWESTERN UNITED STATES (See abstract for talk no. 9)
- J. L. Varsek and F. A. Cook
- 28) RESIDUAL STATICS ESTIMATION WITH SIMULATED ANNEALING EXPERIMENTS - 1985 LITHOPROBE SEISMIC REFLECTION SURVEYS 128
- K. Vasudevan, F. Cook and A. Van der Velden

- 29) AN INTERACTIVE COMPUTER PROGRAM TO DETERMINE
PALEOSTRESS AXES USING DATA FROM STRIATED FAULTS 129

T. Villemin and H. A. K. Charlesworth
- 30) NATURE AND KINEMATICS OF SHEAR ZONES IN THE
SOUTHERN TAIL OF THE NELSON BATHOLITH, SOUTHEAST
BRITISH COLUMBIA 130

J. Vogl and P. Simony
- 31) CRUSTAL THICKENING BENEATH THE CANADIAN EASTERN
CORDILLERA 131

D. White, I Asudeh, and C. Zelt
- 32) PALEOMAGNETICALLY OBSERVED TILTS IN THE SOUTHERN
OMINECA BELT 132

M.. Wingate
- 33) CRUST AND UPPER MANTLE VELOCITY STRUCTURE OF THE
INTERMONTANE BELT, SOUTHERN CANADIAN CORDILLERA 133

B. C. Zelt, et. al.

ORAL PRESENTATIONS

BALANCING FOOTHILLS CROSS SECTIONS WITH SEISMIC DATA

Willem Langenberg, Alberta Geological Survey, Alberta Research Council, Box 8330, Station 'F', Edmonton, Alberta, T6H 5X2, and **Dave Halwas**, Esso Resources Canada Limited, Box 2480, Stn. M, Calgary, Alberta, T2P 3M9

Structural cross sections can be made more viable, and consequently better balanced by the inclusion of seismic data. Examples from three cross sections through the Cadomin (Alberta) area show how this task was accomplished.

Velocities of seismic waves were determined from time-depth plots, which were obtained from sonic logs of petroleum wells. Reflections on the seismic sections were tied to stratigraphic horizons and faults through synthetic seismograms. Depth conversions provided points in three dimensional space on stratigraphic horizons and faults, that were included in the cross sections. Frameworks for balanced cross sections were constructed using the TRIPOD Structural Geological Information System. Line length balancing techniques provide criteria to finish the cross section in areas of insufficient reliable reflectors.

The cross sections of the Cadomin area provide a complete transect of the outer foothills. They show considerable amounts of folding and both east and west verging thrust faults. The east verging Grave Flats Thrust is the same fault as the Folding Mountain Thrust of the Hinton area and it forms the boundary between inner and outer foothills. The west verging Pedley Thrust is the upper detachment of the Coalspur Triangle Zone at the eastern edge of the deformed belt. The basal detachment ramps up from Paleozoic to the Blackstone Formation. The west verging Mercoal Thrust represents a failed triangle zone, formed during an earlier stage than the Coalspur Triangle Zone. The seismic sections reveal a lateral ramp (from Blackstone to Wapiabi formation) in the Mercoal Thrust.

**Structural and stratigraphic evidence for Lower Cambrian rifting in the McNaughton Formation,
Rocky Mountain Main Ranges, British Columbia and Alberta.**

W. H. Lickorish

Department of Geology and Geophysics, University of Calgary, 2500 University Drive N. W.
Calgary, Alberta, T2N 1N4

Abstract

An orthoquartzite marker of regional extent has been recognised at the base of the Lower Cambrian McNaughton Formation in the Lake Louise Area. Further north, by Jasper, the same marker is found near the top of the thicker succession traditionally mapped as McNaughton Formation. The package of quartz sandstones and conglomerates beneath this marker is referred to as the Jasper Formation.

In the Western Main Ranges the Jasper Formation thins westward with a wedge shaped geometry from a thickness of about 1000m to locations where it is absent altogether. A fault has been traced in the Sullivan River area which displaces strata beneath the quartzite marker, but not the marker itself. In the foot-wall the McNaughton quartzite marker truncates strata of the Upper Proterozoic middle Miette Group, while in the hanging wall the marker lies sharply on, but with no apparent angularity, a thick succession of the Jasper Formation. Sedimentary structures within the Jasper Formation suggest fluvial deposition with palaeoflows axial to these structural trends.

The evidence suggests deposition of the Jasper Formation occurred syn tectonically with normal faulting as axial fluvial systems in hanging-wall half grabens bounded by uplifted, eroding foot-wall blocks. The ensuing post-rift marine transgression occurred with the basal McNaughton quartzite covering the eroded foot-wall blocks with marked unconformity.

REINTERPRETATION OF THE CLACHNACUDAINN TERRANE AND STANDFAST CREEK
FAULT, SOUTHERN OMINECA BELT, BRITISH COLUMBIA

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

ABSTRACT

Stratigraphic, structural, and metamorphic evidence from recent fieldwork indicates that the Clachnacudainn terrane is an integral part of the Selkirk allochthon. Major isoclinal folds in the lower Paleozoic Hamill Group, Badshot Formation, and Lardeau Group extend throughout the terrane and into the overlying allochthon. Regional metamorphic isograds are not appressed or omitted across the Standfast Creek fault (the upper boundary of the terrane). These observations suggest that the fault is an insignificant tectonic feature that is attributable to fold limb attenuation and/or local brittle displacement on a scale of metres. The Clachnacudainn terrane therefore cannot be a distinct terrane or a high grade salient of the Shuswap metamorphic complex that was denuded in the Eocene. The relatively large volume of late- to post-tectonic plutonism in the Clachnacudainn igneous complex is the main aspect that distinguishes the terrane from the remainder of the allochthon.

Composite deformation, intradeformational leucogranite magmatism and thermal history, northern Monashee Mountains, Omineca Belt, B.C.

R.J. Scammell

Department of Geological Sciences, Queen's University, Kingston, Ontario, Canada K7L 3N6

INTRODUCTION

Rocks in the southern Omineca Belt can be broadly divided into three fault-bounded packages which record different but related thermal histories, and represent zones of the crust that were positioned at different crustal levels immediately prior to Eocene extension (Carr and Brown 1989, 1990; Johnson and Brown, 1989). The study area lies in the hanging-wall of a crustal-scale thrust fault (the Monashee décollement), and is composed of rocks which were at mid-crustal levels immediately prior to Eocene extension. These rocks comprise a polydeformed sillimanite-grade sequence of sedimentary and igneous rocks which are part of the pericratonic Kootenay Terrane lying to the west and north of the Monashee Terrane (Wheeler and McFeely 1991), and are believed to be part of Upper Proterozoic strata of the Windermere Supergroup and therefore of North American affinity (Scammell and Dixon 1989, 1990, Scammell 1990).

In order to elucidate the relationships between deformation, metamorphism and cooling, structural studies have been integrated with U-Pb zircon, xenotime, monazite, titanite and rutile chronometry, incremental heating studies of $^{40}\text{Ar}/^{39}\text{Ar}$ from hornblende, and apatite fission track chronometry. In general, the systematics of the applied dating techniques are well behaved. Second-order complexities result from inheritance and Pb-loss in the U-Pb system, excess Ar plus high-T discordance in the $^{40}\text{Ar}/^{39}\text{Ar}$ system, and partial annealing of fission tracks coupled with abundant inclusions in apatite.

COMPOSITE DEFORMATION

Previous applications of traditional chronological designations to structural elements in the study area, and within the thrust sheet to the north and south, has delineated several common structural elements. These comprise a composite foliation defined by peak metamorphic mineral assemblages and denoted S_{1+2} , and three fold sets, denoted F_1 , F_2 and F_3 (Raeside and Simony 1983, Sevigny and Simony 1989, Scammell 1990, 1991, Journeay 1986). The S_{1+2}

foliation is considered to be a product of transposition during both F_1 and F_2 folding, as denoted by the subscripts, and both synchronous and later recrystallization. It is herein also considered a composite foliation, but in the sense of Tobisch and Paterson (1988, 1990). That is, the foliation is a *diachronous* steady state structure consisting of coplanar elements which are morphologically similar, and are continually being modified by various transitory processes which contribute to its definition. It is therefore not always possible to separate out the various elements which define it on a chronological basis. In view of this fact, chronologic subscripts are abandoned, and the foliation is denoted as S_T following Williams and Compagnoni (1983), and Tobisch and Paterson (1988, 1990).

The applied approach is to use the ubiquitous transposition foliation as a first order datum marker for the purposes of structural correlation. This approach leads to subdivision of structural elements into two broad categories: (i) pre- to syn-transposition foliation structures which include the transposition foliation, multiple folds, a penetrative mineral elongation lineation, shear zones, and general shear flow structures and (ii) post-transposition foliation structures that clearly overprint the pre- to syn-transposition foliation structures, and include multiple folds, relatively discrete low-grade shear zones and brittle joints and faults (see Scammell 1990, 1991 for detailed descriptions).

Structures and fabrics which have kinematic significance (e.g. S-C tectonites, asymmetric pull-aparts, asymmetrical extensional shear bands) and indicate a strain history dominated by general noncoaxial flow, are of two types based on their distribution and relationships to metamorphism. The first occur throughout the area, are coplanar with S_T defined by near "peak" metamorphic mineral assemblages, and record dominantly upper-plate to-the-east and rarely -west ductile shearing. They are most common in zones which range from discrete meter thick ductile shear zones at higher structure levels, to a broad zone in excess of 1000 meters in thickness composed of well-layered mylonitic rocks at the base of the thrust sheet marked by the Monashee décollement. The second are defined by low-grade mineral assemblages, record down-to-the-west normal motion, and form relatively discrete shear zones in late leucogranite or marble horizons.

INTRADEFORMATIONAL LEUCOGRANITES

Two-mica leucogranitic rocks are ubiquitous, comprise 10-100% of exposed rocks at mesoscopic scales, and are estimated to comprise approximately 30% of the rocks in the study

area. They are syn-orogenic in terms of the mountain belt, but in detail show both post- and pre-tectonic relationships to different structural elements formed during the process of mountain building. U-Pb mineral geochronometry places some constraints on ages and duration of formation of some structural elements, and demonstrates that leucogranites in the study area are intradeformational.

The U-Pb data indicate crystallization of two-mica leucogranites at 136 ± 2 , and from 105-96 and 67-57 Ma. The ca. 136 Ma leucogranite contains rafts of host rocks which display S_T . Therefore S_T predates 136 Ma. The 105-96 Ma suite is folded and sheared, demonstrating that general noncoaxial flow operated after this time. The 67-57 Ma leucogranites occur as dikes several meters to 10's of meters thick, and are distinctive in their geometries with 67-60 Ma leucogranites occurring as subhorizontal sheets, and 57 Ma leucogranites being subvertical or dipping steeply to the west or east. All 67-57 Ma leucogranites cross-cut pre- to syn-transposition foliation structures, indicating that general noncoaxial flow did not occur after this time. One ca. 60 Ma old leucogranite body is cut by a relatively discrete down-to-the-west normal shear zone indicating that deformation after 60 Ma was dominantly west-vergent normal motion. The low metamorphic grade associated with motion on this shear zone indicates significant cooling occurred after 60 Ma. Mylonitic rocks in the high strain zone associated with the Monashee décollement are cross-cut by a ca. 57 Ma leucogranite dike, indicating that transport of the thrust sheet on this surface had ceased by this time.

If tectonic stresses are the fundamental controls of emplacement for horizontal intrusive sheets as modeled by Brisbin (1986) and McCarthy and Thompson (1988), then the subhorizontal orientation of the 67-60 Ma sheets indicates that the minimum principal stress was oriented in a subvertical orientation during their emplacement. This orientation for the minimum principal stress suggests a changed stress field relative to earlier stress states, but is only compatible with a stress regime of horizontal compression or an isotropic state of stress. The latter would generate randomly oriented intrusive sheets and is therefore not believed to apply to this leucogranite suite. An overall asymmetric reduction in all principal stresses may have brought about this change in orientation of principal stresses, and induced decompression melting in part of the crust. This reduction is compatible with both horizontal compressional of the lithosphere and coeval removal of material at upper crustal levels through some combination of erosion and tectonic denudation. The steeply dipping to subvertical orientations of 57 Ma leucogranite dikes suggests that the minimum compressive stress at the

time of their intrusion was oriented subhorizontal with an east-west trend. Therefore the 67-57 Ma suite of leucogranites could record a transition from subhorizontal maximum principal stress to subhorizontal minimum principal stress, and may record the transition from compressional to extensional tectonics.

THERMAL HISTORY

"Peak" metamorphism is inferred to have occurred from 104-94 Ma on the basis of U-Pb ages of metamorphic monazite in Sil-Ksp-migmatitic schists and the ca. 136 Ma leucogranite. U-Pb, $^{40}\text{Ar}/^{39}\text{Ar}$ and fission track data indicate the cooling path has four components: (1) rapid cooling from ca. 700 °C at 100 Ma to 530 °C at 89 Ma, (2) slow cooling (reheating?) from 89-68 Ma, (3) rapid cooling from ca. 470 °C at 68 Ma to 100 °C at 41 Ma, and (4) slow cooling from 41 Ma to the present. U-Pb titanite and $^{40}\text{Ar}/^{39}\text{Ar}$ plateau ages from hornblende decrease with structural depth and increasing bulk shear strain, and geographically from north to south.

SUMMARY AND DISCUSSION

The recognition of composite transposition structures and general noncoaxial flow structures within the thrust sheet emphasises the role and dominance of general noncoaxial flow in the strain history of the lower levels of the thrust sheet. Structural relationships demonstrate east-vergent general noncoaxial flow dominated the deformation regime at this structural level from prior to 136 Ma to possibly 57 Ma. This deformation regime resulted in moderate to extreme shear strain manifested in multiple folds, strong composite and transposition foliations, progressively rotated structures and shear zones. The increase in intensity of the shear component towards the base of the thrust sheet is consistent with models of heterogeneous noncoaxial flow within thrust sheets (Sanderson 1982, Ramsay and Huber 1987). The area appears to have been a broad zone of shearing. This deformation regime also masks earlier deformation events (which based on regional observations, are likely to exist), and in part hinders the identification of structures which are required to corroborate the existence of macroscopic structures including Scrip Nappe (see Scammell 1991).

The 105-96 Ma leucogranites are interpreted to be products of anatexis due to crustal thickening based on structural relationships, and the coincidence in the timing of their crystallization and "peak" metamorphism (104-94 Ma). There is no isotopic evidence for

metamorphism prior to ca. 104 Ma.

Rapid cooling from 100-89 Ma is previously unrecognized, and if it occurred, could be a product of increased erosion rates, tectonic denudation or thrusting over cooler crust. The existence of an inverted metamorphic field gradient in the footwall of the Monashee décollement (Journeay 1986, Scammell 1986) may indicate that thrusting produced the inferred cooling at this time. The diachroneity of compressional structures coupled with the timing of cooling indicates that cooling was diachronous with transport of the thrust sheet. High-grade compression and extension occurred during ca. 89-57 Ma, and may overlap in time. Rapid cooling from 68-40 Ma is most likely a product of an exhumation regime dominated by tectonic denudation. This inferred extension may have initiated decompression melting at deeper crustal levels and generation of some of the 67-57 Ma leucogranites which were emplaced into 530-400 °C host strata. Since down-to-the-west discrete shear zones were active at greenschist grade temperatures (300-450 °C), the cooling curve limits their activity to have occurred sometime during ca. 55-45 Ma. These late shear zones are believed to be a manifestation of both east and west dipping crustal scale normal faulting which was also active in the southern Omineca Belt at this time (Parrish et al. 1988).

Rocks in the study area show close relationships between deformation, metamorphism and magmatism at mid-crustal levels. A general model is that metamorphism and anatexis are a consequence of deformation related to crustal thickening. Metamorphism coupled with deviatoric stress leads to geometrical and reaction softening. Anatexis may result in melt softening. Any one or a combination of these softening processes could lead to a change in deformation style where general noncoaxial flow dominated, the formation of a large scale intracrustal zone of shear, and further crustal thickening. Erosion, tectonic denudation or thrusting over cooler crust, or any combination of these processes, results in cooling, strain hardening and the localization of strain within the thrust sheet, and exhumation.

A final note of caution regards interpretation of LITHOPROBE seismic reflection data collected to the south of the area which images these former mid-crustal rocks. This study demonstrates that this sequence of rocks is geometrically and compositionally complex. They are probably as complex as any mid-crustal rocks imaged anywhere. Fortunately crustal-scale thrust and normal faulting have exposed these complex rocks at the surface so that one can evaluate potential sources of seismic reflectors. In the case of Line 19 parts of the reflection pattern are characterized by discontinuous and crossing arcuate events which hinder the tracing

of thick mylonite zones to depth, and leads to non-unique interpretations of the detailed reflection pattern. Crossing arcuate patterns can be generated by complex folding, or discontinuous multi-level subhorizontal reflectors including intrusive sheets or mafic boudins, or both (see Smithson and Johnson 1989, and references cited therein). The difficulty in interpreting this complex reflection pattern lies in evaluating the source of reflections, particularly when a large range of potential sources are known to exist in the imaged terrane. Thick well layered mylonite zones are known to exist at the surface, and should generate strong subsurface reflections. Complex large-scale folding, discontinuous mafic rock dominated sequences, and multiple subhorizontal leucogranite sheets which cross-cut folded strata will all contribute in an unconstrained manner to increasing the detailed complexity of the reflection image, and indicate detailed interpretation of the image in terms of only shear zones may not be realistic.

ACKNOWLEDGEMENTS

Financial support for this project has been supplied through a variety of grants awarded to J.M. Dixon of Queen's University. They including an NSERC operating grant, 1988/1989 and 1989/1990 EMR Research Agreements, 1990 NSERC Matching Funds and a 1988/1989 B.C. Geoscience Research grant. Major sources of funds were 1989 and 1990 LITHOPROBE Supporting Geoscience grants awarded to J.M. Dixon. The author acknowledges an NSERC post-graduate scholarship. R.R. Parrish is thanked for his comments on some of the ideas presented herein. U-Pb data was generated with assistance from the staff at the GSC Geochronology Laboratory in Ottawa, $^{40}\text{Ar}/^{39}\text{Ar}$ data was generated at the Geochronology Laboratory at Queen's University with the assistance of D.A. Archibald and Y. Chen, and fission track data was generated by A.M. Grist in the Fission Track Research Laboratory at Dalhousie University.

REFERENCES

- Brishin, W.C., 1986: Mechanics of pegmatite intrusion; *American Mineralogist*, v.71, p. 644-651.
- Carr, S.D., and Brown, R.L., 1990: Southern Cordilleran LITHOPROBE Transect: evidence for crustal thickening and collapse of the Omineca Belt, Valhalla Complex to Okanagan valley, British Columbia; *Geological Association of Canada, Program with Abstracts*, v. 15, p. A22.
- Carr, S.D., and Brown, R.L., 1989: Crustal structure and tectonic chronology near the LITHOPROBE line in the Thor/Odin-Pinnacles-Cherryville-Vernon area, southeastern British Columbia: a progress report; *in*, LITHOPROBE Cordilleran Workshop 1989, p. 27-36.
- Johnson, B.J., and Brown, R.L., 1989: Preliminary analysis of crustal structure of the southern Omineca Belt along the Trans-Canada Highway, southeastern British Columbia; *in*, LITHOPROBE Cordilleran Workshop 1989, p. 37-44.
- Journeay, J.M., 1986: Stratigraphy, internal strain and thermo-tectonic evolution of northern Frenchman Cap dome: an exhumed duplex structure, Omineca Hinterland, S.E. Canadian Cordillera; unpublished Ph.D. thesis, Queen's University, Kingston, Ontario, Canada.
- McCarthy, J., and Thompson, G.A., 1988: Seismic imaging of extended crust with emphasis on the western United States; *Geological Society of America Bulletin*, v. 100, p. 1361-1374.
- Parrish, R.R., Carr, S.D., and Parkinson, D.L., 1988: Eocene extensional tectonics and

- geochronology of the southern Omineca Belt, British Columbia and Washington; *Tectonics*, v. 7, p. 181-212.
- Raesside, R.P., and Simony, P., 1983: Stratigraphy and deformational history of the Scrip Nappe, Monashee Mountains, British Columbia; *Canadian Journal of Earth Sciences*, v. 20, p. 639-650.
- Ramsay, J.G., and Huber, M.I., 1987: *The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures*; Academic Press, London, 700pp.
- Sanderson, D.J., 1982: Models of strain variation in Nappes and thrust sheets: a review; *Tectonophysics*, v. 88, p. 201-233.
- Scammell, R.J., 1986: Stratigraphy, structure and metamorphism of the north flank of the Monashee Complex, southeastern British Columbia: a record of Proterozoic extension and Phanerozoic crustal thickening; unpublished M.Sc. thesis, Carleton University, Canada, 205p.
- Scammell, R.J., 1990: Preliminary results of stratigraphy, structure and metamorphism in the southern Scrip and northern Seymour ranges, southern Omineca Belt, British Columbia; *Geological Survey of Canada, Paper 90-1E*, p. 97-106.
- Scammell, R.J., 1991: Structure between Scrip Nappe and Monashee Terrane, southern Omineca Belt, British Columbia; *in* *Current Research, Part A*, Geological Survey of Canada, Paper 91-1A, p. 261-269.
- Scammell, R.J., and Dixon, J.M., 1989: Stratigraphy along the north flank of Frenchman Cap dome, southern Omineca Belt, British Columbia (82M/10, 15); British Columbia Ministry of Energy, Mines and Petroleum Resources, *Geological Fieldwork, Paper 1989-1*, p. 55-60.
- Scammell, R.J. and Dixon, J.M., 1990: Preliminary results of geological mapping within the Kootenay Terrane north of LITHOPROBE Transect Line 19, southern Omineca Belt, British Columbia; *in*, LITHOPROBE Cordilleran Workshop March 3-4, 1990, p. 30-37.
- Sevigny, J.H., and Simony, P.S., 1989: Geometric relationship between the Scrip Nappe and metamorphic isograds in the northern Adams River area, Monashee Mountains, British Columbia; *Canadian Journal of Earth Sciences*, v. 26, p. 606-610.
- Smithson, S.B. and Johnson, R.A., 1989: Crustal structure of the western U.S. based on reflection seismology; *in* Pakiser, L.C. and Mooney, W.D., *Geophysical framework of the continental United States: Boulder, Colorado*, Geological Society of America Memoir 172, p. 577-612.
- Tobisch, O.T. and Paterson, S.C., 1990: The Yarra granite: an intradeformational pluton associated with ductile thrusting, Lachlan Fold Belt, southeastern Australia; *Geological Society of America Bulletin*, v. 102, p. 693-703.
- Tobisch, O.T. and Paterson, S.C., 1988: Analysis and interpretation of composite foliations in an area of progressive deformation; *Journal of Structural Geology*, v. 10, p. 745-754.
- Williams, P.F. and Compagnoni, R., 1983: Deformation and metamorphism in the Bard area of the Sesia Lanzo Zone, Western Alps, during subduction and uplift; *Journal of Metamorphic Petrology*, v. 1, p. 117-140.
- Wheeler, J.O., and McFeely, P. (comp.), 1991: Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America; Geological Survey of Canada, Map 1712A, scale 1:2,000,000.

STRUCTURE OF THE OKANAGAN VALLEY FAULT SYSTEM NEAR SHUSWAP LAKE, S.E. BRITISH COLUMBIA

Brad Johnson, Dept. of Earth Sciences, Carleton University and Ottawa-Carleton Geoscience Centre, Ottawa, Ontario K1S 5B6.

One of several normal fault systems in the southern Omineca belt that accommodated Early Eocene crustal extension, the Okanagan Valley fault system forms the western boundary of the Shuswap metamorphic core complex. Over most of its >450 km length, the Okanagan fault and mylonites in its footwall dip gently westward, and forms a discrete break between high-grade footwall rocks and lower-grade hangingwall rocks. Northwest of Shuswap Lake, the fault takes a 40-km step to the left, and is next seen as a discrete break near the east side of Adams Lake. The Adams Lake segment of the fault is on strike with, and is inferred to be connected to, the North Thompson River fault.

In the region between Shuswap Lake and Adams Lake, strain related to west-directed extension is distributed heterogeneously through two-mica granites, which are concentrated in a zone up to 2 km thick and form about 80% of the rock within it. The mylonitic foliation in these granites is folded, forming a broad antiform-synform pair that mimics the geometry of reflectors in the middle and lower crust imaged on LITHOPROBE reflection profile 19. Preliminary U-Pb zircon and monazite data suggest that the granite is Paleocene or Early Eocene in age, and hence that the mylonitic fabric and the broad folds that deform it are Paleocene or younger. This in turn suggests that some of the deep crustal reflection geometry is related to extension.

**SUMMARY AND IMPLICATIONS OF RESULTS FROM SUPPORTING GEOSCIENCE
FIELD MAPPING AND GEOCHRONOLOGY PROJECTS IN THE SOUTHERN
CORDILLERA ADJACENT TO LITHOPROBE PROFILES 4-10 AND 19**

**CARR, S. D., CROWLEY, J. L., JOHNSON, B. J., BROWN, R. L. AND COLEMAN, V. J.
DEPARTMENT OF EARTH SCIENCE AND OTTAWA-CARLETON GEOSCIENCE
CENTRE, CARLETON UNIVERSITY, OTTAWA, ONTARIO K1S 5B6**

The Monashee décollement of the southern Canadian Cordillera: a crustal-scale shear zone linking the Rocky Mountain Foreland Belt to lower crust beneath accreted terranes (Brown, Carr, Johnson, Coleman in collaboration with Cook and Varsek)

The Monashee décollement, a crustal-scale shear zone in the Omineca Belt of the southern Canadian Cordillera, is interpreted as correlating with the sole thrust of the Rocky Mountain Foreland Belt. It is exposed on the margins of the Monashee complex, an elongate domal culmination that comprises mainly Early Proterozoic gneisses of North American basement. The hanging wall of the décollement consists of deformed and metamorphosed North American continental margin and oceanic accreted terranes. Field relations, kinematics and geochronology indicate that the shear zone has experienced a complex history that included protracted easterly-directed shear of hanging-wall rocks and imbrication of basement rocks in its footwall. U-Pb zircon dating of syn- and post-kinematic leucogranites in the décollement zone demonstrates that the final stages of thrusting occurred in the Late Paleocene. The cessation of thrusting and the onset of crustal extension in the southern Omineca Belt correspond to the end of thrusting in the Foreland Belt.

Layered reflections observed in LITHOPROBE seismic reflection data correlate with sheared and transposed rocks in both the hanging wall and footwall of the Monashee décollement; the décollement is imaged as reflections, cutoffs and correlatable reflection segments. The Monashee décollement extends eastward in the subsurface to the Rocky Mountain Trench and is inferred to be the westward continuation of the sole thrust of the Foreland Belt. It extends westward in the middle crust beneath the Intermontane Superterrane and can be traced into the lower crust, where its westward continuation becomes ambiguous. Basement gneisses of probable North American cratonic origin occur in the southern Omineca Belt and are projected westward in the subsurface beneath the Intermontane Belt. This implies that accreted rocks of the Intermontane Superterrane are thin crustal slices that have been transported northeasterly onto the attenuated margin of North America.

Middle to lower crust beneath the Monashee décollement in the Omineca Belt does not appear to have been involved in significant penetrative Tertiary extensional strain; however, strong subhorizontal reflections near the base of the crust beneath the western

Intermontane Belt may be a result of superimposed extensional shearing and could be the locus for balancing extension observed at higher crustal levels.

Reinterpretation of the Clachnacudainn terrane and Standfast Creek Fault (Crowley)

Stratigraphic, structural, and metamorphic evidence indicates that the Clachnacudainn terrane is an integral part of the overlying Selkirk allochthon. Metasedimentary rocks within and immediately above the terrane are correlated with the lower Paleozoic Hamill Group, Badshot Formation, and Lardeau Group. Although the Hamill Group is the only unit that can be traced continuously across the Standfast Creek fault (the upper boundary of the terrane), the stratigraphy in the terrane is interpreted to continue upward into the allochthon over major west-verging anticlines which occur near the fault. The stratigraphy also outlines folds within the Clachnacudainn terrane. Structural style is consistent across the fault, as the same three phases of deformation are recognized in the hanging wall and footwall. The sillimanite-kyanite-staurolite-muscovite regional metamorphic assemblage at the base of the Clachnacudainn terrane is progressively overlain by lower grade assemblages, with garnet grade rocks occurring in the immediate hanging wall and footwall of the Standfast Creek fault. This requires that regional metamorphic isograds are not appressed or omitted across the fault.

Since the Clachnacudainn terrane has stratigraphic, structural, and metamorphic continuity with the overlying Selkirk allochthon, it is suggested that the Standfast Creek fault is an insignificant tectonic feature. The minor amount of stratigraphic omission along the southern portion of the fault is attributed to fold limb attenuation and/or local brittle displacement on a scale of metres. The northern portion of the fault is partly an intrusive contact and partly a set of brittle, steeply east-dipping normal faults. The Clachnacudainn terrane therefore cannot be a distinct terrane or a high grade salient of the Shuswap metamorphic complex that was denuded by ductile extensional faults in the Eocene. The relatively large volume of pre- to post-tectonic granitoid plutonism in the Clachnacudainn igneous complex is the main aspect that distinguishes the terrane from the remainder of the allochthon. Zircon from the Albert stock, one of the many post-tectonic granitoids, will be dated by the U-Pb method in order to determine an upper age limit on the regional metamorphism and penetrative ductile strain.

West margin of Shuswap Complex, Trans-Canada Highway to Adams Lake (Johnson)

Adjacent to the Trans-Canada Highway, rocks that lie structurally above the Monashee décollement and beneath the Eagle River segment of the Okanagan Valley fault include migmatites that contain the assemblage sillimanite + K-feldspar, as well as abundant dykes and sheets of pegmatite. Immediately above the Monashee décollement, synmetamorphic mylonites display shear fabrics that indicate upper-plate-eastward sense of shear, consistent with the direction of thrusting. In contrast, mylonites in the immediate footwall of the

Okanagan fault consistently display indicators of the opposite sense of shear, interpreted as a result of west-side-down normal slip on the Okanagan fault at mid-crustal levels. On ridges adjacent to the Trans-Canada Highway north of Three Valley Gap, pegmatite that has been deformed by east-directed compression is Paleocene in age (preliminary U-Pb zircon data; Parrish and Johnson, 1991). This corroborates geochronological arguments by Carr (1990, 1992) that Eocene crustal extension commenced either very shortly after or during the last stages of east-directed thrusting and orogenic thickening, and is consistent with the petrological evidence that both east and west-directed mylonites formed at about the same crustal level under the same conditions of metamorphism.

An east-west cross section drawn south of the Trans-Canada Highway shows that the rocks between the Monashee décollement and the Okanagan fault are subhorizontally layered (Johnson, 1989). Efforts to balance this section on a crustal scale predicted that the Monashee décollement should be subhorizontal west of where it is exposed, and that the Okanagan fault should root in the middle crust (Johnson and Brown, 1989). Both of these predictions are supported by LITHOPROBE reflection data (Cook et al., 1992).

The Okanagan fault forms a discrete break between high-grade footwall rocks and lower-grade hanging wall rocks at least as far north as Four Mile Creek, on the east side of the Anstey Arm of Shuswap Lake (Johnson 1990, 1991). Near the east shore of Adams Lake, 40 km to the west, a left-stepped en echelon segment of the Okanagan fault system is expressed as a sharp break between upper to middle greenschist-facies rocks of the Eagle Bay Assemblage and sillimanite-bearing migmatites that display west-directed mylonitic fabrics (Johnson and Brown 1990). In the region between Shuswap Lake and Adams Lake, plastic strain related to west-directed extension is distributed heterogeneously through two-mica granites that are concentrated in a zone up to 2 km thick. The mylonitic fabric within this shear zone is broadly folded, forming an antiform/synform pair that mimics the crustal-scale subsurface structure imaged on LITHOPROBE profile 19 (Cook et al. 1992).

The broad folds that deform the mylonitic foliation must be younger than the two-mica granite, which preliminary U-Pb zircon and monazite data suggest is Paleocene or Early Eocene in age. These folds have been interpreted as having formed as a result of differential uplift of the footwall of the Adams Lake segment of the Okanagan fault system, in response to tectonic removal of its hanging wall (Johnson 1991). The reflection profile from LITHOPROBE line 19 shows strongly layered reflections in the upper and middle crust that correlate with east-directed Mesozoic to Paleocene thrusts, a wedge-shaped domain in the lower crust characterized by discontinuous east-dipping reflections, and subhorizontal Moho reflections (Cook et al. 1992). The east-dipping reflectors lie beneath the east-dipping limb of the antiform that fold the mylonitic foliation. If there is a one - to - one correlation between the surface structure and crustal structure, then the eastward dip of reflectors in the southwestern part of profile 19 must also have been caused by crustal extension, in which case weakly reflective material in the lowermost crust most likely represents a zone into which rheologically weak lower crust or magma flowed plastically (Johnson 1991).

Alternatively, the east-dipping reflections could represent the root of a west-directed Middle Jurassic thrust belt (Johnson and Brown 1990).

Publications resulting from LITHOPROBE funded research

- Bosdachin, R. 1989. Structure, stratigraphy, and tectonothermal evolution of the central western flank of the Monashee complex, southeastern British Columbia. M.Sc. thesis, Carleton University, Ottawa, Ont.
- Bosdachin, R., and Harrap, R. M. 1988. Stratigraphy and structure of the Monashee complex and overlying rocks adjacent to the Trans-Canada Highway, west of Revelstoke, B. C. *In* Current research, part E. Geological Survey of Canada, Paper 88-1E: 19-23.
- Brown, R. L. 1991. Field oriented geoscience projects designed to constrain interpretation of lines 1 to 10 and 19. *In* LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Calgary, Alberta, March 1991: 56-60.
- Brown, R. L., and Carr, S. D. 1990. Lithospheric thickening and orogenic collapse within the Canadian Cordillera. Pacific Rim 90 Congress, Australian Institute of Mining and Metallurgy, Vol. II: 1-10.
- Brown, R. L., and Journeay, J. M. 1987. Tectonic denudation of the Shuswap metamorphic terrane of southeastern British Columbia. *Geology*, **15**: 142-146.
- Brown, R. L., Carr, S. D., Johnson, B. J., Coleman, V. J., Cook, F. A., and Varsek, J. L. 1991. The Monashee décollement of the southern Canadian Cordillera: a crustal-scale shear zone linking the Rocky Mountain Foreland Belt to lower crust beneath accreted terranes. *In* Thrust tectonics. *Edited by* K. R. McClay. Chapman and Hall: 344-347.
- Carr, S. D. 1989. Implications of Early Eocene Ladybird granite in the Thor-Odin - Pinnacles area, southern British Columbia. *In* Current research, Part E. Geological Survey of Canada, Paper 89-1E: 69-77.
- Carr, S. D. 1990. Late Cretaceous - early Tertiary tectonic evolution of the southern Omineca Belt, Canadian Cordillera. Ph.D. thesis, Carleton University, Ottawa, Ont.
- Carr, S. D. 1991a. U-Pb zircon and titanite ages of three Mesozoic igneous rocks south of the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia. *Canadian Journal of Earth Sciences*, **28**: 1877-1882.
- Carr, S. D. 1991b. Geology of the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia. *Canadian Journal of Earth Sciences*, **28**, in press.
- Carr, S. D. 1991c. Tectonic evolution of the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia. *In* LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Calgary, Alberta, March 1991: 61-75.
- 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*, in press.

- Carr, S. D., and Brown, R. L. 1989. Thor-Odin - Pinnacles - Cherryville - Vernon area, southern British Columbia: a progress report. *In* LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Vancouver, British Columbia, February 1989: 27-36.
- Carr, S. D., and Brown, R. L. 1990. Southern Cordilleran LITHOPROBE transect lines 6 to 10: Crustal structure and tectonic chronology. *In* LITHOPROBE southern Canadian Cordillera transect workshop proceedings, March 1990, Calgary, Alberta: 10-18.
- Carr, S. D., Parrish, R. R., and Brown, R. L. 1987. Eocene structural development of the Valhalla complex, southeastern British Columbia. *Tectonics*, 6: 175-196.
- Coleman, V. J. 1989. The Cariboo duplex at the southern boundary of the Monashee complex, southern British Columbia. *In* Current research, Part E. Geological Survey of Canada, Paper 89-1E: 89-93.
- Coleman, V. J. 1990. The Monashee décollement at Cariboo Alp, southern British Columbia. M.Sc. thesis, Carleton University, Ottawa, Ont.
- Cook, F. A., Simony, P. S., Coflin, K. C., Green, A. G., Milkereit, B., Price, R. A., Parrish, R., Patenaude, C., Gordy, P. L., and Brown, R. L. 1987. LITHOPROBE southern Canadian Cordilleran transect: Rocky Mountain thrust belt to Valhalla gneiss complex. *Geophysical Journal of the Royal Astronomical Society*, 89: 91-98.
- Cook, F. A., Green, A. G., Simony, P. S., Price, R. A., Parrish, R. R., Milkereit, B., Gordy, P. L., Brown, R. L., Coflin, K. C., and Patenaude, C. 1988. LITHOPROBE seismic reflection structure of the southeastern Canadian Cordillera: Initial results. *Tectonics*, 7: 157-180.
- 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 I: Foreland Thrust and Fold Belt to Fraser River fault. *Tectonics*, in press.
- Crowley, J. L., Coleman, M. E. and Brown, R. L. 1991. Preliminary results of fieldwork: Standfast Creek fault zone, southern British Columbia. *In* Current Research, Part A. Geological Survey of Canada, Paper 91-1A: 293-301.
- Crowley, J. L., Brown, R. L., and Crowley, S. E. 1992. Reinterpretation of the Clachnacudainn terrane and Standfast Creek fault, southern Omineca Belt, British Columbia. *In*, Current Research, Part A. Geological Survey of Canada, Paper 92-1A: 63-70.
- Harrap, R. M. 1990. Stratigraphy and structure of the Monashee terrane in the Mount English area, west of Revelstoke, B.C. M.Sc. thesis, Carleton University, Ottawa, Ont.
- Johnson, B. J. 1988. Progress report: stratigraphy and structure of the Shuswap metamorphic complex in the Hunters Range, eastern Shuswap Highland. British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork 1987, Paper 1988-1: 55-58.

- Johnson, B. J. 1989. Geology of the west margin of the Shuswap terrane near Sicamous - implications for Tertiary extensional tectonics (82L, M). British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork 1988: 49-54.
- Johnson, B. J. 1990. Geology adjacent to the western margin of the Shuswap metamorphic complex (parts of 82L, M). British Columbia Ministry of Energy, Mines and Petroleum Resources, Mineral Resources Division, Open File 1990-30.
- Johnson, B. J. 1991. Structure of the margin of the Shuswap metamorphic complex in the Shuswap Lake - Adams Lake region. In LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Calgary, Alberta, March 1991: 76-79.
- Johnson, B. J., and Brown, R. L. 1989. Preliminary analysis of crustal structure of the southern Omineca Belt along the Trans-Canada Highway, southeastern British Columbia. In LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Vancouver, British Columbia, February 1989: 37-44.
- Johnson, B. J., and Brown, R. L. 1990. Crustal structure of the Omineca Belt along line 19 of LITHOPROBE southern Canadian Cordillera transect. In LITHOPROBE southern Canadian Cordillera transect workshop proceedings, Calgary, Alberta, March 1990: 19-26.
- Parrish, R., and Johnson, B. 1991. Revelstoke to Chase: the Omineca Belt. In Geology and tectonic elements of south-central British Columbia - Transect: Revelstoke to Hope, Kamloops Exploration Group, Field trip guidebook, Part 1: 1-8.
- Journeay, M., and Brown, R. L. 1986. Major tectonic boundaries of the Omineca Belt in southern British Columbia: a progress report. In Current Research, Part A. Geological Survey of Canada, Paper 86-1A: 81-88.
- Ranalli, G., Brown, R. L., and Bosdachin, R. 1989. A geodynamic model for extension in the Shuswap core complex, southeastern Canadian Cordillera. Canadian Journal of Earth Sciences, **26**: 1647-1653.
- Scammell, R. J., and Brown, R. L. 1990. Cover gneisses of the Monashee Terrane: a record of synsedimentary rifting in the North American Cordillera. Canadian Journal of Earth Sciences, **27**: 712-726.

Regional three-dimensional crustal structure of the eastern Cordillera, southern Canada and northwestern United States

John L. Varsek and Frederick A. Cook
Dept. Geology and Geophysics, University of Calgary,
Calgary, Alberta, T2N 1N4

Introduction

This report summarizes the results of an integrated geophysical and geological study on the crustal structure of the western Foreland and Omineca belts (Varsek, 1992). Approximately 1300 km of reflection data, observed on 24 profiles and recorded mainly in the middle to late 1980s by LITHOPROBE and COCORP were examined, and include data from southeast British Columbia between the western Rocky Mountains and the Valhalla complex (profiles 1-5; Cook et al., 1988), from southcentral British Columbia between the Valhalla complex and the Coast belt (profiles 6-10, 19; Cook et al., 1992), from northern Montana between the western Rocky mountains and the Priest River complex (COCORP, 1988; Yoos et al., 1991), and from northern Idaho to northcentral Washington between the Priest River complex and the Okanagan complex (profiles W1-W5, W8; Potter et al., 1986; Figure 1). A valuable attribute of these data is that the overlapping, subparallel arrangement of the seismic profiles, including some strike-line segments, provides regional three dimensional coverage of this tectonically extended intra-continental subduction complex over an area of 350 x 350 km and to depths of 50 km.

Specific objectives are determination of: (1) structural linkages between internal and external regions, (2) western extent of the North American craton, (3) western extent of deformation that can be related to the eastern Cordillera, (4) structural origin of the basement and metamorphic complexes, (5) configuration and development of accretionary sutures, (6) origin of along-strike structural variations, (7) controls and modes of crustal extension, and (8) the relation of the Moho to overlying structures.

The data were interpreted with the objective of obtaining regionally consistent reflection patterns easily related to, and thus constrained by known geology (Figure 1). The structural linkage between the Foreland and Intermontane (accreted composite terrane) belts is reasonably well constrained because intervening structures are exposed within structural and metamorphic culminations of the Omineca belt (Parrish et al., 1988), and these can be correlated or projected downdip into the deep crust of the flanking regions. A summary of the seismic interpretation is posted on the regional geologic map (Figure 1) and regional cross sections (Figure 2) to show the spatial relationships between crustal-scale reflection structures and major tectonic elements. Only those geometric features that can be confidently identified on the reflection data and that exhibit regional continuity are shown.

Results

Three dimensional structure

LITHOPROBE and COCORP reflection profiles show that North American supracrustal cover rocks, and in places basement rocks, are deformed into an overall west-dipping structural package of folds and thrust ramps that increase in amplitude to the west. However, cross-cutting reflection fabrics, constrained by correlation to exposed

faults and deformed belts, indicate that deformation of pre-existing structures occurred within the Omineca and western Foreland belts. For example, pre-Late Cretaceous contractional faults of the Purcell anticlinorium are truncated in the middle crust by interpreted eastward correlatives of the Gwillim Creek shear zones (Figure 3). Other examples include (1) east-dipping, lower crustal reflectors that are truncated by the west-dipping Monashee ramp and that may be correlative with west-verging upper crustal nappes within the Kootenay Arc to the east (Brown et al., 1986), and (2) apparent truncation of the complexly deformed Kootenay Arc by listric, west-dipping upper crustal reflectors that may be correlative with the Benard fault (Varsek and Cook, 1990).

The Omineca belt contains a west-facing crustal-scale ramp system that formed, in part, during the Late Cretaceous to Paleocene, and that may extend along-strike over a distance of 350 km from the west flank of the Monashee complex to the west flank of the Priest River complex (Figure 4). It is overlain by a crustal-scale antiform that in places may have formed above blind thrusts. The thickness of the craton probably varies along strike as the Monashee and Priest River basement ramps are separated by a cratonic embayment, named the Kootenay embayment (Figure 4). This is evident in a map view of the 7.0 s isochron measured between the Rocky Mountain basal detachment (RMBD; the deepest level to which Late Cretaceous to early Tertiary contractional faults can be followed) and the Moho (Figure 2). East of the Monashee and Priest River complexes, the RMBD is interpreted to approximately follow the craton-cover contact, based on (1) field observations that indicate no basement rocks are exposed, and (2) reflection data observations that indicate faults which overlie the basement culminations merge into the RMBD at, or west of, the Purcell anticlinorium. Prior to Eocene extension, this embayment may have been even more pronounced since the measurement on profile 1 is on relatively unextended crust as compared to the measurements near the Monashee complex (profile A1) and Priest River complex (profiles W4 and W5; Figure 1). This embayment spatially corresponds to the south-plunging Monashee and Valhalla complexes, the north-plunging Purcell anticlinorium near the International border, the Kootenay Arc structural salient, and regional trends in the lower Paleozoic shelf to basin transition. Within the Kootenay embayment the Monashee decollement and Gwillim Creek shear zones appear to be part of an anomalously thick, regional duplex that originates in the lower crust beneath the Intermontane belt and extends eastward to a leading edge branch line located near the craton-cover contact at the Rocky Mountain trench. From the northern United States into British Columbia, increasing northward tectonic overlap of accreted terranes onto thick cratonic crust and associated basement thickening spatially coincide with the increased northward width and depth of the early Tertiary foreland basin. The southern Alberta recess of the Rocky Mountains appears to be the result of shortening at a restraining bend formed by the northwest-trending Monashee-Priest River basement ramp.

Structural culminations.

These seismic reflection data have important implications for the tectonic origin of structural culminations of the western Foreland and Omineca belts. To eliminate, or reduce, the effects of extensional faulting on these observations, comparisons were made in regions that did not appear to be structurally attenuated, or transposed by major denudational faults.

1. The Monashee basement culmination geometrically resembles a crustal-scale basement duplex, as proposed by Brown et al. (1986) and Monger et al. (1986), although

the ages of faults underlying the Monashee decollement are uncertain. In contrast to the Monashee complex where domal reflections span nearly the entire crust, the Priest River complex appears to be a thin, upper crustal feature situated at the top of a cratonic basement ramp; it is underlain by relatively sparse, discontinuous reflections that are characteristic of the autochthonous craton. A long-standing difficulty in the interpretation of the relationship between outcrops of basement rocks and structural salients is whether they originated at cratonic promontories or whether they represent greater tectonic transport (e.g. Thomas, 1983). These reflection data indicate that exposures of basement rocks either coincide with promontories, represented by the Monashee and Priest River complexes, or that they were tectonically stripped from these areas and transported to the northeast (e.g. Malton gneiss).

2. The Vernon (Pinnacles), Colville, and Eagle River antiforms are crustal-scale folds that formed on significant basement ramps. The Vernon(Pinnacles) antiform may have formed as thrust sheets were wedged above blind thrusts, or, alternatively, as a decollement fold (fault propagation fold). In contrast, the Eagle River antiform appears to be a fault bend fold formed over a deep thrust ramp within the Monashee terrane.

3. The Valhalla complex is interpreted to be a compressional culmination that was exposed during extension, and in comparison to adjacent areas, is positioned where the interval between the Gwillim Creek shear zone and the RMBD attains greatest thickness.

4. The south plunge of the Valhalla and Monashee complexes appears to be, in part, related to lateral variations in tectonic thickening. For example, the southern flank of the Monashee complex is explained by a southward decreasing interval between the Monashee decollement and interpreted basal faults beneath it. The south plunge of the Valhalla complex appears to be related to southward thinning of the interval between the Gwillim Creek shear zone and RMBD, from the LITHOPROBE (profile 5) to the COCORP (profile W4) transects (Figure 1).

5. The Purcell anticlinorium appears to have formed by a combination of structural processes, including (i) thrust imbrication of Belt-Purcell strata on widely spaced faults and backrotation of upper thrust sheets to the west, (ii) juxtaposition of this thrust stack over ramping basal faults, and (iii) possible antithetic rotation of its west flank into major east-dipping extensional faults. Its north-plunge may be related to a lateral ramp in the RMBD, possibly to differential uplift on out-of-sequence faults in southern British Columbia, and to a lesser degree, the Sylvanite anticline, a north-plunging, antiformal? duplex with a structural relief of about 20 km.

Crustal extension and structural nature of the Moho

Eocene extension did not significantly mask earlier contractional structures within the Foreland, Omineca and Intermontane belts, at least in the upper and middle crust (Cook et al., 1992; Varsek et al., in press). On these reflection data the Omineca belt appears to be a crustal-scale lens (boudin) superimposed on a crustal-scale ramp-antiform pair. It is separated from the Foreland belt to the east by the crust-penetrating Slokan Lake fault (SLF). It is uncertain whether the SLF flattens into, or cross cuts the Moho; however, it projects downdip to eastward thickening crust beneath the Purcell anticlinorium (based on refraction data, D. White, pers. comm., 1991). Extensional faults bounding the metamorphic complexes of the Omineca and Intermontane belts all flatten into the adjacent, horizontally layered lower crust (Cook et al., 1992; Varsek et al., in press). Extensional faulting within the Omineca belt increases from north to south and is evident in the greater lateral extent of the ramp-antiform pair on the COCORP transect and apparent southward thinning of the crustal isochron (about 0.5 s) between the

LITHOPROBE and COCORP transects. There is no evidence for inflow of material into the core complexes as proposed by Block and Royden (1990), because dipping reflection fabrics located in the interior of some of these complexes correlate to east-directed contractional features that pre-date extension. Apparently in this area, relatively uniform crustal thinning is maintained during extension because thinning of the middle and lower crust in the regions of thickly laminated reflections is compensated by emplacement of an upper crustal lid that resided above the core complexes.

With the possible exception of the Slocan Lake fault, all extensional and compressional structures within the crust appear to flatten into the lower crust or Moho; conversely, the Moho does not appear to overprint overlying features. For example, the Monashee ramp system flattens into the lower crust beneath the Vernon antiform (Figure 2) where it is probably ductilely extended. However, these reflections continue to dip gently westward beneath the Intermontane belt and flatten into the Moho beneath the eastern Coast belt (Varsek et al., in press). These observations suggest that the structural evolution of the crust is essentially decoupled from the mantle over great distances, and that the crust-mantle transition coincides with a fundamental and long-lived zone of weakness. Indeed, in hinterland settings the entire middle and lower crust may behave as a shear zone, and, consequently, it is possible that the strain may be distributed into conjugate zones. As a result, the east-dipping lower crustal reflections observed in the footwall of the basement ramps could be, in part, extensional features that transfer strain (e.g. Reston, 1990) from horizontally laminated, and probably ductilely stretched, middle and lower crust of the western Omineca and Intermontane belts to the east-dipping, crust-penetrating Slocan Lake and Purcell Trench? faults. Alternatively, these reflections could be contractional features since their conjugate orientation to the west-dipping crustal-scale ramp invites comparison to (1) shear zone arrays (e.g. extensional fissures), and (2) Reidel shears (R1, same sense of shear as the ramp) that may have formed within a cooler and possibly more mafic footwall (based on velocities from refraction data; Cumming et al., 1979).

Closing Remarks

From the reflection geometries and associated geologic constraints, we observe that crustal-scale structures are influenced by the configuration of the former continental margin and that this inheritance governed the location of major late contractional structures, which, in turn, appear to have controlled younger extensional features. Further studies on orogen-parallel structural variability, especially in regions that share a common tectonostratigraphic record, will provide an essential link between transect based investigations and comparative studies of collisional orogens (e.g. Allmendinger et al., 1987). Important applications include the prediction of crustal structure from the distribution of surface elements in areas where reflection data are lacking, and development of models for the structural and geochemical evolution of the crust.

Acknowledgements

As is typical of regional studies, we received helpful commentary from many individuals, including Richard Brown, Sharon Carr, Bradford Johnson, Murray Journeay, Jim Monger, Randy Parrish, Raymond Price, and Philip Simony.

References

- Allmendinger, R.W., K.D. Nelson, C.J. Potter, M. Barazangi, L.D. Brown, and J.E. Oliver, 1987, Deep seismic reflection characteristics of the continental crust, *Geology*, v. 15, p. 304 - 310.
- Block, L., and L.H. Royden, 1990, Core complex geometries and regional scale flow in the lower crust, *Tectonics*, v. 9, p. 557 - 567.
- Brown, R.L., J.M. Journey, L.S. Lane, D.C. Murphy, and C.J. Rees, 1986, Obduction, backfolding, and piggyback thrusting in the metamorphic hinterland of the southern Canadian Cordillera, *J. Struct. Geol.*, v. 8, p. 255-268.
- COCORP, 1988, Atlas, edited by Nelson, K.D., Institute for the Study of Continents, Cornell University, Ithaca, New York.
- Cook, F.A., A.G. Green, P.S. Simony, R.A. Price, R.R. Parrish, B. Milkereit, P.L. Gordy, R.L. Brown, K.C. Coflin, and C. Patenaude, 1988, LITHOPROBE seismic reflection structure of the southeastern Canadian Cordillera: Initial results, *Tectonics*, v. 7, p. 157-180.
- Cook, F.A., J.L. Varsek, R.M. Clowes, E.R. Kanasewich, C.S. Spencer, R.R. Parrish, R.L. Brown, S.D. Carr, B.J. Johnson, and R.A. Price, 1992, LITHOPROBE crustal reflection cross section of the Southern Canadian Cordillera: Foreland thrust and fold belt to Fraser River fault, *Tectonics*, v.11, p. 12 - 35..
- Cumming, W.B., R.M. Clowes, and R.M. Ellis, 1979, Crustal structure from a seismic refraction profile across southern British Columbia, *Can. J. Earth Sci.*, v. 16, p. 1024-1040.
- Gordy, P.L., F.R. Frey, and D.K. Norris, editors, 1977, Geological guide for the Canadian Society of Petroleum Geologists 1977 Waterton-Glacier Park field conference, 93 pgs, Canadian Society of Petroleum Geologists, Calgary, Alberta.
- Monger, J.W.H., G.J. Woodsworth, R.A. Price, R.M. Clowes, R.P. Riddihough, R. Currie, T. Hoy, V. Preto, P.S. Simony, P. Snavely, and C.J. Yorath, 1986, Transect B2, southern Canadian Cordillera, North American Continent-Ocean Transects, Geological Society of America, Boulder, Colo.
- Potter, C.J., W.E. Sanford, T. Yoos, E. Prussen, R. Keech II, J.E. Oliver, S. Kaufman, and L.D. Brown, 1986, COCORP deep seismic reflection traverse of the interior of the North American Cordillera, Washington and Idaho, *Tectonics*, v. 5, p. 1007-1027.
- Price, R.A., 1981a, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains, *Geol. Soc. Spec. Publ. London*, v.9, p. 427-448.
- Thomas, W.A., 1983, Continental margins, orogenic belts, and intracratonic structures, *Geology*, v. 11, p. 270 - 272.

- Varsek, J.L., 1992, Cordilleran crustal structure, southern Canada and northwestern United States, PhD thesis, Univ. Calgary, Calgary, Alberta.
- Varsek, J.L., and F.A. Cook, 1991, Seismic reflection geometry of a folded and detached accretionary complex: Kootenay arc, British Columbia, *Geology*, v. 19, p. 159-162.
- Varsek, J.L., F.A. Cook, R.M. Clowes, J.M. Journeay, J.W.H. Monger, R.R. Parrish, E.R. Kanasevich, and C.S. Spencer, in press, 1992, LITHOPROBE crustal reflection structure of the southern Canadian Cordillera II: Coast Mountains transect, *Tectonics*.
- Wheeler, J.O., A.J. Brookfield, H. Gabrielse, J.W.H. Monger, H.W. Tipper, and G.J. Woodsworth, 1988, Terrane map of the Canadian Cordillera, *Geol. Surv. Can. Open File Map 1894*, scale 1:2 000 000.
- Yoos, T.R., C.J. Potter, J.L. Thigpen, and L.D. Brown, 1991, The Cordilleran foreland thrust belt in northwestern Montana and northern Idaho from COCORP and Industry seismic reflection data, *Am. Assoc. Petr. Geol. Bull.*, v. 75, p. 1089 - 1106.

Figure Captions

Figure 1: Geologic map of the southern Foreland and Omineca belts showing major tectonic units, and locations of the LITHOPROBE and COCORP profiles (modified from Wheeler et al., 1988 and Parrish et al., 1988). Interpreted seismic profiles are at true scale assuming an average crustal velocity of 6 km/s. Geologic cross-sections of the Rocky Mountains are by Price (1981) and Gordy et al. (1977). Circled asterisks show position of the craton isochron = 7.0 s. The inset map shows the distribution of morphogeological belts, the modern plate tectonic regime of the northern Cordillera, and location of the study area. Abbreviations for this, and subsequent figures are listed in Table 1.

Figure 2: Structural cross sections of the Foreland and Omineca belt along the LITHOPROBE and COCORP transects. Only those structures that can be confidently correlated regionally are shown; lithologic interpretations are less certain. The circled asterisks mark the craton isochron = 7.0 s. The regional LITHOPROBE and COCORP sections are aligned along the Rocky Mountain Trench. Profile 19 is aligned with profile 7 at the inferred apex of the Monashee complex.

Figure 3: Schematic area-balanced reconstruction of the Purcell anticlinorium in southern British Columbia as it may have appeared before the Late Cretaceous. Dashed lines indicate faults that are restored in the next stage. (a) Present day crustal cross section based on reflection geometry and correlation to exposed faults and stratigraphy. (b) After restoration for displacement on the extensional Slocan Lake and Okanagan Valley faults. (c) After restoration for displacement on basal contractional faults of the Foreland-Omineca belt. (d) After restoration for displacement on the Gwillim Creek shear zone. Bracket in (d) indicates the position of the proposed counterpart of the

Purcell anticlinorium in the footwall of the K reflector (interpreted eastern counterpart of the Gwillim Creek shear zone).

Figure 4: Schematic block diagram illustrating crustal structure between the Monashee and Priest River basement complexes prior to cessation of Late Cretaceous to Paleocene contraction. Seismic control is indicated by solid lines on the elevated blocks. The basal thrust system east of the basement complexes is interpreted to approximately follow the craton-cover contact. It is scoop-shaped, convex to the east at the latitude of the Valhalla complex, and is bounded to the north and south by cratonal promontories. This surface has a narrow taper in the central region, whereas, to the north and south it probably consists of two ramps separated by a flat. Differential uplift on lateral ramps of the basal detachment results in plunging structural culminations, such as the Purcell anticlinorium between the COCORP and LITHOPROBE transects. Structural trends in the Kootenay Arc and southern Alberta Rocky Mountains, and facies trends reflected by the lower Paleozoic basin to platform transition parallel the inferred cratonal embayment. Increasing northward overlap of the accreted terranes onto thick cratonic crust, and probable shortening within the craton (northern block), corresponds with increasing width and depth of the early Tertiary foreland basin.

Table 1: Geological legend for the southern Foreland-Omineca belts

Terranes and Plates

EP	Explorer plate
JFP	Juan de Fuca plate
Ko	Kootenay, pericratonic
NA	North America, craton and cover
PP	Pacific plate
Qn	Quesnel, oceanic island arc
SM	Slide Mountain, oceanic marginal basin

Other geological units

CA	Colville antiform
Ccx	Clachnacudainn complex
CMC	Cascade Metamorphic Core
ERA	Eagle River antiform
KA	Kootenay Arc
Kcx	Kettle complex
Lcx	Lincoln complex
OKcx	Okanagan complex (spelled Okanogan in the United States)
M	Moho
Mcx	Monashee complex
PA	Purcell anticlinorium
RG	Republic graben
PRcx	Priest River complex
RN	Riondel Nappe
Scx	Shuswap complex
TG	Toroda graben
TMcx	Tenas Mary complex
TO	Thor-Odin culmination
VA	Vernon antiform
Vcx	Valhalla complex

Faults

AF	Ainsworth fault
BCF	Bacon Creek fault
BF	Beaven fault
BMF	Bodie Mountain fault (GWF)
BnF	Benard fault
BoT	Bourgeau thrust
BRT	Bull River thrust
CF	Cherryville fault
ChF	Chappon fault
CRF	Columbia River fault
CWF	Coldwater fault
DT	Dogtooth thrust
ENF	East Newport fault
ERF	Eagle River fault
FF	Flathead fault
GC	Gwillim Creek shear zone
GF	Granby fault

GWF	Greenwood fault (BMF)
HeT	Hefty thrust
HF	Hozameen fault
HLF	Hall Lake fault
JJF	Jumpoff Joe fault
LbT	Libby thrust zone
LeT	Lewis thrust
McT	McConnell thrust
MD	Monashee decollement
MF	Moyie fault
MFT	Mount Forster thrust
MtF	Methow River fault
OVF	Okanagan Valley fault
PT	Pinkam thrust
PTF	Purcell Trench fault
PuT	Purcell thrust
PyF	Pasayten fault
QF	Quilchena Creek fault
QLF	Quesnel Lake fault
RCF	Redding Creek fault
RMBD	Rocky Mountain basal detachment
RMT	Rocky Mountain trench
RSF	Red Shirt fault
RuT	Rundle thrust
RWF	Redwall fault
SCF	Standfast Creek fault
SLF	Slocan Lake fault
SMF	Saint Mary fault
TF	Torrent fault
VSZ	Valkyr Shear zone
WaF	Waldron fault
WF	Waneta fault
WiT	Wigwam thrust
WNF	West Newport fault

Igneous, Metamorphic and sedimentary units

eTg	early Tertiary granite
eTq	early Tertiary quartz diorite
eTsy	early Tertiary syenites
lKg	Late Cretaceous granite
mKg	mid-Cretaceous granite
mJg	Mid-Jurassic granite
T	Tertiary sedimentary and volcanic rocks
Tr-Kg	Triassic to Cretaceous granites
Pz	Paleozoic (platform, basin)
Pw	Late Proterozoic Windermere supergroup
Pp	Middle Proterozoic Belt-Purcell supergroup (u=upper, l=lower)

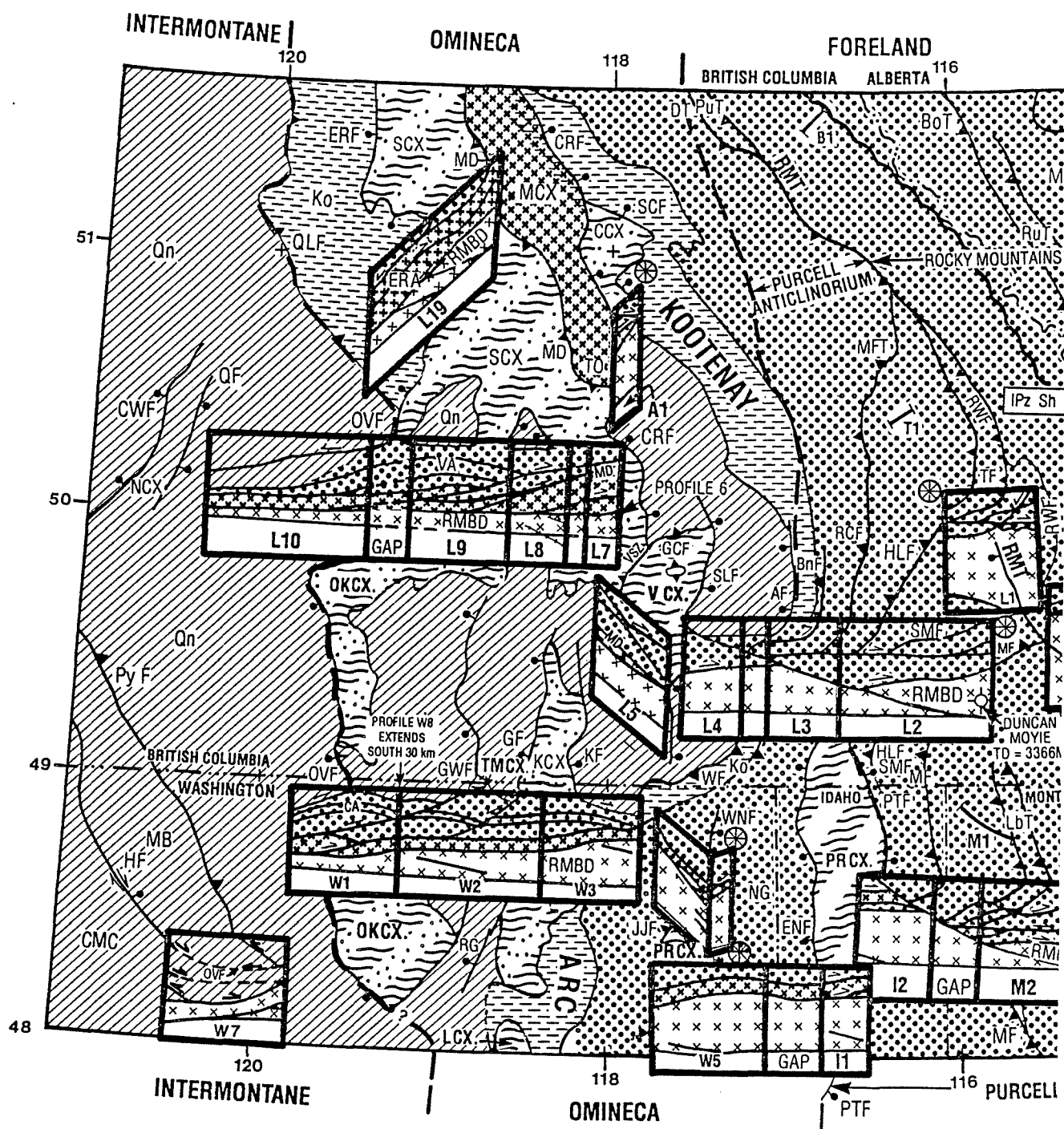


Figure 1 (left)

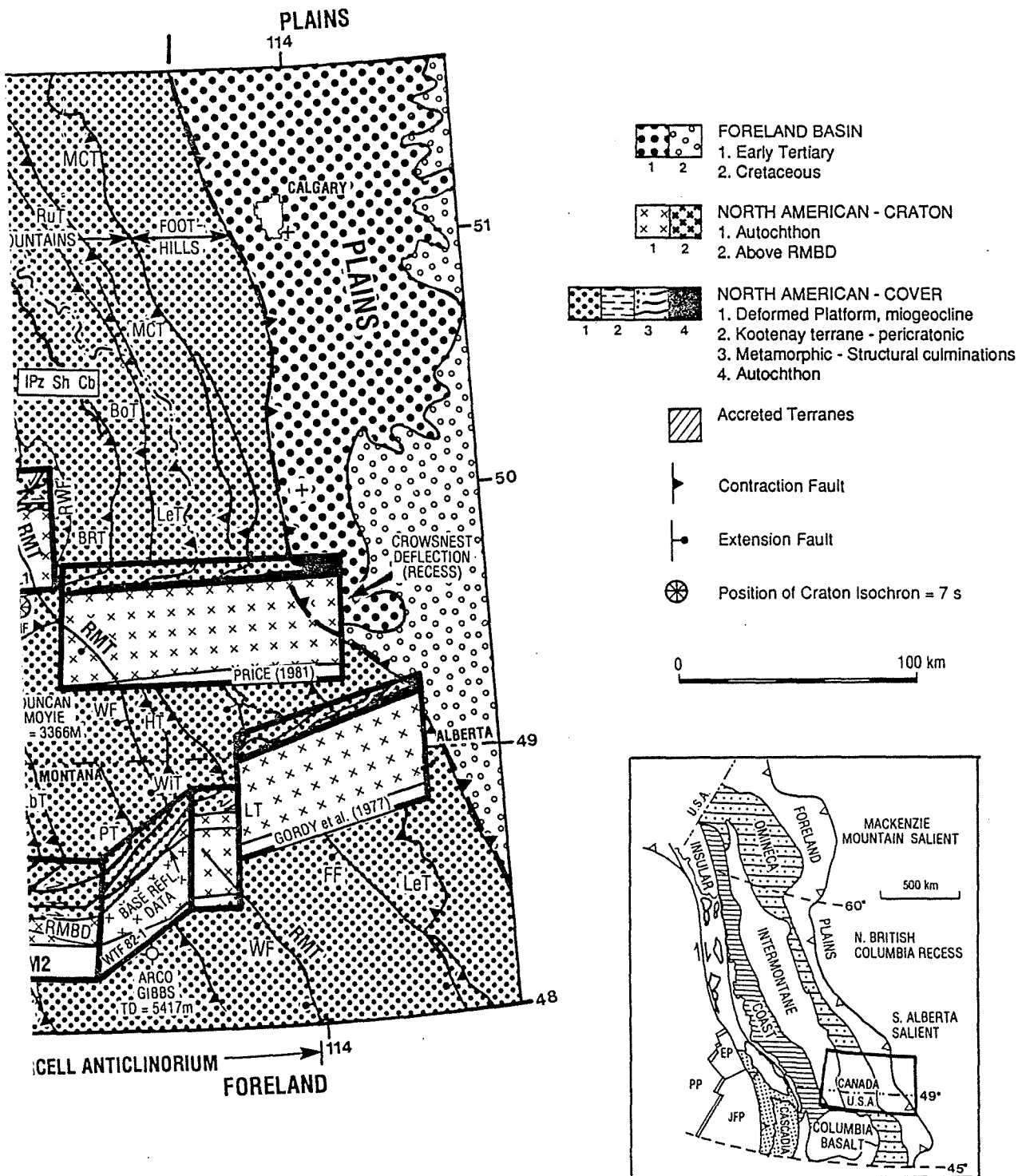


Figure 1 (right)

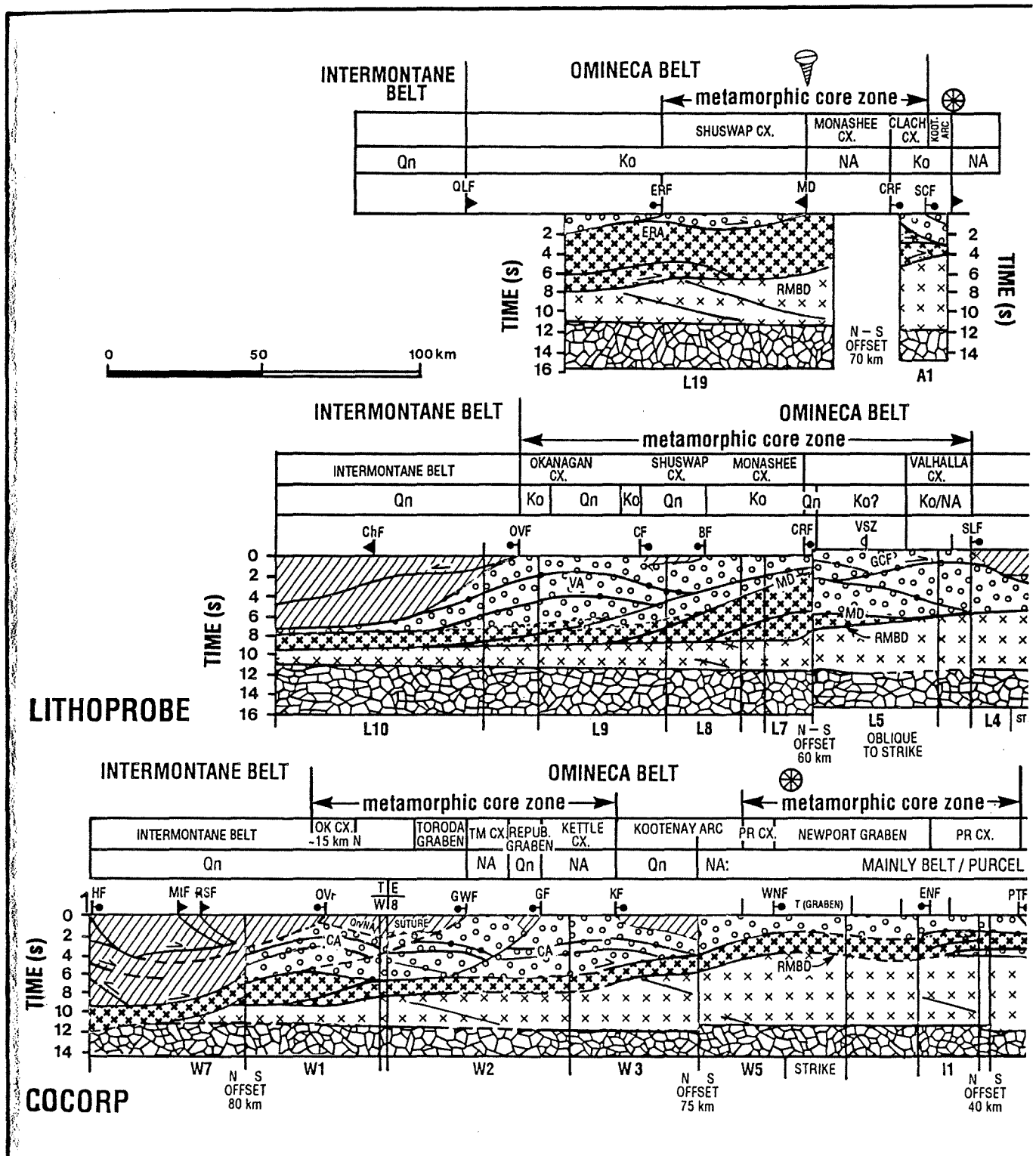


Figure 2 (left)

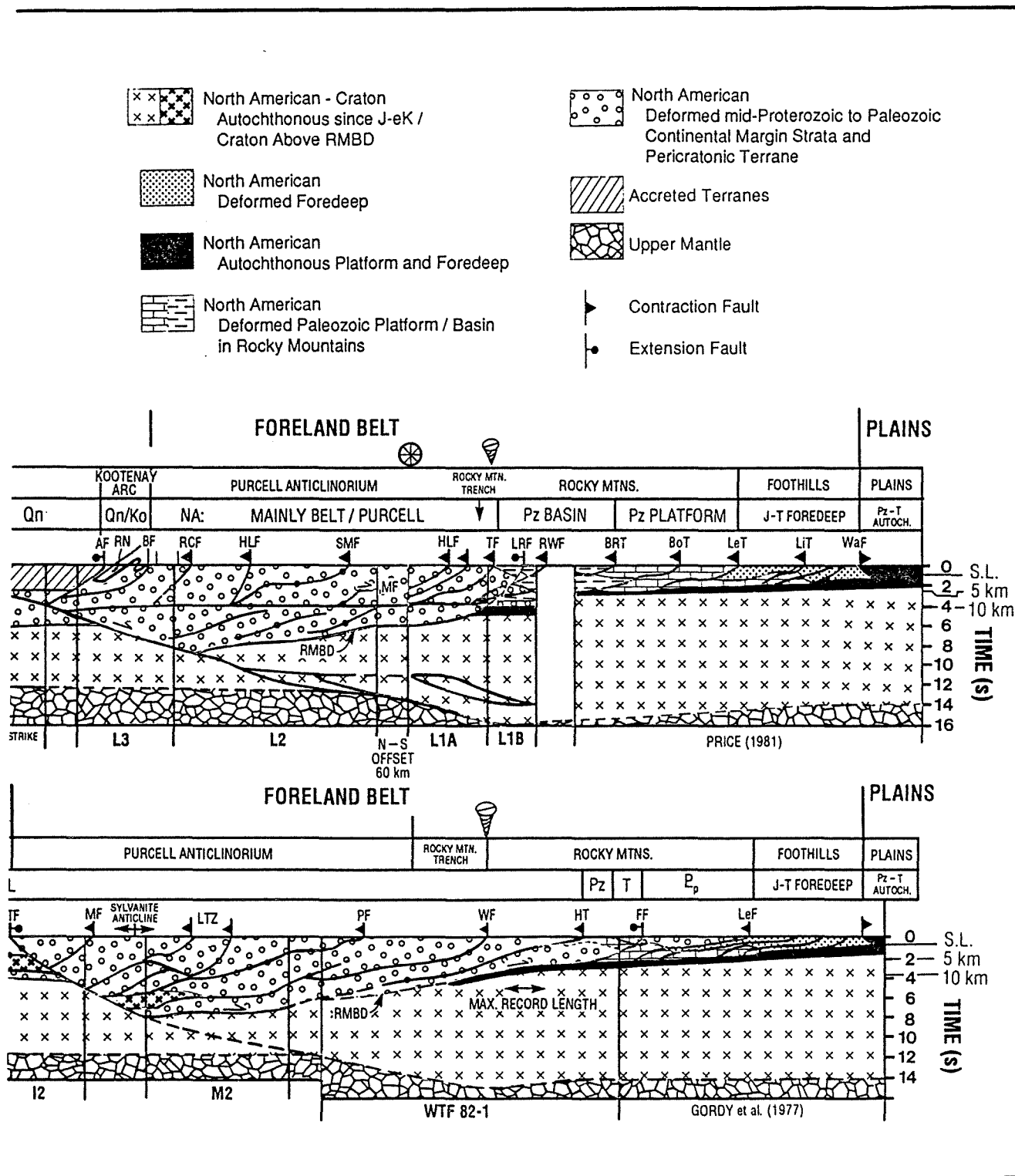
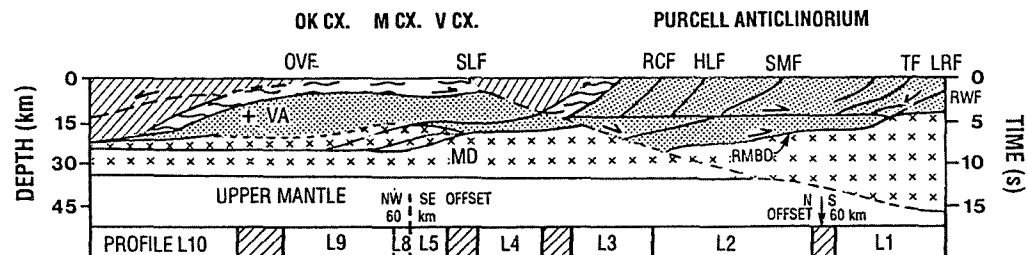


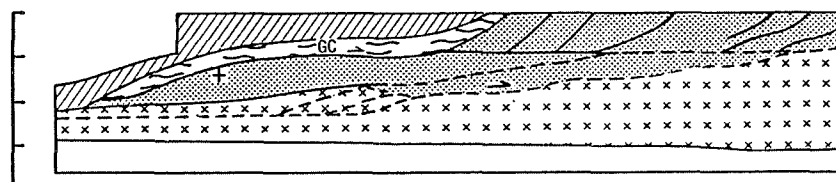
Figure 2 (right)

A. PRESENT

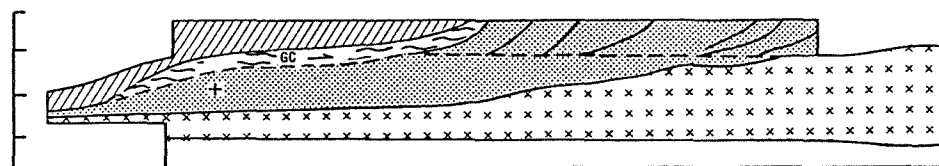


- North American Craton
- North American Passive margin sediments
- Kootenay Terrane Pericratonic
- Accreted Terranes

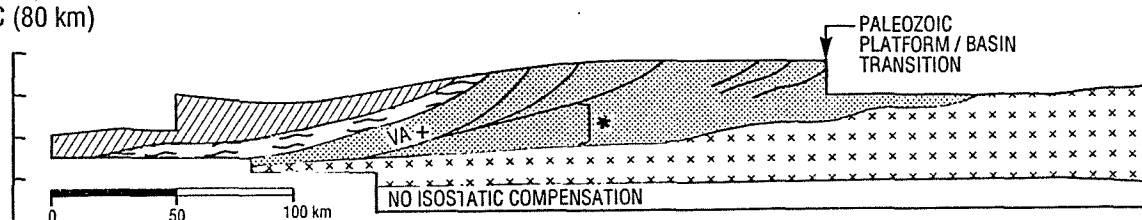
B. PALEOCENE
SLF (30 km)
OVE (50 km)



C. LATE CRETACEOUS
Basal Faults (80 km)



D. LATE CRETACEOUS
GC (80 km)



PALEOZOIC
PLATFORM / BASIN
TRANSITION

* PROPOSED FOOTWALL
COUNTERPART TO THE
PURCELL ANTICLINORIUM

Figure 3

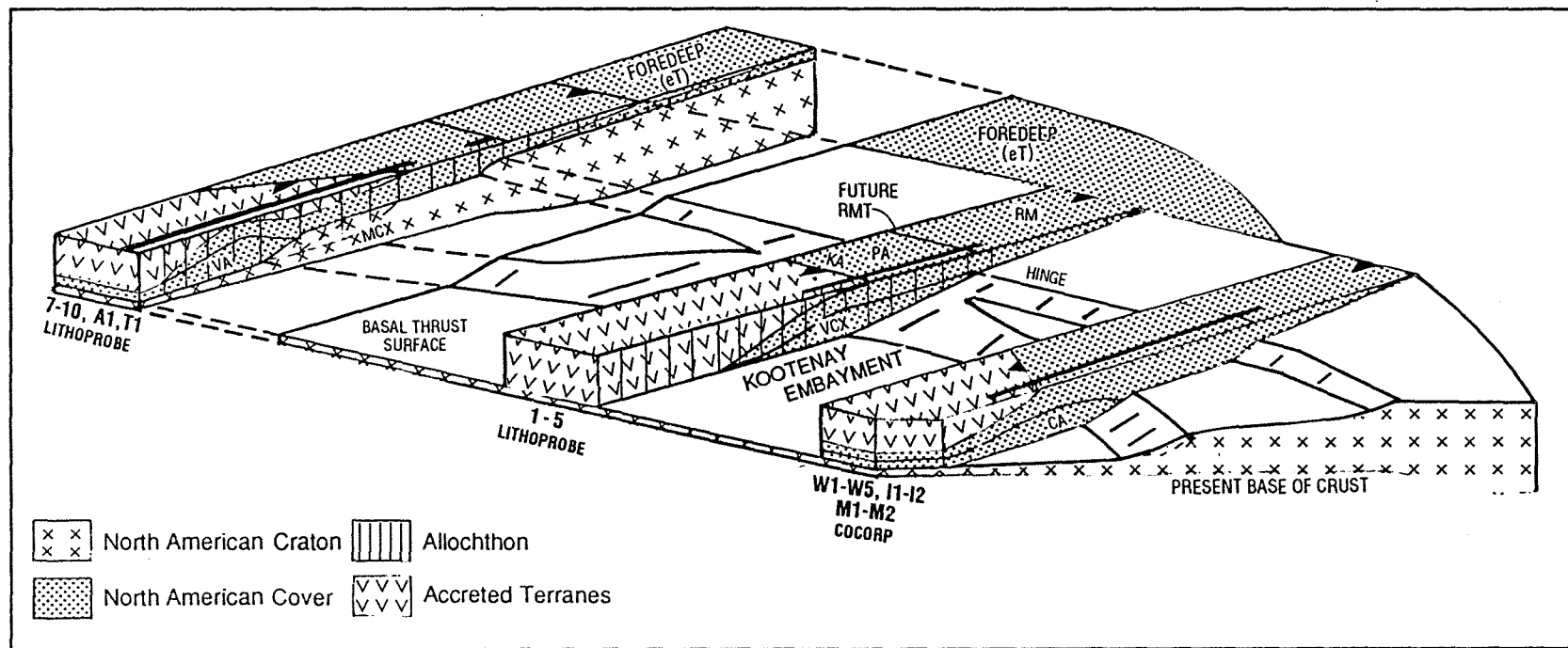


Figure 4

EARLY AND MIDDLE EOCENE CRUSTAL STRETCHING IN THE SOUTH-
CENTRAL CANADIAN CORDILLERA: PASSIVE UPPER CRUSTAL
RESPONSE TO DUCTILE BOUDINAGE OF THE LOWER CRUST ABOVE A
FLUID UPPER MANTLE

Raymond A. Price
Department of Geological Sciences
Queen's University
Kingston, Ontario

Early and Middle Eocene stretching of the continental crust in the southern Canadian Cordillera involved ductile boudinage of the lower continental crust above an apparently fluid upper mantle, and passive brittle stretching of the upper crust over the lower crustal boudins. The direction of stretching was inclined at 45 degrees to the axis of crustal thickening during the preceeding late Mesozoic and Paleocene interval of terrane convergence, and therefore, it cannot be ascribed to gravitational collapse of tectonically thickened continental crust. However, it can be linked to large-scale, right-lateral, strike-slip displacements between the North American craton and the Cordilleran accreted terranes.

LITHOPROBE seismic reflection imaging has shown that mylonite zones marking extension faults on the flanks of structural culminations that expose lower crustal rocks, can be traced into zones of sub-horizontal shear at middle to lower crustal depth. It also has shown that beneath the horizontally stretched middle and upper continental crust, along which there is more than 20 km of surface structural relief, the Moho is almost horizontal. It rises less than 5 km from about 12.0 s (two-way-travel time) on the east, beneath the Monashee and Valhalla complexes, to about 10.5 s on the west, near the Fraser River fault zone.

Horizontal stretching of upper crustal rocks has been greatest above the structural culminations, which have been exposed by lateral downward displacement of their supracrustal cover. In contrast, horizontal stretching of

lower crustal rocks has been greatest beneath the structural depressions, in which the displaced supracrustal rocks have accumulated. Stretching of the upper crust and the lower crust are both strongly inhomogeneous, but they are completely complementary. Inhomogeneous crustal stretching has produced a crustal section of almost uniform thickness between the Fraser River fault zone and the Monashee and Valhalla complexes.

The near horizontal configuration of the interface between the continental crust and the upper mantle appears to have been produced by the horizontal extension. It represents a fluid equilibrium configuration that implies homogeneous ductile (fluid) deformation of the upper mantle during inhomogeneous plastic and brittle horizontal stretching of the lower crust and upper crust respectively.

On a regional scale, the crustal stretching has produced a series of north-northeast trending structural culminations (crustal boudins) and depressions (neck zones) that are 20 - 40 km wide and 100 - 300 km long. These trend north-northeast across the south-central Canadian Cordillera, and intersect the northwest trend of the late Mesozoic and Paleocene compressional structures, and the axis of crustal thickening in the southeastern Canadian Cordillera at about 45 degrees. The direction of stretching recorded by tectonite fabrics in the Early and Middle Eocene fault zones is generally perpendicular to the trend of the culminations and depressions.

The regional pattern of east-southeast horizontal stretching outlined by both the small-scale and the large-scale structures shows that the stretching was oblique to the horizontal compression and crustal thickening that preceded it. Thus the horizontal stretching cannot be explained in terms of gravitational collapse of tectonically thickened continental crust; however, it can be linked to large-scale, right-lateral, strike-slip displacements between the North American craton and the Cordilleran accreted terranes.

Radiometric dating of deformation in the Monashee décollement zone, in the core of the Monashee complex, shows that this northeast-verging

compressional structure was active until the beginning of Eocene time, just before the onset of the crustal extension. Most of the faults and the tectonite fabrics within the Monashee complex (and presumably within the other structural culminations as well) formed during compressional deformation, prior to the onset of the horizontal crustal stretching. The preservation of these older structures and tectonite fabrics within the culminations precludes the possibility that the culminations formed by lateral flow of a fluid lower crustal layer from structural depressions into structural culminations, as suggested, for example, by Wernicke (1991).

The radiometric dating of northeast-verging thrust displacement on the Monashee décollement as latest Paleocene implies that the Monashee décollement is the tectonically unroofed and isostatically uplifted western part of the same regional décollement that extends under the foreland thrust and fold belt to the eastern edge of the Rocky Mountain Foothills belt, because northeast-verging displacement on the Monashee décollement was contemporaneous with, and fed into, the northeast-verging thrusting along the regional décollement that occurred during the last stages of the development of the structures of the eastern Foothills. The regional décollement of the foreland thrust and fold belt is presently 10 to 15 km deep under the Rocky Mountain trench and the eastern Purcell Mountains. It probably was as much as 10 km deeper in the Early Eocene, prior to later Tertiary erosion and isostatic uplift. Early and Middle crustal stretching of the upper crust above the Monashee complex probably removed about 25 km of upper crustal rock, inducing an en masse isostatic uplift of the lower crust, and the Monashee décollement, by about 20 km.

Basement ages in southern B.C. and the nearby parts
of the U.S.A., reviewed.

R. St J. Lambert and V. E. Chamberlain

Dept of Geology, University of Alberta, Edmonton, T6G2E3
Dept of Geology, University of Idaho, Moscow, ID, 83843

The correlation of the basement, meaning essentially the pre-Belt/Purcell PreCambrian, from the area east of the Rockies to the west thereof, is as yet far from resolved. The review by Armstrong et al., 1991 (Canadian Journal of Earth Sciences, 28, 1169-1201), goes some way towards giving an answer, but several loose ends remain. In general, the Cordilleran basement is polymetamorphic, and much appears to have a sedimentary parentage. Thus the Rb-Sr and Sm-Nd systems are probably of open-system character, in many cases quite definitely so, and initial ratios, so necessary for isochrons, will be highly variable. Where the host gneisses do appear to have an igneous character, even zircon ages may not be true igneous crystallization ages, as there is often evidence of partial melting, which may, or may not, have the correlative of re-setting the U-Pb system in zircon.

There are some fairly consistent patterns in the geochronological data. Rb-Sr isochrons (almost all actually being "scatterchrons") and Sm-Nd model ages (and occasional scatterchrons) usually give greater ages than the best zircon ages from the same rocks, and the model ages may be highly incorrect because of open-system behaviour. On this critical basis, we see three basement age provinces in the area between 53 and 43 deg. N., and west of the SRMT.

(1) In the north of this region there may be both Archean and 2300-2100 Ma units, though neither can be said to be proven. There are real ages around 2000 Ma, but ages less than 1900 Ma are confined to late intrusives in the Malton block, but these are widespread in that particular basement and set it apart from all others.

(2) The central area, from about 50 to 48 deg. N., contains no rocks which are certainly older than 1900 Ma., from either the published or our own data as reported in previous Cordilleran workshops. The basement gneisses are of controversial origin and uncertain history: many clearly belong to the group that has suffered partial melting and partial re-setting of isotopic systems. The best ages of primary rock-formation are in the range 1900-1700 Ma.

(3) South of 48 deg., that is to the south of the Lewis and Clark line, or the northern limit of the Columbia River Basalt Group, all basement units so far dated are in the range 1700-1400 Ma as far south as the Snake River Plain, where Archean ages are hinted at.

If this tripartite subdivision of major crust-forming events is sustained by further work and is correct, correlation with the shield to the east is not possible, at least by the conventional drawing of north-east trending boundaries.

ORIGIN OF THE PACIFIC OCEAN: PRE-PANTHALASSA PLATE RECONSTRUCTIONS CONSTRAINED BY PROVENANCE STUDIES

Gerald M. Ross, Geological Survey of Canada, 3303-33rd St. N.W., Calgary, Alberta T2L 2A7
Randall R. Parrish, Geological Survey of Canada, 601 Booth st., Ottawa, Ontario K1A 0E8

The timing and geometry of continental break-up that led to the formation of the proto-Pacific (Panthalassa) ocean is a long-standing controversy. Recent models suggest that a composite of Australia and Antarctica lay offshore of western North America (Laurentia) during the Middle Proterozoic (ca. 1500-1200 Ma). In order to test this postulation we have examined the ages and isotopic characteristics of detrital minerals within the Middle Proterozoic Belt-Purcell Supergroup. Recent stratigraphic studies provide strong evidence for an intracratonic origin for the Belt basin with a tectonically active western margin, thus suggesting sediment derivation from the west, a region that now lies outboard of the $Sr_1=0.706$. We have dated individual detrital zircon, monazite, and xenotime grains from westerly-derived clastic units, and obtained Sm-Nd isotopic data when possible on the same grains. Most U-Pb data are essentially concordant; exceptions are noted below. The results are as follows:

The Revett Fm. (Ravalli Group, lower Belt) contains grains with ages of 1590-1600 Ma and a discordant grain with $^{207}Pb/^{206}Pb$ age of 1780 Ma: the ca. 1600 Ma age is very unusual in North America and effectively dates the "Belt Island", long postulated to be the Revett source in southeast Washington and northeast Oregon. Detrital zircons from the Missoula Group (Bonner and Mt. Shields formations; upper Belt Supergroup) form a distinct group at 1.67-1.86 Ga with two ca. 2.6 Ga grains. U-Pb ages from monazite range from 1.64-1.79 Ga, and together with Nd isotopic data (T_{DM} model ages of 2.05-3.36 Ga) suggest variable interaction with previously differentiated crust. The Buffalo Hump Fm. in northeast Washington is considered correlative with the Bonner Fm. and contains detrital zircons of ca. 1840 Ma and, surprisingly, 1070-1244 Ma (several grains). Monazites have U-Pb ages 1753-1774 Ma and Nd signatures similar to the Bonner data.

Several major conclusions can be drawn from these data. 1590-1600 Ma ages have no known possible source within North America (although 1576 Ma augen gneiss is present in the Priest River Complex), and 1.64-1.75 Ma ages are uncommon to rare in Precambrian rocks to the immediate south and east; together these data confirm previous Sm-Nd whole rock and stratigraphic conclusions of a western source for the Belt basin. The ages in the Buffalo Hump Fm. indicate that the top of the Belt Supergroup may be substantially younger (<1070 Ma) than previously inferred (1250 Ma) if the Buffalo Hump is indeed part of the Belt Supergroup. Finally these data help to constrain pre-Paleozoic plate reconstructions; from the 1590-1600 and 1645-1750 Ma source ages and related Nd data we suggest that the basement blocks of southcentral Australia (Gawler, Musgrave and Willyama) were joined to the western side of Laurentia, adjacent to the Belt basin, prior to Late Proterozoic formation of the Panthalassa Ocean.

Geochemical Studies of Syntectonic Fluids Along the Southern Cordilleran Lithoprobe Transect

Nesbitt, Bruce E. and Muehlenbachs, Karlis, Dept. of Geology, University of Alberta, Edmonton, Albt. T6G 2E3.

INTRODUCTION

The original objectives of our southern Cordilleran Lithoprobe research program were to 1) Document the origins of crustal fluids, 2) Examine the evolution of crustal fluid chemistry, 3) Examine the effects of regional structure on fluid movement, 4) Document the effects of crustal fluids on the geochemistry of the rocks, 5) Determine the relationships between regional crustal fluids and metalliferous mineralization. We believe that we have been very successful in meeting these objectives and in the process, discerned several previously unsuspected aspects and phenomena involved in syntectonic hydrogeological regimes. In addition, we have demonstrated the substantial benefits which can be obtained from regional mapping of geochemical phenomena for information on the origins, movement and evolution of crustal fluids. Also during the course of the study, we have improved, refined and expanded procedures for the investigation of the effects of crustal fluids - procedures which are currently being applied to similar studies associated with the Alberta Transect and hopefully, will be applied in studies along the 60° North Transect.

RESULTS OF GEOCHEMICAL INVESTIGATIONS

Over the four years of the project, approximately 800 samples of quartz-carbonate vein material and other rocks have been collected throughout southern B.C. These samples have been analysed for information on fluid inclusions and oxygen, carbon and hydrogen isotopes. Sr isotopic analyses are in progress. In addition, the funding has been used to partially support the research of three M.Sc. students and a post-doctoral fellow.

Oxygen Isotope Results

Approximately 400 $\delta^{18}\text{O}$ values have been determined on samples of vein quartz and carbonate, whole rock samples, and mineral separates. Values for vein quartz typically range from 10 to 18 ‰ (SMOW). The values in general reflect regional $\delta^{18}\text{O}$ patterns with lower values, 10 to 15 ‰, coming from veins in regions dominated by igneous rocks and higher values coming from areas with a larger component of sedimentary rocks. Whole rock $\delta^{18}\text{O}$ values are typically in the range of 6 to 12 ‰ for metaigneous rocks and 8 to 28 ‰ for metasedimentary rocks.

There are three prominent exceptions to the generalizations above, where $\delta^{18}\text{O}$ values are considerably less than average values.

1. Eocene volcanics and quartz veins covering an area of approximately 100 km² around and to the west of Okanagan Falls yield anomalously low $\delta^{18}\text{O}$ values of -2 to 4 ‰. Two major epithermal Au-Ag occurrences (Dusty Mac and Vault) are contained within this region. Veins and whole rock samples from these deposits yield similarly low $\delta^{18}\text{O}$ values.

2. Gneissic and plutonic units associated with the Slocan, Valhalla and Okanagan extensional faults yield low $\delta^{18}\text{O}$ values of -2 to 5 ‰, even though the rocks do not show distinct evidence of low temperature alteration. In addition, low $\delta^{18}\text{O}$ syenites of the Arrow Lake region may indicate the existence of a significant fault in this region as well.

3. Approximately half of the exposed volume of carbonate units in the Rockies from Canal Flats to Jasper have undergone a major depletion in $\delta^{18}\text{O}$ to the extent that $\delta^{18}\text{O}$ values have been reduced by 5 ‰ or more.

All three of the examples cited above indicate interaction of the rock units with large volumes of low $\delta^{18}\text{O}$ meteoric water. Due to the areally extensive nature of the low $\delta^{18}\text{O}$ carbonates in the Rockies, this low $\delta^{18}\text{O}$ region documents the largest volume of fluid-rock interaction. The low $\delta^{18}\text{O}$ gneisses associated with the extensional faults record the deepest penetration of surface fluids, since the alteration event did not substantially alter the gneissic mineralogy. The low $\delta^{18}\text{O}$ values associated with the epithermal deposits indicates the economic significance of the convection of meteoric water.

Carbon Isotope Results

A strong lithologic control is observed in the distribution of $\delta^{13}\text{C}$ values of vein carbonate throughout the southern Cordillera. In Phanerozoic units of the Rockies, $\delta^{13}\text{C}$ values for vein carbonate vary from -3 to 1 ‰, reflecting the large carbonate component of these units. In the Proterozoic units of the Miette in the Rockies, $\delta^{13}\text{C}$ values are substantially lighter, -7 to -15 ‰, indicating a significant component of organic carbon. Near Lake Louise, $\delta^{13}\text{C}$ values of vein carbonate rise to the -3 to 0 ‰ range, reflecting an influx of fluids from Phanerozoic units.

West of the Rocky Mountain Trench, $\delta^{13}\text{C}$ values of vein carbonates in the Proterozoic units are similar to those observed in the Miette with most values at -5 ‰ or lower. Further west $\delta^{13}\text{C}$ values are generally in the -3 to -10 ‰ range with higher values near carbonate units and lower values near major faults.

Hydrogen Isotope Results

Vein quartz in the Phanerozoic units of the Rockies consistently yields fluid inclusion δD values less than -110 ‰ indicating the derivation of these fluids from meteoric waters. This observation is consistent with the results obtained from the $\delta^{18}\text{O}$ studies. In the Proterozoic units, an early vein event is characterized by δD values in the -40 to -80 ‰ range, which is indicative of a fluid origin from metamorphic devolatilization. A second, cross-cutting vein set records the influx of surface fluids with δD values of -120 ‰ or less.

In the greenschist facies, upper plates of the southern Omineca extensional complex and in the region around the Fraser Fault, δD values of inclusion fluids record the widespread convection of surface fluids to depths of 10 km or more. Even in amphibolite facies gneisses of the Omineca, δD values of both inclusion fluids and hydrous silicates record the influx of surface fluids. Further north in the Omineca beyond the influence of the extensional system, δD values of inclusion fluids indicate the involvement of metamorphic devolatilizational fluids in the Jurassic, compressional evolution of this region.

The δD results of this study are particularly important since they are among the first definitive evidence for the large scale circulation of meteoric water during regional tectonic processes and document the fact that many "metamorphic" quartz veins are in fact formed from deeply convected surface fluids.

The economic implications of these results are also significant since it has been shown in this study that mesothermal Au-quartz veins in the Canadian Cordillera are invariably formed from convected surface fluids. Correspondingly, none of the regions where metamorphic devolatilizational fluids dominated have any indication of the development of Au mineralization.

Fluid Inclusion Studies

The results of fluid inclusion studies of the veins indicate widespread regional homogeneity in fluid characteristics and distinctive differences between regions, which are summarized below:

Rocky Mountains: Homog. T = 100 - 200°C, < 7 eq.wt % NaCl, No CO_2

Purcell-Kootenay Arc: Homog. T=250-350°C, 5 to 16 eq.wt.% NaCl, 5 to 20 mole % CO₂
Kootenay Arc: Significant CH₄ in addition.

Omineca: Homog. T = 250 to 350°C, < 7 eq.wt % NaCl, 5 to 20 mole % CO₂

Fraser Fault Region: Homog. T = 250 to 350°C, < 7 eq.wt % NaCl, 5 to 20 mole % CO₂

In addition, vein style, epigenetic mineralization within each of these regions has been found to possess inclusion characteristics that are similar to those of the regional veins. This observation indicates that vein type mineralization is in general a product of regional hydrogeological processes.

DISCUSSION

Throughout the project, numerous correlations have been observed between the various geochemical studies and the seismic results. The most distinctive correlations are the low $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values observed for vein quartz and carbonate near the extensional faults.

More regionally, distinctive hydrogeological regimes can be identified and correlated with the results of the seismic profiles. In compressional-thrust regimes, vertical permeability is limited leading to horizontally extensive, fluid-rock interactions, which generally have limited vertical extents. In addition at deep levels in thrust systems, metamorphic devolatilizational fluids become volumetrically important in the syntectonic fluids. In vertically fractured regimes (Omineca extensional complex; Fraser strike-slip Fault), vertical movement of fluids is facilitated leading to deep influx and convection of surface fluids.

As interesting as the results of the southern Cordilleran geophysical-geological study have been, there is still a clear need for a second transect farther north in the Cordillera. Much of fluid regime of the southern Cordillera is dominated by hydrogeological processes associated with the Omineca extensional complex. Consequently, only in relatively isolated locations can fluid regimes associated with accretion of the exotic terranes be investigated. The 60°N Transect would provide an extremely useful, complementary opportunity to document syntectonic fluid regimes without the interesting but obscuring overprint associated with the development of the Omineca Core Complex.

LITHOPROBE RELATED PUBLICATIONS

- Nesbitt, B.E. and Muehlenbachs, K., 1991 Stable isotopic constraints on the nature of the syntectonic fluid regime of the Canadian Cordillera: Geophysical Research Letters, v. 18 p. 963-966.
- Nesbitt, B.E., and Muehlenbachs, K. in preparation, Syntectonic Fluid Regimes of the Southern Omineca
- Nesbitt, B.E., 1991, Synorogenic hydrogeological regimes in the Canadian Cordillera and their impact on the formation of ores by igneous processes: Japan-U.S. Cooperative Science Program: Magmatic Contributions to Hydrothermal Systems, P. 107-109.
- Nesbitt, B.E., 1991, Accretion, crustal hydrogeology and the generation of epigenetic ores in the Canadian Cordillera: Geol. Soc. Amer., Program with Abstracts, v. 23, p. A21
- Nesbitt, 1990, Mesothermal lode gold deposits of the Canadian Cordillera: Geological Assoc. Canada, Program with Abstracts, v. 15 p. A95.
- Nesbitt, B.E., and Muehlenbachs, K., 1990, Synorogenic fluid regimes of the southern Canadian Cordillera: Lithoprobe Cordilleran Workshop 1990, p. 58-63.
- Nesbitt, B.E., and Muehlenbachs, K., 1990, Fluid origins and movement during the tectonic evolution of the southern Canadian Cordillera: AGU Chapman Conference on Crustal Scale Fluid Transport Magnitude and Mechanisms.

- Nesbitt, B.E., and Muehlenbachs, K., 1989, Origins and movement of fluids during deformation and metamorphism in the Canadian Cordillera: *Science*, v. 245, p. 733-736.
- Nesbitt, B.E., 1989, Origin of metamorphic fluids in the Canadian Cordillera and their relation to the genesis of mesothermal gold deposits: *Int. Geol. Correlation Program*, Project No. 291, Organizational Meeting, Vienna Austria
- Nesbitt, B.E., and Muehlenbachs, K., 1989, Constraints on the depth of surface water convection during metamorphism and deformation in the Canadian Cordillera: *Geological Society of America*, v. 21, p. 85.

MAGNETOTELLURIC SOUNDINGS, STRUCTURE AND FLUIDS
IN THE CANADIAN CORDILLERA

D. Ian Gough and Jacek A. Majorowicz

Department of Physics, University of Alberta
Edmonton, Alberta T6G 2J1

101 magnetotelluric (MT) soundings in the frequency range 0.016 - 160 Hz have been made by the University of Alberta group during the years 1982-1990, in the Cordillera between 50° and 54°N. This programme is complementary to the MT component of the LITHOPROBE Southern Cordillera Transect (SCT) in extending conductive structures along strike and enabling them to be mapped. Along the SCT the Phoenix data provide denser coverage and extend to lower frequencies, and thus to greater depths. Our frequency range penetrates into the middle to lower crust. At this Workshop we offer highlights from a forthcoming paper (Gough and Majorowicz 1992) which will appear in CJES in April 1992.

The MT sounding programme began with the knowledge, from magnetometer array studies, that much of the crust of the region is electrically highly conductive. Fig. 1 shows the known extent of the Canadian Cordilleran Regional (CCR) conductor in relation to the five tectonic belts. Fig. 2 shows our sounding sites, on a simplified geological map showing Tertiary basalts, Mesozoic intermediate volcanics, Jurassic/Cretaceous plutonics, Paleozoic to early Tertiary granitoid plutonics, and Archean to Paleozoic gneisses. Major faults (Fraser, Yalakom, Rocky Mountain Trench) are shown. The map locates three transects across the Intermontane and Omineca belts for which we discuss crustal structure in terms of electrical resistivity.

All phases and apparent resistivities discussed in this paper are those of the Berdichevsky determinant impedance Z_{det} . Fig. 3 shows phase pseudosections along the transects AB, EF and GH (Fig. 2). Low phases, shaded, indicate relatively resistive crust, which we associate with granitoid intrusive rocks having low fracture densities and thus low content of saline water (Majorowicz and Gough 1991). On this interpretation, each section shows granitoid rocks extending from the Coast Plutonic belt under a southwestern strip of the Intermontane belt, and a second belt of intrusions near the Intermontane-Omineca border. Highly conductive rocks, shown by high phases, lie beneath the intrusions and at all depths near the line of the Fraser Fault fracture zone. In Fig. 4 we present maps of phases at periods of 1 s and 10 s. These correspond roughly to upper crustal and midcrustal depths. The resistive plutonic rocks in the southwestern Intermontane belt are prominent in both maps.

Pseudosections of apparent resistivity for transects AB and EF resemble the corresponding phase pseudosections so as to show that static shift effects are not large. It is therefore reasonable to construct first-order resistivity-depth sections for these two transects. These are shown in Fig. 5. It is instructive to compare Figs. 3 and 5, to see how true depths in a section relate to $\log$ (frequency) in a pseudosection. Note the resistive masses, which we regard as batholiths, adjoining the Coast Plutonic Complex, covered by a thin skin of more conductive volcanics. Very conductive rocks occur at all depths in the Fraser Fault zone in transect EF, and near its northward projection in transect AB. Very conductive rocks lie beneath the Omineca belt in both transects. We attribute the high conductivity at all depths under the active faults to saline water in numerous fractures. In Fig. 6 we show the major fractures with shading to indicate high conductivities in the upper crust associated with some of them. Similar high conductivities through the crust are reported elsewhere for the Fraser Fault, from LITHOPROBE data

(Jones et al. 1992). The total picture is consistent with mantle upflow under the Intermontane and Omineca belts, as proposed by Gough (1986).

REFERENCES

- Gough, D.I., Mantle upflow tectonics in the Canadian Cordillera, *J. Geophys. Res.*, 91, 1909-1919, 1986.
- Gough, D.I. and J.A. Majorowicz, Magnetotelluric soundings, structure and fluids in the southern Canadian Cordillera, *Can. J. Earth Sci.*, in press (1992).
- Jones, A.G., R.D. Kurtz, D.E. Boerner, J.A. Craven, G.W. McNeice, D.I. Gough, J.M. DeLaurier and R.G. Ellis, Electromagnetic images of the Fraser River Fault system, *Geology*, in press (1992).
- Majorowicz, J.A. and D.I. Gough, Crustal structures from MT soundings in the Canadian Cordillera, *Earth & Planet. Sci. Lett.*, 102, 444-454, 1991.

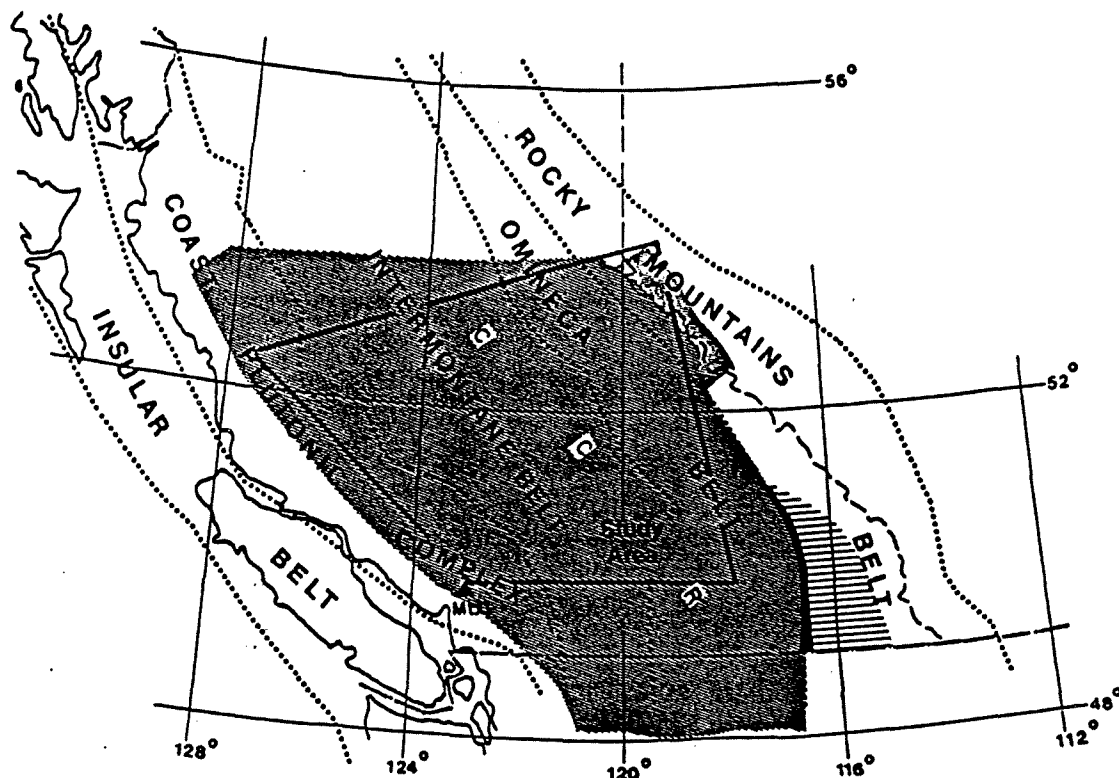


Fig. 1 The MT study area in relation to tectonic belts and the CCR conductor. This extends into the Rockies north of 52°N, and has its limit along the Kootenay Arc (heavy black line) from 49 to 51°N. The Purcell Geanticline is shaded.

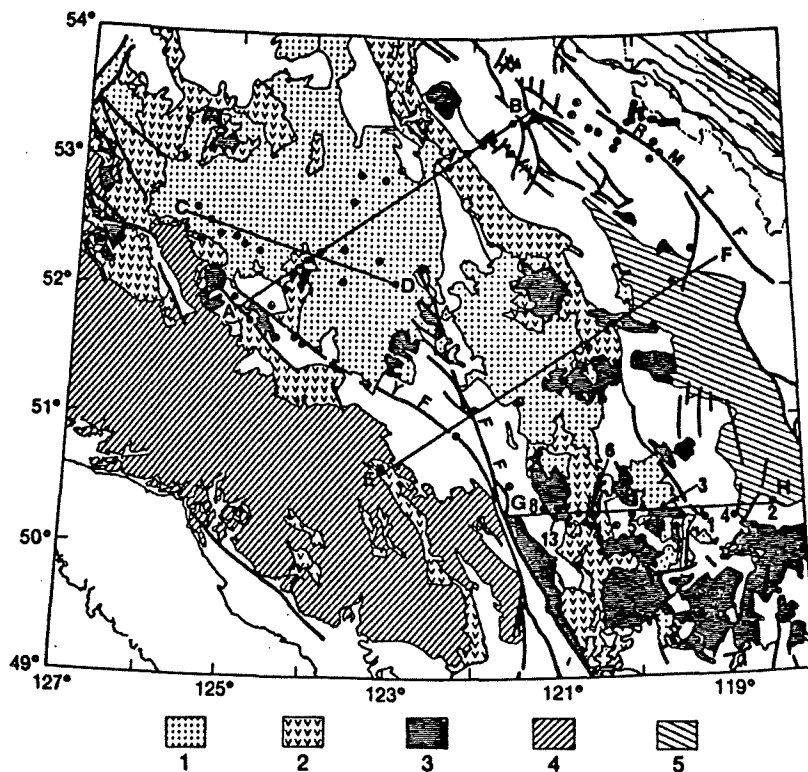


Fig. 2 Transects AB, EF and GH locate pseudosections in Fig. 3 and sections in Fig. 5. Dots show MT soundings. The simplified geology locates five rock types: 1: Tertiary and late Mesozoic basalts; 2: Mesozoic intermediate volcanics; 3: Jurassic/Cretaceous plutonics and ultramafics; 4: Paleozoic to early Tertiary granitoid intrusives; 5: Archean to Paleozoic gneisses. Major faults are shown. FF, Fraser River Fault; YF, Yalakom Fault; RMTF, Rocky Mountain Trench Fault.

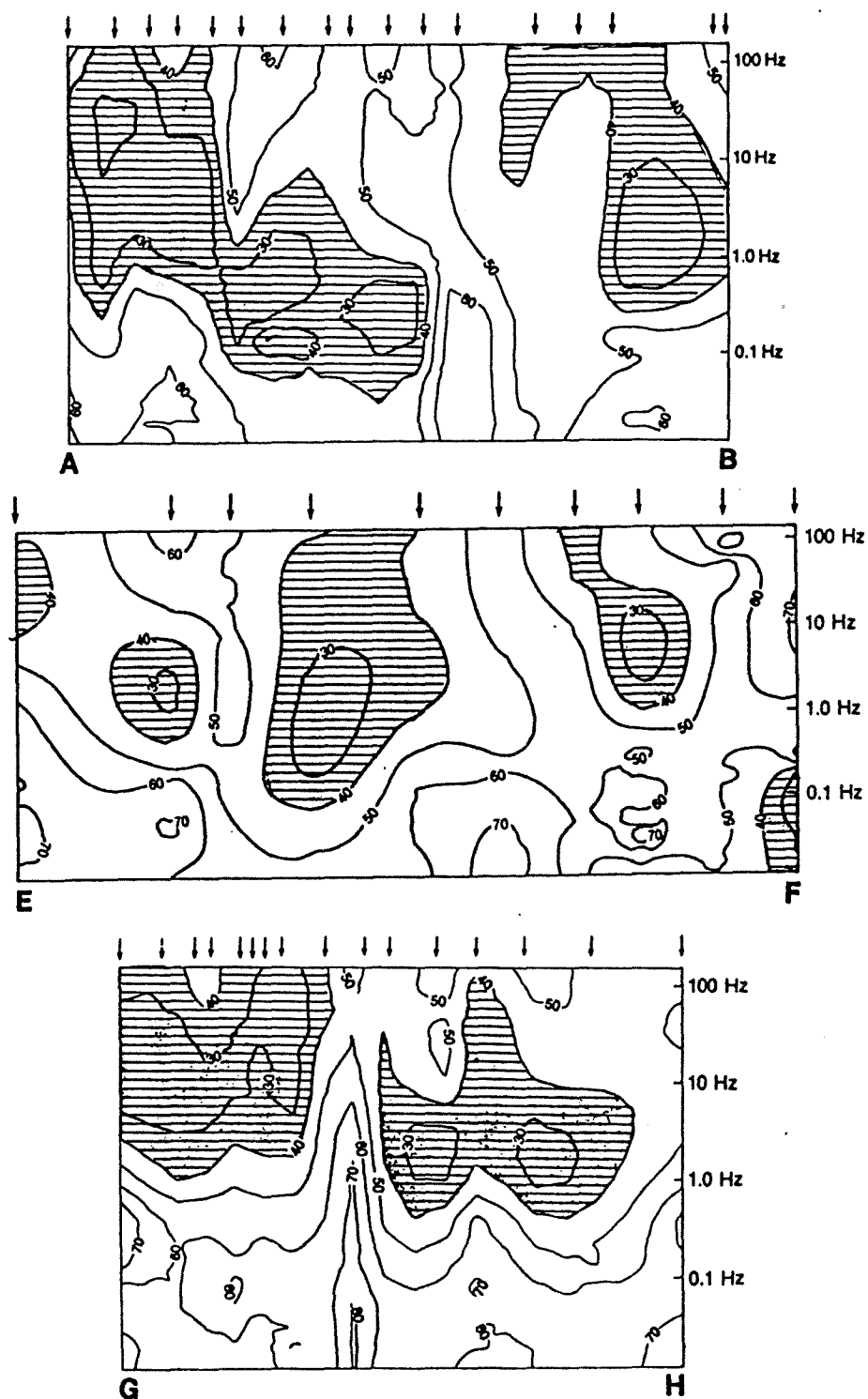


Fig. 3 Phase pseudosections for Z_{det} along transects AB, EF and GH, located in Fig. 2. Phases below 40° , corresponding to higher resistivities, are shaded. Arrows locate MT sounding sites.

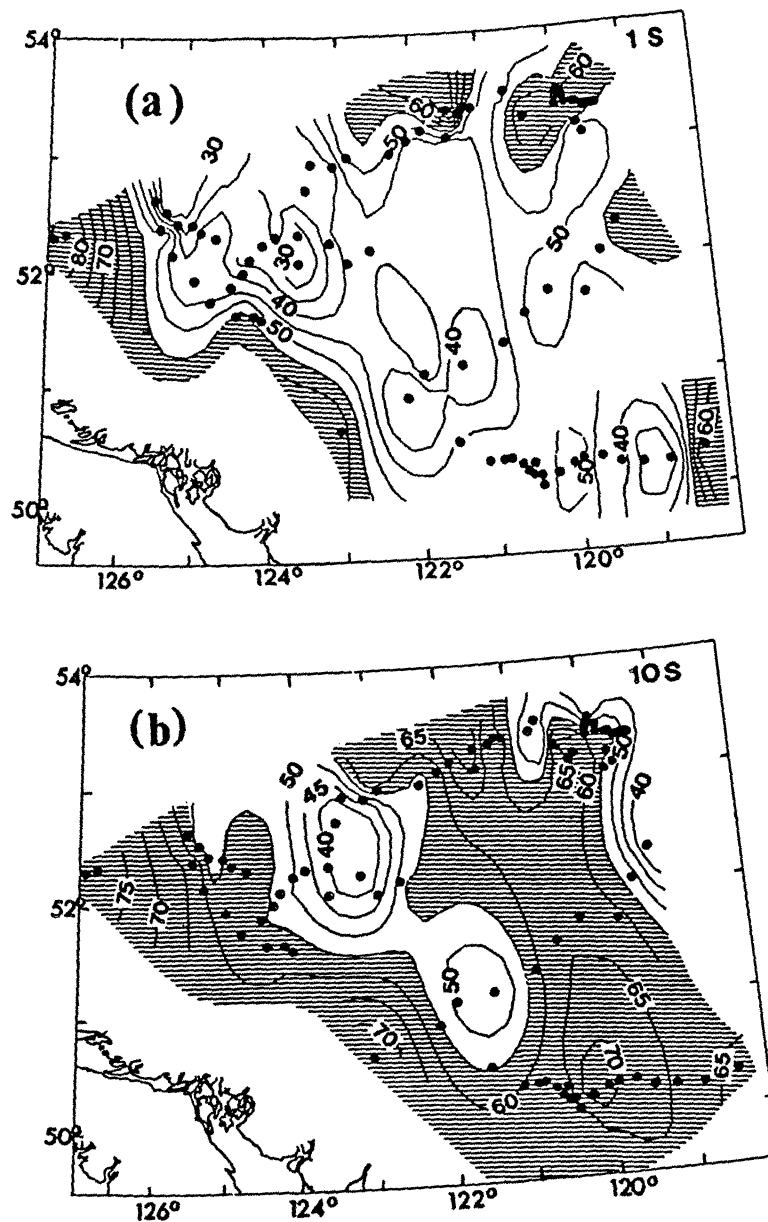


Fig. 4 Phase maps for periods 1 and 10 seconds (frequencies 1 and 0.1 Hz). Phases greater than 55°, indicating lower resistivities, are shaded.

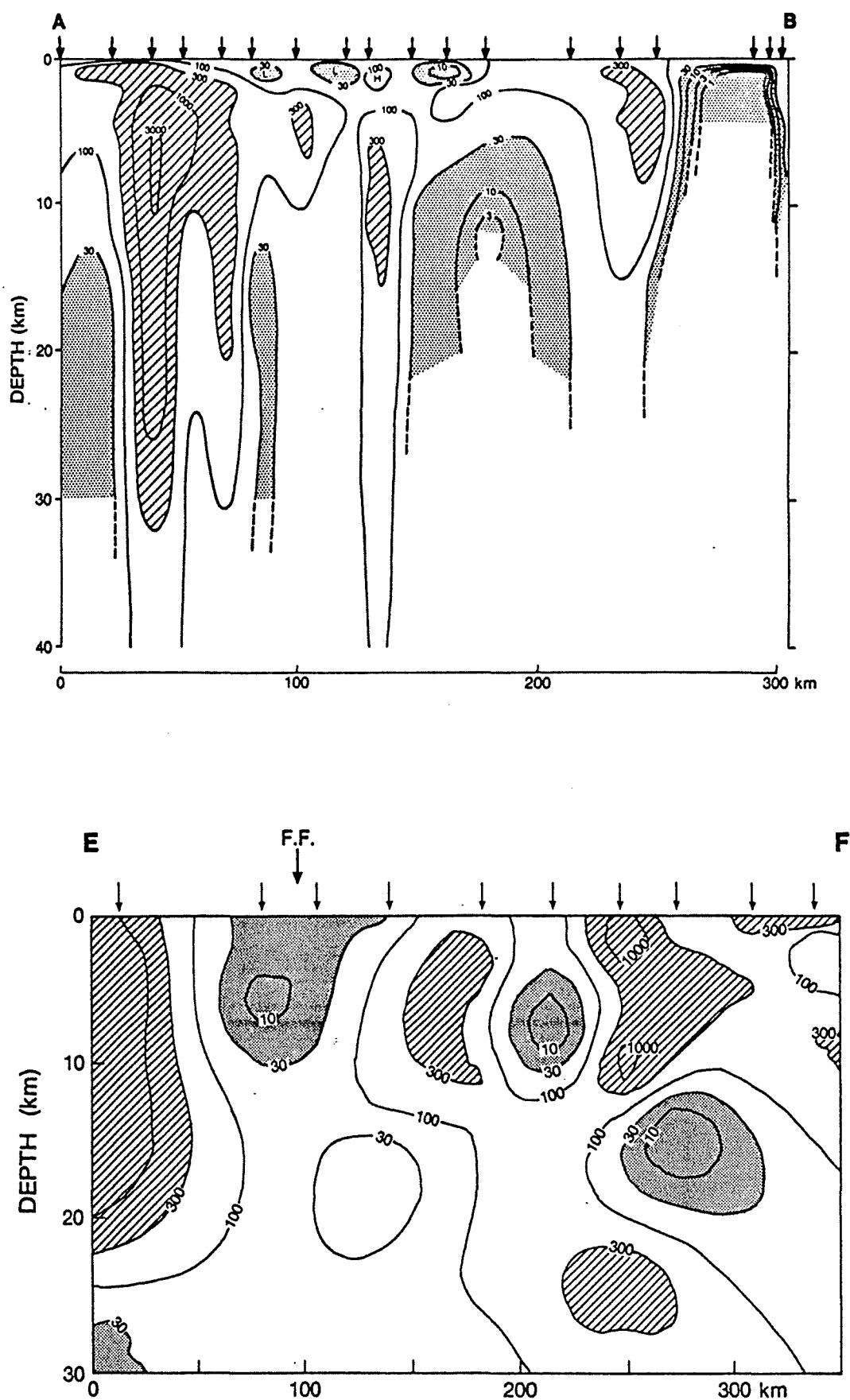


Fig. 5 Resistivity-depth sections along transects AB and EF (Fig. 2), from one-dimensional inversions at the sites shown by arrows. Line shading shows resistivities greater than 300 ohm.m, stippling less than 30 ohm.m.

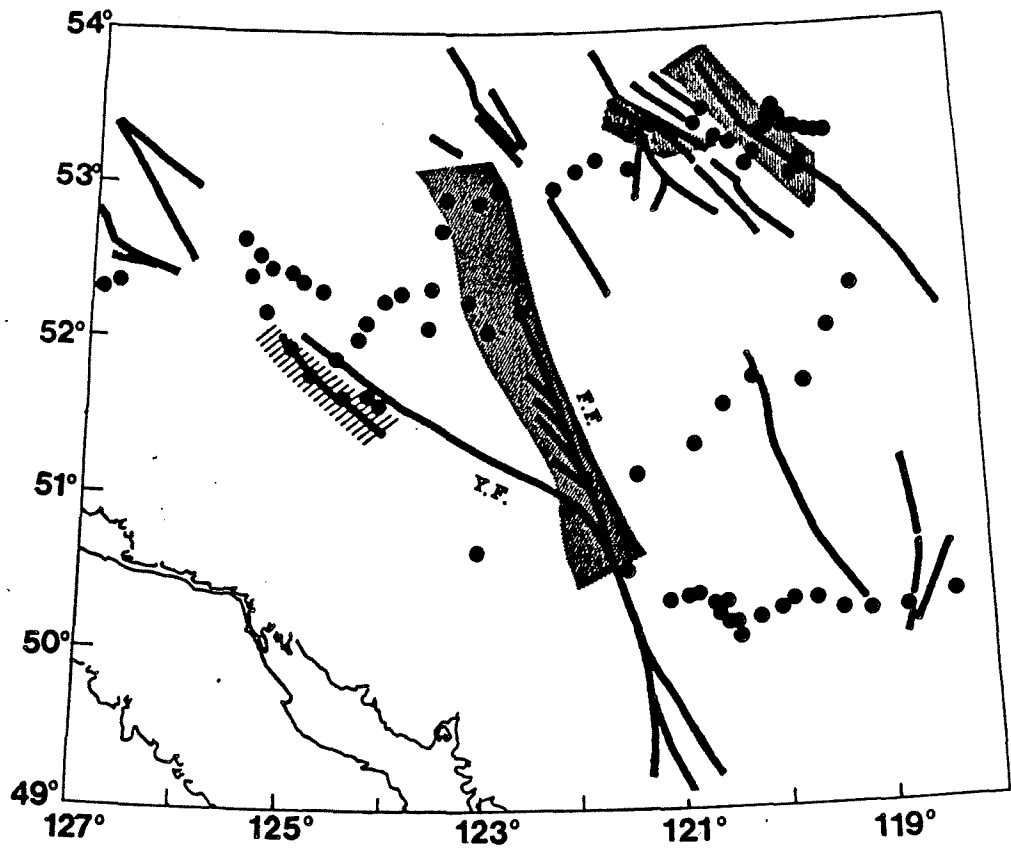


Fig. 6 Major faults and highly conductive zones in the upper crust. Heavy line shading shows resistivities less than 100 ohm.m, light shading about 300 ohm.m.

CORRELATION BETWEEN THE DEPTH TO THE LOWER-CRUSTAL HIGH CONDUCTIVITY LAYER AND HEAT FLOW IN THE CANADIAN CORDILLERA

J.A. MAJOROWICZ, D.I. GOUGH

Department of Physics, University of Alberta, Edmonton, Canada

T.J. LEWIS

Geological Survey of Canada, Pacific Geoscience Centre, Sidney, B.C., Canada

INTRODUCTION

Magnetotelluric (MT) soundings have been made across the Intermontane, Omineca and Coast Plutonic belts of the Canadian Cordillera between latitudes 50.0 and 53.5 deg. N. The study area is shown in Fig. 1a on a map of the tectonic belts in the Canadian Cordillera. The frequency range, 0.016 to 130 Hz, gives penetration into the middle to lower crust. The locations of the MT sites are shown on a map (Fig. 1b) outlining major faults and highly conductive zones of the upper crust (Gough and Majorowicz, 1991). In general a resistive upper crust is underlain by a zone of very high conductivity as shown by the magnetovariational deep soundings (see Gough 1986a for the references) and MT studies (Majorowicz and Gough (1991) and Gough and Majorowicz (1991)). Saline fluids in interconnected spaces in the middle to lower crust may account for the transition in conductivity as suggested by Gough (1986b), Kurtz et al, (1986, 1990) and Hyndman and Shearer (1989). The temperature range of 400 - 500 deg C was suggested first by Berdichevsky et al, (1972) and more recently by Jones (1987) as important for electrical conductivity in the crust. Lewis et al, (1988) and Lewis et al, (1991) showed that the 450. deg C isotherm coincides with the brittle-ductile transition in southern B.C. and also with the top of the electrical conductor found by Kurtz et al, (1986) across Vancouver Island. The position of the 400-500 deg. C or 450 deg. C isotherms in the Canadian Cordillera is controlled mostly by the surface heat flow since reduced heat flow is close to 60 mW/m² and the depth scale is 10 km (Lewis et al, 1985). To check the hypothesis that the 400-500 (450) deg. C isotherm coincides with the top of the mid-crustal electrical conductor we compared heat flow and MT results for the mid-lower crust. Such a correlation was investigated earlier by Adam (1978) for the global compilation of the data.

TOPOGRAPHY OF THE CONDUCTOR

The depth to the upper surface of this Canadian Cordilleran Regional (CCR) electrical conductor varies in the range of 10 km to 30 km at most sites as indicated by 1D inversions of the resistivities and phases in the available frequency range of 0.016 to 130 Hz at most sites and 0.0001 Hz to 130 Hz at eight sites (see Gough and Majorowicz, 1991). An example of the 1D inversion from one of the sites is shown (Fig. 2).

A contour map of the topography of the top of the regional electrical conductor is shown in Figure 3. This is based on 1D inversions for 42 of almost 100 of our soundings in the study area plus 1D inversions for the area from Kurtz et al, (1990) and from Jones et al, (1988). The data were selected to give a first-order picture of regional features free of static shift and 3D effects. The mean value of the depth to the top of the regional conductor is close to 20 km (SD=6.5 km) as shown by the statistical analysis. In general the upper crustal resistive layer is thickest in the north western part of the study area in the Intermontane Belt (20-30 km), and thinner

in eastern and south eastern B.C., in particular in the Omineca Belt (see Figure 3).

COMPARISON WITH HEAT FLOW

The analyses of MT phases and 1D inversions shows a marked difference in the electrical resistivity structure of the crust between the SE and NW regions of the study area. This correlates with a significant difference in heat flow as shown (Figure 4). Most of the heat flow values below 80 mW/m^2 (mainly in the $60 - 75 \text{ mW/m}^2$ range) are in the north western part of the study area and correlate with an area of greater depth to the conductor. In the east and south most of the heat flow values are higher than 80 mW/m^2 and mainly in the $80 - 100 \text{ mW/m}^2$ range. The heat flow pattern suggests a lesser depth to the 450°C isotherm in this high heat flow area. Heat flow for the whole area is close to 80 mW/m^2 and the heat flow data are from Lewis (1991, DNAG). Unpublished thermal data from wells in central B.C. were also used.

The depths to the lower crustal conductor, contoured in Fig.3, show a general resemblance to the heat flow contoured in Fig.4. Fig.5a shows values of the depths to the conductor at 76 grid points in Fig.3 plotted against values of heat flow read from Fig.4. The correlation coefficient is 0.7. The correlation compares reasonably well with the correlation based on the global data compilation by Adam (1978) and Hyndman and Shearer (1989). The comparison of the relationships is shown in Figure 5b.

TEMPERATURE CONTROL OF THE LOWER CRUSTAL CONDUCTIVE ZONE

The temperature of 450°C is considered important since the change from brittle to ductile deformation coincidental with this temperature may anneal cracks and restrict porosity of low permeability grain boundaries (Hyndman and Shearer, 1989). The saline water in this zone can cause a low resistive layer, whose top will correlate with the $400-500^\circ \text{C}$ (450°C) isotherm. This would explain the correlation observed here, of the depth to the lower crustal conductor with heat flow. The depth to the top of the electrical conductor is greater than 20 km in the low heat flow area and less than 15 km in the high heat flow area. The range of the depth to the 450°C isotherm is similar to the depth to the top of the electrical conductor. The reduced heat flow should be in the $50 - 60 \text{ mW/m}^2$ range in the area of the deep electrical conductor and the reduced heat flow should be in the $60 - 70 \text{ mW/m}^2$ range in the areas where the electrical conductor is shallow. The above geothermal conditions are quite possible in the Cordillera. Lewis et al. (1991 DNAG) claim that the Omineca Crystalline and Intermontane Belts of the southern Canadian Cordillera form one heat flow province since they fit the required observation: Q lineary related to A . However it is noticed that all of the data from Intermontane in the south are clustered and thus do not form a linear relation. It is possible that they do not belong to a single heat flow province. The 450°C isotherm curve for the case of constant thermal conductivity, $k=2.5 \text{ W/mK}$, and variable reduced heat is shown in Fig.5b against the 300°C and 400°C isotherms calculated by Hyndman and Shearer for the global data compilation, based on the simplified assumption about reduced heat flow being equal to 60% of the surface heat flow. Our curve (2) is close to the curve (1) based on the statistical relation (Figure 5a). The strong correlation between the depth to the lower-crustal high conductivity layer and 450°C isotherm (Figure 6) and heat flow is evidence for mantle upflow and suggests that its present location, in southern British Columbia, is under the Omineca belt.

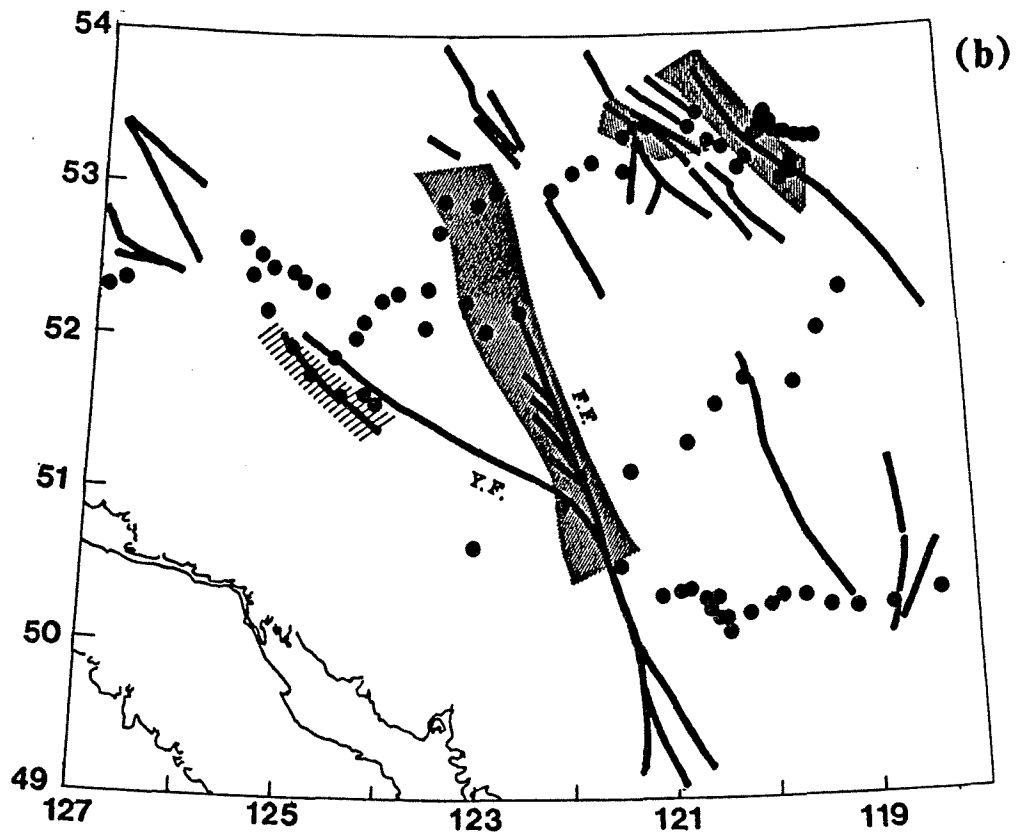
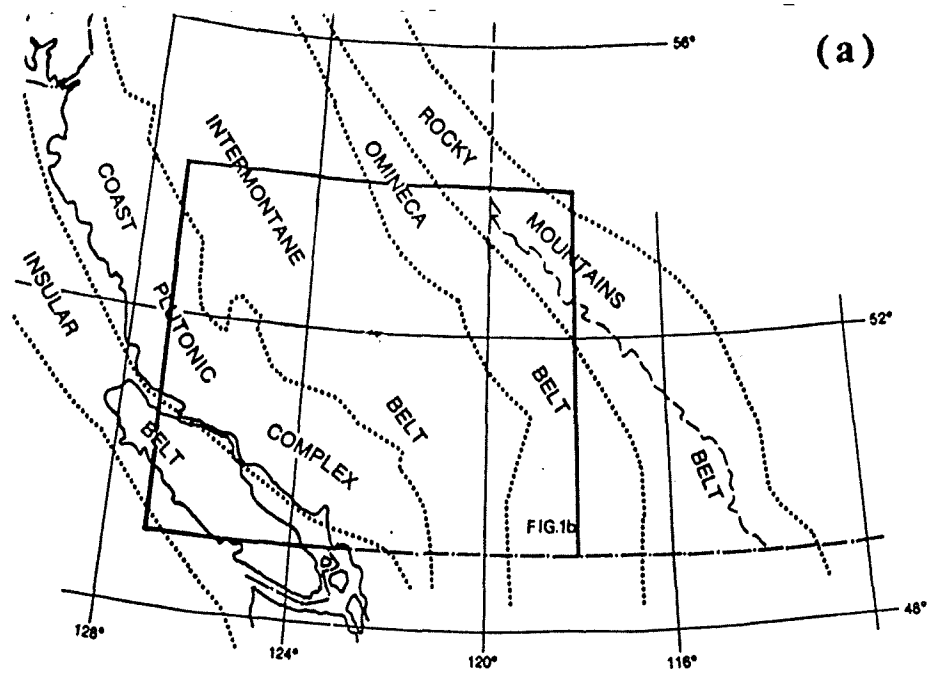


Figure 1. The study area in which magnetotelluric soundings have been made. Dots show positions of magnetotelluric soundings. FF, Fraser Fault; YF, Yalacom Fault.

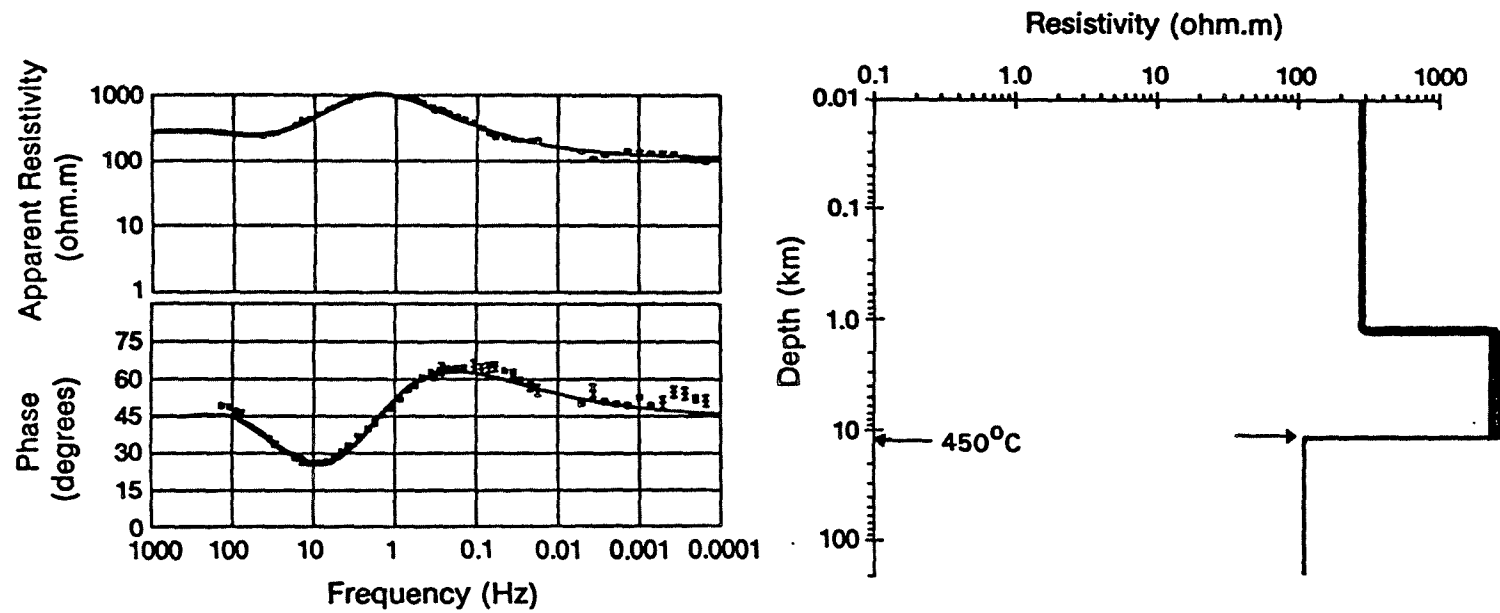


Figure 2. 1 D inversion of apparent resistivity and phase to resistivity vs depth, at one deep sounding site using Dawes-Monte Carlo method (Sule, 1985; after initial Fisher inversion procedure (Fisher et al, 1981)).

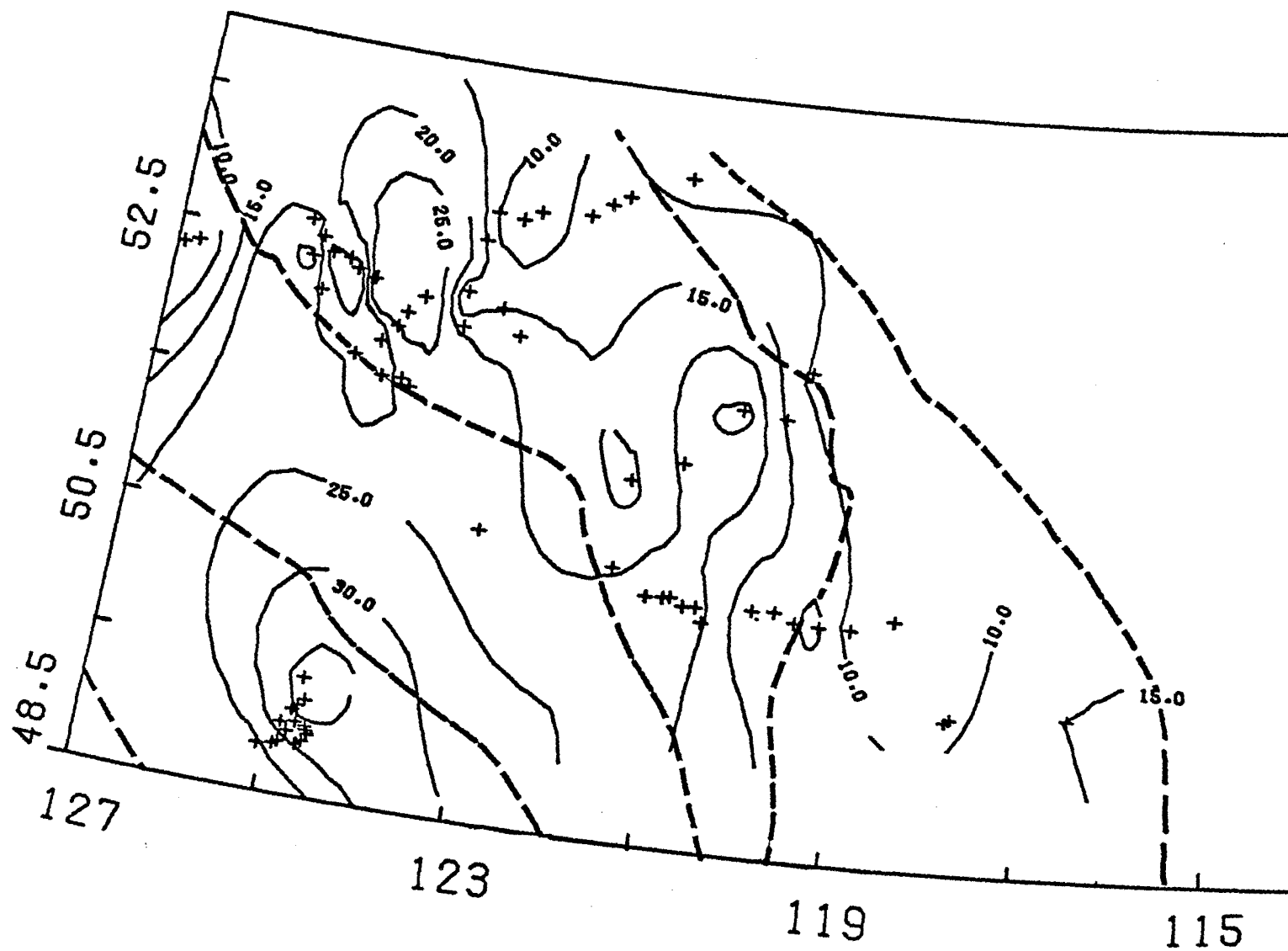


Figure 3. A provisional map of the topography of the regional electrical conductor based on 1D inversions of the MT data. Depth is given in km.

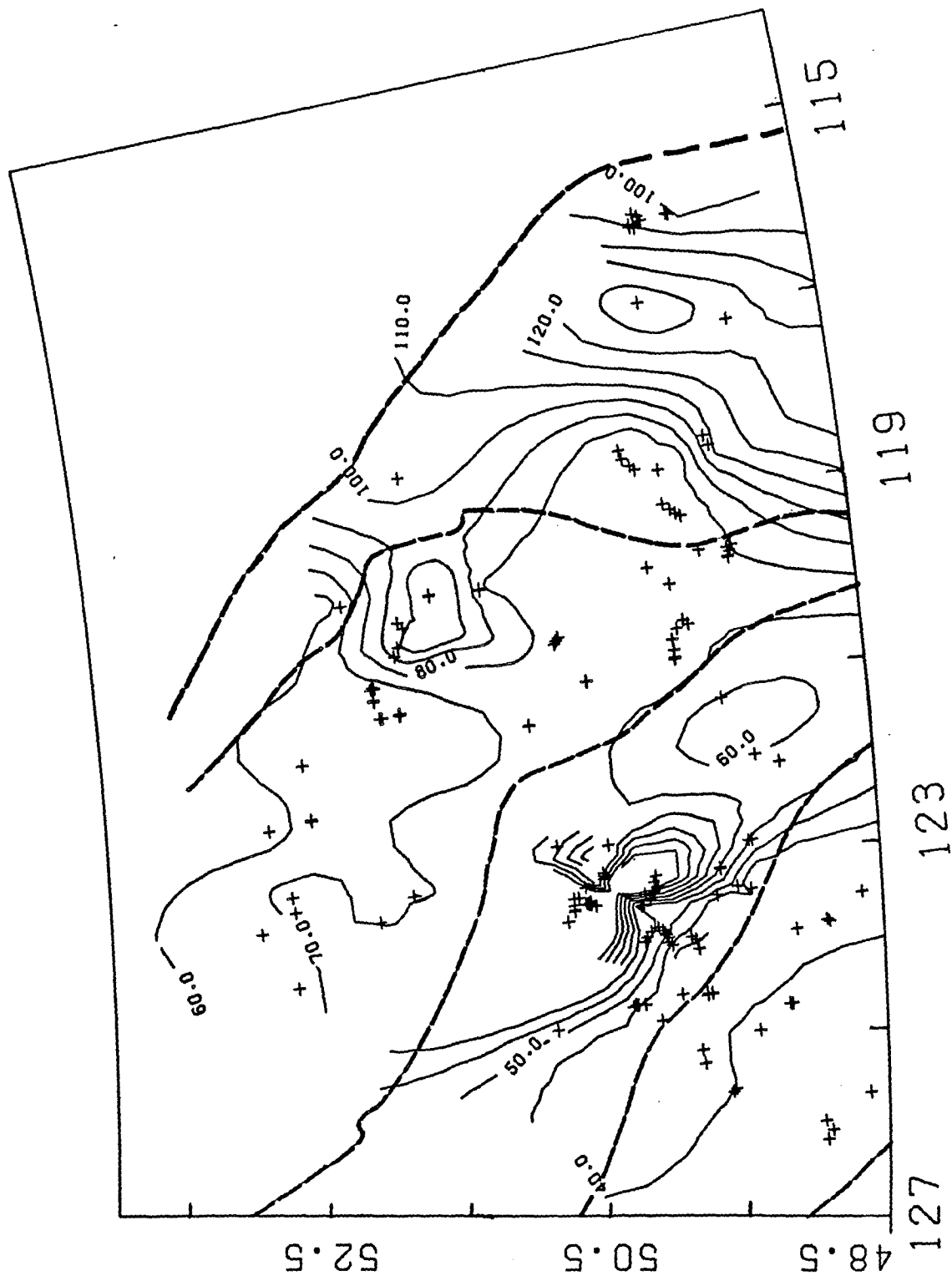


Figure 4. Heat flow contour map (in mW/m^2).

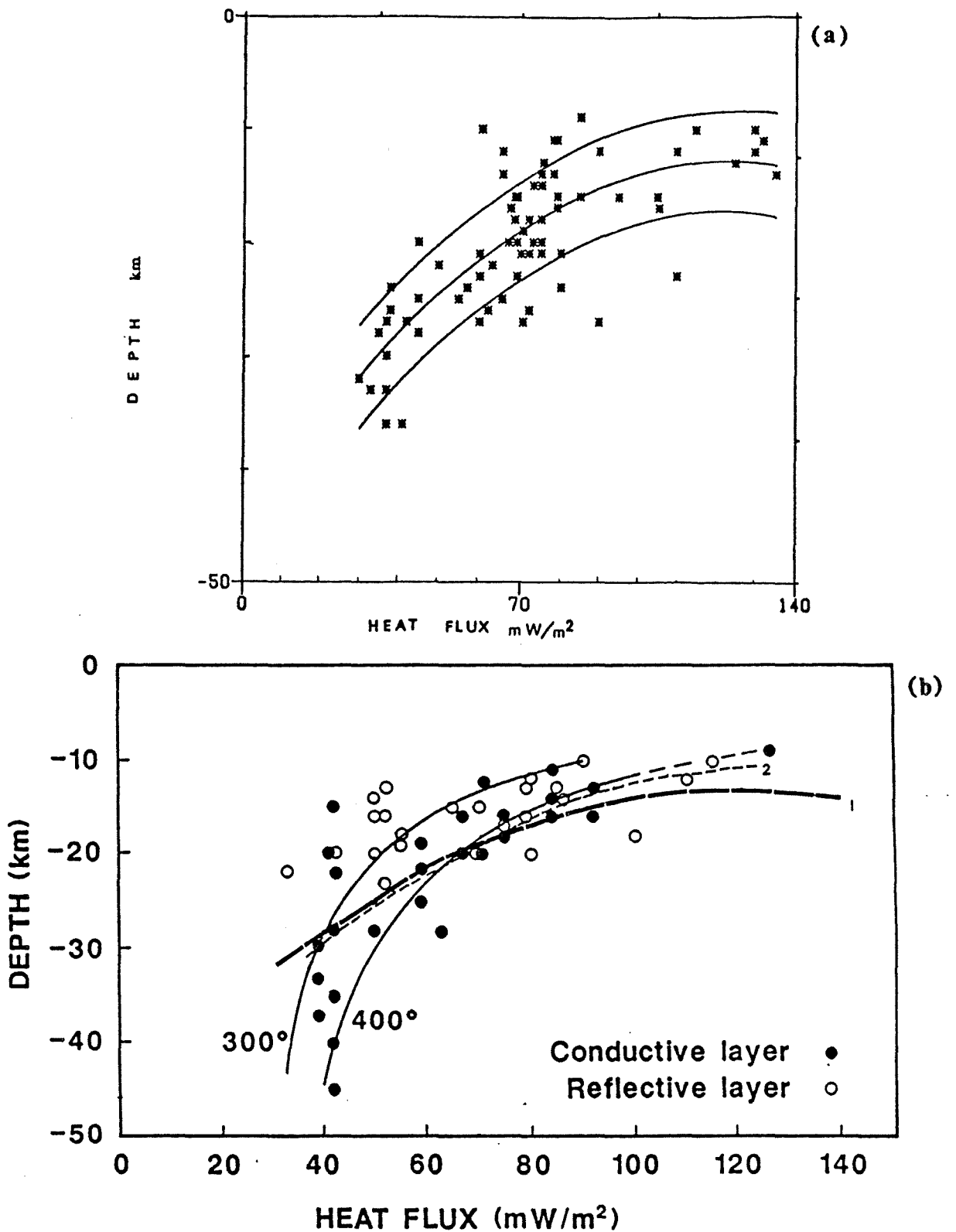


Figure 5. a. Depth to the conductor vs heat flow for the southern Canadian Cordillera, b. Comparison of the statistical relationship from Fig. 5a (curve 1) against the global compilation (from Hyndman and Shearer, 1989). An average global relation between heat flow and crustal heat production was used to generate the 300 deg. C and 400 deg. C curves (Hyndman and Shearer, 1989). The 450 deg. C isotherm for the Canadian Cordillera (this study) is shown (curve 2).

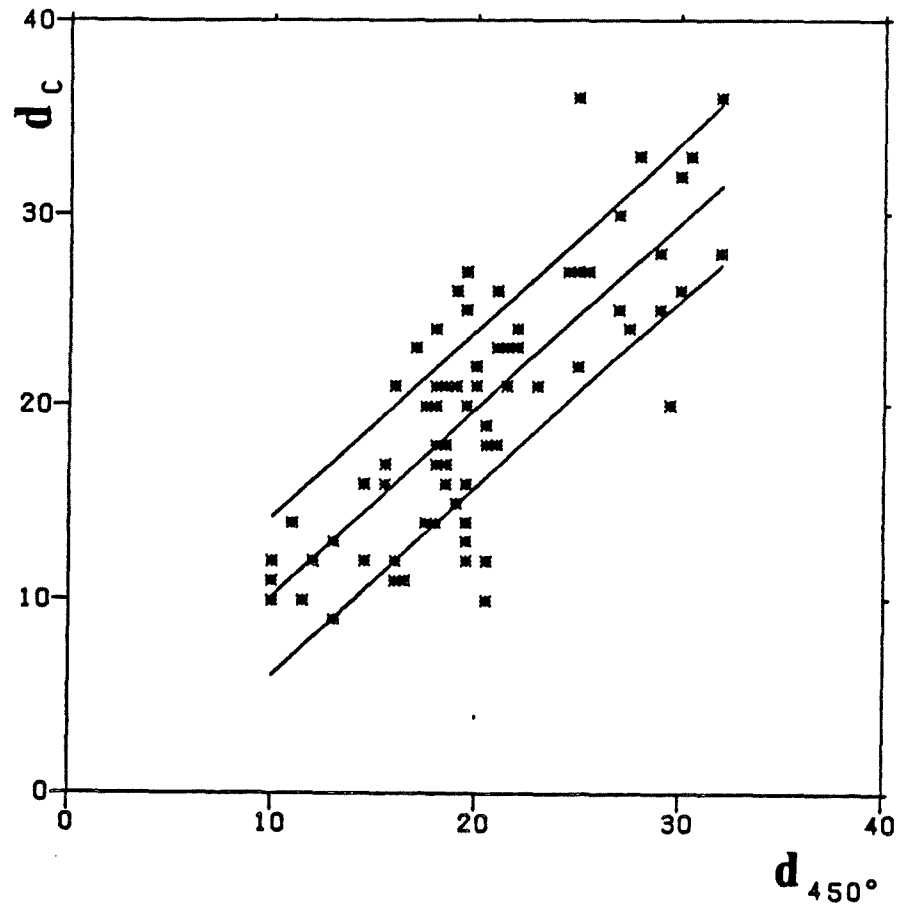


Figure 6. Scatter diagram for the depth (d_c) to the lower crustal conductor at 76 grid points, from Fig. 3 plotted against depth to 450 deg. C isotherm. The depths to the 450 deg. C isotherm surfaces were estimated from observed heat fluxes assuming reduced heat flow 50 mW/m² in the Intermontane Belt and 60 mW/m² in the Omineca Belt. The depths to the 450 deg. C isotherm in the southwest corner of the study area, affected by subduction are from Lewis et al, (1988). Correlation coefficient is 0.79.

REFERENCES

- Adam, A., 1978, Geothermal effects in the formation of electrically conducting zones and temperature distribution in the earth, P.E.P.I., 1978, 21-28.
- Berdichevsky, M.N., L.L. Vanyan, I.S. Feldman, and G. Porstendorfer, 1972, Conducting layers in the earth's crust and upper mantle, *Gerlands Beitr. Geophysik*, 81, 3/5, 187-196.
- Feldman, I.S., 1976, On the nature of conducting layers in the Earth's crust and upper mantle. In: A. Adam (Ed), *Geoelectric and Geothermal Studies*; KAPG Geophysical Monograph; Akademiai Kiado, Budapest.
- Fisher, G., P.A. Schnegg, M. Peguiron, B.V. Le Quang, 1981, An analytic one dimensional magnetotelluric inversion scheme, *Geophys. J. R. Astr. Soc.*, 67, 257-278.
- Gough, D.I., 1986a, Mantle upflow tectonics in the Canadian Cordillera, *J. Geophys. Res.*, 1909-19919.
- Gough, D.I., 1986b, Seismic reflectors, conductivity, water and stress in the continental crust, *Nature*, 323, 143-144.
- Gough, D.I., 1991, Mantle upflow..(submitted to C.J.E.Sci.).
- Gough, D.I. and J.A. Majorowicz, 1991, Magnetotelluric soundings, structure and fluids in the Canadian Cordillera, *Can. J. E. Sci.*, (accepted).
- Hyndman, R.D. and P.M. Shearer, 1989, Water in the lower continental crust: Modelling magnetotelluric and seismic reflection results, *Geophys. J. Int.*, 98, 343-365.
- Jones, A.G., R.D. Kurtz; D.E. Boerner, J.A. Craven, G.W. Mc Neice, D.I. Gough and J.M. DeLaurier, 1990, Electromagnetic investigation over the Southern Cordilleran LITHOPROBE Transect: 1991 status report. LITHOPROBE Cordilleran Workshop 1990 Extended Abstracts, 67-74.
- Jones, A.G., 1987, MT and reflection: an essential combination, *Geophys. J. R. astr. Soc.*, 89, 7-18.
- Jones, A.G., R.D. Kurtz, D.W. Oldenburg, D.E. Boerner and R.Ellis, 1988, Magnetotelluric observations along the LITHOPROBE southeastern Canadian Cordilleran transect, *Geophys., Res., Lett.*, 15, 677-680.
- Kurtz, R.D., J.M. DeLaurier and J.C. Gupta, 1986, A magnetotelluric sounding across Vancouver Island detect the subducting Juan de Fuca plate, *Nature*, 321, 596-599.
- Kurtz, R.D., J.M. DeLaurier and J.C. Gupta, 1990, The electrical conductivity distribution beneath Vancouver Island: a region of active plate subduction, *J. Geophys. Res.*, 95, 10929-10946.
- Lachenbruch, A.H., 1971, Vertical gradients of heat production in the continental crust, 2. Theoretical detectability from near surface measurements, *J. Geophys. Res.*, 3842-3851.
- Lewis, T.J., 1991, Heat flux in the Canadian Cordillera, (DNAG)
- Lewis, T.J., W.H. Bentkowski and R.D. Hyndman, 1991, Crustal temperatures near the Lithoprobe southern Cordilleran transect: 1991 status report, *Lithoprobe Cordilleran Workshop 1990 Extended Abstracts*, 31-38.
- Lewis, T.J., W.H. Bentkowski, E.E. Davis, R., D. Hyndman, J.D. Souther and J.A. Wright, 1988, Subduction of the Juan de Fuca plate, *J. Geophys. Res.*, 93, 15207-15225.
- Lewis, T.G., A.M. Jessop and A.S. Judge, 1985, Heat flux measurements in southwestern British Columbia: The thermal consequences of plate tectonics. *Canadian Journal of Earth Sci.*, 22, 1262-1273.
- Majorowicz, J.A. and D.I. Gough, 1991, Crustal structures from MT soundings in the Canadian Cordillera, *Earth & Planet. Lett.*, 102, 444-454.
- Pollack, H.N. and D.S., Chapman, 1977a, Mantle heat flow, *Earth & Planet. Sci. Lett.*, 34, 174-184.
- Sule, P.O., 1985, A broadband magnetotelluric investigation in southeast Scotland.

Ph.D. Thesis, University of Edinburgh.

Wyllie, P.J., in The Structure and Physical Properties of the Earth's Crust (Heacock, J.G. Ed.), Geophys. Monogr. Ser., Am. Geophys. Monogr. Ser., Am. Geophys. Union, Vol. 14, AGU, Washington, Dc, 279-301.

move 180 184 to 178

ACCRETE: A Proposed Plan to Study the Deep Crust under the Accreted Terranes of Southeast Alaska

Lincoln S. Hollister, Princeton University; Maria Luisa Crawford, Bryn Mawr College; and Sue McGeary, University of Delaware

INTRODUCTION

Current models for the growth and evolution of continental crust emphasize accretion of discrete fragments (terrane) of oceanic plateaus, island arcs, accretionary prisms, fragments of continental crust, and entire continents. Despite the success of the terrane concept, a number of fundamental questions remain regarding the process of terrane accretion, and the interaction between terrane accretion, crustal scale thrusting, transform faulting, and igneous and metamorphic events. These questions include the coupling of the mantle with the deeper crust and of the deeper crust with the upper crust, the response of the lithosphere to the juxtaposition of pieces of continental crust with different histories, the geometries of terrane boundaries in the deep crust, the mechanism of formation or modification of the Moho, and the behavior of fluids (melt and aqueous) with the changing stress fields during accretion.

The multidisciplinary studies by TACT across Prince William Sound and the Chugach Mts of southern Alaska (Fuis et al 1991), and by LITHOPROBE across the Cascadia subduction zone and Vancouver Island of British Columbia (Hyndman et al 1990), have provided important new data for interpreting processes of crustal accretion. Data obtained by these projects show that zones containing numerous reflectors, and alternating high and low velocity layers, occur between the top of the Benioff zone and the base of the continental crust. These results stress the importance of entrainment of sediment in subduction zones and of underplating in building new crust from below. The results show the kind of data that can be obtained from the lower crust and how they can be used to distinguish tectonic alternatives.

The goal of ACCRETE is to study terrane accretion in southeast Alaska and the north coast of British Columbia where the convergence directions during terrane accretion progressed from 1) a Mesozoic regime of terrane accretion including a mid-Cretaceous period of subduction with near normal convergence resulting in

formation of a major thrust system to 2) late Mesozoic and early Cenozoic transpressive motion associated with arc volcanism and significant intra-arc deformation to 3) the present margin truncated in the late Tertiary by the Queen Charlotte-Fairweather transform fault. The directions and rates of plate motions are known for the late Mesozoic to Recent in our proposed study area (Engebretson et al 1985, Lonsdale 1988). They are less well constrained for the earlier Mesozoic. In the context of this convergence history, three target problems are identified where deep crustal seismic imaging can advance our knowledge of continental crustal evolution and dynamics during terrane accretion: (1) The mid-Cretaceous thrust problem, (2) The Coast shear zone and Paleogene arc problems, and (3) the Queen Charlotte - Fairweather transform fault problem. We have framed each of these problems in terms of alternate subsurface structures that could be imaged by seismic reflection and refraction experiments. This note outlines the first two of these exercises.

Advantages for deep seismic imaging across the ACCRETE study area include (1) deep crustal levels on both sides of terrane boundaries have been exhumed and are exposed at the surface, (2) waterways suitable for marine geophysical transects cross all major geologic boundaries, and nearby shorelines provide surface geologic control, (3) there has been minimal post-orogenic extension, and (4) there is intensive current research interest in the area, with the accumulation of a significant geological data base and growth of geological insight.

MID-CRETACEOUS THRUST PROBLEM

There are two end-member alternative models for the accretion of the Insular Superterrane in southeast Alaska (Figs. 1, 2) and formation of the mid-Cretaceous thrust system. One proposes that terrane juxtaposition occurred during the Jurassic and was followed by formation of a marginal basin during extension and thinning of the lithosphere (McClelland and Gehrels 1990, Rubin & Saleeby 1991); in this model (the "accordion tectonic" model, model A), the mid-Cretaceous thrust belt formed during subsequent closing of the marginal basin. The second (the "mid-Cretaceous accretion" model, model B) holds that the mid-Cretaceous thrust system formed by closure of an ocean basin that lay between two terranes separated by an active subduction zone (Monger et al 1982, Saleeby 1983).

The accordion tectonic model calls for deposition of sediment of the Gravina belt (Figs. 1, 2) in the marginal basin, on thinned continental crust. If Jurassic terrane accretion was related to subduction, the lithospheric extension associated with formation of the Gravina basin is likely to have obscured evidence of that Jurassic subduction. The mid-Cretaceous plutons, which intruded concurrently with the thrusting (Crawford et al 1967; Crawford and Crawford 1991) are not likely to have been generated from the sediment of the Gravina belt because, according to the accordion tectonic model, there was no subduction during the mid-Cretaceous to have carried these sediments deep enough to be melted. These melts would likely have been generated by mantle derived magma and possibly melting at the base of the extended crust.

The mid-Cretaceous accretion model calls for oceanic crust and sediment of the Gravina belt to have been entrained within a subduction zone between the Insular superterrane and North America. TACT and LITHOPROBE results show that accretionary prism sediments can be entrained to great depth during ocean-continent plate convergence. The underplated sediments extend to depths of at least 40 km under the Chugach Mts and under Vancouver Island. Although subduction in southeast Alaska probably stopped by about 55 Ma, when plate reconstructions (Lonsdale, Engebretson) indicate there was no longer a component of compression between the Kula plate and this portion of North America, we can expect to image remnants of the Cretaceous and early Tertiary subduction zones in southeast Alaska because, as shown by seismic results from central California (presented in a special section in the April, 1991 Journal of Geophysical Research), structures associated with subduction are preserved in the lower crust long after the cessation of subduction, initiation of a transform regime, and transfer of the locus of transform motion.

For the mid-Cretaceous accretion model, the mid-Cretaceous plutons could have been derived from mantle derived magma and partially melted lower crust, or from subducted sediment and oceanic crust. To test for the latter possibility, which is unique to the mid-Cretaceous accretion model, further detailed geochemistry similar to that done by Arth et al (1988) in southeast Alaska is required.

Convergence according to the accordion model does not require that the mid-Cretaceous thrusts pass through the crust (Model A) as

does the mid-Cretaceous accretion model (Model B). Thus, if the thrust zones exposed at the surface flatten with depth, the mid-Cretaceous accretion model would be difficult to support. If the thrusts are found to pass through the crust, the important conclusion would be made that thrusts that have resulted in inverted metamorphism do pass through the crust. Because of the close association of the mid-Cretaceous plutons with the thrusts in space and time, this result will constrain models for the origin and emplacement of calcalkaline plutons.

Thus, primary distinctions between the two tectonic models for the mid-Cretaceous thrust system lie in predictions of the subsurface seismic velocity structure and the geometry of seismic reflectors. Key structural units, particularly the rocks within the Gravina belt have distinctive physical properties which should allow their recognition in the subsurface using geophysical methods. The Gravina belt rocks are micaceous and show pronounced foliation. Based on analogues studied by TACT in southern and central Alaska, they ought to display pronounced seismic anisotropy with a sharply lower velocity normal to foliation. Shooting strike and dip profiles with a large range of offsets over the Gravina belt will provide information on P and S seismic velocity anisotropy in the highly foliated Gravina belt rocks. If we find that this unit and associated structures can be traced through the crust and into the upper mantle, a point in favor of the mid-Cretaceous accretion model will have been made. If the Gravina belt is floored by continental crust, a point in favor of the accordion tectonic model will have been made.

An important result from this phase of the ACCRETE program will be understanding the nature of thrusts during thick-skinned thrusting. Do large scale upper- and mid-crust thrusts, such as those of southeast Alaska, pass through the entire continental crust, or do they flatten out within the crust? Do megathrusts pass through the entire crust only along relic Benioff zones between pieces of collided bouyant crust? By following structures from the surface into the crust, which should be possible along our proposed transects, this question would be answered even if the question of timing of the accretion proves to be unresolvable.

If we find a fossil mid-Cretaceous subduction system preserved within the upper mantle under the crust along our transects (Model B), then we will also have shown that an ocean basin can close without leaving a relic (such as ophiolite) of the subducted oceanic

crust within the suture zone. A commonly held opinion is that the absence of ophiolite from an orogenic belt implies that that belt did not form by subduction-related collision of pieces of bouyant crust but rather by closure of an intracratonic basin or back-arc basin.

COAST SHEAR AND PALEOGENE ARC PROBLEMS

The Coast shear zone separates the Paleogene arc to the east from the mid-Cretaceous thrust belt and associated plutons to the west. The problems to be investigated concern the nature of the shear zone and the controls of emplacement of the Paleogene plutons.

Much of the Paleogene arc is composed of tonalite which requires a temperature of over 900°C to be wholly liquid; occurrences of cumulate amphibole in the Paleogene plutons imply the tonalite magmas that formed the plutons were nearly wholly liquid when these textures formed (Crawford et al 1987). Granulite facies metamorphism attributed to the intrusion of these tonalite magmas also attests to high temperatures of intrusion (Hollister 1975, 1982). It is difficult to explain such high magmatic temperatures solely by processes associated with melting within tectonically overthickened crust. The evidence points to such melts as resulting from mixing of mantle derived basaltic magma and melt generated by anatexis of the lower crust (Hyndman & Foster 1988) or from melting at high temperatures within a subduction complex. The former presence of mafic magmas in the lower crust should be manifested by horizontal reflectors (Mooney and Meissner, 1991; Nelson, 1991) of material with moderately high p-wave velocities (7.1-7.8 km/sec). High resolution seismic reflection and refraction studies strongly suggest that interplating and underplating of mafic magmas as sills are common features (Nelson 1991, Furlong & Fountain 1986, Mooney & Braile 1989) in the lower crust and across the crust-mantle boundary. We expect such features under the Paleogene arc if the tonalite melts of the arc were generated by the interaction of basaltic magma and the lower crust.

The coincidence in time of a change in direction of Kula plate motion from slightly northeasterly to slightly northwesterly and of copious injection of 54-56 Ma tonalite melts into the Paleogene arc suggests that extension within the Coast batholith to accomodate the added volume represented by the tonalite plutons may have occurred as a response to the change in Kula plate motion. According to Nelson (1991) the small amount of extension called for by this

pluton emplacement would not be expected to generate deep crustal, nearly horizontal reflectors as observed in many areas of large amounts of known extension and hence high strain (McCarthy and Thompson 1988), although we expect that where late, discordant 50 Ma plutonism was dominant, original layered horizons would have been disrupted.

At the present surface, the Coast shear zone separates the Paleogene arc from the mid-Cretaceous thrust belt, which it truncates. Along the entire eastern side of the Coast shear is a narrow zone of tonalite plutons that are slightly older (about 60 Ma) than the bulk of the plutons within the arc. The surface structure of the Coast shear definitely post-dates intrusion of this approximately 60 Ma tonalite complex; and unpublished results indicate that deformation within the Coast shear, at amphibolite facies temperatures, occurred at about 55 Ma (Cook and Crawford, in review). The shear zone is vertical at the surface, but a fundamental question is whether it remains vertical to the Moho, or flattens out into the mid to lower crust.

The predicted difference in attitude between reflectors within the crust of the Paleogene arc and those of the mid-Cretaceous thrust system, as well as velocity contrasts across the shear zone, should define the location and nature of the Coast shear at depth. An important feature of the proposed transect is that a gently dipping layered section that formed at 15-20 km within the Paleogene arc, with density contrasts at a scale that would make good reflectors in the deep crust, has been recognized at the surface (Hollister and Crawford 1990). Furthermore, based on the high quality subsurface images obtained on rocks similar to those of the Gravina belt along the TACT transect, we expect that we will be able to image the Gravina belt into the subsurface from west of and up to the Coast shear zone. Most of the Paleogene arc, from near the surface to the Moho, should have high densities (and therefore velocities) appropriate for the granulite facies (Hollister and Crawford 1990), whereas the mid-Cretaceous thrust system should have a more normal crustal velocity profile. Thus, assuming a continuation into the subsurface of the distinctly contrasting lithologic units exposed at the surface, we expect to recognize the location of the Coast shear at depth from velocity discontinuities across it and from the truncation of reflectors. If the Coast shear flattens with depth, then its pronounced planar fabric should produce distinctive seismic reflectors.

Figure 3 explores the development of the early Cenozoic Coast shear zone and its relation to regional batholith emplacement. Model A proposes that a precursor Coast shear zone was vertical to the Moho and was invaded by deep crustal plutons; such an important vertical shear may have originated as a transcurrent shear zone, possibly a transform boundary of the Kula plate. Model B suggests that the earlier major crustal thickening phase, caused by mid-Cretaceous thrusting and magmatism, led to construction of a crustal welt much like the crust under the modern Andean Altiplano. In this case, the Coast shear zone marks the eastern wall of a rheological buttress against which the collapsing crustal welt pushed, and sub-horizontal mid crustal reflectors within the Paleogene arc would have formed by shear during the extension. Our unpublished data suggest that the Coast shear here may indeed be at a rheological boundary.

In summary, the ACCRETE project will focus on terrane accretion by convergent and transpressive tectonics. We will document the nature of the mid-Cretaceous convergent tectonic event, building on the insights generated by TACT and LITHOPROBE; and a major component of the ACCRETE project will be acquisition of deep crustal data pertaining to transpressive plate convergence regimes and to the processes associated with the termination of subduction.

THE PROPOSED EXPERIMENTS

We plan to use the research vessel EWING, employing an MCS digital streamer configured with 160-25 meter sections, with a total active length of 4 km. The seismic source will consist of an 8385 cu. in. airgun array configured as four similar five-gun subarrays with individual gun volumes spanning the range of 120-850 cubic inches. Long listening times will be required to image deep reflectors. MCS record lengths will be 18 seconds, with 250 Hz sampling, recorded on EWING's Digicon DSS240 system. The shot interval will be 20 seconds for the MCS profiles, a 50 meter spacing at a nominal 5 knots, and 60 seconds for the onshore/offshore recording. The EWING will navigate the inland waterways of southeast Alaska, including the fjords that cross the Coast Mountains; where the MCS streamer cannot be deployed, the EWING will be used as a signal

source for 100-150 Reftek land recorders. These recorders will utilize three-component seismometers, and will be equipped with external hard disks capable of recording 72 hours of 3-component data at 100 Hz sampling. The instruments will be programmed to turn on and record continuously in two different windows producing 3 crossing vertical-incidence to wide-angle profiles. The wide-angle profiles will have offsets ranging from several km to more than 200 km, with instrument spacing of 5 to 10 km (locally 1-3 km), and shot spacing of 100-150 m. For the wide-angle profiling, we prefer to repeat the MCS tracks, shooting less frequently (60s, ~100-150m) to prevent long offset P waves from one shot from interfering with S waves from the previous shot. Recently obtained examples of P and S wave data from Greenland may be similar to what we can expect to record. The three-component land receivers recorded signals from marine airguns fired every minute (~100m) to 250 km offset and show abundant S-wave energy. Since Southeastern Alaska is a geophysical frontier area having a mix of near surface lithologies ranging from unmetamorphosed sediments to highly metamorphosed sedimentary rocks and igneous rocks, we expect to record S waves in some areas and not in others. The Reftek instruments will be deployed from two 40 foot launches.

REFERENCES

- Arth, J.G., Barker, F., and Stern, T.W., 1988, Coast batholith and Taku plutons near Ketchikan, Alaska: petrography, geochemistry, and isotopic character. *Am. J. Sci.*, 288-A, 461-489.
- Brew, D. A., and Ford, A. B., 1978b, Megalineament in southeastern Alaska marks southwest edge of Coast Range batholithic complex. *Can. J. Earth Sciences*, 15, 1763-1772.
- 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. *Can. J. Earth Sciences* 24, 31-51.

- Coney, P. J., Jones, D. L., and Monger, J. W. H., 1980, Cordilleran suspect terranes. *Nature*, 288, 329-333.
- Cook, R.D., and Crawford, M.L., in review, Exhumation and tilting of the western metamorphic belt of the Coast orogen in southeastern Alaska.
- Crawford, M.L. and Crawford, W.A., 1991, Magma emplacement in a convergent tectonic orogen, southern Revillagigedo Island, southeastern Alaska. *Can. J. Earth Sci.*, 28, 929-938.
- Crawford, J. L., Hollister, L. S., and Woodsworth, G. J., 1987, Crustal deformation and regional metamorphism across a terrane boundary, Coast plutonic complex, British Columbia. *Tectonics*, 6, 343-361.
- Engelbreton, D. C., Cox, A., and Gordon, R. G., 1985, Relative motions between oceanic and continental plates in the Pacific Basin. *Geol. Soc. Amer. Special Paper*, 206, 1-59.
- Fuis, G.S., Ambos, E.L., Mooney, W. D., Christensen, N. I., and Geist, E., 1991, Crustal Structure of Accreted Terranes in Southern Alaska, Chugach Mountains and Copper River Basin, from Seismic Refraction Results. *J. of Geophys. Res.*, 96, 4187-4227.
- Furlong, K.P. and Fountain, D.M., 1986, Continental crustal underplating: thermal considerations and seismic-petrologic consequences. *J. Geophys. Res.*, 91, 8285-8294.
- Gehrels, G. E., and Berg, 1984, Geological Map of southeastern Alaska. U.S.G.S. Open File Report 84-886.
- Gehrels, G. E., McClelland, W. C., Samson, S. D., Patchett, P. J., and Jackson, J. L., 1990, Ancient continental margin assemblage in the northern Coast Mountains, southeast Alaska and northwest Canada. *Geology*, 18, 208-211.
- Gehrels, G. E., and Berg, 1988, A review of the regional geology and tectonics of southeastern Alaska. U.S.G.S. Open File Report 88-659.
- Goodwin, E. B., and McCarthy, J., Composition of the lower crust in west-central Arizona from three-component seismic data. *J. Geophys. Res.*, 95, 20,097-20,109, 1990.

- Goodwin, F. B., and McCarthy, J., 1990, Composition of the lower crust in west central Arizona from three-components seismic data. *Jour. Geophys. Res.*, 95, 20,097-20,109.
- Hollister, L. S., and Crawford, M. L., 1990, Crustal formation at depth during continental collision. In: *Exposed Cross-Sections of the Continental Crust* (Eds: Salisbury, M. and Fountain, D.), Kluwer Academic Publishers, 215-225.
- Hollister, L. S., 1975, Granulite facies metamorphism in the Coast Range crystalline belt. *Can. J. Earth Sci.*, v. 12, p. 1953-1955.
- Hollister, L. S., 1982, Metamorphic evidence for rapid (2mm/yr) uplift of a portion of the Central Gneiss Complex, Coast Mountains, B.C. *Can. Mineral.*, 20, 319-322.
- Hyndman, D. W., and Foster, D. A., 1988, The role of tonalites and mafic dikes in the generation of the Idaho Batholith. *Journal of Geology*, 96, 31-46.
- Hyndman, R. D., Yorath, C. J., Clowes, R. M., and Davis, E. E., 1990, The northern Cascadia subduction zone at Vancouver Island: seismic structure and tectonic history. *Can. J. Earth History*, 27, 313-329.
- Lonsdale, P., 1988, Paleogene history of the Kula Plate: offshore evidence and onshore implications. *Geol. Soc. Am. Bull.*, 100, 733-754.
- McCarthy, J. and Thompson, G.A., 1988, Seismic imaging of extended crust with emphasis on the western United States. *Geol. Soc. Am. Bull.*, 100, 1361-.
- McClelland, W.C. and Gehrels, G.E., 1990, Geology of the Duncan canal shear zone: evidence for Early-Middle Jurassic deformation of the Alexander terrane, southeastern Alaska. *Geol. Soc. Am. Bull.*, 102, 1378-1392.
- McGeary, S., 1989, Reflection seismic evidence for a Moho offset beneath the Walls boundary strike-slip fault. *J. Geol. Soc. London*, 146, 261-269.

- Monger, J. W. H., Price, R. A., and Tempelman-Kluit, D. J., 1982, Tectonic accretion and the origin of the two major metamorphic and plutonic belts in the Canadian Cordillera. *Geology*, 10, 70-75.
- Mooney, W.D. and Braile, L.W., 1989, The seismic structure of the continental crust and upper mantle of North America. In: Bally, A.W. and Palmer, A.R. (eds) *The Geology of North America-an overview*: Boulder, Colorado, Geological Society of America, 39-52.
- Mooney, W.D. and Meissner, R., 1991, Continental crustal evolution observations. *EOS*, 72, 537-541.
- Nelson, K.D., 1991, A unified view of craton evolution motivated by recent deep seismic reflection and refraction results. *Geophys. J. Int.*, 105, 25-35.
- Plafker, G., Nokleberg, W. J., and Lull, J. S., 1989, Bedrock geology and tectonic evolution of the Wrangellia, Peninsular, and Chugach terranes along the Trans-Alaska Crustal Transect in the Chugach Mountains and southern Copper River Basin, Alaska. *J. Geophysics Res.*, 94, 4254-4255.
- Rubin, C. M., and Saleeby, J. B., 1991, Tectonic framework of the upper Paleozoic and lower Mesozoic Alava sequence: A revised view of the polygenetic Taku terrane in southern Alaska. *Can. J. Earth Sci.*, 28, 881-893.
- Saleeby, J. B., 1983, Accretionary tectonics of the North American Cordillera. *Annual Review of Earth and Planetary Sciences*, 15, 45-73.
- Woodsworth, G. J., Crawford, M. L., and Hollister, L. S., 1983, Metamorphism and structure of the Coast Plutonic Complex and adjacent belts, Prince Rupert and Terrace areas, British Columbia. Geological Association of Canada, 1983, Annual Meeting, Guidebook, p. 62.

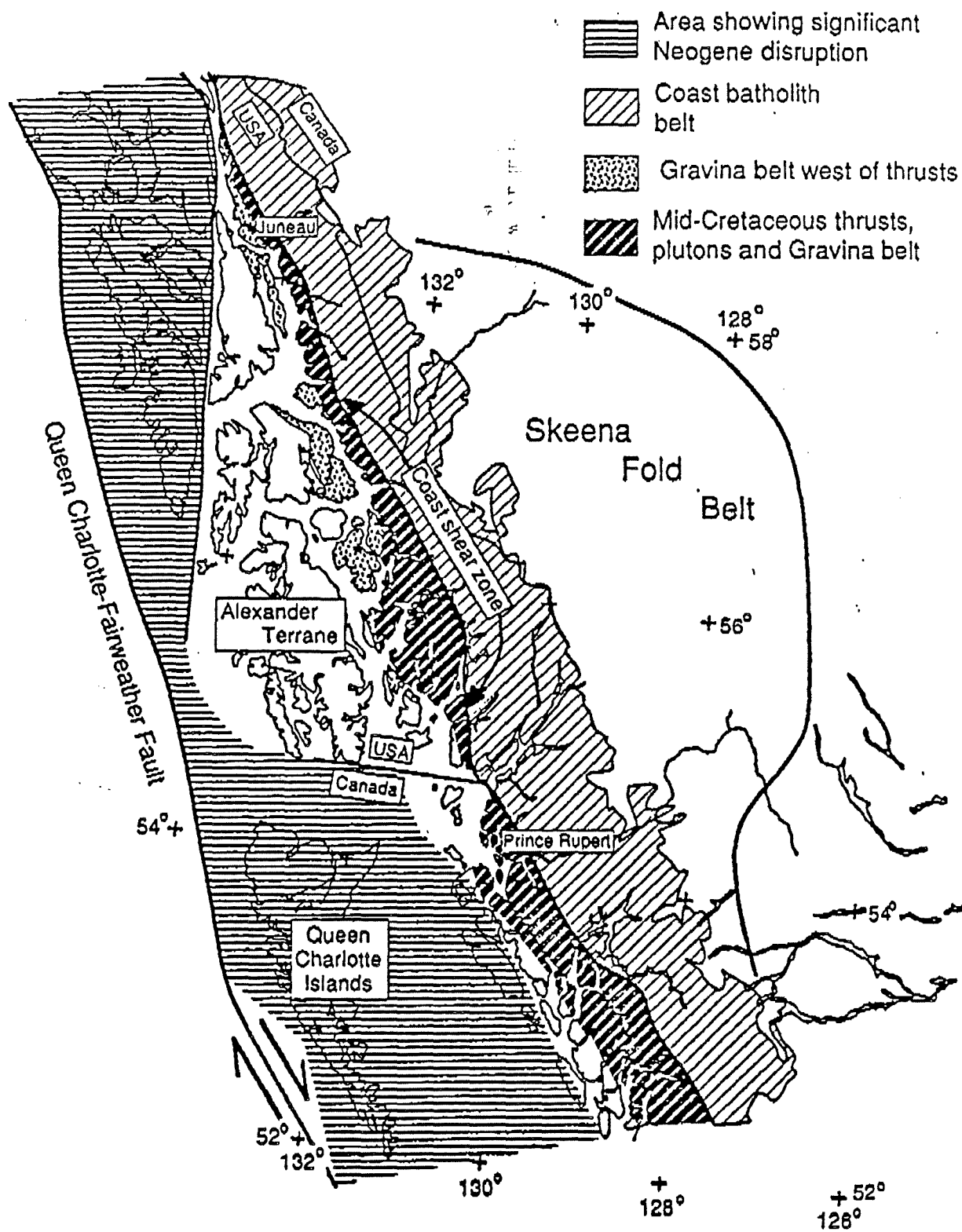
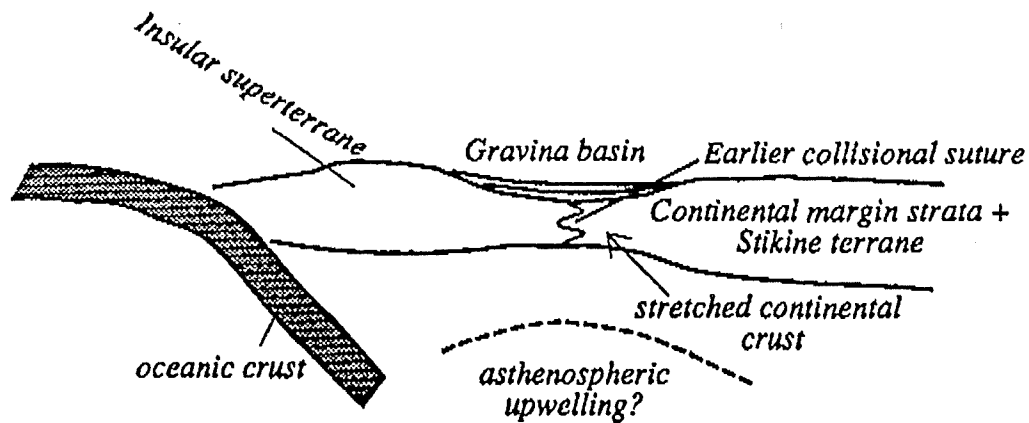


Figure 1

Middle Cretaceous megathrust and Inverted metamorphic belt

Model A: Intra-arc thrust

PRE-MIDDLE CRETACEOUS



MIDDLE CRETACEOUS THICK-SKINNED THRUSTING

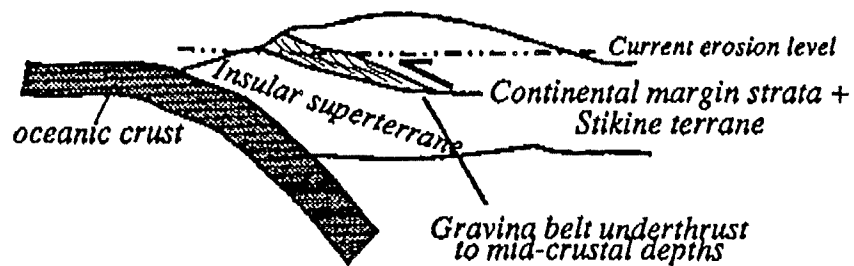
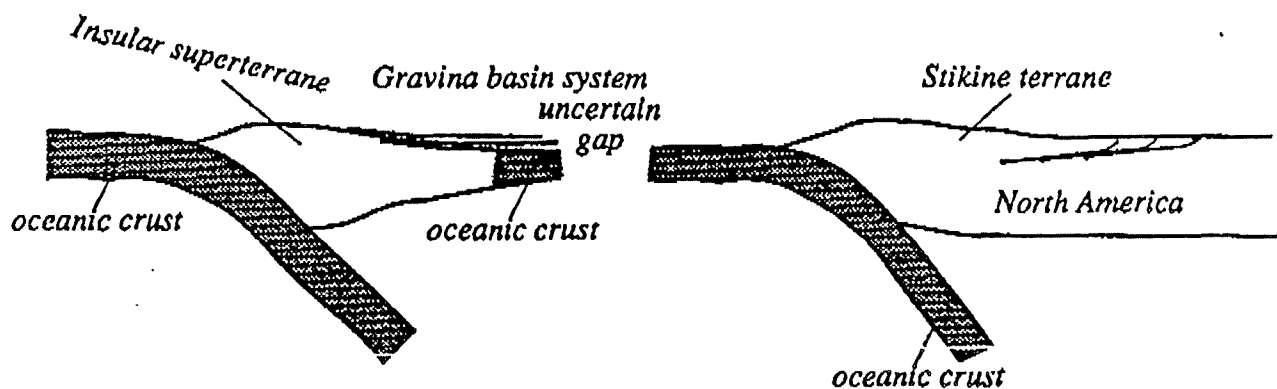


Fig. 2 a.

Middle Cretaceous megathrust and inverted metamorphic belt

Model B: Oceanic Arc Collision

PRE-MIDDLE CRETACEOUS



MIDDLE CRETACEOUS THICK-SKINNED THRUSTING

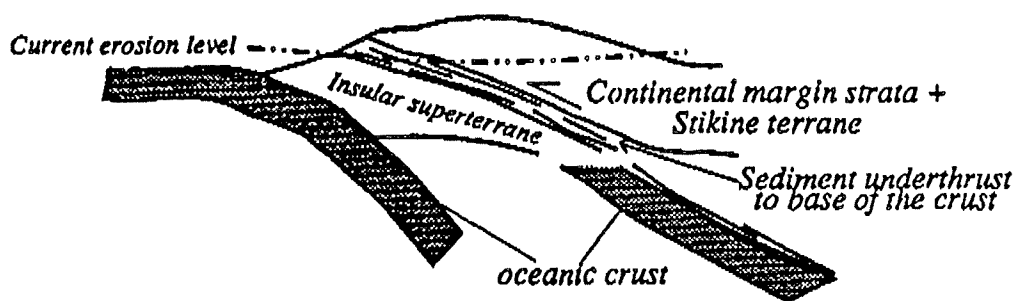
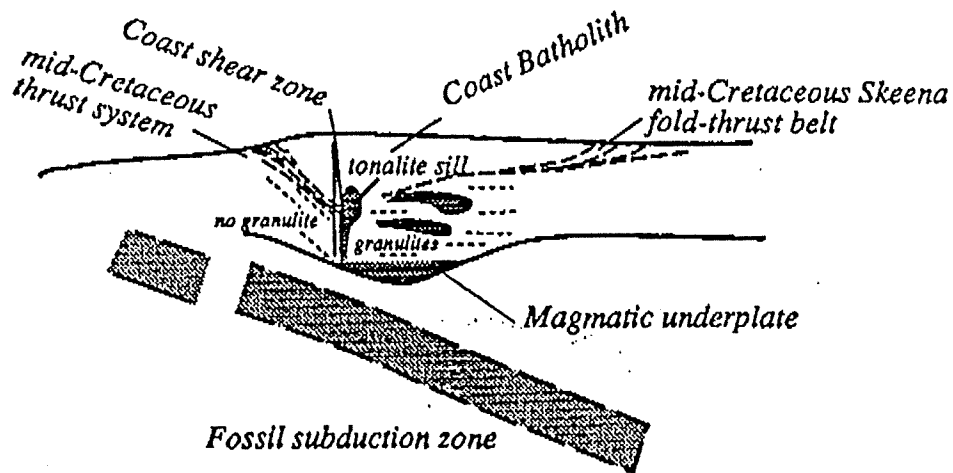


Fig. 2 b

Eocene Modification

MODEL A. Coast shear zone vertical



MODEL B. Coast shear zone listric

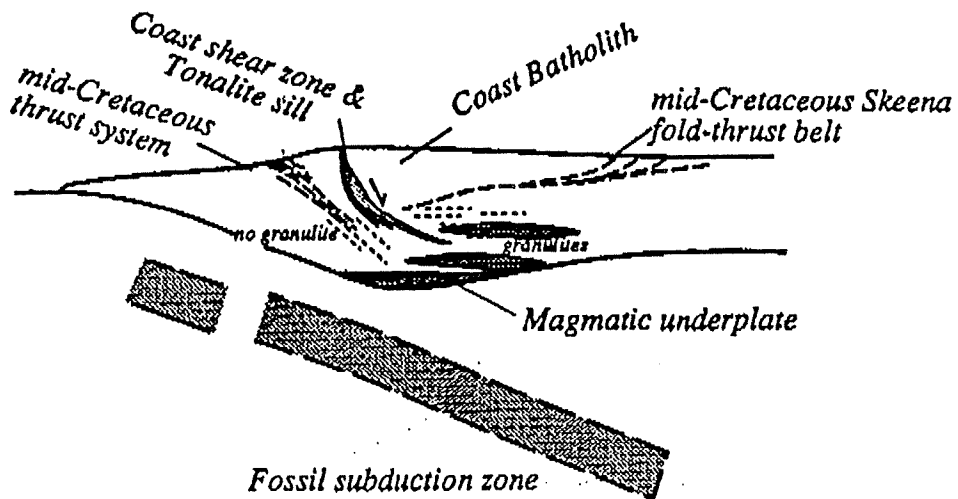


Fig. 3

Tectonic Framework of the Eastern Coast Belt

Murray Journeay, Cordilleran Division, G.S.C., 100 W. Pender Street, Vancouver, B.C. V6B 1R8

The Eastern Coast Belt (ECB) straddles the boundary between the Intermontane and Insular superterrane of the southern Canadian Cordillera. It is made up primarily of fault-bounded crustal fragments and overlap assemblages of Late Paleozoic to Late Mesozoic age. Stitching these tectonic assemblages together are Late Cretaceous and Early Tertiary magmatic arc sequences of the Coast Plutonic Complex. Geological mapping during the 1991 field season focused on contact relationships between volcanic arc and oceanic assemblages of the Cadwallader Group, Bridge River and Bralorne-East Liza Complexes, and overlying turbidities and volcanoclastic successions of the Tyaughton and Methow basins. These maps document a stratigraphic link between greenstone and chert of the Bridge River Terrane and overlying basin successions of the Cayoosh Assemblage (Methow Basin), and establish the existence of an important quartz-rich clastic facies that likely records the impingement and/or emergence of volcanic arc and crystalline basement terranes in the Late Jurassic and Early Cretaceous.

The structural framework of the ECB is defined by a network of northwest-trending contractional and strike-slip fault systems that record a complex history of post-middle Cretaceous shortening and transpression. The results of new mapping (Journeay et al., 1991) combined with that of Schiarizza et al., (1989; 1990) allow a partial reconstruction of the deformation history for the region.

96-91 Ma: Southwest-vergent folding and associated thrusting of terranes throughout the southern Coast Belt. The main locus of displacement during this episode of crustal shortening was along the Bralorne-McGillivray Pass-Twin Lakes Fault System. This fault system marks the western margin and the basal detachment for oceanic rocks and overlying basin successions of the Bridge River Terrane, and is likely out-of-sequence with respect to other contractional fault systems of the Central and Western Coast Belts (Journeay, 1990). Left-lateral oblique slip faults of the Tyaughton Creek System are interpreted to have formed late in this episode of crustal shortening and may have accommodated an important component of orogen-parallel displacement.

91-86 Ma: Northeast-vergent folding and associated thrusting. major structures of the ECB that are known to have been active during this period of deformation include northwest-striking faults and folds of the Castle Pass System and southwest-dipping thrust faults in the western Bendor Range and northern Lillooet Ranges. these structures cut southwest-vergent thrust faults and are interpreted to have been active during gold mineralization in the Bralorne district (91-86 Ma; Leitch, 1990). however, we can not rule out the possibility that northeast-vergent faults may have been active at deeper crustal levels over a longer period of time.

86-68 Ma: Oblique, southwest-vergent thrusting and associated dextral strike-slip faulting. The Downton Creek Fault marks the boundary between western and eastern assemblages of the Bridge River Complex, and may be linked to southwest-vergent thrusting in the imbricate zone of the Shulaps Complex. Kinematic linkages between these structures and major dextral strike-slip fault systems of the ECB, such as the Yalakom Fault, are uncertain.

68-48 Ma: Detachment and northwestward displacement of the Bridge River Complex along the Cayoosh Creek Fault. Recumbent isoclinal folds in the lower plate of the Cayoosh Creek Fault may reflect either the distributed strain associated with northwestward overthrusting of the Bridge River Complex, or the effects of older (96-91 Ma) southwest-vergent thrusting. Linkages between these structures and the Yalakom Fault are probable, but can not be proven.

The Mission Ridge Fault and steep southwest-dipping brittle shears along the Marshall Creek Fault represent outward-dipping extensional faults that flank metamorphic rocks of the Bridge River Complex. These structures cut dextral strike-slip fabrics of the Marshall Creek Fault, and record a two-stage history of displacement; down-to-the-northeast displacement along the Mission Ridge Fault, followed by down-to-the-southwest displacement along the Marshall Creek Fault (Coleman, 1990). These structures pre-date dextral transcurrent displacement along the Fraser River Fault System.

ELECTRIC NOTEBOOK AND GIS, PINE PASS (93O) S.W., B.C.

L.C. Struik, A. Atrens, and A. Haynes

Geological Survey of Canada, Cordilleran Division, 100 West

Pender Street, Vancouver, B.C., V6B 1R8

Geological field notes, for the 1:250,000 scale Pine Pass southwest (93O) mapping project, were successfully taken for the past two field seasons on the ASCII editor of the .5kg Atari Portfolio handheld computer. Drawings were made with pencil and paper. The notes were entered with position and tag control. A computer program (GEOF), on the DOS platform, assists in editing the note format and generates comma-delimited data files from the ASCII notes. The comma-delimited data has been imported into dBASE IV, FIELDLOG, and Arc/Info databases, and is sufficiently generic to import into any database. For the Pine Pass project the data was translated in the field with GEOF from the ASCII editor notes to comma-delimited files, and entered into FIELDLOG, which was used for database queries and the plotting of geological data to AutoCAD diagrams.

With this method, digital data collected at the outcrop can be searched, plotted on maps, and statistically and graphically manipulated completely by computer on the same day it is collected. Direct field entry of data eliminates transcribing handwritten notes into GIS databases.

In the case of the Pine Pass map area GEOF, FIELDLOG and AutoCAD were used to plot the locations of stations, fossils, samples, minerals, rock types and the attitudes of structures, to draw the geological contacts and cartographic symbols. The data was plotted and superimposed onto the publicly available 1:250,000 scale digital topographic base for Pine Pass map area supplied by Energy Mines and Resources' Surveys and Mapping Sector. With this information a preliminary bedrock geological map of the Pine Pass SW map area was made at 1:250,000 scale a week after the field season. The map was computer drafted with a laser printer and the copy used for the 1992 Current Research Paper on the Pine Pass geological mapping project. A full scale map was plotted on a roll pen plotter.

All of the data collected at the observation site with the ASCII editor can be imported into a database either as unique variables or as character strings. All of the digital data therefore can be manipulated and used electronically. Queries can be made on any of the data so that the database system can substitute completely for the hand written notes. All of the data can be manipulated, searched, and used while in the field.

Atari Portfolio is the registered trademark of Atari Corp.

FIELDLOG is a program of the Ontario Geological Survey.

AutoCAD is the registered trademark of AutoDesk Inc.

dBASE IV is a trademark of Borland Corporation.

Arc/Info is the trademark of Environmental Systems Research Institute

Regional Geology, Structure and Tectonics of the Teslin Suture Zone
in Northwest Teslin Map Area, Yukon

R.A. Stevens and P. Erdmer
Department of Geology, University of Alberta

The Teslin suture zone in northwest Teslin map area includes three metasedimentary and three metaigneous rock units of Paleozoic and/or Mesozoic age. They are: a graphitic phyllite unit, a siliceous schist and quartzite unit, marble, hornblende megacrystic greenstone, metamorphosed tonalite to quartz diorite and metagabbro. Rocks from the map area have been metamorphosed under greenschist to lower amphibolite facies. Temperature estimates of between 380-550°C have been determined using Garnet-Biotite exchange thermometry. Pressure estimates of between 6-10 Kbar are loosely constrained by the phengite component of white mica. Ductile deformation under the above metamorphic conditions produced protomylonite and mylonite over much of the area, particularly in the siliceous schist and quartzite unit. On average mylonitic foliations and schistosity strike northwest and dip northeast.

Detailed mapping along two east-trending transects about 20 km apart reveals that the suture zone has domains of contrasting structural style with different fabric orientations. In both transects, a western domain of L-S tectonite with well formed mineral lineations passes to the east into a domain dominated by ductile flexural-slip folding with mineral lineations parallel to fold axes, which in turn passes to the east into a domain of poorly formed L-S tectonite with variable fabric orientations. Moderately well constrained shear-sense indicators from the first two domains of the southern transect suggest thrust movement with the hanging wall transported roughly westward. The southern transect intersects a fourth domain farther east that includes L-S tectonite with moderately well formed mineral lineations. Although the structural style of the first three domains is similar, the orientation of fabrics is different in the two transects. Particularly, the orientation of schistosity and mylonitic foliation which switches from northeast dipping in the southern transect to southwest dipping in the northern transect. Together, the structural domains represent a change in deformation from west to east within a single package of rocks, not individual structural slices separated by major faults. This, combined with the fact that deformation decreases to the east suggests that deformation began in the west, propagated to the east and changed style as it went.

Current models on the formation of the suture zone place the rocks as having been deformed within the deep-seated portion of a west dipping Permo-Triassic subduction complex outboard of North America. This package of rocks was subsequently thrust eastward onto North American strata during the Early Jurassic, and the Teslin suture zone represents the root zone to this obducted package of rocks. At present many of the geological features of the suture zone in northwest Teslin map area are consistent with this model. However the northeasterly dipping fabrics with apparent top-to-the-west reverse shearing suggest that west-verging structures may play an important role in the structural evolution of the suture zone. One possibility is that these west verging structures represent back-thrusting within the package of rocks that was thrust eastward over the North America margin.

PRESSURE-TEMPERATURE EVOLUTION OF BLUESCHISTS AND ECLOGITES
FROM PINCHI LAKE, BRITISH COLUMBIA

GHENT, E. D., STOUT, M. Z., Dept. Geology and
Geophysics, U. of Calgary, Calgary, Alberta, T2N
1N4; ERDMER, P., Dept. Geology, U. of Alberta,
Edmonton, Alberta, T6G 2E3, Canada.

Blueschists and retrogressed eclogites occur along the Pinchi Fault Zone (near 54°30'N and 124°W) in British Columbia. This fault separates rocks of contrasting geologic histories and the blueschists and eclogites occur with ultramafic rocks as fault-bounded blocks. The eclogites occur as tectonic blocks, a few m in size; whereas blueschists occur in coherent km-sized tracts (= kst). Eclogites contain garnet-omphacite-rutile-quartz, with glaucophane, lawsonite, and titanite. Tectonic blocks of eclogite from two different localities have recorded different P-T histories. In one tectonic block P-T estimates for garnet inclusions in clinopyroxene and lawsonite ($T \sim 565^{\circ}\text{C}$, $P > 9$ kbar) suggest that garnet and omphacite initially equilibrated outside of the stability field of lawsonite. A decrease in temperature, as recorded in garnet rims and matrix clinopyroxene, resulted in crystallization of lawsonite and other retrogressive minerals. In the second tectonic block, clinopyroxene inclusions in garnet suggest temperatures near 350°C ($P > 9.5$ kbar) and garnet rims equilibrated with matrix clinopyroxene (stable with lawsonite) suggest temperatures near 435°C at $P > 14.5$ kbar ($P_{\text{S}} = P_{\text{H}_2\text{O}}$). Blueschists (kst) contain glaucophane-lawsonite-quartz $\pm$ omphacite and, locally, talc-phengite. The mineral assemblages in these rocks suggest P-T conditions similar to those during retrogression of the eclogites, that is, $T < 400^{\circ}\text{C}$ and $P > 10$ kbar.

The Lay Range Assemblage: Where, What, When?

Filippo Ferri, Steve Dudka and Chris Rees

Geological Survey of British Columbia.

The Upper Paleozoic Lay Range Assemblage outcrops in northeast central British Columbia. The assemblage forms a narrow, fault-bounded belt following, for the most part, the Manson fault zone. It is bounded to the east by North American continental margin rocks of the Cassiar terrane and ocean floor rocks of the Slide Mountain terrane. To the west lie Mesozoic volcanic arc rocks of Quesnellia. Rocks assigned to the Lay Range Assemblage have been recognized as far south as Germansen Landing and extend northwestward to the north end of the Lay Range, a distance of some 100 kilometres.

Work to date indicates that there are four fault-bounded lithologic packages within the Lay Range Assemblage. These are (in order of abundance): 1) A mafic tuff unit composed of green to light green and maroon mafic tuff, tuffaceous siltstone, lapilli tuff, agglomerate, basalt and lesser argillite, chert, gabbro and limestone. Tuffs can be rich in quartz and graded quartz-rich sands are a minor but conspicuous part of this sequence. 2) A mafic-ultramafic unit composed of basalt, gabbro and serpentinite. 3) A quartz-eye tuff unit made up of grey to dark grey, massive quartzo-feldspathic bearing tuff. and 4) An argillite-grit-limestone unit composed of black argillite, shale, phyllite, dark grey to black limestone, quartzite and quartz-feldspar wacke. The involvement of the Lay Range Assemblage within the Manson fault zone has obscured the stratigraphic relationships between the various units but preliminary field observations suggest that the mafic tuff unit sits above the quartz-eye tuff unit.

Fossil data from the Lay Range Assemblage is limited. Limestone lenses from the southern part of the mafic tuff unit have yielded Permian conodonts, whereas limestones in the Lay Range have produced middle Pennsylvanian fusulinids.

Preliminary trace element results from basalts and coarse fragmentals of the mafic tuff and mafic-ultramafic units do not indicate a particular trend. Basalts are calc-alkaline to tholeiitic and contain TiO_2 contents intermediate between those of arc and ocean floor environments. Only a few analyses of the coarse fragmentals are available and these vary from calc-alkaline to alkaline basalts and contain TiO_2 contents indicative of an arc setting.

The Lay Range Assemblage is presently correlated with the Harper Ranch Terrane, a subterrane of Quesnellia and a possible basement to the Mesozoic arc rocks. However, it is also approximately correlative with the Upper Paleozoic Slide Mountain Terrane, locally represented by the Nina Creek Group, which is interpreted to have formed in an oceanic, possibly back-arc setting. The Nina Creek Group abruptly adjoins the Lay Range Assemblage to the southeast; sedimentary units within it contain lenses of wacke rich in feldspar and volcanic fragments, the most likely source of which is the Lay Range Assemblage.

The Lay Range Assemblage is interesting because it has potential affinities with neighbouring terranes, helping to reconstruct the tectonic setting of this part of the Cordillera in the Late Paleozoic. We suggest that the volcanics of the Lay Range Assemblage represent an environment transitional between the ocean floor Nina Creek Group to the east and an arc terrane (Harper Ranch Terrane?) to the west. This work may be an opportunity to demonstrate contiguous and contemporaneous arc and ocean-floor formation in the Late Paleozoic, supporting a model of back-arc extension.

Emplacement of the Cache Creek terrane as constrained by new isotopic and elemental geochemistry from northwestern British Columbia (104M, N)

Mitch Mihalynuk, Moira Smith

British Columbia Geological Survey Branch, 553 Superior Street, Victoria, BC, V8V 1X4

and Janet Gabites

Department of Geological Sciences, University of British Columbia, 6339 Stores Road, Vancouver, BC, V6T 2B4

Since the late seventies a variety of models have been proposed to explain the distribution of terranes in northern British Columbia and southern Yukon. Existence of "deformed continental margin" rocks of the Yukon Tanana and Nisling terranes outboard of the Stikine terrane is enigmatic and has prompted several authors to suggest that the Cache Creek and Stikine terranes are part of an allochthon emplaced over the ancestral margin of North America (megathrust hypothesis). A corollary of the megathrust hypothesis is that both the Cache Creek and Stikine terranes are floored by evolved crust. If so, post-emplacement igneous rocks, sourced from below the Cache Creek or Stikine terrane, should show some indication of this evolved continental material.

Presented here are three new data sets from five intrusions and one felsic volcanic suite (Fig. 1a) ranging in age from Late Triassic to Early Tertiary that cut or overlie Stikine and Cache Creek terranes: (1) Rb-Sr and initial $^{87}\text{Sr}/^{86}\text{Sr}$ determinations; (2) U-Pb geochronology; and (3) REE and trace element analyses.

$^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios range between 0.7034 and 0.7047. Such ratios point to a relatively primitive magma source region.

U-Pb (zircon) age determinations on the Fourth of July batholith, Surprise Lake batholith and Table Mountain volcanic suite return ages of: *c.* 172 (an average of 2 samples), *c.* 84 and *c.* 81 Ma respectively. Deformed strata of the Cache Creek terrane are intruded and thermally metamorphosed by the Fourth of July batholith, thus limiting the age of Cache Creek emplacement to before 172 Ma. Within the limits of error, Table Mountain and Surprise Lake magmatic events are coeval. The fractions analyzed show very little evidence of lead inherited from an evolved Precambrian source.

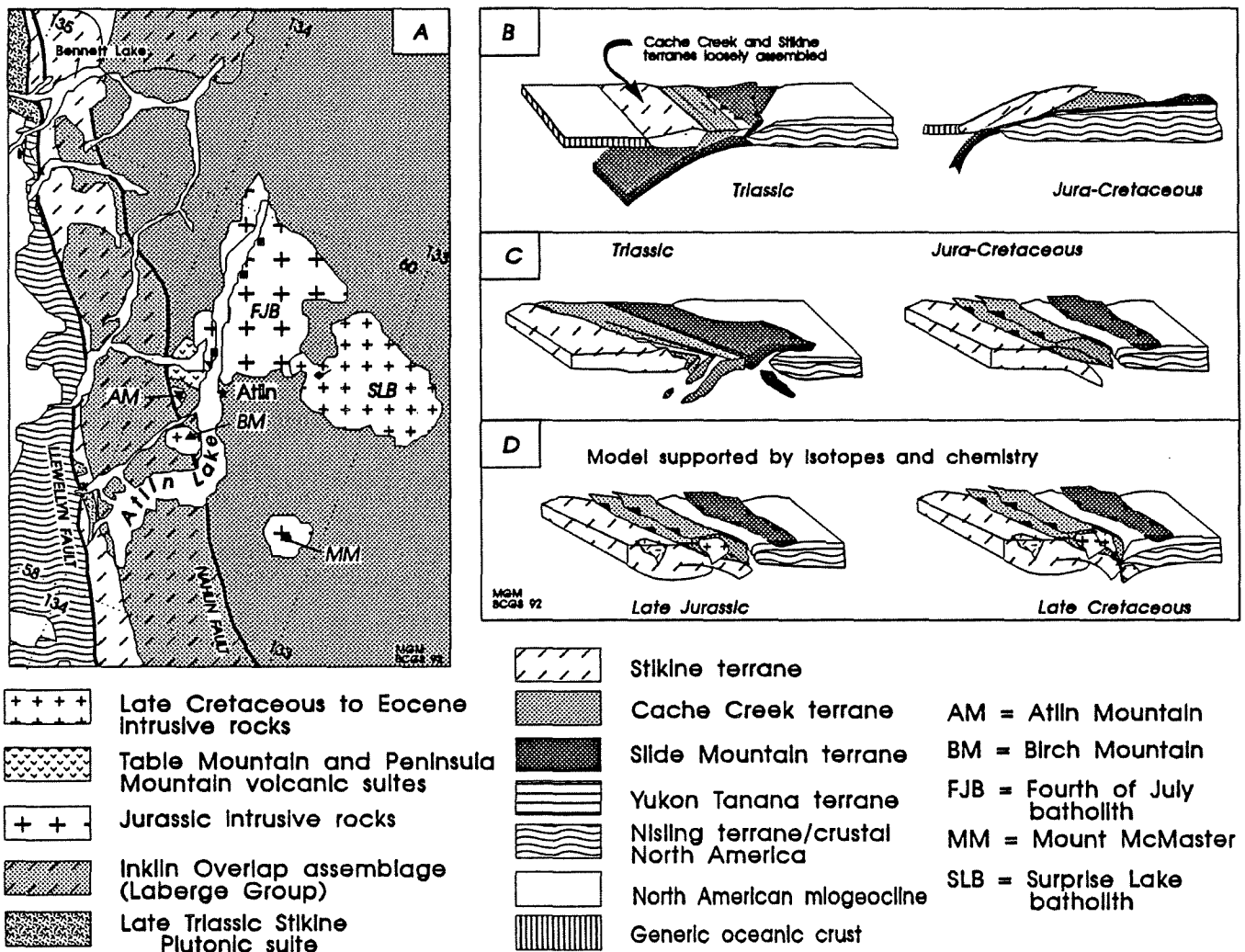
REE and trace element geochemistry indicate a magma source region of volcanic arc character and of surprising homogeneity given the range of ages. Late Triassic Stikine plutonic rocks are clearly comagmatic with arc volcanic rocks which they both crosscut and nonconformably underlay. Thus, all magmatic rocks for which REE data is presented appear to be derived from the primitive Stikine arc or a nearly identical source.

None of our data support a continuation of the ancestral North American margin beneath the Cache Creek and Stikine terranes (Fig. 1b), but rather are more consistent with the classical models which emplace the Cache Creek terrane southwestward over the Stikine terrane as suggested by Monger

(1977, Fig. 1c) with only minor modifications (Fig. 1d). These data support a new view of northern Cordilleran evolution (see Nelson and Mihalynuk, this volume).

MONGER, J.W.H. 1977. Upper Paleozoic rocks of the western Canadian Cordillera and their bearing on Cordilleran evolution. *Canadian Journal of Earth Sciences*, 14: 1832-1859.

Figure 1



THE CACHE CREEK OCEAN: CLOSURE OR ENCLOSURE?

JoAnne Nelson and Mitch Mihalynuk - British Columbia Geological Survey Branch,
553 Superior St., Victoria, B.C., V8V 1X4

The Cache Creek terrane is an enigma in the Canadian Cordillera. Its Late Permian Tethyan faunas, Late Triassic blueschists, melange belts and overall oceanic character combine to give it a strongly exotic signature; and yet it is bordered on all sides by more parochial terranes - Quesnellia and Stikinia, and the Yukon-Tanana terrane to the north. The .706 initial $^{87}\text{Sr}/^{86}\text{Sr}$ line forms a horseshoe around its northern end, sketching a possibility of continuous pericratonic basement. Recent work has added weight to this hook-like geometry, in documenting faunal, geological and isotopic linkages between Quesnellia, Stikinia and the Yukon-Tanana terrane - linkages that suggest at least a loose affiliation between all of these terranes in Late Paleozoic to Early Mesozoic time, prior to the emplacement of the Cache Creek terrane between them. The crucial linkages include: Devonian-Mississippian granitoids; McCloud faunas in Permian limestones of pericratonic North America (Sierras-Klamaths), Quesnellia and Stikinia that suggest a shallow-water connection; detrital zircon populations in the Nisling and Yukon-Tanana terranes that are compatible with North American sources, particularly the Canadian shield; and direct ties between Stikinia and the Yukon-Tanana terrane and Quesnellia and the Yukon-Tanana terrane.

In this paper we propose that the present-day terrane geometry in which Quesnellia-Yukon-Tanana-Nisling-Stikinia wrap around and enclose the Cache Creek terrane is a direct relict of their Early Mesozoic relationships. We model the composite terrane QYS as a continuous Late Triassic arc that was subsequently deformed into an orocline around the Cache Creek terrane. Two mechanisms for this process are offered: early (Permo-Triassic) indentation of the arc to form two festoons separated by a hinge zone in the Yukon-Tanana terrane, followed by Late Triassic-Early Jurassic back-arc rifting behind the Nisling-Stikinia segment to rotate it against the Quesnellia segment. Closure was complete by Middle Jurassic time, when the two limbs of the orocline collided, ending submarine deposition in the Cache Creek ocean and initiating emplacement of Quesnellia onto the margin of North America.

Analogues for these processes can be found in the modern southwest Pacific Ocean. The Mariana arc is currently being indented and segmented by end-on collision of the Caroline Ridge. The Banda arc is curved into an acute angle and engulfed on both sides by continental crust through interaction of the Australian, Pacific and Asian plates. In general, rotations of large crustal elements are a common result of collisions in the real world because of three-plate interactions and the irregular shapes of the plates. The unique aspect of the orocline in the Canadian Cordillera, its extreme degree of closure, may be due to later collision with the composite Wrangellia-Alexander terrane.

NEW PALEONTOLOGIC AND LITHOGEOCHEMICAL DATA FROM THE NATION LAKES AREA AND ITS IMPLICATIONS FOR THE QUESNEL AND STIKINE ARCS

Kim Bellefontaine and JoAnne Nelson, British Columbia Geological Survey Branch,
553 Superior St., Victoria, B.C., V8V 1X4

New paleontological and lithogeochemical data from the Nation Lakes area have important tectonic implications for arcs constructed on Quesnellia and Stikinia. Late Pliensbachian ammonite fossils in intervalcanic sediments date the youngest volcanics ever found in the Takla arc of Quesnellia. A slightly older Early Pliensbachian ammonite locality conformably overlies a thick volcanic pile. This older fossil suggests that volcanism in the Quesnel Terrane was contemporaneous with volcanism of the Telkwa Formation of the Hazelton Group in the Stikine Terrane. Not only was volcanism contemporaneous in the two terranes, but the major phase of arc construction ceased in both arcs during the onset of a Cordillera wide marine transgression marked by widespread shale deposition in Pliensbachian time. A hiatus in volcanism along an arc is a sign of cessation in subduction. It is interesting that these two apparently separate arcs experienced changes in their subduction and volcanic histories at the same time.

The chemistry of Sinemurian volcanism in the Quesnel and Stikine arcs is quite different. Hazelton volcanism is predominantly calc-alkaline whereas Takla-Nicola-Rossland volcanism is diagnostically alkaline. Variations in chemistry within an arc are to be expected. For example, the chemistry of the Triassic rocks within Quesnellia changes from alkaline in the south to calc-alkaline in the north. Modern examples of chemical variance within arcs are common and include the Mariana and Sunda arcs. Chemical variation can occur spatially and temporally across an arc and laterally along the axis of an arc.

Given the similarities between the Early Mesozoic arcs on Stikinia and Quesnellia, in addition to other, earlier parallels such as faunas of McCloud affinity, the juxtaposition of these two terranes across the oceanic Cache Creek terrane poses a fundamental enigma in the reconstruction of the Cordillera.

EARLY CARBONIFEROUS PLUTONISM IN STIKINIA, STIKINE AND ISKUT RIVERS AREA, NORTHWESTERN BRITISH COLUMBIA

Drobe John R., Logan, James M., B.C. Geological Survey Branch, 123-553 Superior Street, Victoria, B.C. V8V 1X4; and McClelland, William C., Department of Geological Sciences, University of Santa Barbara, Santa Barbara, California, U.S.A. 93106

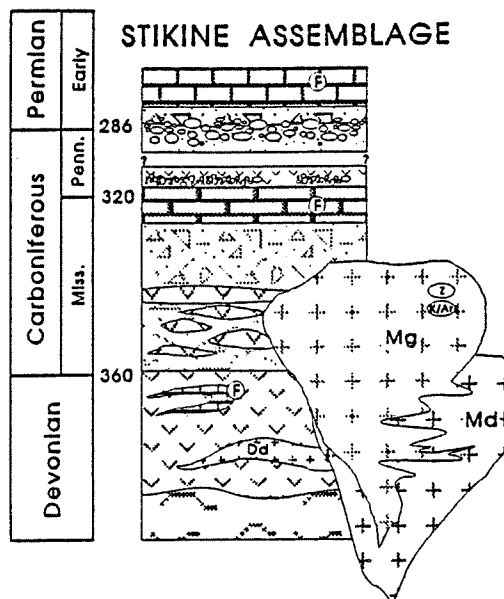
Recent 1:50 000 scale regional mapping between Iskut and Stikine rivers in northwestern British Columbia has outlined a 570 km² granitic intrusive, the Forrest Kerr pluton (FKP). The FKP intrudes Devonian-Mississippian rocks, is nonconformably overlain by early Permian and younger rocks and is the first early Carboniferous intrusive recognized in the Stikine terrane.

In this part of Stikinia, the Paleozoic Stikine assemblage comprises rocks from Early Devonian to Early Permian in age. Devonian rocks are divided into a lower package of quartz sericite schist and graphitic schist, and an upper package of massive intermediate, mainly pyroclastic, volcanic rocks and interbedded marble containing Early Devonian stromatoporoid *Favosites* sp.. Overlying this sequence is a predominantly subaqueous bimodal sequence of basalt and lesser rhyolite. These rocks conformably underly fossiliferous mid-Carboniferous limestone, but their stratigraphic relationship with the older Devonian volcanic rocks is still unresolved. Lithologically, both appear to be products of island arc volcanism. The younger volcanics are coeval and possibly comagmatic with granitic plutonism.

The FKP is a composite body comprising a felsic phase, which ranges from biotite granite to tonalite, and an older mafic phase of mainly hornblende diorite and gabbro. A raft of clinopyroxene hornblendite and hornblende clinopyroxenite occurs isolated within the granite. The FKP is bisected into two, roughly equal bodies, across a northeast trending graben structure which roots in the Forrest Kerr fault zone. Preserved in this structure are Permian conglomerate, limestone and Triassic and Jurassic volcanic and carbonate rocks.

Contact relationships with the margins of the body vary along its length. In the More Creek area, dikes and sills of foliated granite intrude the Devonian-Mississippian rocks. Early Permian conglomerate and limestone nonconformably overlie the pluton along its western edge. The eastern edge of the pluton appears faulted against Late Triassic rocks of the Stuhini Group. To the south, in the Forrest Kerr area, the FKP appears thrust eastward over Early Devonian limestone along its eastern edge; the extent and exact relationship of this contact, however, is unclear. Roof pendants of Mississippian or older sedimentary rocks, including limestone, occur along its western edge.

Both felsic and mafic phases of the FKP are equigranular in texture. Magmatic compositional layering occurs in the mafic portions and there are local tectonic foliations and folded gneissic zones. In thin section, most quartz displays strong undulose extinction and albite twins within plagioclase grains are commonly kinked. Metamorphism is limited to lower greenschist grade. Blue opalescent quartz grains occur locally within hornblende diorite.



Early workers assigned a post-Early Permian to pre-Middle Triassic age to plutonic rocks in the valley of Forrest Kerr creek (Read *et al.*, 1989). Recent K/Ar cooling dates on biotite from granite of the FKP gave an Early Mississippian age of 342 ± 12 Ma. Preliminary results from ongoing U-Pb zircon studies support a Devonian-Early Mississippian age for the FKP.

Elsewhere in the cordillera, granitic rocks of Late Devonian-Early Mississippian age have been recognized within the Eastern Alaskan Range, fault slices of the Slide Mountain, Yukon-Tanana, Bridge River, and Kootenay/Monashee terranes. The outboard position of the FKP and correlative volcanic rocks, relative to the above volcanic-plutonic complexes which developed at least in part over sialic crust, suggests there may have also been wholly ensialic arc-type volcanism at this time.

The Tally Ho Shear-Llewellyn Fault Zone: controls on timing and types of interactions between Nisling and Stikine Terranes in Northern British Columbia and Southern Yukon Territory.

Craig J.R. Hart, Department of Geological Sciences, The University of British Columbia, 6339 Stores Road, Vancouver, BC, V6T 2B4

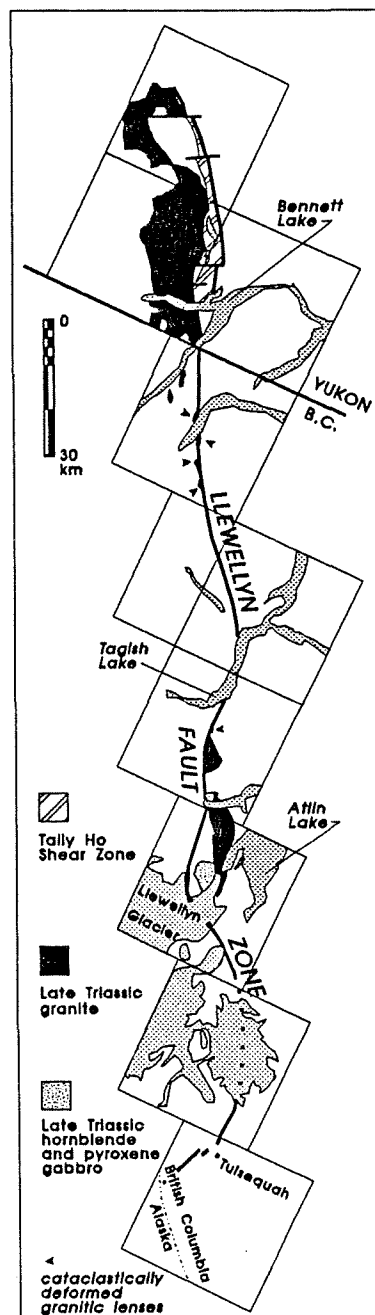
Mitch G. Mihalynuk, British Columbia Geological Survey Branch, 533 Superior Street, Victoria, BC, V8V 1X4

Recent geological mapping of over 220 km of the Intermontane-Coast Crystalline belt contact on both sides of the Yukon-British Columbia border, has defined: (1) the distribution of lithologically distinctive, Late Triassic granitic rocks; and (2) the extent and nature of a major crustal structure - the Tally Ho Shear-Llewellyn Fault Zone (THS-LFZ).

Late Triassic granitic rocks comprise the Bennett Batholith in the Yukon which intrudes dominantly pericratonic rocks of the Nisling Terrane. The eastern margin of this batholith is truncated by the THS-LFZ. Approximately 100 km south, lithologically identical granitic rocks form the Willison pluton which intrudes rocks of Stikine Terrane and whose western contact is cut by the THS-LFZ. Cataclastically deformed lenses of the Late Triassic granite occur at several localities along the fault zones between the major dissected portions.

The Bennett Batholith has returned a U-Pb zircon age of 220 Ma. The Willison pluton also yields a date of 220 Ma from recalculated K-Ar hornblende data. In addition, both plutons give similar initial strontium ratios of approximately 0.7045.

The THS-LFZ represents a complex, long-lived structure whose history can be divided into temporally



distinct, dominantly ductile and brittle regimes. The THSZ records pervasive, ductile, deformation associated with mainly sinistral motion between 220 and ≥ 180 Ma. Younger, brittle fabrics of the LFZ overprint the THSZ and record dextral motion during middle through Late Cretaceous time.

Geological and isotopic evidence suggest that the Bennett Batholith and the Willison pluton were intruded as a single body which formed a magmatic linkage between Nisling and Stikine Terranes in the Late Triassic. Subsequent to intrusion, decoupling across the terrane boundary resulted in a major shear zone that dissected and sinistrally displaced the batholith by an unknown amount. Changes in relative plate motions during Cretaceous time resulted in dextral motion and a **net** dextral displacement of 100 km seen today. That terranes may have migrated southward prior to Cretaceous dextral transport may partly account for paleomagnetic discrepancies between Cretaceous, and Jurassic and older rocks.

JURASSIC ACCRETION OF NISLING TERRANE ALONG THE WESTERN MARGIN OF STIKINIA, COAST MOUNTAINS, NORTHWESTERN BRITISH COLUMBIA

Lisel Currie, Ottawa-Carleton Geoscience Centre, Ottawa, Ontario.

Abstract:

Previously, all metamorphic rocks in the Tagish Lake area of northwestern British Columbia were included in Nisling Terrane, but based on their age and lithology some of these are now included in Stikinia. The Late Mississippian and older Boundary Ranges metamorphic suite is correlated with Devonian to Mississippian bimodal arc volcanic rocks of the Stikine Assemblage. The Permian Wann River gneiss is correlated with mid-Permian Asitka Group volcanic rocks and possible Permian volcanic rocks in the Iskut map-area. The Early Jurassic Tagish Lake suite plutons are correlated with Early to Middle Jurassic volcanic and plutonic rocks of Stikinia. The Florence Range metamorphic suite continues to be included in Nisling Terrane. It is distinguished from Stikinia by its lack of Triassic and Jurassic plutons and volcanic rocks. The Nisling-Stikinia terrane boundary is a zone of ductile shear and imbrication that separates the Florence Range metamorphic suite from the Wann River gneiss and Hale Mountain granodiorite (Tagish Lake suite). A planar fabric that is related to movement on the terrane boundary, is younger than the Early Jurassic Hale Mountain granodiorite (U-Pb zircon, 185 ± 1 Ma) that it deforms, and older than the undeformed Early Cretaceous Taku granite (U-Pb zircon, 129 ± 2 Ma) that cross-cuts it. Based on the local cooling history, deformation fabrics and stable mineral assemblages, the fabric likely formed at lower amphibolite facies conditions between 170 and 185 Ma ago. The shear fabric is the oldest feature that links these terranes, and therefore the shear zone is interpreted as the terrane boundary that formed during accretion of Nisling Terrane to Stikinia during Middle Jurassic time.

EVIDENCE AGAINST MAJOR STRIKE-SLIP DISPLACEMENT ON THE KALTAG FAULT, NORTHERN YUKON

Larry S. Lane, Geological Survey of Canada, Calgary, Alberta

The Kaltag Fault has figured prominently in strike-slip models of Mesozoic plate tectonic evolution of the western Arctic Ocean, and has been described as a paleo-plate margin with hundreds to thousands of kilometres of displacement. Reconnaissance mapping by the Geological Survey and others had previously defined stratigraphic facies trends providing broad constraints on strike-slip displacement, but very poor exposure and widespread unconformities have precluded precise constraints based on the geology alone. Recently released gravity and aeromagnetic surveys of the region provide precise constraints on possible strike-slip on the Kaltag Fault as well as on adjacent structures. The east margin of the Arctic Alaska plate is not offset. Neither is the magnetic anomaly of the Devonian Dave Lord pluton which is bisected by the trace of the Kaltag Fault. Any strike-slip displacement in this area is limited to the resolution of the aeromagnetic data, implying a maximum displacement on the order of 2-3 km. Cretaceous-Tertiary strike-slip of up to 130 km on the Alaskan Kaltag Fault cannot be accommodated through Arctic Yukon, and is probably accommodated on the Tintina Fault, as suggested by others. Any postulated transform emplacement of Arctic Alaska cannot be accommodated by motion on the Kaltag Fault or adjacent structures.

DETRITAL ZIRCON CONSTRAINTS ON THE PROVENANCE OF THE HARMONY AND VALMY FORMATIONS, NEVADA, AND BEARING ON CORDILLERAN EVOLUTION

Moiria T. Smith, B.C. Geological Survey, 553 Superior St., Victoria, B.C. V8V 1X4, and George E. Gehrels, Dept. of Geosciences, University of Arizona, Tucson, AZ 85721

U-Pb isotopic analysis of 47 single detrital zircon grains from lower Paleozoic clastic strata of the Roberts Mountains allochthon (RMA) in Nevada help to constrain their long-disputed provenance. The RMA is an outer continental margin assemblage consisting of quartz-rich and quartzo-feldspathic sandstone, shale, chert, argillite, limestone, basalt and tuff that was emplaced over miogeoclinal strata during the Devonian-Mississippian Antler Orogeny. It is loosely correlative with the Kootenay terrane (Smith and Gehrels 1989) and other displaced continental margin assemblages in the Canadian Cordillera. The RMA has been modelled both as parautochthonous to and derived from North America, or as an exotic, west-derived accretionary terrane. To investigate this controversy, two sedimentary units were selected for zircon analysis: mature quartz arenite of the Middle Ordovician Valmy Formation, thought to represent the most likely unit of North American derivation; and immature quartzo-feldspathic wacke of the Late Cambrian Harmony Formation, for which petrologic evidence argues against a source area to the east.

Grains from the Valmy Formation yield concordant to slightly discordant ages of 1055 (2 grains), 1830-1960 (9 grains), 2075 (1 grain), 2270-2420 (3 grains), 2670-2570 (6 grains), and 3240 (1 grain) Ma. These ages are consistent with ultimate derivation of most grains from the western Canadian shield, and suggest a link between the Valmy Formation and the coeval Eureka Quartzite of the miogeocline. Our data support the postulate of Ketner (1968), who used geometrical and petrologic arguments to show that the Eureka Quartzite might be derived from Cambrian quartzite eroded off the Peace River arch.

Grains from the Harmony Formation yield concordant to slightly discordant ages of 680-710 (8 grains), 1020-1330 (14 grains; also noted by Wallin 1990), 1750 (1 grain), 1920 (1 grain), and 2565 (1 grain) Ma. A predominance of ~700 Ma and 1.02-1.33 Ga grains, displaying little evidence of abrasion and noted in immature wacke, requires a relatively proximal source region comprising igneous rocks of these ages. However, the nearest known sources of significant size are the distant Pan-African and Grenville orogenic belts to the south and east.

Grains of Grenville age (c. 1100 Ma) commonly comprise subordinate populations in other off-shelf continental margin assemblages (e.g., Mortensen 1990; Gehrels *et al.* 1991; J. Nelson, pers. comm.) in the Belt Supergroup (Ross and Parrish, in review) in paragneiss of in the southern Omenica belt (Ross and Parrish 1991) and have limited distribution as entrained xenocrysts in diatremes which intrude deformed North American strata (e.g., Parrish and Reichenbach 1991; Jefferson and Parrish 1988). Zircons in the range of 670-780 Ma are known from off-shelf continental margin assemblages (e.g., Gehrels *et al.* 1991; Ross and Parrish, 1991; Smith and Gehrels 1991; J. Nelson, pers. comm.), volcanic rocks (Roots and Parrish 1988), and numerous small intrusions and gneissic bodies (e.g., Aleinikoff *et al.* 1990; Evenchick *et al.* 1984; McDonough and Parrish 1991; Parrish and Scammel 1988) that intrude continental margin strata along the length of the Cordillera from the southern Kootenay Arc to eastern Alaska. These observations suggest that the Cordilleran continental margin was the site of tectonic and magmatic activity during at least two broadly defined periods (~670-780 and ~1100-1300 Ma) prior to latest Precambrian rifting.

Evidence for these events ought to be reflected in the western side of this rift. In this context, data for the Harmony Formation are not consistent with current scenarios (e.g., Moores 1991) that place the Transantarctic Mountains adjacent to the western United States during Late Proterozoic time. Thus, new evidence from the Harmony Formation, and from other U-Pb isotopic studies along the continental margin to the north, may require revisions to plate reconstructions and to models of the Proterozoic tectonic history of the continental margin.

- Aleinikoff, J.N., Dusel-Bacon, C., Foster, H.L., Nokleberg, W.J. 1990. A summary of isotopic constraints on the history of the Yukon-Tanana terrane, east-central Alaska. G.A.C.-M.A.C. Program with Abstracts, 15: A1
- Evenchick, C.A., Parrish, R.R., and Gabrielse, H. 1984 Precambrian gneiss and Late Proterozoic sedimentation in north-central British Columbia. *Geology*, **12**: 233-237.
- Gehrels, G.E., McClelland, W.C., Samson, S.D., and Patchett, P.J. 1991. U-Pb geochronology of detrital zircons from a continental margin assemblage in the northern Coast Mountains, southeast Alaska. *Canadian Journal of Earth Sciences*, **28**: 1285-1300.
- Jefferson, C.W., and Parrish, R.R. 1988. Late Proterozoic stratigraphy, U-Pb zircon ages, and rift tectonics, Mackenzie Mountains, northwestern Canada. *Canadian Journal of Earth Sciences*, **26**: 1784-1801.

- Ketner, K.B. 1968. Origin of Ordovician quartzite in the Cordilleran miogeosyncline. U.S. Geological Survey, Professional Paper 600-B, pp. B169-B177.
- McDonough, M.R., and Parrish, R.R. 1991. Proterozoic gneisses of the Malton Complex near Valemount, British Columbia: U-Pb ages and isotopic signatures. Canadian Journal of Earth Sciences, **28**: 1202-1216.
- Moore, E.M. 1991. Southwest U.S.-east Antarctic (SWEAT) connection: A hypothesis. Geology, **19**: 425-428.
- Mortensen, J.K. 1990. Significance of U-Pb ages for inherited and detrital zircons from Yukon-Tanana terrane, Yukon and Alaska. G.A.C.-M.A.C Program with Abstracts, **15**: A91.
- Root, C.F., and Parrish, R.R. 1988. Age of the Mount Harper volcanic complex, southern Ogilvie Mountains, Yukon. *in*, Radiogenic Age and Isotopic Studies, Report 2. Geological Survey of Canada, Paper 88-2, pp. 29-35, 1988.
- Parrish, R.R., and Scammel, R.J. 1988. The age of the Mount Copeland syenitic gneiss and its metamorphic zircons, Monashee Complex, southeastern British Columbia. *in*, Radiogenic Age and Isotopic Studies, Report 2. Geological Survey of Canada, Paper 88-2, pp. 21-28.
- Parrish, R.R., and Reichenbach, I. 1991. Age of xenocrystic zircon from diatremes of western Canada. Canadian Journal of Earth Sciences, **28**: 1232-1238.
- Ross, G.M., and Parrish, R.R. 1991. Detrital zircon geochronology of metasedimentary rocks in the southern Omineca Belt, Canadian Cordillera. Canadian Journal of Earth Sciences, **28**: 1254-1270.
- Smith, M.T., and Gehrels, G.E. 1989. Lower Paleozoic eugeoclinal strata in the Kootenay Arc, NE Washington and SE British Columbia: A northward continuation of Roberts Mountains allochthon-type outer continental margin facies. Geological Society of America, Abstracts with Programs, **21**: 146.
- Smith, M.T., and Gehrels, G.E. 1991. Detrital zircon geochronology of upper Proterozoic to lower Paleozoic continental margin strata of the Kootenay Arc: implications for the early Paleozoic tectonic development of the eastern Canadian Cordillera. Canadian Journal of Earth Sciences, **28**: 1271-1284.
- Wallin, E.T. 1990. Provenance of selected lower Paleozoic siliciclastic rocks in the Roberts Mountains allochthon, Nevada. Geological Society of America, Special Paper 255.

POSTER PRESENTATIONS

(Listed Alphabetically)

Geochronology of Mesozoic Granitoids in the Southern Canadian Cordillera

Alan D. Brandon and Richard St J. Lambert

Department of Geology, University of Alberta, Edmonton,
Alberta, T6G 2E3

Introduction

Granitoid rocks along the Lithoprobe Southern Canadian Cordillera Transect are exposed within several geologic formations ranging from Proterozoic age Purcell-Windermere metasediments in the eastern part of the transect to Paleozoic-Mesozoic age rocks of Terrane 1 within the Omineca Crystalline Belt further west (Figure 1). Within the present geochronological framework, it is thought that the majority of these granitoids were intruded and crystallized in two phases, one in the Mid-Jurassic and the other in mid-Cretaceous (Armstrong et al., 1988). These conclusions are based on an incomplete radioisotope age database and field relations. In many instances, the major batholiths only have K-Ar ages reported, which have been interpreted as representing metamorphic and uplift ages rather than crystallization ages (Archibald et al., 1983; Archibald et al., 1984). Furthermore, Rb-Sr mineral isochron ages are discordant with U-Pb zircon ages and Rb-Sr whole rock ages for the Raft and White Creek batholiths, respectively (Calderwood et al., 1990; Wanless et al., 1968a), and these dates appear to also represent resetting owing to thermal overprints after crystallization.

It is important to precisely constrain the range of crystallization ages for the Mesozoic batholiths along the Lithoprobe transect in the southern Canadian Cordillera in order to test models on the physiothermal conditions which led to crustal melting, and to relate these granitoids to possible metamorphic and tectonic events which have affected this complex region of continental crust. In this paper, we report our results for Rb-Sr whole rock-apatite geochronology on several of the major batholiths in the region including the Raft, Fry Creek, White Creek, Bugaboo, Horsethief Creek, and Whatshan intrusions. For the most part, our results combined with reliable dates from earlier studies confirm that most of the Mesozoic granitoid magma generation in this region was

restricted to two events about 10 m.y. in length from approximately 170 to 160 Ma and 115 to 105 Ma, respectively, although a preliminary reference isochron for Whatshan does not fall within either of those events.

Results

Figures 2-4 display whole rock-apatite Rb-Sr age relations. Rb and Sr abundances on whole rocks powders were obtained by XRF at Washington State University using the techniques described by Hooper and Johnson (1987). Experimental accuracy was determined by replicate analysis of USGS standards BCR-1 and AGV-1, with 1σ standard deviation for Rb ranging from $\pm 1.80\%$ to 1.19% and for Sr ranging from 0.42% to 0.27% (Table 2, Brandon, 1989). $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were measured on a VG MM30 mass spectrometer at the University of Alberta using the methodology reported in Trønnes and Brandon (1992). Regressions were calculated according to the method of York (1969), with 1σ uncertainties in $^{87}\text{Rb}/^{86}\text{Sr}$ at $\pm 2\%$ and 2σ in $^{87}\text{Sr}/^{86}\text{Sr}$ of ± 0.00008 on the measured ratio. Apatite was used to constrain the 0-intercept $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of isochrons for several of the plutons. Apatite has almost negligible Rb contents and consequently $^{87}\text{Rb}/^{86}\text{Sr}$ ratios approaching zero. Also, Sr diffusion in apatite is such that for most post-crystallization thermal modification conditions which will redistribute Rb and Sr in feldspars, micas, etc., the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in apatite will retain those of the magmas from which the apatite crystallized from (Creaser and Gray, 1992). Therefore, in situations where other minerals in granitoids may reflect post-crystallization overprints and yield younger isochrons, apatite can be used to help constrain Rb-Sr whole rock ages.

Figure 2 shows Rb-Sr whole rock age relations for the Raft and Whatshan plutons. The Whatshan granodiorite samples give an age of 150.1 ± 3.5 Ma. Our samples essentially yield a two point isochron and must be viewed with caution. This date is in conflict with U-Pb zircon ages of 77 Ma of Carr (1991). However, assuming that this pseudochron date is correct suggests that Whatshan may be a composite intrusion with both Jurassic and Cretaceous crystallization ages.

The samples analyzed from the Raft batholith range from dioritic to biotite-muscovite granite in composition. These samples yield an age of 164.0 ± 2.2 Ma. This date is in agreement with a U-Pb zircon age for Raft

of $168 \pm 14/-12$ Ma reported by Calderwood et al. (1990), and confirms a Mid-Jurassic crystallization age for Raft. A whole rock-mineral Rb-Sr isochron of 104.3 ± 3.3 Ma was also obtained by Calderwood et al. (1990) which is discordant with both our whole rock Rb-Sr isochron and the U-Pb zircon age, and this younger age must represent resetting of minerals for the Rb-Sr system, and is interpreted by Calderwood et al. (1990) to reflect selective loss of ^{87}Sr .

Figure 3 displays whole-apatite Rb-Sr age relations for the Bugaboo, Fry Creek, and Horsethief Creek plutons. The whole rock samples for these plutons consist of granodiorite and granite, except one sample from Bugaboo (Bug-7) is an aplite vein, and one sample (Hor-6) from Horsethief Creek is a cognate xenolith of quartz monzodiorite. All three plutons define mid-Cretaceous ages from 107.0 ± 0.4 Ma for Bugaboo to 115.4 ± 3.5 Ma for Fry Creek. The calculated initial $^{87}\text{Sr}/^{86}\text{Sr}$ for all three plutons are similar, from 0.70773 ± 6 to 0.70831 ± 10 . These results suggests that all three plutons are genetically related.

Rb-Sr age relations for the White Creek batholith are shown in Figure 4. The White Creek batholith is a composite intrusion which ranges in composition from quartz monzodiorite along the rim of the batholith, which grades into granodiorite then into porphyritic granodiorite (with centimeter size alkali feldspar phenocrysts) towards the center of the batholith. Within the core of the White Creek batholith, a unit of peraluminous biotite-muscovite granite has intruded and crosscut the earlier units. Trace element and isotopic data for the White Creek batholith indicates that there were three separate batches of magma including, 1), the rim quartz monzodiorite and adjoining granodiorite, 2), the porphyritic granodiorite, and 3) the core two mica granite (Brandon, PhD thesis in progress).

Wanless et al. (1968a) obtained a Rb-Sr whole rock isochron of 115 ± 5 Ma isochron of for the core two mica granite (Figure 4). Our results (which include aplite samples 5, 6, 24, and 25) do not correspond to an isochron but scatter around the isochron obtained by Wanless et al. (1968a) suggesting either initial isotopic inhomogeneity or Rb-Sr resetting by later thermal events. $\delta^{18}\text{O}$ compositions for whole rock-quartz pairs for three of these samples (4, 8, and 26) probably reflect an influx of oxygen during hydrothermal alteration which could have also affected the Rb-Sr

system in this unit (Brandon, PhD thesis in progress). An Rb-Sr whole rock-apatite isochron of 105.9 ± 0.6 Ma was obtained for the porphyritic granodiorite which included one pegmatite sample (9). The samples from the exterior unit of quartz monzodiorite and granodiorite do not yield an isochron because of their narrow range in Rb/Sr ratios. However, the samples from this unit correspond well to a 105.9 Ma reference line with a lower $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio of 0.70726 (i.e. the measured ratio for apatite from sample 18). Our results, combined with the results from Wanless et al. (1968) suggests that although the White Creek batholith is composite in nature, the separate units were crystallized within the same period between 105 to 115 Ma. These ages also correspond to those of Fry Creek, Horsethief Creek, and Bugaboo, and the similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for these three plutons and the rim unit of White Creek suggests that these plutons are all part of the same magmatic event and genetically related.

Discussion and Conclusions

Table 1 summarizes crystallization age relations for Mesozoic granitoids within Figure 1. Rb-Sr whole rock ages are generally concordant with U-Pb zircon ages when both ages are available for any given pluton. Rb-Sr whole rock-mineral ages are slightly younger for the Galena Bay and Baldy plutons, but in most instances the mineral systems have been reset and are therefore recording younger thermal events (i.e. data of Wanless et al., 1968; Archibald et al., 1983; Archibald et al., 1984 which is not shown). Most of the K-Ar and Ar-Ar ages also appear to represent post-crystallization ages (not shown), although K-Ar ages for both the Nelson and Mt. Toby intrusions are within the range for Mid-Jurassic dates by the more reliable U-Pb and Rb-Sr whole rock methods (Table 1).

In conclusion, our study, combined with earlier age determinations suggest that the majority of granitoid magma in this region during the Mesozoic was produced in two pulses. The first pulse lasted 10 to 15 m.y. during the Mid-Jurassic from about 173 to 162 Ma. The 150.1 age from the Whatshan pseudochron may indicate that this magmatic event was substantially longer, however, without a better determination of these rocks combined with careful study of the field relations for this composite batholith, any interpretation should be viewed with caution.

The U-Pb zircon and Rb-Sr whole rock-apatite ages (i.e. crystallization ages) for the mid-Cretaceous granitoids range from about 116 Ma to 107 Ma for all of the plutons. Therefore this second pulse of granitoid magma generation was also about 10 m.y. in duration.

References

- Archibald, D.A., Glover, J.K., Price, R.A. Farrar, E., and Carmichael, D.M., 1983, Geochronology and tectonic implications of magmatism and metamorphism, southern Kootenay Arc and neighbouring regions, southeastern British Columbia. Part I: Jurassic to Mid-Cretaceous, Canadian Journal of Earth Sciences, v.20, p.1891-1913.
- Archibald, D.A., Krogh, T.E., Armstrong, R.L., and Farrar, E., 1984, Geochronology and tectonic implications of magmatism and metamorphism, southern Kootenay Arc and neighbouring regions, southeastern British Columbia. Part II: Mid-Cretaceous to Eocene: Canadian Journal of Earth Sciences, v.21, p.567-583.
- Armstrong, R.L., 1988, Mesozoic and Early Cenozoic magmatic evolution of the Canadian Cordillera: *In*: Clark, S.P., Burchfiel, B.C., and Suppe, J., Eds., Processes In Continental Lithospheric Deformation, Geological Society of America Special Paper 218, p.55-91.
- Brandon, A.D., 1989, Constraints on magma genesis behind the Neogene Cascade arc: Evidence from major and trace element variation of high-alumina and tholeiitic volcanics of the Bear Creek area: Journal of Geophysical Research, v.94, p.7775-7798.
- Calderwood, A.R., van der Heyden, P., and Armstrong, R.L., 1990, Geochronometry of the Thuya, Takomkane, Raft, and Baldy batholiths, south-central British Columbia: Geological Association of Canada, Program with Abstracts, V.15, p. A19.
- Carr, S.D., 1991, Tectonic evolution of the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia: Proceedings of the Lithoprobe Cordilleran Workshop, University of Calgary Publ., p.61-75.
- Creaser, R.A., and Gray, C.M., 1992, Preserved initial $^{87}\text{Sr}/^{86}\text{Sr}$ in apatite from altered igneous rocks: A case study from the Middle Proterozoic of South Australia: submitted to Geochimica et Cosmochimica Acta.
- Einarsen, J.M., 1991, Structural setting and geochemistry of granitic stocks in the Quesnellia-North America boundary of southeastern B.C.: Geological Society of America, Abstracts with Programs, v.22, no.3, p.20-21.
- Hooper, P.R., and Johnson, D., 1987, Major and trace element analyses of rocks and minerals by automated X-ray spectrometry, report, Department of Geology, Washington State University, Pullman.
- Lambert, R.StJ., and Chamberlain, V.E., 1988, Cordillera revisited, with a three-dimensional model for Cretaceous tectonics in British Columbia: Journal of Geology, v. 96, p. 47-60.
- Monger, J.W.H., and Berg, H.C., 1987, Lithotectonic terranes of Western Canada and Southeastern Alaska: Map MF-1874B, United States Geological Survey, p.1-12.
- Parrish, R.R., and Armstrong, R.L., 1987, The ca. 162 Ma Galena Bay stock and its relationship to the Columbia River fault zone, southeast British Columbia: *in* Radiogenic Age and Isotopic Studies: Report 1, Geological Survey of Canada, Paper 87-2, p. 25-32.
- Parrish, R.R., and Wheeler, J.O., 1983, A U-Pb zircon age from the Kuskanax batholith, southeastern British Columbia: Canadian Journal of Earth Sciences, v.20, 1751-

1756.

- Parrish, R.R., Carr, S.D., and Parkinson, D.L., 1988. Eocene extensional tectonics and geochronology of the southern Omineca Belt, British Columbia and Washington: *Tectonics*, v.7, p.181-212.
- Trønnes, R.G., and Brandon, A.D., 1992, Mildly peraluminous high-silica granites in a continental rift: the Drammen and Finnemarka batholiths, Oslo Rift, Norway: *Contributions to Mineralogy and Petrology*, in press.
- Wanless, R.K., Loveridge, W.D., and Mursky, G., 1968a, A geochronological study of the White Creek batholith, southeastern British Columbia: *Canadian Journal of Earth Sciences*, v.5, p.375-386.
- Wanless, R.K., Stevens, R.D., Lachange, G.R., and Edmonds, C.M., 1968b, Age determinations and geological studies, K-Ar isotopic ages, report 8: Geological Survey of Canada, Paper 67-2A, p.1-53.
- York, D., 1969, Least squares fitting of a straight line with correlated errors: *Earth and Planetary Science Letters*, v.5, p.320-324.

Table 1. Crystallization age determinations for Mesozoic granitoids in the southern Canadian Cordillera Lithoprobe Transect. The data is in Ma and is compiled from Parrish and Wheeler (1983), Kuskanax; Calderwood et al. (1990) U-Pb for Raft; Parrish and Armstrong (1987), Galena Bay; Nguyen et al. (1968) and Wanless et al. (1968b), K-Ar for Nelson; Ghosh and Lambert, unpublished data, U-Pb for Nelson; Wanless et al. (1968a), Mt. Toby, Carr (1991), U-Pb for Whatshan; Archibald et al. (1983), Mine Stock; Calderwood et al. (1990), Baldy; Einarsen (1991) and Einarsen (personal communication, 1991) for Salmo and Wallack Creek; and Wanless et al. (1968a) for 115 Ma on White Creek. All other determinations are from this study.

Intrusion	K-Ar	U - Pb	Rb - Sr
Kuskanax		173 +/-5	
Raft		168 +/-14/-12	164.0 +/-2.2
Galena Bay		161.6 +/-0.5	156.7 +/-2.4 (wr-mineral)
Nelson	165-174	164	
Mt. Toby	166		
Mine Stock		171	
Whatshan		77	150.1 +/-3.5
Baldy		115.9 +/-4.6	98.5 +/-2.2 (wr-mineral)
Salmo			115
Wallack Creek			115
Bugaboo			107.0 +/-0.4
Horsethief Creek			109.5 +/-7.2
Fry Creek			115.4 +/-3.5
White Creek			115 +/-5
			105.9 +/-0.6

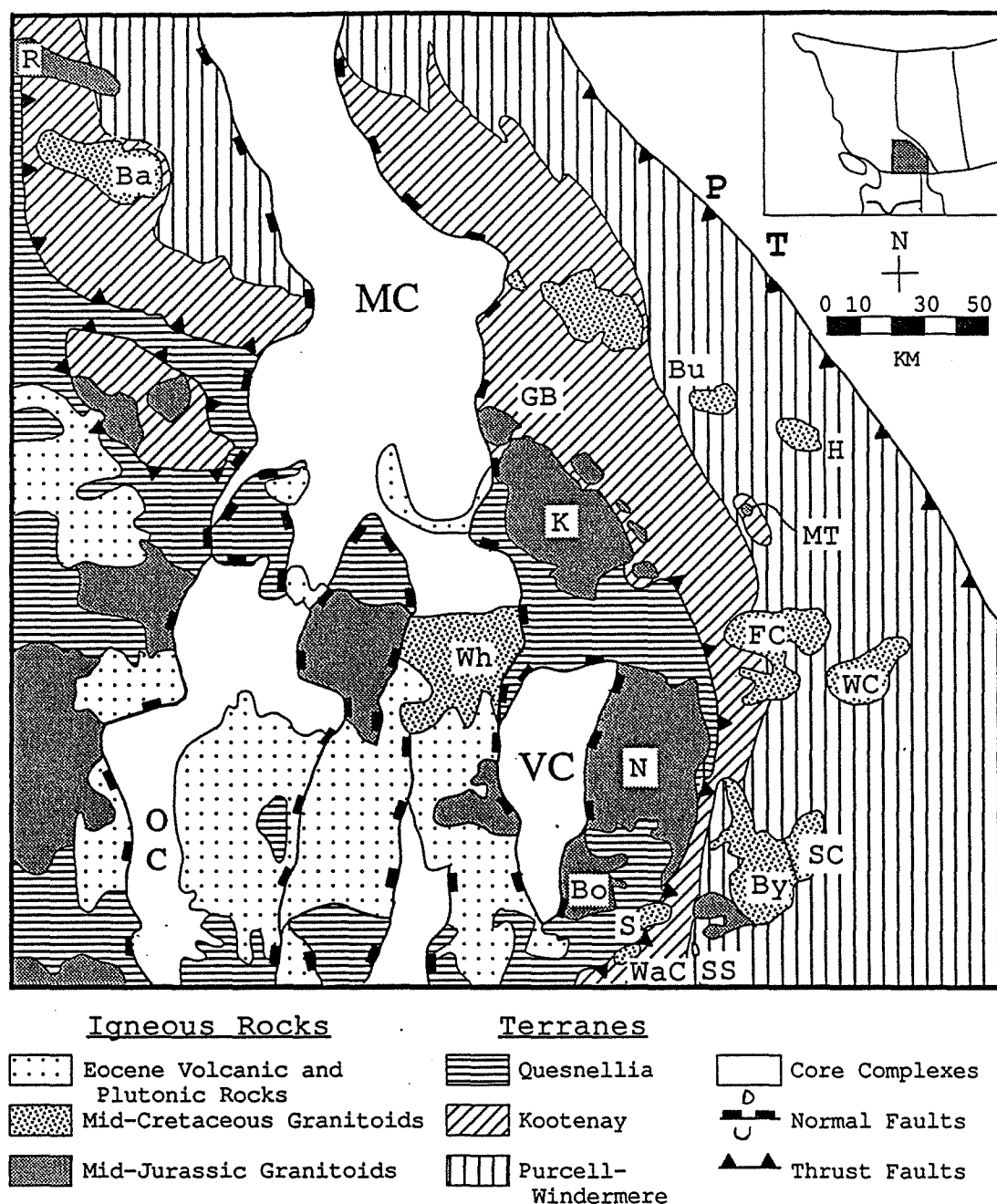


Figure 1. Tectono-magmatic map of the southern Omineca Crystalline Belt (modified from Parrish et al., 1988; Lambert and Chamberlain, 1988; and Monger and Berg, 1987). Several of the metamorphic core complexes include SC - Shuswap complex, OC - Okanagan complex, VC - Valhalla complex. the plutons include Ba - Baldy, Bo - Bonnington, Bu - Bugaboo, By - Bayonne, FC - Fry Creek, GB - Galena Bay, H - Horsethief Creek, K - Kuskanax, MT - Mt. Toby, N - Nelson, R - Raft, S - Salmo, WaC - Wallack Creek, WC - White Creek, and Wh - Whatshan. The Purcell thrust is labelled PT.

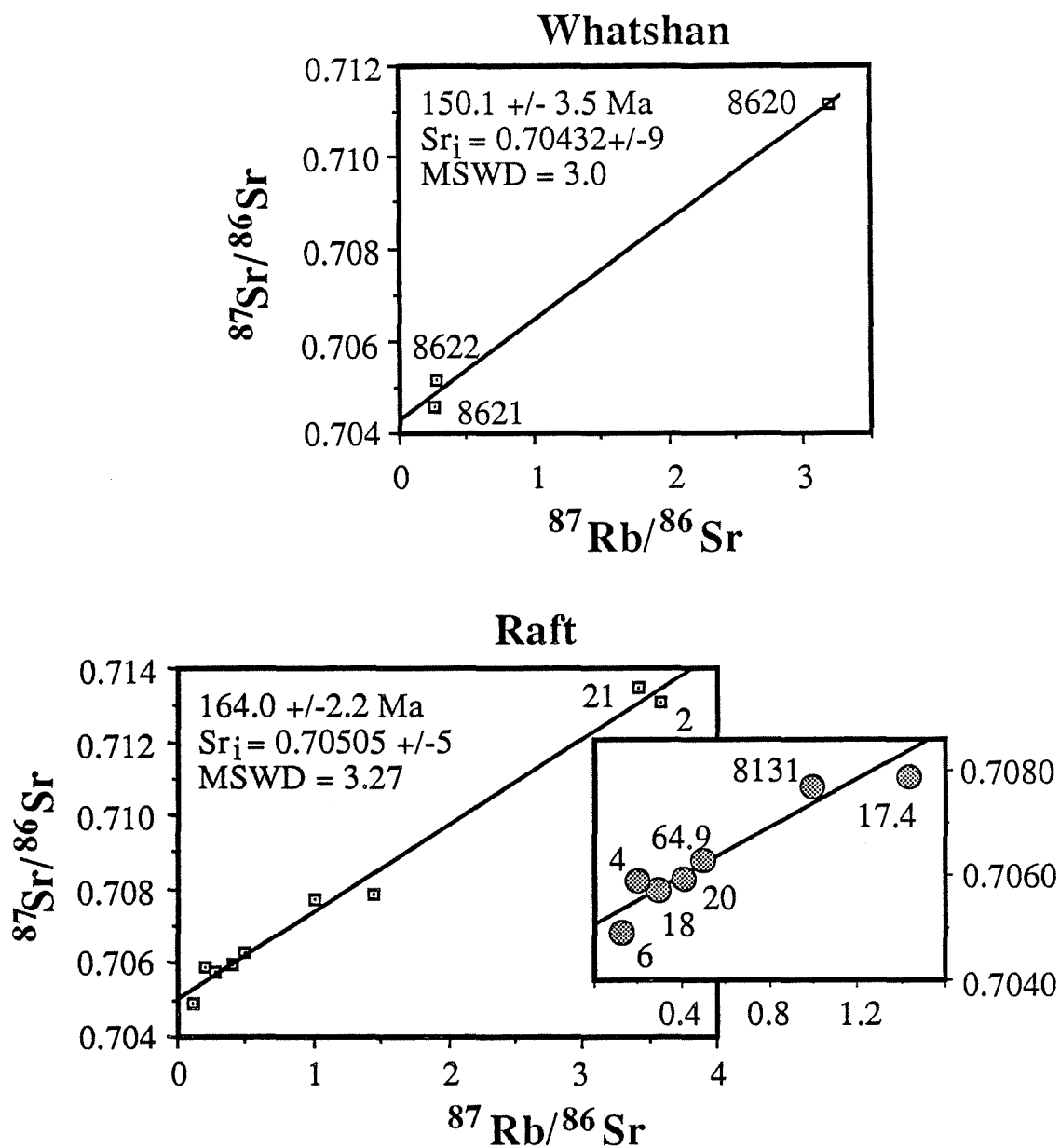


Figure 2. Rb-Sr age relations for the Whatshan and Raft plutons.
Sample numbers are listed beside each point.

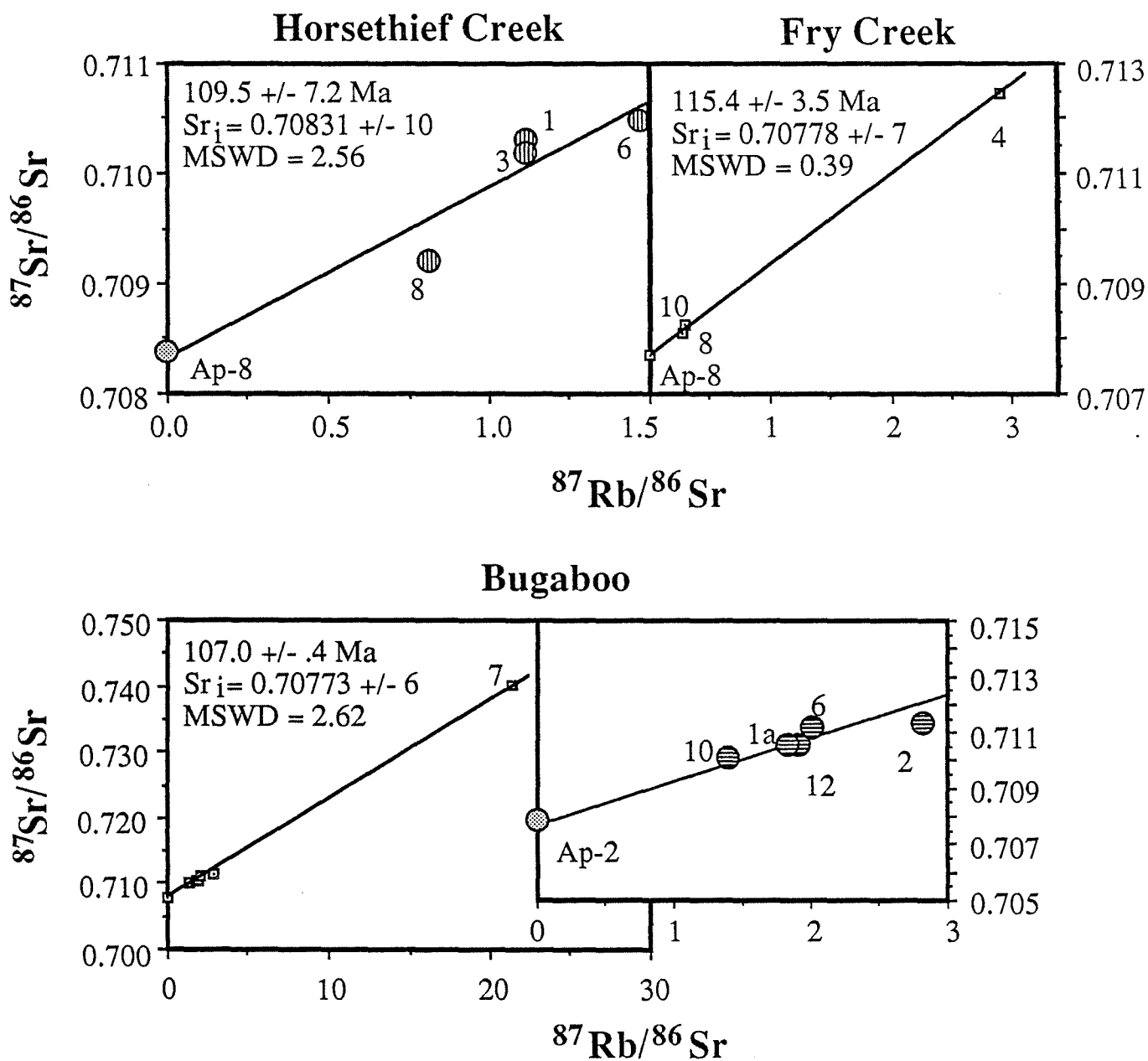


Figure 3. Rb-Sr age relations for the Horsethief Creek, Fry Creek, and Bugaboo plutons. Ap are for apatite analyses.

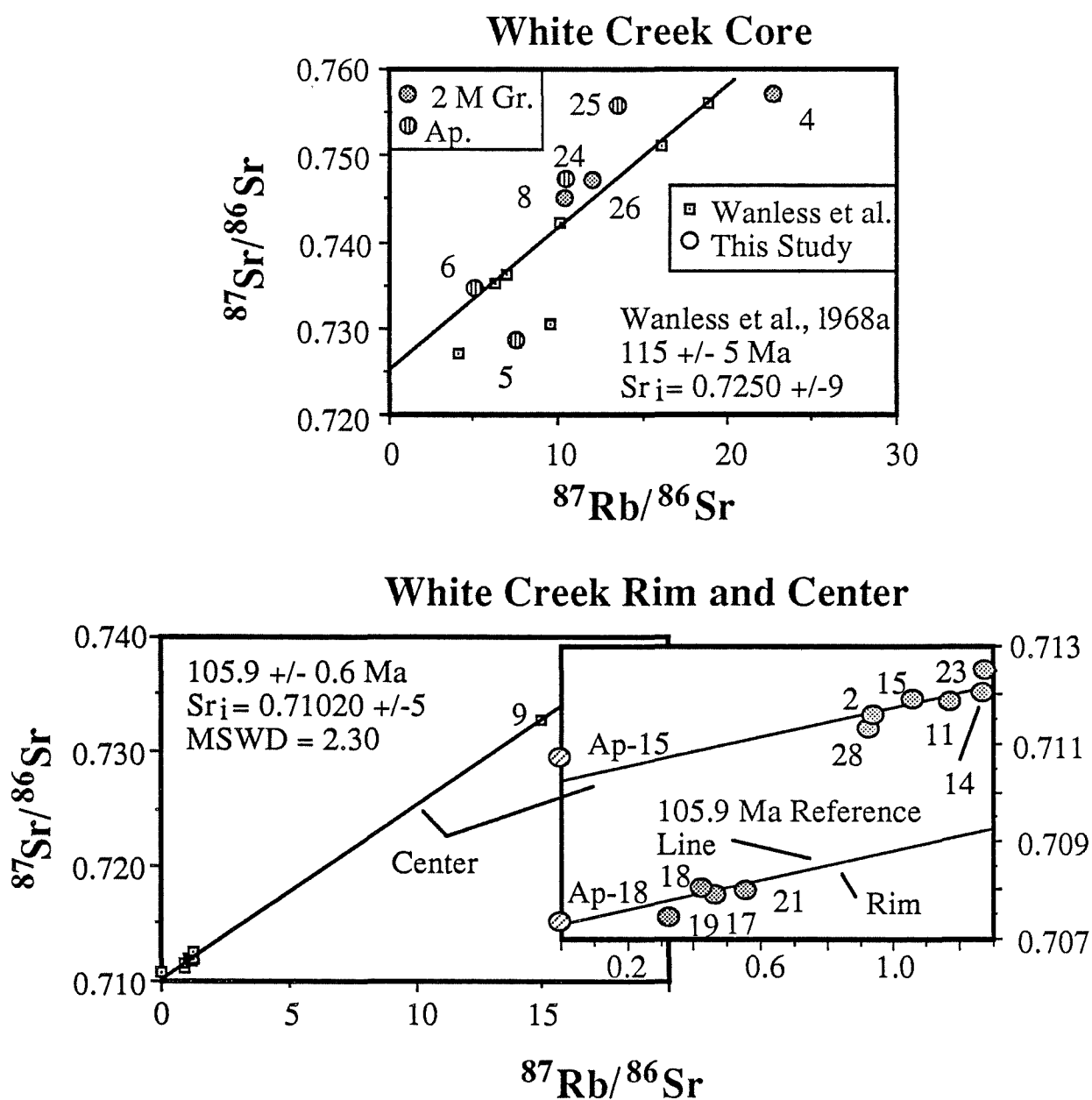


Figure 4. Rb-Sr age relations for the White Creek composite batholith.

Structural elements in western Telegraph Creek map area (104G) and their western extensions into Chutine map area (104F)

Derek A. Brown. B.C. Geological Survey Branch, Victoria, B.C.

Stikine Project regional 1:50 000-scale mapping has documented "basement" Stikine assemblage trends, a pre-Triassic (?) orogenic event, Permo-Triassic contacts, pre-Toarcian (187-178 Ma) northeast-directed (?) deformation, and post-Toarcian southwest-directed deformation. Recent observations incorporated with previous work by Souther (1959, 1972) provide new constraints on the geological evolution of northwestern Stikinia.

The project area, incised by the Stikine and Chutine rivers, lies southwest of Telegraph Creek. Here narrow belts of Paleozoic Stikine assemblage strata are unconformably overlain by Upper Triassic Stuhini Group sedimentary and volcanic rocks, except in three localities, where geographically restricted Middle Triassic argillite/chert lie above the Stikine assemblage. Hazelton Group volcanic flows of Toarcian age are unconformably overlain by Sustut and Sloko groups in a small area southeast of the confluence of the Chutine-Stikine rivers. In this succession the absence of the Bowser Lake Group can be attributed to either non-deposition resulting from a paleo-topographic high or erosion prior to Sustut deposition.

The intrusive rocks of the Triassic-Jurassic Hickman batholith and Eocene Coast Belt respectively underlie most of the eastern and southwestern portions of the project area. An Early to Middle Jurassic east-trending belt is conspicuous north of the Scud River. North-trending bounding faults east and west of the Hickman batholith were difficult to locate. Small Alaskan-type ultramafic and syenite bodies are irregularly distributed throughout the area. Large plutons that characterize the central map area are absent north of the Stikine River.

Permian limestone massifs delineate 3 structural trends: N, NW, and NE. Their orientation can be explained by regional compressional faults, for example Cone Mountain and Jimjack faults. The bend from NW to E-trending, southwest of the Chutine River, remains enigmatic partly because the closure is underlain by an Eocene pluton. This bend is mimicked by thinner limestone pendants farther to the south.

A pre-Triassic (?) orogenic event is evident within Stikine assemblage structural culminations in the northwestern corner of the project area. The undated, greenschist grade phyllitic volcanic and sedimentary rocks are believed to be Carboniferous or older based on regional lithological correlations.

Permo-Triassic contacts have been documented in several localities, including: (1) toe of Scud Glacier -- Late Permian tuffaceous limestone and chert overlain by pyroxene-rich wacke correlated with Stuhini Group, (2) Permian limestone north of Chutine River unconformably overlain by Middle to Late Triassic chert then Stuhini Group, (3) pre-Permian (?) deformed and metamorphosed phyllite overlain unconformably by zeolite (?) grade Stuhini Group.

Pre-Toarcian deformation is documented near the headwaters of Strata Creek where folded and faulted Stuhini Group Norian sedimentary rocks are unconformably overlain by gently-dipping Hazelton Group Toarcian flows and breccia.

Post-Toarcian southwest-directed ductile deformation involves foliated granodiorite and metavolcanic rocks of the Stikine assemblage in a northeast-dipping mylonitic fault zone over 500 m wide. The footwall comprises a 185 Ma granodiorite pluton, the Cone Mountain pluton. Kinematic indicators include C-S fabrics and mica fish within foliated granodiorite and asymmetric southwest-verging folds of Permian limestone. Faulted limestone strata with older above younger fusulinid species provides additional support of this compressional event. This event may be coeval with displacement along the Middle Jurassic King Salmon Fault system, 125 km to the north.

Acknowledgements:

Geological mapping for Stikine Project was ably conducted by D. Carmichael, C. Greig, M. Gunning, M. McDonough, I. Neill, and J. Timmerman.

Geochronometric age determinations were obtained by J. Harakal and M.L. Bevier. Essential fossil identifications and their ages were provided by W. Bamber, F. Cordey, Rai Lin, M. Orchard, A. Sweet, H. Tipper, and T. Tozer.

References:

Brown et al.: Geological Fieldwork, *B.C. Ministry of Energy, Mines and Petroleum Resources*, Papers 1989-1, pages 251-267; 1990-1, pages 141-151; 1992-1, pages 179-195; Open Files 1989-7, 1990-1, 1992-2.

Logan, J.M. and Koyanagi, V.M. (1989a): Geology and Mineral Deposits of the Galore Creek Area, Northwestern B.C. (104G/3&4); *in* Geological Fieldwork 1988, *B.C. Ministry of Energy, Mines and Petroleum Resources*, Paper 1989-1, pages 269-284.

Logan, J.M. and Koyanagi, V.M. (1989b): Geology and Mineral Occurrences of the Galore Creek area (104G/3&4); *B.C. Ministry of Energy, Mines and Petroleum Resources*, Open File 1989-8.

Souther, J.G. (1959): Chutine, British Columbia; *Geological Survey of Canada*, Map 7-1959.

Souther, J.G. (1971): Geology and Mineral Deposits of Tulsequah Map Area; *Geological Survey of Canada*, Memoir 362, 76 pages.

Souther, J.G. (1972): Telegraph Creek Map Area; British Columbia; *Geological Survey of Canada*, Paper 71-44, 38 pages.

Wheeler, J.O. (1967): Tectonics, *in* Canadian Upper Mantle Report, *Geological Survey of Canada*, Paper 67-41, pages 3-30.

Wheeler, J.O. and McFeely, P. (comp.; 1991): Tectonic Assemblage Map of the Canadian Cordillera and adjacent parts of the United States of America, *Geological Survey of Canada*, Map 1721A, scale 1:2 000 000.

**Low Velocity Layers in the Cordilleran Crust:
Evidence from Wide-Angle Seismic Studies**

by

M. J. A. Burianyk, E. R. Kanasewich and N. Udey

Seismology Laboratory

Institute of Geophysics, Meteorology and Space Physics

Department of Physics

University of Alberta, Edmonton, Alberta, T6G 2J1

The seismic refraction/wide-angle reflection data from the SCoRE '90 program conducted in south-east British Columbia is of high resolution and good quality. Besides detailed first arrival information from the upper crust, the shot records of the data set feature strong arrivals from below the crust, elaborate reflection patterns from the base of the crust and intriguing amplitude variations. Just as important are the presence of definite wide-angle reflections from heterogeneities within the crust.

An initial interpretation of the north-south profile of SCoRE '90, sub-parallel to geologic strike, has been carried out. This interpretation is based on travel-time analysis of the redundant ray paths from the arrivals, using damped least-squares inversion. The resulting model is characterized by six main features. First a thin surface layer about 1 km thickness has velocities of 5.5 -5.6 km/s. Second, the upper crust extends to depths of 12-15 km with a consistent velocities of 6.0-6.2 km/s Third, we have found that certain wide-angle reflections can be interpreted as being from the Monashee Decollement. Subsequent

least-squares inversion shows a step-like structure to this feature. Fourth, the lack of unmistakable first arrivals (head waves) from the mid-crust suggests an anomalous layer. This layer's structure and velocity can be modelled by the hyperbolic curve of crustal wide-angle reflections and indicates a low velocity zone (LVZ). Inversion gives the LVZ at between 15-28 km depth and velocities generally vary between 5.5 km/s (top of layer) and 6.4 km/s (bottom of layer). Fifth, the depth to Moho is about 37 km. Sixth, the upper mantle velocity is 7.9-8.0 km/s and sub-Moho arrivals indicate layering in the upper mantle with velocities of about 8.3 and 8.6 km/s. A much less detailed interpretation of the two major shot records of an east-west profiles tends to confirm these crustal features.

In general, the interpretation is not inconsistent with the interpretation of LITHOPROBE's Line 6 Seismic Reflection profile, which is coincident with part of the north-south refraction line. Also, the present interpretation does seem to support models of Basin and Range style tectonism.

One of the most interesting aspects of this model is the low velocity zone. This LVZ does correspond well with mid-crustal fluid saturated zone independently hypothesized from heat flow data, magneto-telluric and some seismic reflection analysis. But, though the parameters of the LVZ have been extracted by inversion of a large number of redundant ray paths from many shots, it is recognized that travel-time analysis of seismic data alone is not sufficient for a robust model. Therefore careful modelling of the amplitudes of various arrivals by various methods will be presented. The data of the north-south profile is of high enough quality that meaningful comparisons between the real and synthetic seismograms from various models can be done. This will allow us to confidently propose a final model of the crust of the south-east Canadian Cordillera.

**STRUCTURAL GEOLOGY OF THE MISTY THRUST, KANANASKIS
COUNTRY, ALBERTA: STUDY OF RELATIONS BETWEEN THRUSTING,
FOLDING AND TRANSVERSE FAULTING USING PALEOSTRESS AND
KINEMATIC ANALYSIS.**

**Sébastien Castonguay, Dept. of Geological Sciences, Queen's University,
Kingston, Ont. K7L 3N6.**

The Misty thrust fault is typical of the thrust faults of the Rocky Mountain Front Ranges. It occurs within the McConnell thrust sheet, and carries Carboniferous and Devonian rocks of the miogeocline-shelf sequence over Jurassic and Cretaceous rocks of the foreland basin sequence. Although it is a relatively small structure, the Misty thrust presents many of the characteristics of the Front Ranges thrust faults, but it also provides an opportunity to analyze the relationships between thrust faults, N-E trending transverse faults, and particularly, the development of large lateral ramps.

The abundance of transverse faults in this area is enigmatic. They have been interpreted as tear faults formed by local lateral stress concentrations during thrusting, and as displacement transfer structures between major thrusts. However, previous studies have shown that some transverse faults may be reactivated normal faults, probably related to Hudsonian basement fabric.

Like many Front Ranges thrusts, the Misty thrust follows a horizon within the massive limestone of the Upper Devonian Palliser Formation as a preferential gliding zone, instead of the less competent Devonian strata just below. Southward, the Misty thrust cuts up-section abruptly along strike through the entire Paleozoic succession. The elucidation of the stratigraphic and structural controls on the location of thrust faults is critical for the interpretation of the oil and gas reservoir structures in the subsurface.

Modern studies of mesostructures using paleostress and kinematic analysis can yield information about the mechanical evolution of a propagating thrust fault and its associated structures. Regional mapping (1:20,000) of the Misty thrust, and collection of mesoscopic subfabric data will be conducted during the summer of 1992, as a Master's thesis project, aimed at elucidating these relationships.

RELATIONSHIP BETWEEN CORDILLERAN AND PROTEROZOIC STRUCTURES IN THE COLVILLE HILLS, NORTHWEST TERRITORIES

Elizabeth A. Clark and Frederick A. Cook
University of Calgary, Calgary, Alberta, T2N 1N4

The Colville Hills are a series of ridges in the Interior Plains of the Northwest Territories, underlain by small scale (less than 500 m displacement) Late Cretaceous anticlines and thrusts. These structures are related to Cordilleran deformation but are situated 200 km in front of the main Cordilleran deformation belt. The mechanism for transmission of stress from the Cordillera to these structures has long been a matter of speculation. Thin-skin thrusting (oblique or dip slip) above a detachment in the Cambrian Saline River Formation (D.Cook 1983; D.Cook and Aitken 1973) or in the Proterozoic (F.Cook and Coflin 1990), and near vertical strike-slip faulting (Davis and Willott 1978) have all been suggested.

An extensive petroleum industry seismic database in this area reveals that the Phanerozoic cover is only 750 to 1750 m (0.3 to 0.7 s) thick, and that below the relatively undeformed Phanerozoic section large scale Proterozoic structures tens of kilometers wide can be observed. These structures have been studied extensively in three dimensions and are interpreted as having formed during Proterozoic thrusting and folding (Clark and F.Cook 1990; F.Cook 1988).

A fundamental spatial relationship between Cordilleran and Proterozoic structures is revealed from comparison of the surface geology map to maps of subsurface Proterozoic structures. The minor Cretaceous thrusts appear to form parallel to and on the flanks of the large Proterozoic structures. The seismic data also clearly show that the small thrusts penetrate into the Proterozoic section. We suggest that Cretaceous deformation resulted in reactivation of a major Proterozoic decollement and related faults. The Cretaceous thrusts are listric into the upper Proterozoic, and through shortening and uplift on older faults displacement zig-zags down to the major decollement.

Structures in the Colville Hills and the northern Franklin Mountains to the southwest have two primary strike orientations, and appear to reverse their vergence along strike. D.Cook (1983) proposed that this pattern of structures is related to right-lateral strike-slip movement on the Tintina trench. This model appears to be valid, with the level of detachment deep in the Proterozoic stratigraphy, and the specific locations of Cretaceous structures controlled by pre-existing Proterozoic structures.

Clark, E.A., and Cook, F.A., 1990. *GAC Annual Meeting*, v.15, p.A24.

Cook, D.G., 1983. In *Rocky Mountain Foreland Basins and Uplifts*, Rocky Mountain Association of Geologists, pp. 315-338.

Cook, D.G., and Aitken, J.D., 1973. In *Arctic Geology*, American Association of Geologists, pp. 13-22.

Cook, F.A., 1988. *Geol. Soc. Amer. Bull.*, v.100, pp. 877-890.

Cook, F.A., and Coflin, K.C., 1990. *Marine Geology*, v. 93, pp. 303-316.

Davis, J.W., and Willott, R., 1978. *Bulletin of Canadian Petroleum Geology*, v. 26, pp. 105-122.

Structure of the Cariboo Mts. near McBride, B. C.

**Charles A. Ferguson, Department of Geology and Geophysics,
University of Calgary, Alberta T2N 1N4 (403) 220-3271**

Late Proterozoic and Lower Cambrian Windermere and Cariboo Groups strata are deformed into a 40 km wide northwest-plunging D_2 fan structure between Isaac Lake on the west and the Southern Rocky Mountain Trench (SRMT) on the east. The lower 2/3 of the section consists of turbidite sandstones and mudstones (upper Kaza Group and Isaac Fm.) that are deformed into km-scale folds. The axial planes of these folds, and an associated post-metamorphic crenulation cleavage (S_2), fan from 50° NE-dips near Isaac Lake through vertical to 60° SW-dips along the west wall of the SRMT. The upper 1/3 of the section consists of a massive carbonate platform (Cunningham Fm.) overlain by bedded carbonates, mudstones, and quartzites (Yankee Belle and Yanks Peak Fms.). These strata are broadly folded, and cut by reverse faults that grow out of D_2 shear zones in axial regions of folds in the lower multilayer.

D_1 is expressed as a bedding parallel or east-vergent cleavage (S_1) that developed during peak greenschist metamorphic conditions. D_1 is associated with megascopic folds only along the west wall of the SRMT where they become confused with east-vergent D_2 folds.

Upper and Middle Kaza Group strata along the west wall of the SRMT are faulted against an assemblage of isoclinally folded and top-to-the-NE sheared marble, quartzite, conglomerate, and calcareous phyllite that underlie the Trench floor near McBride. The Trench assemblage as a whole resembles Lower Cambrian strata indicating a stratigraphic throw of at least 4 km along the fault. A well-developed SW-dipping axial planar syn-metamorphic S_1 cleavage in the Trench assemblage is crenulated by a steeper post-metamorphic S_2 fabric. Top-to-the-NE motion on this fault is believed contemporaneous with the D_1 syn-metamorphic event in the adjacent Cariboo Mts.

A series of D_3 strike-slip and oblique-slip NW-trending faults account for no more than 15 km of dextral slip between Isaac Lake and the SRMT. An enigmatic D_4 event evidenced by northerly-trending upright crenulations may be associated with late north-trending faults.

**PROBLEMS IN REGIONAL CORRELATIONS OF HARDRYNIAN STRATA -
SOUTH CENTRAL BRITISH COLUMBIA AND ADJACENT ALBERTA**

**Stephen E. Grasby
Dept. Earth Sciences, Carleton University**

ABSTRACT

Four regional stratigraphic correlations have been proposed for Windermere strata in south central British Columbia and adjacent Alberta: 1) Conventional correlations suggest the mid-marble and SPA units in the Monashee and Selkirk mountains are correlated with the Cunningham and Issac formations in the Cariboo Mountains and the Carbonate and Slate divisions in the northern Purcell Mountains, 2) The recent "double wedge model" suggests the mid-marble and SPA in the Monashee and Selkirk Mountains, and the carbonate and slate division in the Purcell Mountains, are correlated with a marble and SPA unit thought to stratigraphically underlie the Kaza Group in the Cariboo Mountains, 3) The third model is similar to the "double wedge" except the Carbonate and Slate divisions in the Purcell Mountains are correlated with the Cunningham and Issac Formation, 4) The Pleasant Valley Thrust theory suggests strata underlying the Kaza Group in the Cariboo Mountains is Paleozoic. If true, it raises the possibility that some of what is considered to be Hardrynian Horsethief Creek Group in the Monashee and Selkirk mountains may be Paleozoic.

There are two possible "marker" horizons that may be used better define regional correlations, the Old Fort Point Formation (or "the marker"), and the Semipelite-Amphibolite unit (SPA). The Old Fort Point Formation is thought to represent a regional sea level high stand that occurs throughout the Windermere basin. It's unique occurrence in the Miette Group supports its use as a marker. The SPA unit occurs in the northern Selkirk, Monashee and southern Cariboo mountains. The SPA has generally been considered a regional marker in Windermere Strata. However the proposed Pleasant Valley Thrust brings the age of the SPA into question. It may represent one or more rifting events.

Before further progress can be made in reconstruction of the Windermere basin, it is essential to better define the regional stratigraphy. Possible approaches to this problem include establishing geochemical signatures and regional mapping of the two possible marker units, and age dating of the SPA. These problems will be part of a Ph.D. thesis undertaken at Carleton University.

DEFORMATION STYLES NEAR THE LEADING EDGE
OF THE FOLD-AND-THRUST BELT
PINCHER CREEK, ALBERTA

S.N. HIEBERT and D.A. SPRATT
UNIVERSITY OF CALGARY

ABSTRACT

Mechanics, style and limit of deformation in the fold and thrust belt of the southeast Canadian Cordillera is generally well understood. However, exceptions to these general deformation rules have been mapped at surface, their relationship to dominant structural trends unclear. Presented here are several surface and subsurface examples of anomalous structures involving Cretaceous stratigraphy of the Foothills Belt near Pincher Creek Alberta. Both seismic and field evidence suggest that a series of structures previously mapped as vertical transverse faults can be interpreted as a duplex which plunges obliquely to regional trends. Several models are proposed for its structural evolution. Surface exposures elsewhere, along the exposed leading edge of a major thrust sheet support the existence for minor tear faults in the Foothills Belt. The example shown occurs along strike to a footwall duplex, interpreted to be a steep lateral ramp acting as a collective merge point from which displacement bifurcates through the duplex.

Although the eastern limit of deformation is generally well marked in the fold and thrust belt, there are exceptions to the assumed position of this edge. Outboard of the Triangle Zone, both surface dips and well penetration depths suggest Tertiary stratigraphy may be involved in shortening further east than previously thought. Effects of compressional deformation can be observed at surface as far east as 65 km outboard of the core of the Triangle Zone.

Seismic data indicates that displacement occurs along low angle ramps (8° - 15°) and long flats, contributing to greater overall shortening across the Foothills Belt than previously thought, approximately 60%.

THE LOWER JURASSIC ROSSLAND GROUP IN SOUTHEASTERN BRITISH
COLUMBIA - TECTONIC EVOLUTION AND PRECIOUS METAL DEPOSITS

Trygve Höy and Kathryn Dunne

The Rossland Group is an arcuate belt of lower Jurassic rocks in the southern Omineca Belt of southeastern British Columbia. Dramatic changes throughout the Archibald Formation, the basal clastic succession in the group, from alluvial fan deposits in the southwest through turbidite facies to deep-water argillite and siltstone in the northeast, indicate early growth faulting along a basin margin. Volcanic rocks of the overlying Elise Formation record effusive shoshonitic volcanism followed by eruption of intermediate and mafic pyroclastic rocks. Coarse clastic rocks of the Hall Formation, at the top of the Rossland Group, were deposited in fault-bounded successor basins. Elise Formation shoshonite rocks may record arc volcanism as a subduction zone was dying just prior to plate collision, possibly involving accretion of Quesnellia to the North American craton. Continued compressional tectonics resulted in intense regional deformation. This deformation is tentatively dated by a suite of intrusive rocks, interpreted to be synorogenic, that range in age from 178 Ma to 182 Ma. Large listric normal faults record extensional tectonics prior to intrusion of late Jurassic plutons (ca. 165 Ma).

Mineral deposits in the Rossland Group have produced more than 100 000 kg Au and 300 000 kg Ag. Transitional vein gold deposits of the Rossland Camp are related to intrusion of the Rossland monzonite. The Rossland monzonite, comagmatic with arc volcanics of the Rossland Group, was intruded along major structures that were periodically active from Lower Jurassic to Eocene time.

Feb., 1992

Computer-aided geological mapping in the Rocky Mountain Foothills
of northeastern British Columbia

P.C. Jahans, Department of Geology, University of Alberta

Computer-based methods have been developed for use with a commercial CAD-GIS package and conventional mapping techniques to construct geological maps. These procedures were used to construct 1:50,000 geological maps of three areas (NTS 930/9, 930/10 and 93P/12) in the Pine River area of the Rocky Mountain Foothills in northeastern British Columbia. Outcrop and drillhole data from previous studies and outcrop data collected during the 1991 field season were integrated and interpreted using spreadsheet, database, graphical and structural software packages. The final maps, including geological contacts and symbols, structural features, topographic contours and other physiographic data, are in digital form. The CAD-GIS system provides on-screen editing of the data, is capable of zooming to a small area of the map for more detailed work, and allows output to be plotted at any scale.

Computer programs written for this project include those that can be used 1) to digitize geological contacts and structural features from existing maps, 2) to place digitized data and data already in existing computer files in dBase-compatible databases for graphical display and structural analysis, 3) to convert latitudes and longitudes to UTM coordinates and back, 4) to convert older NAD27 geodetic coordinates to the recently introduced NAD83 geodetic datum, and 5) to build and use a digital elevation model in conjunction with a triangulation procedure to determine the coordinates of outcrops located on aerial photographs. In addition, several microcomputer-based procedures have been established to integrate and analyze large quantities of data existing in different formats and coordinate systems.

ANATOMY OF THE LARAMIDE FOREDEEP IN ALBERTA

Tomasz Jerzykiewicz, Geological Survey of Canada, Calgary.

Laramide stage of the evolution of the Alberta foreland basin is recorded in 4000 m thick post-Wapiabi succession of regressive and terrestrial clastics. Regional stratigraphy, sedimentology and basin-wide mapping of the uppermost Cretaceous and Paleocene allow for subdivision of the Laramide strata into five clastic wedges based by coarse detritus and/or breaks in stratigraphic record heralding significant events in the basin. These events were: 1) Regressions of the Wapiabi and Bearpaw seas from the foredeep at approx. 80 and 75 Ma respectively, and 2) Major changes in the paleodrainage patterns recorded in the Willow Creek-Porcupine Hills, and Coalspur-Paskapoo formations at approx. 68, 63 and 60 Ma. The Laramide clastic wedges differ in external geometry and internal distribution of facies. The Belly River-lower Brazeau wedge of Campanian age, and St. Mary River-upper Brazeau wedge of Maastrichtian age were deformed by subsequent thrusting and partitioned into allochthonous and autochthonous parts which differ significantly in facies and thickness. Position of the foredeep at the beginning of the Laramide Orogeny, estimated on palinspastically restored sections of the Belly River formation in the Crowsnest Deflection area is assumed some 70 km westward relative to the autochthon of the Alberta Syncline. The uppermost Maastrichtian-lowermost Paleocene wedge (Willow Creek and Coalspur), although compressed in its western part (e.g. Entrance Syncline, Coalspur Anticline), consists of autochthonous and parautochthonous strata with depocentre east of the triangle zone. The Paleocene clastic wedges (Porcupine Hills and Paskapoo) are virtually undeformed and their external geometry is established directly from the series of structural cross sections. Their wedge-shaped geometry is best visible between the Paleocene foredeep, which follows the axes of the Alberta Syncline, and the zone of stratigraphic condensation of the Paskapoo sections in the Red Deer Valley area. The foredeep migration from its most western, distal position in the Campanian to its Paleocene locus along the axis of the Alberta Syncline took approx. 20 m.y. and was punctuated by the large-magnitude episodes at approx. 80, 75, 68, 63 and 60 Ma. The sequence of ages for the lower boundaries of the five clastic wedges may indicate tectonic pulses in the orogenic front, although the emerging thrust slices capable of producing proximal sediments were probably separated from the foredeep by a piggyback basin and the foredeep itself was internally partitioned into discrete drainage domains divided by transverse growth fault. The largest growth fault zone is visible in the subsurface of the Highwood River section in the vicinity of Longview in the Maastrichtian St. Mary River Formation. Comprehensive description of this zone require more subsurface work but the present data which include surface sections of the St. Mary River Formations with well developed debris flow facies, and the recognition of the fact that this fault zone is a demarcation zone between two distinctly different facies provinces within the Laramide foredeep makes this zone particularly interesting target for hydrocarbon exploration.

Middle Jurassic Stratigraphy of the South-Central Canadian Cordillera

Middle Jurassic strata of the south-central Cordillera comprise a number of unconformity-bound stratigraphic units, including the Dewdney Creek Group, the Newby Group, the Harrison Lake Formation, the Ashcroft Formation, and the Lillooet Group. Each unit is characterized by argillaceous strata interbedded with variable amounts of volcanoclastic material. With the exception of the Ashcroft Formation, each of these units record the initiation of volcanism in the southern Canadian Cordillera during Aalenian to Bajocian time. Similarities in age, lithology, and depositional environment between the majority of these units suggest a common genesis. However, variations in the size and type of bounding unconformities, basement rocks, and present geologic setting suggest these rocks may be unrelated, tectonically juxtaposed units. Correlation of these strata through paleontologic, stratigraphic and isotopic studies will provide important constraints on the tectonic evolution of the southern Canadian Cordillera. Terrane linkage between the Insular and Intermontane belts is required by early middle Jurassic time if these units are stratigraphic equivalents representing a common middle Jurassic basin. If the units do not comprise a single middle Jurassic depocenter, and instead represent unrelated, yet coeval, basins, tectonic juxtaposition of these units is required after the middle Jurassic.

Preliminary investigation of Aalenian to Bajocian strata north of Lillooet documents sediment gravity flow deposition of fine to coarse volcanoclastic detritus adjacent to a volcanic arc. Deposition in a marine basin proximal to a subaerial arc is indicated by abundant unaltered plagioclase, the abundance and angularity of volcanic lithic clasts, minor tuffaceous interbeds, marine fauna (ammonites), and the presence of wood debris. Paleocurrent data suggest the source terrane lay to the southwest of the depositional site. Similar analyses of coeval strata are ongoing, and will constrain the configuration and regional extent of middle Jurassic basins in the southern Canadian Cordillera.

**VELOCITY STRUCTURE FROM SEISMIC REFRACTION ACROSS THE COAST
PLUTONIC AND INTERMONTANE BELTS**

N.A. McLean, and G.D. Spence, School of Earth and Ocean Sciences,
University of Victoria, Victoria, British Columbia, V8W 2Y2

One phase of LITHOPROBE's seismic program for the Southern Cordillera included a seismic refraction experiment (SCoRE '89) focussing on the Coast Plutonic and Intermontane Belts. A primary objective of the refraction program was to determine if there is any correlation between velocity structure and the spatial range of terranes. In particular, it was hoped that differences in structure could be seen across the boundaries of the Coast Plutonic Complex, either in the west beneath Georgia Strait or in the east at the Fraser Fault.

The experiment consisted of a triangular array of shot points and receivers centered over the Fraser River fault system. Of the three legs of the triangle, one leg (Line 1) ran north-south along strike within the Intermontane Belt (Zelt et al., 1992, submitted to Can. J. Earth Sci.). The other legs were cross-strike lines running from the Intermontane Belt across the Coast Plutonic Complex, one oriented east-west (Line 3) and one oriented northeast-southwest (Line 2).

In the current study, a refraction velocity model was obtained beneath Line 2. Ten shots with an average spacing near 50 km were detonated along the 430 km of Line 2 and were recorded by 265 instruments with a typical spacing of 1.3 km. From this data a 2-D velocity model was interpreted using a combination of traveltimes inversion and amplitude forward modelling. Preliminary results include a varying-thickness near-surface layer with large variations in velocity; higher surface velocities are generally observed in the Coast Plutonic Complex. The maximum thickness of the layer is near 1.5 km whereas the minimum thickness is less than 500 m in the region of the Fraser Fault. The velocity of the upper crust also appears to be correlated to the Fraser Fault. West of the fault system, the upper crust velocity is typically 6.2 km/s, while east of the fault smaller velocities near 5.8 km/s are observed. Reduced velocity in the Intermontane Belt relative to the Coast Plutonic Belt is perhaps consistent with the higher heat flow measured in the Intermontane Belt (Davis and Lewis, 1984; Gough, 1986). Velocities in the upper crust increase with depth down to 7-10 km, below which constant velocity layers produce no large amplitude turning rays. At the current stage of interpretation, velocities in the lower crust are not yet well-determined. However, given the typical range of values for lower crust velocity from 6.4-6.7 km/s (consistent with values determined along Line 1 by Zelt et al., 1992), the depth to Moho lies in the range from 32-37 km. As well, the Moho depth appears to be at least 2-3 km greater in the east portion of the line than in the west.

ALASKAN-TYPE COMPLEXES: U-Pb GEOCHRONOMETRY AND TECTONIC SIGNIFICANCE

Graham T. Nixon and Larry M. Heaman

*B. C. Geological Survey, 553 Superior St., Victoria, B.C. V8V 1X4; and
Geochronology Laboratory, ROM, 100 Queen's Park, Toronto, Ontario M5S 2C6*

U-Pb geochronometry of two Alaskan-type ultramafic-mafic intrusions, the Polaris and Lunar Creek complexes in north-central British Columbia, provide evidence for 1) the longevity of Early Mesozoic arc-related magmatism in Quesnellia; and 2) the timing of deformation associated with docking of the Intermontane Superterrane against miogeoclinal sequences of Ancestral North America. Both complexes lie at the eastern margin of the Intermontane Superterrane within Quesnellia. Analyses of three different zircon fractions in a potassium feldspar-rich pegmatite from the Lunar Creek complex are colinear and exhibit a small amount of inherited Pb component. The best estimate for the final stages of emplacement of this body is 237 ± 2 Ma (mid-Triassic - Ladinian). The Polaris complex forms a transgressive sill-like body that intrudes rocks of the Lay Range Assemblage (Harper Ranch subterrane). U-Pb results for zircon fractions from hornblende-feldspar-quartz segregations in the final crystallization products of the Polaris complex are essentially concordant at 188 ± 2 Ma (late Early Jurassic - Pleinsbachian). An amphibolite-grade thermal aureole has been ductily deformed and kinematic indicators along steeply-dipping reverse faults at the base of the complex yield NE-directed transport of the complex and its wallrocks while they were still hot. These NE-verging structures are correlated with the earliest phase of deformation recognized in the miogeocline (Ingenika Group) to the east across the Swannell Fault (Bellefontaine, 1991). Thus, the zircon date for the Polaris complex (latest Pleinsbachian) is interpreted as the earliest phase of accretion of the Intermontane Superterrane with displaced miogeoclinal rocks of the Cassiar Terrane.

In the Cry Lake map area to the north, the Turnagain Alaskan-type complex is also hosted by a package of Quesnellian rocks that lie in fault (thrust?) contact with miogeoclinal sequences of Ancestral North America. The main phase of regional contraction, previously bracketed as Early Toarcian to middle Bajocian (Thorstad and Gabrielse, 1986), resulted in the emplacement of Slide Mountain and Quesnellia onto the miogeocline, and thrust rocks of the Cache Creek Complex and King Salmon Assemblage (Cache Creek Terrane) onto Stikinia. This deformation coincides precisely with the latest Pleinsbachian accretionary event documented above, and correlates with an important regional unconformity at the base of uppermost Pleinsbachian or Toarcian strata in Stikinia. Post-accretion right-lateral displacement of approximately 65 km has occurred along the northern part of the Kutcho Fault. Permissive evidence for early (syn-accretionary?) sinistral motion is found along the Thibert-Kutcho fault system at the eastern margin of the Cache Creek Terrane where a fault-bounded sliver of rocks correlated with the King Salmon Assemblage have an apparent displacement of at least 100 km. Sinistral motion along major transcurrent faults in the Cordillera may be more common than generally realized and can be accommodated simply by differences in the rate of northward translation of fault-bounded blocks.

MIDDLE DEVONIAN THRUSTBELT DEVELOPMENT IN THE SOUTHERN CANADIAN CORDILLERA - EVIDENCE FROM THE PURCELL MOUNTAINS, SOUTHEASTERN BRITISH COLUMBIA

Kevin G. Root, Shell Canada Limited, Box 100, Calgary, Alberta T2P 2H5.

Middle Devonian foreland strata in the southern Canadian Cordillera comprise the Eifelian Mount Forster Sequence and the overlying Eifelian Harrogate Formation. These successions are restricted to the western part of the Rocky Mountain Belt, and are bounded to the east by the Western Alberta Ridge, which is considered to be a peripheral bulge associated with Middle Devonian thrusting. The Mount Forster Sequence includes the Cedared Formation, Burnais Formation, and Mount Forster Formation, and consists of carbonate, gypsum, and fine-grained clastics in eastern exposures. The sequence thickens to the west, and contains a progressively greater proportion of texturally and mineralogically immature coarse-grained clastics that were derived from Upper Proterozoic and Lower Paleozoic strata. At the westernmost exposure, at Delphine Creek in the Purcell Mountains, the Mount Forster Sequence is up to 540 m thick, and comprises sandstone, pebble and boulder conglomerate, slate, and volcanic flows. The Harrogate Formation exhibits little lateral variation, and comprises carbonate and mudstone.

Direct evidence of Middle Devonian contractional deformation is found at Delphine Creek, where folds developed (1) during Mount Forster deposition, resulting in significant lateral changes in thicknesses and lithologies of lithostratigraphic members, and an intra-Mount Forster angular unconformity with pre-unconformity dips up to about 25°, (2) after Mount Forster deposition but before Harrogate deposition, resulting in an angular unconformity with pre-Harrogate dips locally up to about 80° and (3) during Harrogate deposition, resulting in lateral changes in thickness and facies. A thrust fault with at least several hundred metres of displacement cuts the Mount Forster Sequence and is truncated by the sub-Harrogate unconformity.

**STRUCTURAL RELATIONSHIPS BETWEEN CADWALLADER AND BRIDGE
RIVER TERRANES AND TYAUGHTON AND METHOW BASINS, TASEKO-
BRIDGE RIVER AREA, SOUTHWESTERN BRITISH COLUMBIA**

Paul Schiarizza, B.C. Ministry of Energy, Mines and
Petroleum Resources, Geological Survey Branch, 553 Superior
St., Victoria, B.C. V8V 1X4

The Taseko-Bridge River area, on the eastern margin of the Coast Plutonic complex, is underlain by several partially coeval lithotectonic assemblages that are juxtaposed across mid- to early Late Cretaceous contractional faults and latest Cretaceous to Eocene dextral strike-slip and extensional faults. The structural style, as well as some of the tectonic assemblages, extend southward into the Cascade orogen of northern Washington state.

The Bridge River complex (BRC) comprises Mississippian to upper Middle Jurassic chert imbricated with greenstone, gabbro, serpentinite, clastic sedimentary rocks, limestone and Middle to Late Triassic blueschist. The BRC is stratigraphically overlain by uppermost Middle Jurassic to mid-Cretaceous clastic rocks of the Tyaughton basin (TB). Cadwallader terrane (CT) comprises Upper Triassic to Middle Jurassic arc volcanics and arc-proximal clastic sedimentary rocks that are everywhere structurally interleaved with Permian ultramafic-mafic plutonic and volcanic rocks of the Bralorne-East Liza complex (BELC). The imbricated CT-BELC slices are separated from underlying BRC and TB by a system of mid-Cretaceous southwest-vergent thrust faults and are structurally overlain by the Permian Shulaps ophiolite complex (SC) by similar southwest-vergent thrusts. The stacking order is locally reversed by somewhat younger southwest-vergent thrust, reverse and reverse-sinistral faults and by northeast-vergent thrust faults and folds.

The above assemblages are separated from lithologically distinct Lower Jurassic to mid-Cretaceous clastic rocks of the Methow basin (MB) to the east by the Yalakom fault system, which was the locus of mid-Cretaceous sinistral transpression and Eocene dextral transtension. Relationships described south of the map area suggest that rocks correlative with the Shulaps complex are basement to MB.

The structural relationships suggest that the BRC accumulated as an accretion-subduction complex west of (and beneath?) an arc-basin system represented by CT, MB and their Permian ophiolitic basement (BELC and SC respectively). Triassic-Jurassic subduction apparently ceased in the late Middle Jurassic when the BRC was overlain by the Jura-Cretaceous Relay Mountain Group of TB. Significant thrust imbrication, involving all assemblages within the map area, and accompanied by the development of synorogenic clastic wedges (Taylor Creek Group of TB; Jackass Mountain Group of MB) apparently did not occur until the mid-Cretaceous.

LARGE LATERAL, SOUTH-FACING RAMPS WITH SOUTHWARD DECREASE IN
DISPLACEMENT: EOCENE EXTENSIONAL VALKYR SHEAR ZONE, SOUTHERN
BRITISH COLUMBIA CANADA

P.S. Simony, S.D. Carr and C.R. Corbett

University of Calgary, Calgary, AB., Canada T2N 1N4
Carleton University, Ottawa. ON., Canada K1S 5B6
Suncor Inc. Resources Group, P.O. Box 38, Calgary, AB., Canada
T2P 2V5

INTRODUCTION

Gneiss complexes in southern British Columbia, having many of the attributes of "Cordilleran metamorphic core complexes" occur to the west of the Rocky Mountain Fold and Thrust belt. An upper plate of low grade rocks is separated from a lower plate of high grade rocks by brittle, moderate to low-angle normal faults and by ductile extensional shear zones. The Valhalla Complex, a north-south trending complex, near longitude $118^{\circ}00'W$, is between 10 and 25 km wide and extends from latitude $49^{\circ}10'N$ to latitude $50^{\circ}00'N$. The brittle to ductile, east-dipping Slocan Lake Fault forms the east boundary. The upper plate is underlain by the gently-dipping, Valkyr Shear Zone (VSZ) (Carr *et al* 1987), a ductile extensional shear zone some 2 kilometres thick which lies near the upper limit of Eocene Ladybird Granite sheets and on the map, largely surrounds the gneisses of the lower plate in the core of the Complex. The Valhalla Complex lies within Quesnel Terrane; Early Paleozoic gneisses are overlain by Late Paleozoic to Triassic metasediments and Early Jurassic arc volcanics. The flat-bottomed Mid-Jurassic Nelson Batholith lies in the hanging wall of the Slocan Lake Fault east of the northern portion of the Complex. Farther south the fault cuts two interconnected Mid-Jurassic granodiorite laccoliths. Cretaceous to Eocene quartz monzonite and granite intrude paragneisses of the lower plate as kilometer-thick, gently-dipping sheets.

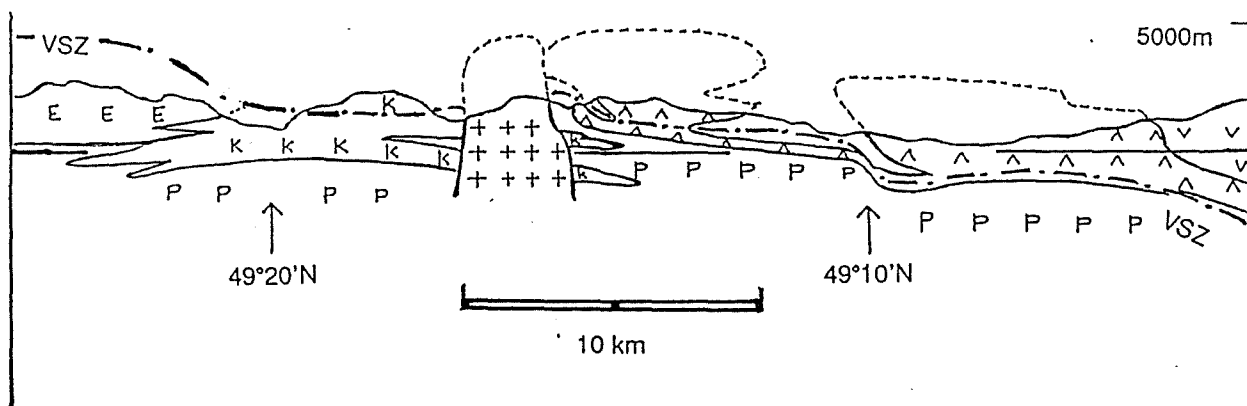
The Slocan Lake Fault dips 30° to 40° east adjacent to the northern portion of the Complex. It approximately parallels the dip of the mylonitic foliation of the underlying Valkyr Shear Zone and seems to merge with it. The Champion Lake Fault, the brittle southern strand of the Slocan Lake Fault, dips steeply east and cuts across the gently-dipping mylonitic fabric. In its central portion, near latitude $49^{\circ}45'N$, the Slocan Lake Fault has approximately 10 km of dip slip, the Champion Lake fault has 4 to 6 km dip slip near lat $49^{\circ}20'N$, 2 to 3 km at latitude $49^{\circ}10'N$ and near zero displacement at latitude $49^{\circ}00'N$.

THE RAMPS

The Valkyr Shear Zone (VSZ) passes over the northern portion of the Complex at an altitude of some 4500 m and, in conjunction with the Slocan Lake Fault has an eastward displacement of the upper plate of about 30 km. The upper plate differs markedly from the lower plate in geology, metamorphism and K/Ar ages Parrish *et al* (1988). At latitude 49°20'N, the elevation of the top of the VSZ drops southward across the east-trending valley of Lower Arrow Lake to the top of the Robson Ridge at an elevation of 1500 m forming a major south-facing lateral ramp. Because, locally, the VSZ is exposed in the hanging wall of the Slocan Lake Fault, the ramp can also be shown to exist in the hanging wall of the fault. From the ramp southward, the displacement on the VSZ seems to decrease; it cuts through Cretaceous and Jurassic plutons without uncoupling the upper from the lower plate, intrusive relationships are identifiable in the shear zone and the sharp contrast in geology, metamorphism and K/Ar ages across the shear zone are lost. Highly inhomogeneous shear strain precludes quantitative integration of shear strain across the VSZ but from the geology one might estimate displacements on the order of 4 to 6 km. At latitude 49°10'N the shear zone dips steeply south under a Jurassic laccolith and flattens near its floor. This more southerly ramp is about 1 km high and its position seems to be related to the geometry of the Jurassic laccolith. The map pattern of the VSZ suggests that its trajectory lies near the upper limit of emplacement of Eocene Ladybird Granite sheets as well as near the base of the flat-bottomed Jurassic granodiorite intrusions. A possible interpretation of this pattern is that the base of the Jurassic bodies approximately limited the rise of the Eocene granite sheets and that the shear zone propagated in the zone of mechanical contrast between the cold upper plate and the hotter, ductile lower plate. The difference in level and in displacement that occur at the Lower Arrow Lake Ramp at 49°20'N, possibly resulted from a northern and a southern shear zone propagating toward each other, near the bases of flat-bottomed plutons, at different levels. The ramp would then have formed in the zone of accommodation between the two shear zones with different displacements.

Carr, S.D., Parrish, R. and Brown, R.L. 1987. Eocene structural development of the Valhalla complex, southeastern British Columbia. *Tectonics* 6, 175-196.

Parrish, R., Carr, S.D. and Parkinson, D.L. 1988. Extensional tectonics of the southern Omineca belt, British Columbia and Washington, *Tectonics* 7. 181-212.



Schematic N-S cross section illustrating relation of Valkyr Shear Zone (VSZ) to plutons and the geometry of ramps at lat. 49°20'N and lat. 49°10'N.

- | | | | |
|---|--|---|------------------------|
| + | Post-tectonic Eocene pluton | ^ | Jurassic laccoliths |
| E | Syn-tectonic Eocene plutonic sheet | v | Jurassic volcanics |
| K | Syn-tectonic Cretaceous plutonic sheet | P | Lower Paleozoic gneiss |

The Triangle Zone and Foothills Structure
in the Grease Creek Area of Alberta.

Gregory S. Soule
University of Calgary

The Triangle Zone at the eastern edge of the Foothills fold and thrust belt is shown to have an en echelon geometry. Four east-dipping backthrusts or 'upper detachment' surfaces were recognized east of the surface expression of the Triangle Zone in Silver Creek. These faults verge to the west and appear to cut up-section in the direction of transport through east-dipping strata. Displacement on these upper detachment surfaces is difficult to estimate as there are very few stratigraphic markers in the Brazeau Group. It is hoped that palynology may help in this regard. Jones (1982) proposed the Grease Creek syncline is a klippe in the hanging wall of a folded, west-verging upper detachment. The field evidence does not support this, however the Grease Creek area does not seem to correspond exactly to the Charlesworth and Gagnon (1985) model either.

GEOLOGY OF THE PILTZ PEAK PLUTONIC COMPLEX, BRITISH COLUMBIA

P. van der Heyden and S. Metcalfe¹
Cordilleran Division, Vancouver

ABSTRACT

The Piltz Peak plutonic complex in the southwestern Intermontane Belt (Chum Creek map area, NTS 92O/7) is composed of weakly to locally strongly strained, greenschist to amphibolite facies metaplutonic and metavolcanic rocks, which may be a southerly extension of the Mt. Alex plutonic complex immediately north of the study area. These rocks are overlain, possibly structurally, by unmetamorphosed volcanic rocks that may correlate with the informal Late Cretaceous Powell Peak formation. Several plutonic phases and deformation episodes can be recognized in the field; relative and absolute ages of most rocks and structures in the area remain unknown. Structures in the Piltz Peak plutonic complex may have formed during early Tertiary extension, superimposed on Jurassic, Cretaceous, and early Tertiary plutonic and metamorphic rocks. Alternatively, ductile and brittle structures in the Piltz Peak plutonic complex may be the result of Middle to Late Jurassic and/or mid- to Late Cretaceous contraction.

¹ Department of Geological Sciences, University of British Columbia, 6339 Stores Road, Vancouver, B.C. V6T 2B4

Residual Statics Estimation with Simulated Annealing Experiments - 1985 LITHOPROBE Seismic Reflection Survey

Kris Vasudevan, Fred Cook and Arie van der Velden
LITHOPROBE Seismic Processing Facility
Department of Geology and Geophysics
The University of Calgary
Calgary, Alberta T2N 1N4
CANADA

ABSTRACT

Reprocessing of seismic lines acquired in southeast British Columbia as part of the LITHOPROBE's southern Canadian Cordilleran transect in 1985 at the LITHOPROBE Seismic Processing Facility has highlighted the significance of the application of statics in improving the images of structural features. Where the statics problems are severe, conventional methods do not work as well as some alternative methods such as simulated annealing method. In this paper, we present the theory behind the simulated annealing method and how it is adapted for residual statics estimation. Results of simulated annealing experiments obtained so far on lines 1A, 1B and 2 suggest that it is effective for improving deep (10-20 km) images.

AN INTERACTIVE COMPUTER PROGRAM TO DETERMINE PALEOSTRESS AXES
USING DATA FROM STRIATED FAULTS

T. Villemin, Université de Savoie, Chambéry and
H.A.K. Charlesworth, University of Alberta, Edmonton

During the last 15 years, several numerical and graphical methods of finding principal paleostress axes in rocks that experienced brittle deformation have been proposed. All methods require the striated faults in a set to be assigned to one or more homogeneous generations, where each generation is associated with a certain stress field. The IBM-PC compatible program STRESS uses the right-dihedra and direct-inversion methods to determine stress axes. It facilitates the establishment of homogeneous generations by using the mouse pointer to move a fault from one generation to another. The main features of the program are as follows.

1) Data can be entered into a STRESS database at the keyboard using a spreadsheet-style window, or by importing data already in text files. The data in a database are grouped according to site, structural type and generation.

2) Fault data from one or more sites and generations may be readily retrieved for display and analysis. Stereograms can simultaneously display one or more fault elements such as fault planes (as poles and great circles), slip vectors, extensional and contractional axes, and related structures such as extensional joints and dykes. Each fault element and associated structure may be represented separately on several kinds of rose and contoured pi diagram.

3) In the right-dihedra method (Angelier & Mechler, 1977), each striated fault is associated with two extensional and two contractional dihedra separated by the fault and its auxiliary plane. Each counting location in a 3D grid is incremented by the numbers of faults which place it in the extensional/contractional dihedra. These numbers can be displayed and used to estimate the minimum/maximum paleostress axes.

4) In the direct-inversion method (Angelier, 1990), the stress tensor is calculated by solving equations whose parameters are computed using the orientations of fault planes and slip vectors. Although a fault's orientation may be unrelated to the stress axes, as might be the case if it originated in an older stress field, the direction and sense of its striae are assumed to be related to a single common stress tensor. The program STRESS first calculates the stress axes and then displays on a stereogram the observed and theoretical striae for each fault. If each fault in a generation is associated with the same stress field, the differences between the observed and theoretical striae should be small. Where the difference is large, the fault should be removed from the generation being analysed, the stress axes recalculated and another stereogram with observed and theoretical striae displayed. This procedure is facilitated by clicking with the mouse pointer on faults to be transferred to another generation.

**Nature and kinematics of shear zones in the southern tail
of the Nelson Batholith, southeast British Columbia**

James J. Vogl and Philip S. Simony

Dept. of Geology & Geophysics, University of Calgary, Calgary, Alberta T2N 1N4

The tail of the Mid-Jurassic Nelson Batholith is composed of several foliated granitic phases that are concordant with the regional structural grain of the Kootenay Arc in southeast British Columbia. The distribution of zones of highly strained granitic and metasedimentary rocks across which different lithologic packages are juxtaposed correspond to the projected traces of the Waneta and Midge Creek faults. It is inferred that the high strain zones are the result of movement along the faults. Observation of the strain zones provides an excellent opportunity to study the nature and kinematics of the faults which are poorly exposed elsewhere in the Kootenay Arc.

Within metasedimentary screens and pendants the fault zones are characterized by melanges of carbonate and granitic material. Mylonite and ultramylonite comprise the granitic portion of the shear zones.

In the shear zones foliations are subvertical and lineations are subhorizontal. Kinematic and shear-sense indicators suggest a non-coaxial flow with a dextral shear sense. Homogeneity of deformation, annealed fabrics and recrystallization of feldspars indicate an anomalously high temperature of deformation relative to the low-grade country rocks. This suggests deformation took place during Jurassic intrusion and cooling of the granitic sheets and provides a qualitative minimum age for movement on the faults.

Crustal Thickening beneath the Canadian Eastern Cordillera

D. White, I. Asudeh, C. Zelt

In 1990, the Southern Cordillera seismic Refraction Experiment (SCoRE90) was conducted in southern British Columbia. The eastern-most profile of this LITHOPROBE survey extends 350 km across the Omineca Crystalline belt to the eastern side of the Rocky Mountain thrust and fold belt, and is generally coincident with the 1985 LITHOPROBE seismic reflection lines in this area. Three hundred seismic recorders were located along this line to record eight in-line shots spaced at 50 km intervals.

The primary objective of the eastern SCoRE90 refraction profile is to better constrain the geometry of the Moho in this area. Interpretation of a previous refraction profile included a step-down of 10 km in the Moho over 80 km distance just to the west of the Purcell anticlinorium. The position of this tentative step-down coincides with an Eocene extension fault (Slocan Lake fault) which appears to penetrate the upper mantle as imaged on the coincident reflection lines and may be related to the proposed change in crustal thickness. Results of travel time inversion for crustal velocity structure (using P_g) and Moho depth for the SCoRE90 line, show an increase in Moho depth of ~ 10 km in the same vicinity as previously proposed. This result is based on an inversion of $P_m P$ arrivals from six of the eight shots, and P_n arrivals from the two end shots, providing good coverage of the 200 km Moho section which is imaged. Comparison of the reflection and refraction Moho depths shows reasonable agreement where the reflection Moho is clearly identified.

PALEOMAGNETICALLY-OBSERVED TILTS IN THE SOUTHERN OMINECA BELT

Michael T.D. Wingate

Paleomagnetism provides a method for observing late-stage tilting in high-grade metamorphic or plutonic terranes, which lack visible indicators of the paleohorizontal immediately prior to tilting. Mid-crustal rocks of the southern Omineca Belt were magnetized in the direction of the geomagnetic field at the time of Eocene uplift and cooling. Stable remanent magnetizations are isolated in oriented rock specimens, and their directions compared to those already observed in undisturbed rocks of this age. If the directions do not agree, then the aberrances, under certain conditions, can be interpreted as apparent tilts of the sampled rocks.

Previous work in the southern Omineca Belt [Bardoux and Irving, 1989; Marquis and Irving, 1990] has revealed apparent tilts antithetic to a series of outward-dipping, north-south trending Eocene normal faults. The previous extent of sampling (32 sites) in the study area has been augmented by 77 new sites. Results of the present study indicate westward apparent tilts of up to 40° in both the hanging-wall and footwall of the Slocan Lake Fault, in part confirming the results of Marquis and Irving [1990]. Further west, in the hanging wall of the Kettle River Fault, syenites of the Eocene Coryell suite exhibit tilts of similar magnitude but to the east, in the opposite direction to that expected in the hanging-wall of the fault. Syenites of the eastern edge of the same pluton, in the vicinity of the town of Rossland, exhibit magnetization directions concordant with the Eocene reference direction, and have not been tilted. These are preliminary results, but they indicate that the pattern of apparent tilts is more complex than that described previously.

Bardoux, M., and Irving, E., *Can. J. Earth Sci.*, 26: 829-844, 1989.

Marquis, G., and Irving, E., *Tectonics*, 9(5): 925-934, 1990.

CRUST AND UPPER MANTLE VELOCITY STRUCTURE OF THE INTERMONTANE BELT, SOUTHERN CANADIAN CORDILLERA*

B.C. Zelt, R.M. Ellis and R.M. Clowes
Department of Geophysics and Astronomy, University of British Columbia
E.R. Kanasewich
Department of Physics, University of Alberta
I. Asudeh
Geological Survey of Canada, Continental Geoscience Division
J. H. Luetgert
United States Geological Survey
Z. Hajnal
Department of Geological Sciences, University of Saskatchewan
A. Ikami†
Department of Earth Sciences, Nagoya University
(†Deceased 1 October, 1991)
G.D. Spence
Department of Physics and Astronomy, University of Victoria
R.D. Hyndman
Geological Survey of Canada, Pacific Geoscience Centre

* This is a condensed version of a paper submitted to the *Canadian Journal of Earth Sciences*

Introduction

The 1989 southern Cordillera refraction experiment (SCoRE '89) was conducted in the southwestern Cordillera (Fig. 1) as part of Lithoprobe's Southern Cordillera transect research program. The specific objectives of this survey were to map the crust-mantle transition and intra-crustal boundaries where such data are either nonexistent or of relatively low resolution.

SCoRE '89 is centered over the Fraser River fault system and spans the three western-most morpho-structural belts (Fig. 1). A roughly triangular arrangement of shots and receivers was employed. Large shots fired at line ends, midpoints, and the center of the triangle, were recorded by all receivers around the triangle, resulting in an extensive fan-shot dataset to enable three-dimensional imaging of crust and upper mantle structure interior to the triangle. The extensive inline dataset will provide well constrained, two-dimensional velocity models along the legs of the triangle that will serve as boundary constraints for the three-dimensional modelling. Two offshore shots located on the Juan de Fuca plate were included to tie the Spence *et al.* (1985) study of the Juan de Fuca subduction zone to the present program. We present a two-dimensional velocity model for Line 1, recorded along strike within the Intermontane belt (Fig. 1).

Seismic Refraction Data

A total of 269 recording instruments were deployed along the 330 km long line giving an average spacing of about 1.2 km. Seven shots (average spacing 55 km) ranging in size from 200–1800 kg of explosives were detonated (Fig. 2). All shots were recorded by all instruments, resulting in a dataset comprising approximately 1850 seismograms of which about 1730 were useful for analysis. Approximately 2700 traveltime picks of first and later arrivals were obtained from these traces. Two of the seven record sections are displayed in true relative amplitude format in Figs. 3a and 4a.

Theoretical traveltimes from the final velocity model shown in Fig. 5 have been included to illustrate the traveltimes fit.

A total of eight distinct phases (see Figs. 3 and 4) are identified and used in the modelling procedure. P_s , P_g and P_n correspond to refracted energy through the relatively low velocity near-surface layer, upper crust and upper mantle, respectively. R_1 and R_2 are reflections from within the upper crust, R_3 is a wide-angle reflection from the base of the middle crust. P_mP is a reflection from the crust-mantle boundary and P^m is a relatively strong reflection from within the upper mantle. Note that not all phases have been identified on all record sections. First arrivals can be easily identified across most sections. Only on the far-offset traces of the SP 19-S record section is the signal-to-noise ratio so that phase identification is difficult. Line 1 is situated within a single terrane (Quesnellia), which may explain the efficiency with which seismic energy was propagated.

Modelling the Refraction Data

Two methods were used concurrently to interpret the data. Traveltimes were modelled using the 2-D ray-trace traveltimes inversion algorithm of Zelt and Smith (1991). The additional constraints provided by amplitude modelling were incorporated into the velocity model using a modified version of the 2-D ray-trace forward modelling algorithm of Zelt and Ellis (1988) which uses the same velocity parameterization as the traveltimes inversion algorithm. The Zelt and Smith (1991) traveltimes inversion routine was favoured over conventional forward modelling of traveltimes because it represents a more objective and efficient procedure, and provides estimates of resolution, uncertainty and nonuniqueness of model parameters (boundary depths and layer velocities). In addition, the high density shot and receiver coverage and presence of both refracted and reflected crustal and upper mantle arrivals on all record sections made this dataset particularly well suited for inversion.

A "layer stripping" approach was used to model the observed data. Typically the inversion routine was used to solve for boundary depths and velocities simultaneously within one or more layers. Amplitudes of phases used in the inversion, and previously modelled phases, were compared (qualitatively) with observed amplitudes. If necessary, velocity gradients and velocity contrasts across boundaries were adjusted (by forward modelling) to improve the match. The resulting velocity gradient and contrast information were used as constraints in another round of traveltimes inversion. This procedure of alternating traveltimes inversion and amplitude forward modelling was repeated until a satisfactory fit of observed and calculated traveltimes and amplitudes was achieved for successively deeper layers. The final model that was chosen gave the best overall fit between observed and calculated traveltimes and amplitudes for all phases from all shots.

The final velocity model for Line 1 is shown simplified in Fig. 5. In this figure several layer boundaries representing gradient changes in the upper crust are omitted. Figure 3b is a synthetic section generated by the model in Fig. 5. To compensate for anelastic attenuation, amplitudes were calculated assuming a Q of 200 in the near surface layer, 400 in layers 2-6 (upper crust) and 1000 for deeper crustal and upper mantle layers. Figure 4b shows a typical comparison of calculated and observed traveltimes. We note that a possible source of error in our 2-D interpretation (not accounted for in the modelling) is the deviation (< 12 km) in recording geometry from a straight line (*e.g.*, see Fig. 2).

Principal Features of the Velocity Model

The important features of the Line 1 velocity model, as constrained by traveltimes inversion and amplitude forward modelling, are shown in Fig. 5. There is a thin (< 2.5 km) near-surface layer of average velocity 4.5 km/s which thins to the north so that beneath SP 1 it is ~ 350 m thick. Velocities in this layer vary between 2.8 and 5.4 km/s with several localized low velocity regions that correlate well with delays seen in P_g . Figure 5 shows regions of the near-surface layer where the average velocity is less than 4.8 km/s. A comparison of surface velocities with a surface geology map (Wheeler and McFeely 1987) shows good correlation between these low velocity surface regions and several Tertiary sedimentary and volcanic bodies and Miocene and Late Triassic plutons of unknown thickness traversed by the line (Fig. 2). The higher velocity regions of the near surface layer are mainly Paleozoic through Cretaceous volcanics.

The upper crust (layers 2–6) is on average ~ 14 km thick. At the top velocities vary between 6.0 and 6.4 km/s. There are two regions of relatively high velocity gradient as inferred from the amplitude modelling of P_g . The first is centered beneath SP 18, the second beneath SPs 17 and 16 (Fig. 5). The absolute values of the gradients in these regions are not well constrained but, as modelled, are approximately six times greater than surrounding values of about 0.015 s^{-1} . These high gradient regions are not correlated with surface features.

Two distinct reflecting horizons are imaged within the upper crust. The first dips slightly ($\sim 3^\circ$) from about 10.5 km depth at 150 km model distance to 13.1 km depth at 100 km. The second reflecting horizon is at a depth of 9 km between 270 and 310 km. Both of these reflecting horizons are modelled as the top of a weak LVZ (layer 6 in Fig. 5) which extends to the base of the upper crust north of 100 km. The negative velocity contrast is small (~ 0.1 km/s) and may not be significant based on the likely uncertainties in the inferred velocities.

The base of the upper crust is near 15 km depth. This boundary is shown as shallowing to the north to about 12 km depth beneath SP 19 on Fig. 5 but this is not well constrained. The positive velocity contrast across the upper/middle crust boundary is about 0.1 km/s north of SP 2. Since there is no evidence to support a similar contrast to the south, we have extended this boundary at a depth of 15 km. This is also consistent with the higher velocities in layer 5 beneath SP 18, resulting in a decreased velocity contrast.

On average the middle crust (layer 7) is 9 km thick with its base dipping from 23 km depth at the south end to 26 km beneath SP 16. The velocities in this layer vary between 6.0 to 6.4 km/s. The average velocity is 6.3 km/s which represents a return to values interpreted above the LVZ present at the base of the upper crust.

The lower crust (layer 8) is ~ 8 km thick, increasing to 13 km near the north end. Velocities at the top of this layer are 6.3–6.6 km/s. At the base of the lower crust velocities range between 6.6 and 6.8 km/s except beneath SP 19 where the high apparent velocity P_mP reflection from SP 1 constrains a region of somewhat higher (7.0 km/s) velocity.

The top of the Moho transition layer is at 32–33 km depth but shallows to 30 km beneath SP 2. This Moho depth is consistent with a much earlier study of a partially reversed refraction profile (Cumming *et al.* 1979; see Fig. 1 for location). The transition layer is about 1.5 km thick and reaches a maximum thickness of 3 km. The base of this layer is at about 33.5 km and it is nearly flat. Although the thickness of the transition layer is not well constrained, we include it because it allows for an improved amplitude fit to P_mP and because, if we interpret this zone to represent

a complex interlayered sequence of high and low velocity material, it probably more realistically represents the true nature of the crust-mantle boundary (Mooney and Brocher 1987). Velocities at the top of the upper mantle decrease from 7.9 km/s in the south to 7.7 km/s in the north. An upper mantle reflector is imaged approximately 15 km beneath the Moho (48 km depth).

Comparison With Lithoprobe Reflection Data

In 1988, Lithoprobe recorded reflection profiles within the southern Intermontane belt (Cook *et al.* 1992). Profile 88–11 crosses Line 1 obliquely approximately midway between SPs 2 and 17 (Fig. 2). The data for Profile 88–11 and a simplified schematic interpretation of the data in the vicinity of Line 1, with time-to-depth conversions based on our refraction model velocities at the location of Profile 88–11, are shown in Fig. 6. Beside the reflection interpretation is a 1-D refraction velocity profile (Fig. 6b) from the model in Fig. 5 at the location of Profile 88–11. Noting that these lines are *not* coincident and allowing for possible crustal anisotropy and lateral averaging in the refraction velocity model, we do not expect a precise correspondence between boundaries at the intersection of the two lines. However, a comparison of the interpretations is instructive.

The crustal section of Cook *et al.* (1992) is interpreted in terms of three major components (Fig. 6c): (1) an upper layer approximately 23 km thick comprising primarily material of the Mesozoic/Paleozoic Quesnellia terrane, possibly thickened by imbrication and/or ductile deformation due to convergence of the terrane with North America; (2) a middle layer approximately 4 km thick which projects eastward updip to the Vernon antiform (140 km east of Line 1) and is probably correlatable with the parautochthonous rocks which form a thick sequence of the upper crust in the eastern Cordillera; and (3) an ~6 km thick lower crust representing the westwardly thinned extension of North American cratonic basement.

The upper crustal section shows a high degree of reflectivity, including several prominent west-dipping reflections (dashed lines in Fig. 6c). These features were likely formed during Mesozoic to early Tertiary compression (Cook *et al.* 1992) and are related to the Central Nicola horst, an Eocene extensional structure bounded to the west by the west-dipping normal Coldwater fault (Fig. 2). The refraction data image two upper crustal reflectors in the vicinity of Profile 88–11. The first, constrained by R_1 , is at a depth of ~11 km and is modelled as the top of a LVZ. The second, constrained by R_2 , is at ~15.5 km depth and corresponds to the base of the LVZ. The first reflector correlates with the Coldwater fault which projects to a depth of about 9–10 km (~3.5 s two-way traveltime (TWTT) in Fig. 6a) beneath Line 1. The Coldwater fault crosses Line 1 about 15 km south of SP 2 (Fig. 2) and thus, while it is possible that R_1 reflections from SP 17 are from this fault zone, this cannot be the source of R_1 from SP 18. The different character of R_1 reflections from SPs 17 and 18 (R_1 from SP 17 is stronger and more coherent) provides further evidence for separate sources of reflectivity.

The second refraction-imaged reflector, at ~15.5 km depth correlates well with the top of a comparatively flat sequence of reflections beginning at ~5.8 s TWTT (16 km) on the reflection section. This is one of several reflections in the upper crustal zone that form an antiformal pattern relating to the Central Nicola horst, approximately 20 km east of Line 1. Given the high reflectivity of the crust as seen in Fig. 6a and the range of possible interpretations as to the positions of these reflectors, such a correlation may be coincidental. Alternatively, R_2 could be imaging a transition from brittle to more ductile crust or a transition into a layered porous medium. The brittle-ductile

transition occurs at a temperature of about 450°C for mafic rocks which, for typical heat flows in the Intermontane belt, occurs at a depth of about 14 km (Lewis *et al.* 1992). The brittle-ductile transition frequently correlates with the top of seismically reflective zones in the deep crust. The data of Cook *et al.* (1992), however, shows strong reflectivity throughout the entire crust in the vicinity of Line 1 (Fig. 6a). It is not possible to uniquely determine the source of the R₂ reflection. However, the correlation between R₂ and reflections associated with the Central Nicola horst suggests that, at least locally (*i.e.*, where the refraction and reflection lines cross), ductile fabrics associated with compressional activity are the most likely source.

The base of the refraction model's middle crust (~24 km) correlates well with the base of the upper crust of the reflection interpretation (22 km). This is interpreted by Cook *et al.* (1992) as the boundary between rocks of the Paleozoic-Mesozoic Quesnellia terrane ($v_p \sim 6.2$ km/s) and parautochthonous North American rocks ($v_p \sim 6.5$ km/s). The strong R₃ reflections generated at this boundary may arise from a ductile shear zone between the two layers which has accommodated motion of Quesnellia during periods of compression and extension or possibly from primary lithologic layering due to igneous layering or mafic sill-like intrusions (*e.g.*, see Holbrook *et al.* 1991). The depth to the R₃ reflector also correlates well with the predicted depth to the 730°C isotherm, which from heat flow data in the Intermontane belt, occurs at about 23 km (Lewis *et al.* 1992). This isotherm sometimes corresponds to the lower limit of crustal reflectivity, although again the data of Cook *et al.* (1992) show strong reflectivity throughout the entire crust (Fig. 6a). The 730°C isotherm corresponds to the top of granulite facies conditions, below which the crust would be expected to be largely dehydrated (Hyndman *et al.* 1991). If fluids do play a major role in the crustal reflectivity of this region then the middle crust of the refraction model may represent a region in which interconnected fluids exist and electrical conductivity is relatively high.

A laterally coherent event in the reflection data at ~9.2 s TWTT (26 km; Fig. 6a), interpreted as a zone of detachment at the top of North American cratonic crust and along which the overlying crust has been thrust eastward (Cook *et al.* 1992) has no identifiable signature in the refraction data. This observation may have some bearing on the nature of this reflective zone since it may not be associated with a significant velocity contrast. The lowest crustal unit of the reflection interpretation represents thin and highly strained rocks that were formerly North American crust (Cook *et al.* 1992). Velocities at these depths range from 6.6–6.8 km/s (Fig. 6b); significantly less than typical lower crustal velocities (*i.e.*, ~7.2 km/s; Chandra and Cumming 1972). Thus, this layer most likely comprises mid-crustal level North American rocks.

Depth to the top of the Moho transition layer (31 km) agrees well with the depth to the reflection Moho (32 km) which has been interpreted as the base of the horizontal zone of reflections at about 10.5 s TWTT in Fig. 6a. The duration of this reflective zone (~0.2 s or ~1 km) is also consistent with the refraction model's crust-mantle transition zone which represents a zone of alternating high velocity (mafic) and low velocity rocks.

Summary and Conclusions

An iterative combination of traveltimes inversion and amplitude forward modelling of seismic refraction data has been used to determine along-strike variations in crust and upper mantle velocity structure within the Intermontane belt. This procedure has proven efficient at providing a well constrained velocity model with estimates of resolution and uncertainty of model parameters. There

is good agreement between the refraction velocity model and an interpretation of Lithoprobe reflection profile 88–11 (Cook *et al.* 1992). Where the two lines intersect, depths to wide-angle reflectors in the crust of the refraction model agree with depths to prominent reflection events. Depths to Moho agree to within 1 km.

Strong reflections are generated from the middle-lower crust boundary and Moho. Weaker reflections are generated at the upper-middle crust boundary and from within the upper crust. The origin of these reflections cannot be determined uniquely from the refraction data. Likely sources include (*e.g.*, Klemperer and BIRPS Group 1987) ductile strain banding, trapped fluids or primary lithologic layering such as mafic sills. Depths to intra-crustal reflectors at 15 and 24 km correlate well with both reflection-imaged reflectors and predicted depths to the 450°C and 730°C isotherms, a temperature range which is compatible with free aqueous porosity (Hyndman *et al.* 1991). The middle-lower crust boundary at ~24 km may represent a transition into a region of greater ductility which accommodated motion of Quesnellia along listric detachment faults during periods of Eocene extensional activity. Rocks immediately below this boundary have been correlated with parautochthonous North American rocks (Cook *et al.* 1992). We see no evidence in the refraction data for lower crustal type velocities above this zone and thus it appears that during accretion, the lower lithosphere of Quesnellia was removed, leaving this terrane “rootless”. In this sense Quesnellia is similar to the northern part of the Chugach terrane in southern Alaska which is interpreted (in one scenario) as a wedge which overrode the deeper part of a neighboring terrane; losing its root in the process (Fuis and Plafker 1991). Fuis and Mooney (1990) interpret an analogous tectonic history for the Franciscan terrane in central California. The fate of Quesnellia’s lower lithosphere is unknown, although presumably it was recycled in the mantle.

An upper mantle reflector, approximately 16 km beneath the Moho, may represent the base of the lithosphere which is known to be thin throughout much of the Intermontane belt. Our depth agrees well with the depth to the top of an upper mantle low velocity zone, approximately 15–20 km beneath the Moho, found by Wickens (1977) in his study of Rayleigh and Love wave phase velocities.

There are lateral variations in velocity and depth to reflecting boundaries but we find no evidence for rapid changes in velocity over short lateral distances (except in the near surface layer) or dips greater than ~5°. This may relate to the along-strike orientation of the refraction line which prevents us from imaging large-scale convergent and extensional structures associated with the development of the crust of this region of the Cordillera. These aspects will be considered in the continuing analysis of the extensive 3-D dataset of SCoRE ‘89.

References

- CHANDRA, N.N., and CUMMING, G.L. 1972. Seismic refraction studies in western Canada. *Canadian Journal of Earth Sciences*, 9: 1099–1109.
- 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 I: Foreland Thrust and Fold Belt to Fraser River Fault. *Tectonics*. (In press.)
- CUMMING, W.B., CLOWES, R.M., and ELLIS, R. M. 1979. Crustal structure from a seismic refraction profile across southern British Columbia. *Canadian Journal of Earth Sciences*, 16: 1024–1040.
- FUIS, G.S., and MOONEY, W.D. 1990. Lithospheric structure and tectonics from seismic-refraction and other data. *In* The San Andreas fault system. *Edited by* R.E. Wallace. United States Geological Survey Professional Paper 1515, pp. 206–236.

- FUIS, G.S., and PLAFKER, G. 1991. Evolution of deep structure along the Trans-Alaska Transect, Chugach Mountains and Copper River Basin, southern Alaska. *Journal of Geophysical Research*, **96**: 4229–4253.
- HOLBROOK, W.S., CATCHINGS, R.D., and JARCHOW, C.M. 1991. Origin of deep crustal reflections: Implications of coincident seismic refraction and reflection data in Nevada. *Geology*, **19**: 175–179.
- HYNDMAN, R.D., LEWIS, T.J., and MARQUIS, G. 1991. Comment on "Origin of deep crustal reflections: Implications of coincident seismic refraction and reflection data in Nevada". *Geology*, **19**: 1243.
- KLEMPERER, S.L., and the BIRPS GROUP 1987. Reflectivity of the crystalline crust: hypotheses and tests. *Geophysical Journal of the Royal Astronomical Society*, **89**: 217–222.
- LEWIS, T.J., BENTKOWSKI, W.H., and HYNDMAN, R.D. 1992. Crustal temperatures near the Lithoprobe southern Canadian Cordilleran transect. *Canadian Journal of Earth Sciences*. (In press.)
- MOONEY, W.D., and BROCHER, T.M. 1987. Coincident seismic reflection/refraction studies of the continental lithosphere: a global review. *Reviews of Geophysics*, **25**: 723–742.
- SPENCE, G.D., CLOWES, R.M., and ELLIS, R.M. 1985. Seismic structure across the active subduction zone of western Canada. *Journal of Geophysical Research*, **90**: 6754–6772.
- WHEELER, J.O., and MCFEELY, P. 1987. Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America. Geological Survey of Canada, Open File 1565, scale 1:2,000,000, 2 sheets.
- WICKENS, A.J. 1977. The upper mantle of southern British Columbia. *Canadian Journal of Earth Sciences*, **14**: 1100–1115.
- ZELT, C.A., and ELLIS, R.M. 1988. Practical and efficient ray tracing in two-dimensional Media for rapid traveltimes and amplitude forward modelling. *Canadian Journal of Exploration Geophysics*, **24**: 16–31.
- ZELT, C.A., and SMITH, R.B. 1991. Seismic traveltimes inversion for 2-D crustal velocity structure. *Geophysical Journal International*, **108**: 16–34.

FIGURE CAPTIONS

Fig. 1. Location map for the 1989 Southern Cordillera refraction experiment (SCoRE '89) showing the three principal recording lines and locations of shot points (triangles). In this paper we present results for Line 1, the north-south running line within the Intermontane belt. Dotted line crossing Line 1 represents approximate location of a previous refraction survey in the Intermontane belt (Cumming *et al.* (1979). Inset map identifies the morpho-structural belts of the Canadian Cordillera.

Fig. 2. Location of shotpoints (numbered triangles with size proportional to charge; see Table 1) and receiver sites ("+" symbols) along Line 1. Dotted lines show the location of Lithoprobe reflection profiles; 88–11 which crosses Line 1 is emphasized. Generalized surface geology is from Wheeler and McFeely (1987). Line 1 is situated entirely within Quesnellia.

Fig. 3. (a) Observed record section for SP 1 plotted in true relative amplitude format. Distance scale refers to model distance (see Fig. 5). Data have been bandpassed filtered between 2 and 10 Hz. Labelled theoretical traveltimes calculated from the model in Fig. 5 are superimposed. Note that the theoretical traveltimes curves do not necessarily imply that all traces spanned by the curve have been picked. (b) Synthetic record section for SP 1. In both panels the reduction velocity is 8 km/s and amplitudes have been scaled proportional to distance to the 1.5 power.

Fig. 4. (a) Observed record section for SP 2. See Fig. 3 caption for plotting parameters. (b) Comparison of observed (short vertical bars with height equal to twice the uncertainty of the pick) and calculated (line) traveltimes.

Fig. 5. Simplified velocity model for Line 1 (vertical exaggeration $\sim 2.8:1$). Depth refers to depth from sea level. Numbers within model represent P-wave velocities in km/s. Velocities shown are not values at nodes, rather they represent average velocities over a region indicated by the spacing of the numbers. Depth refers to depth from sea level. Triangles along top of model represent shot point locations. Arrow between SP 2 and 17 indicates location of Lithoprobe reflection Profile 88–11. M = top of Moho transition layer. R_1 , R_2 , R_3 , P_mP and P^m denote reflecting boundaries which generate these phases. Numbers at the right side of the model correspond to layer numbers discussed in the text. Surface geology from Wheeler and McFeely (1987).

Fig. 6. (a) Migrated and coherency filtered reflection data from Lithoprobe reflection profile 88–11 (Cook *et al.* 1992). Location of the intersection of Line 1 is shown at top. Location of the surface trace of the west-dipping Coldwater fault (CWF) is also shown. Dashed lines show region covered in (c). (b) One-dimensional velocity profile from the refraction model in Fig. 5 at the location of Profile 88–11. Labelled reflection phases indicate depth to corresponding reflecting boundaries imaged in refraction data. (c) Schematic interpretation (no vertical exaggeration) of Profile 88–11 in the vicinity of Line 1 (modified from Fig. 9 of Cook *et al.* 1992) with time-to-depth conversion based on refraction velocities shown in (b). Dashed lines within upper crustal unit represent several west dipping reflections. The uppermost reflection (CWF) is interpreted as the Coldwater Fault by Cook *et al.* (1992). Dotted lines between (b) and (c) show possible correlations between refraction and reflection interpretations discussed in text.

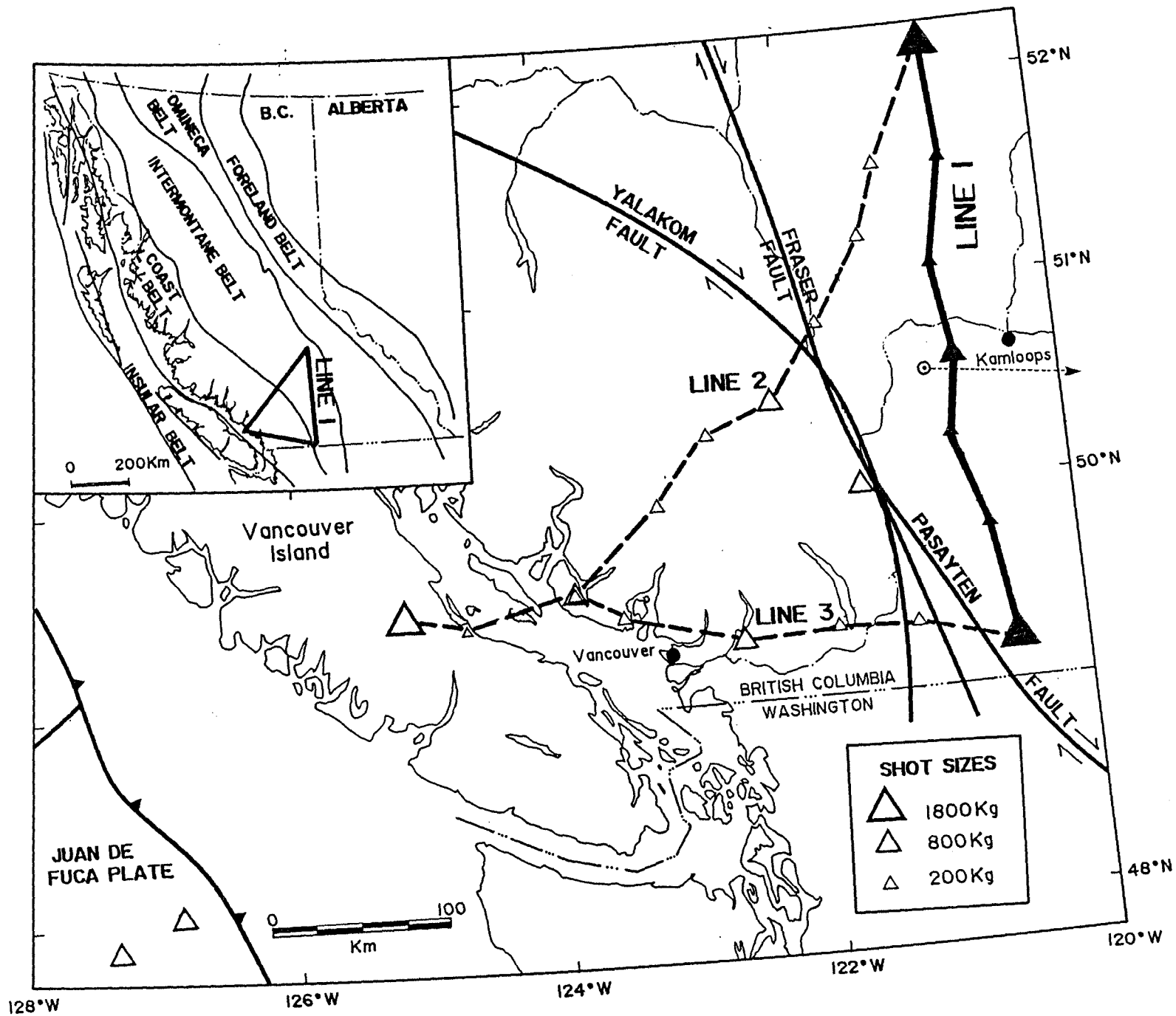


Fig. 1

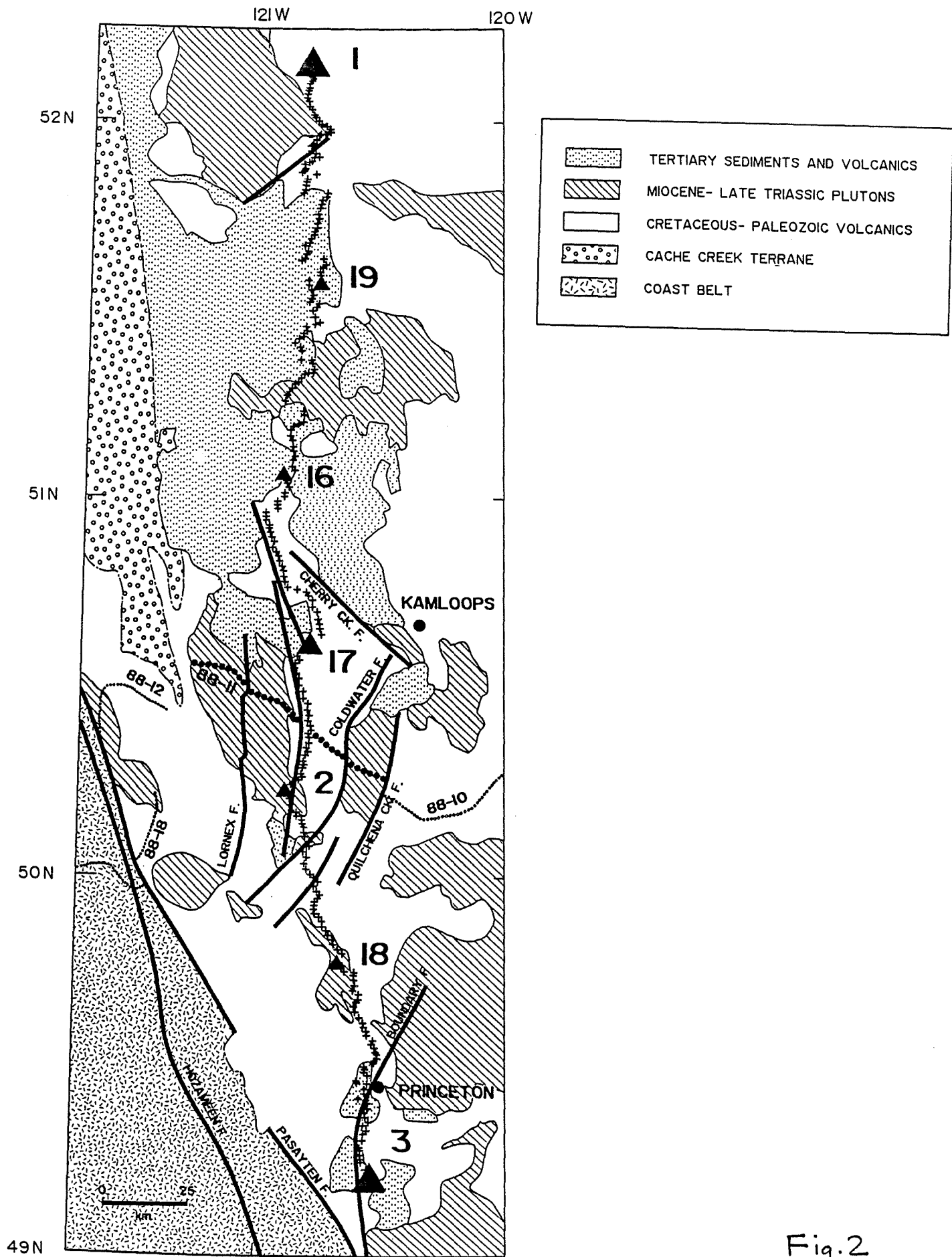
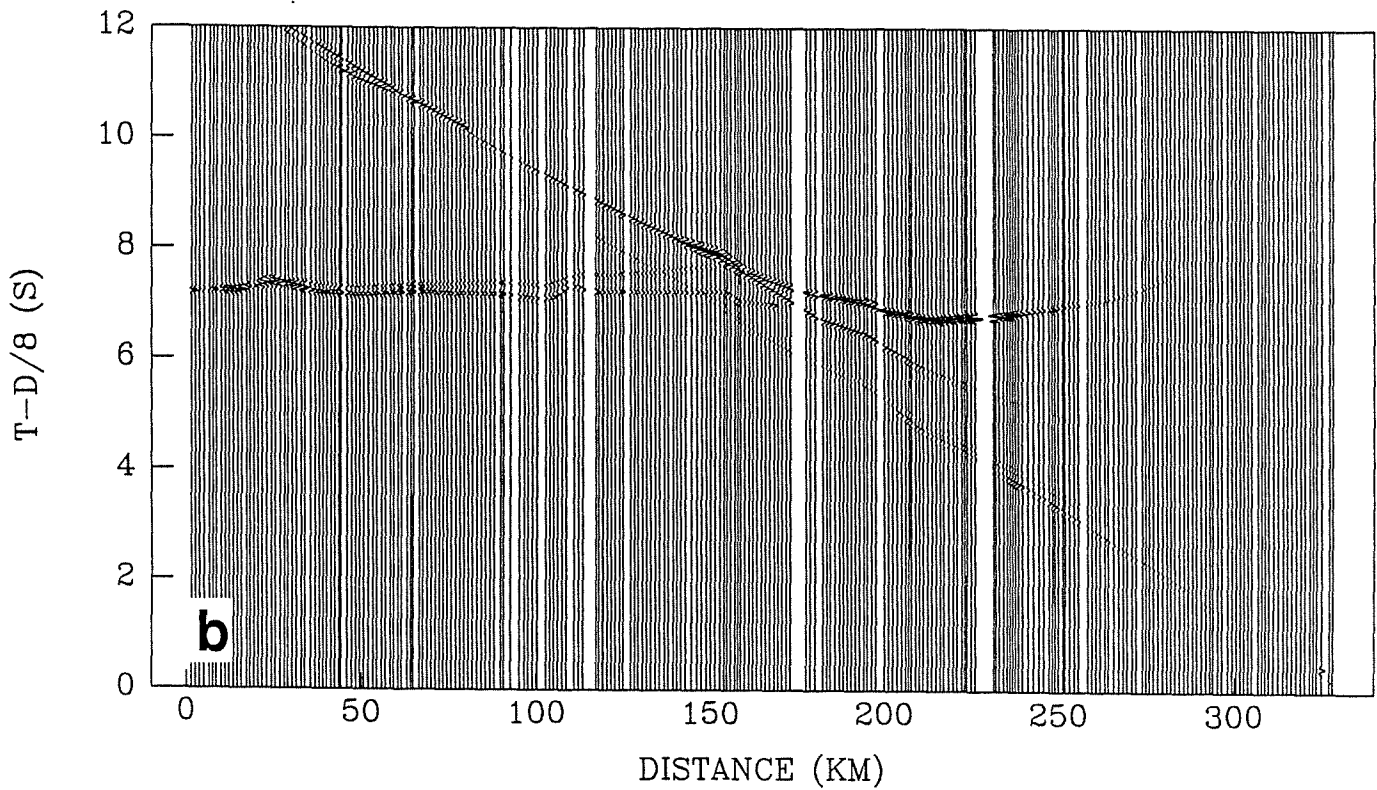
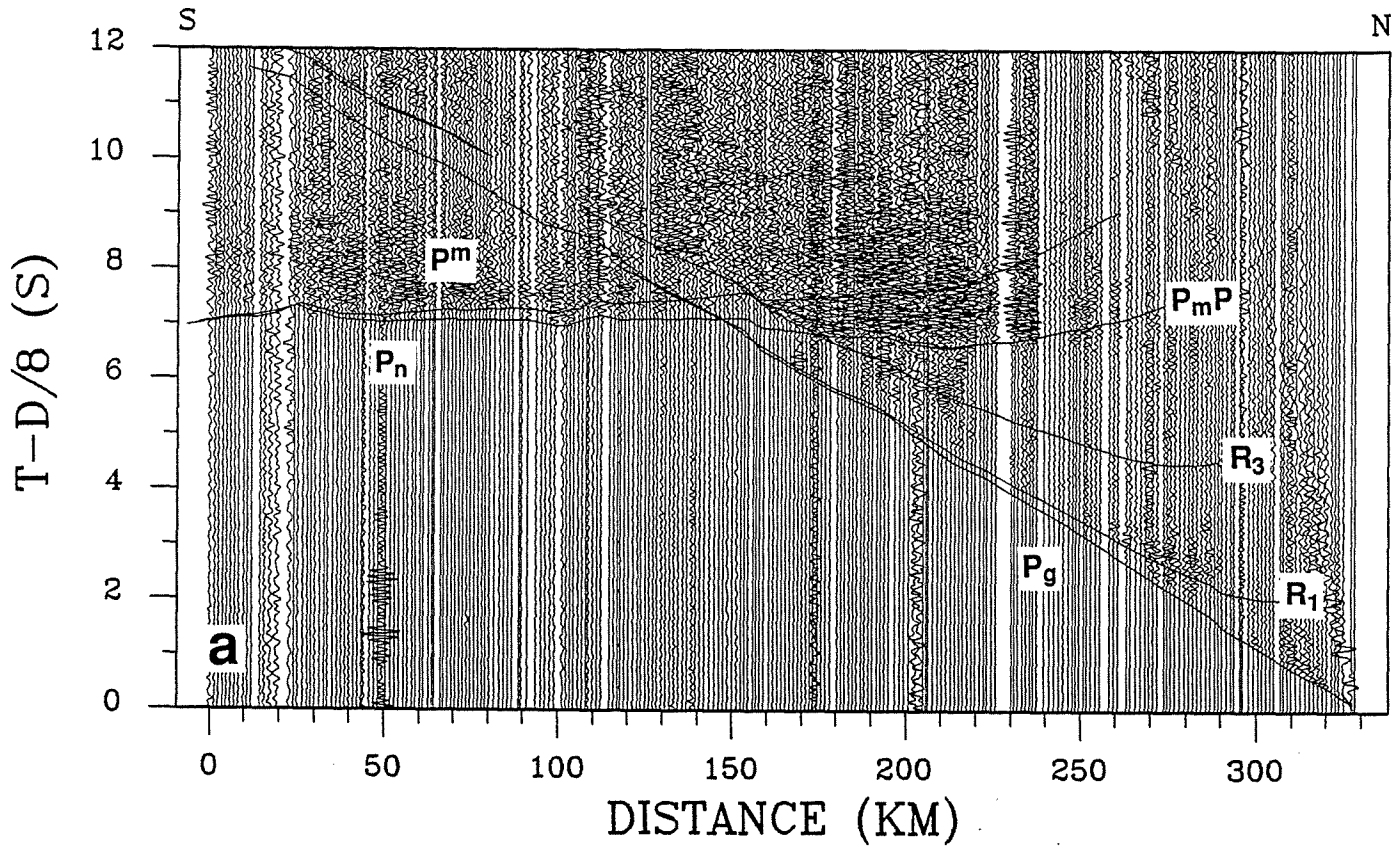


Fig.2

LINE 1 SHOT 01



LINE 1 SHOT 02

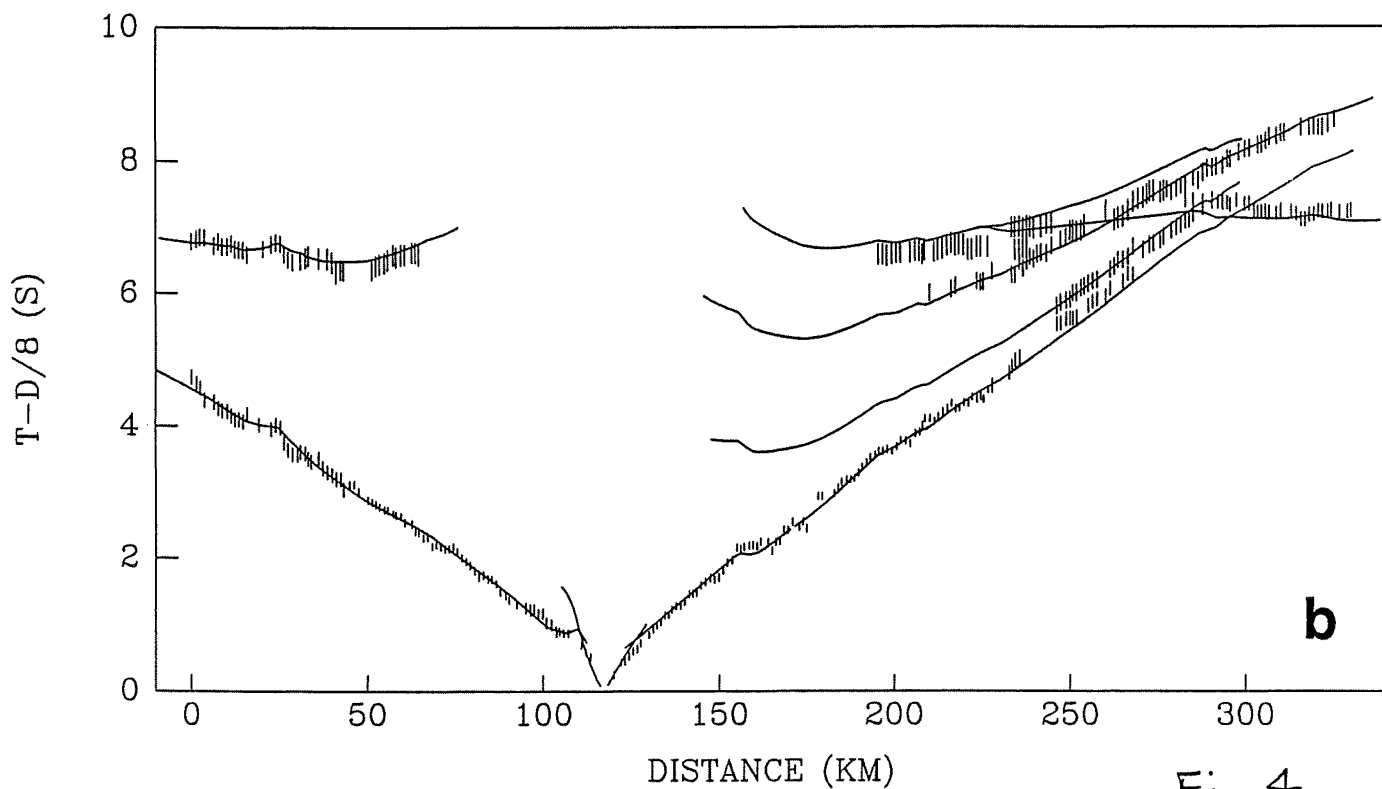
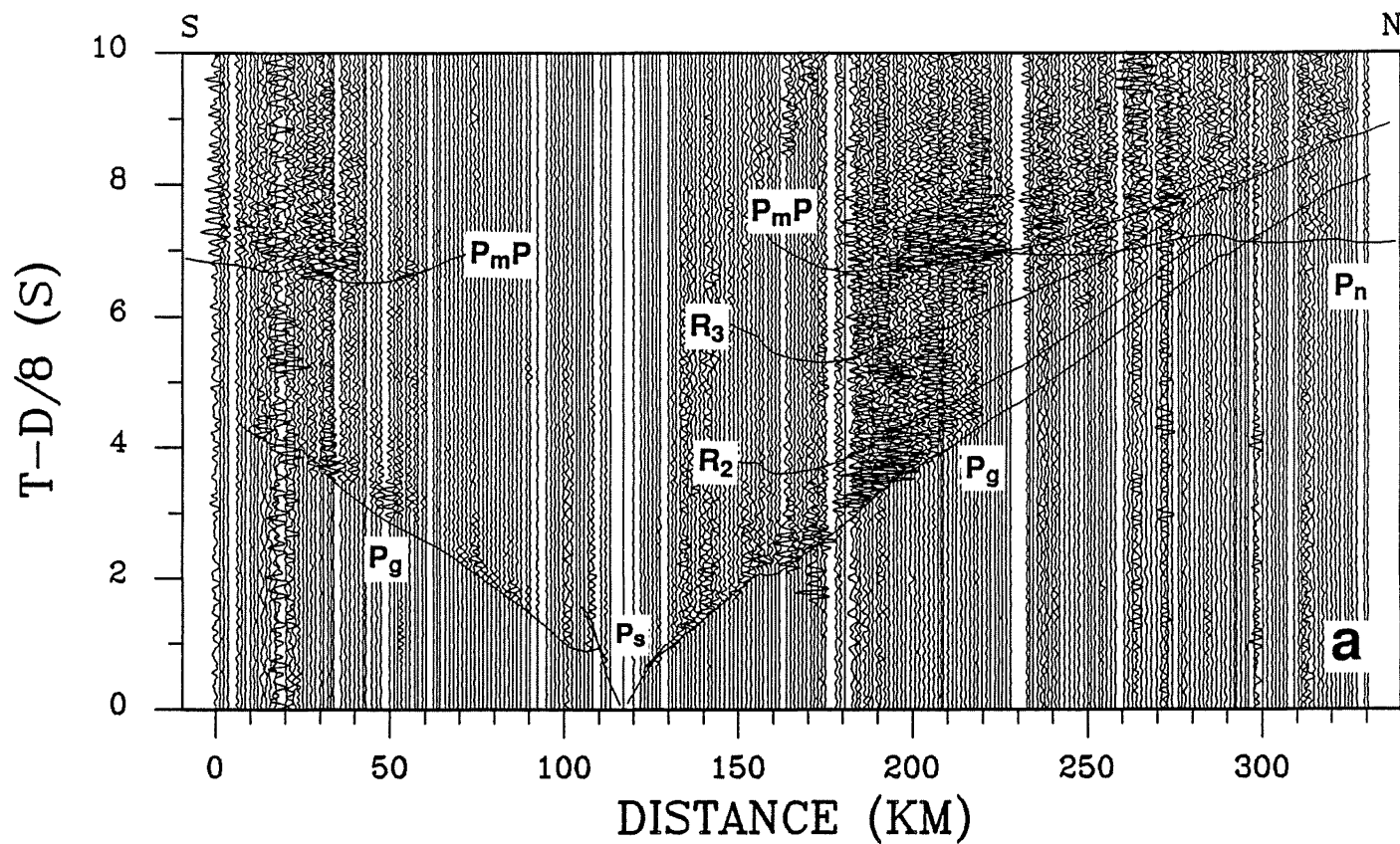


Fig. 4

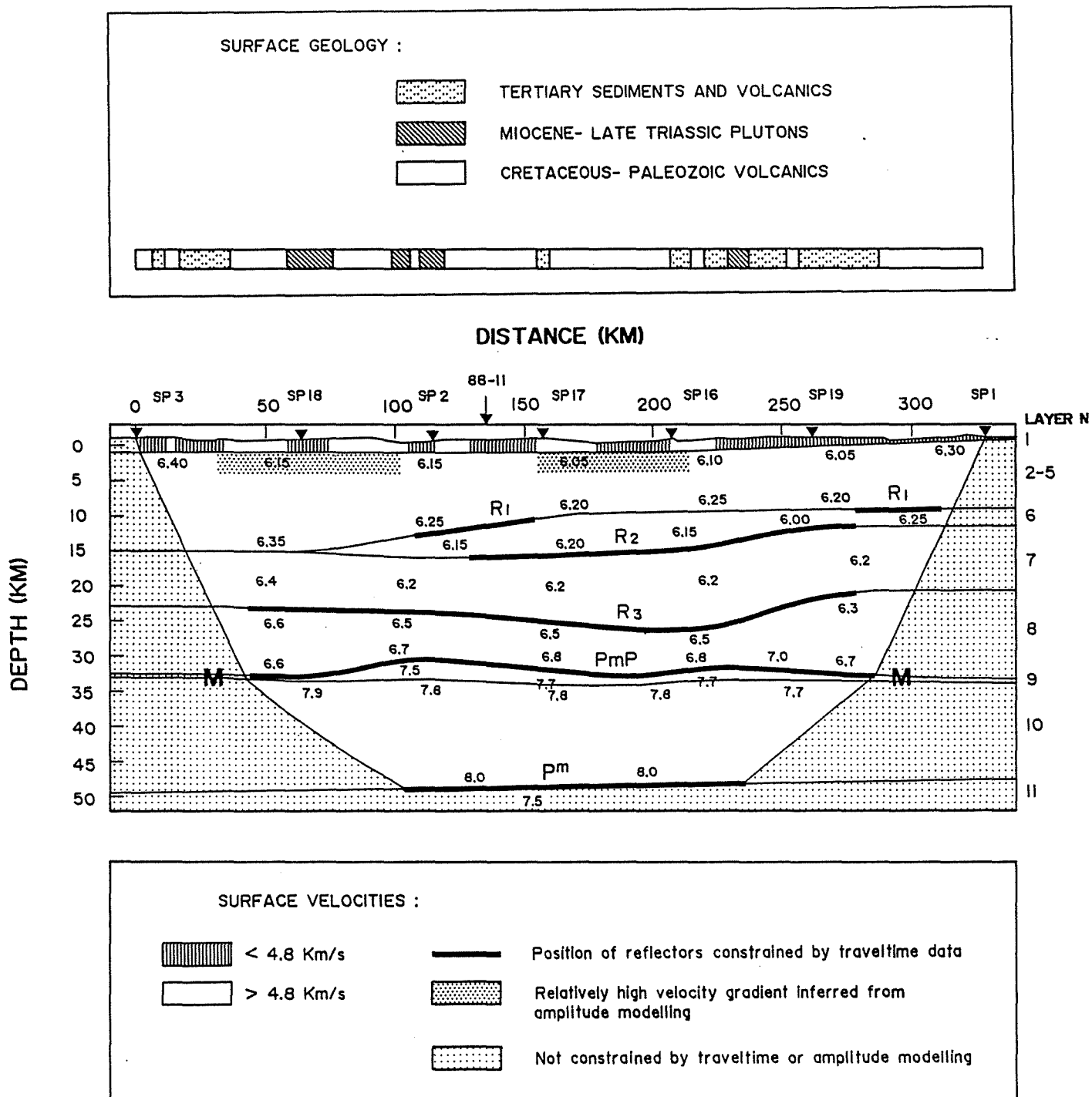


Fig. 5

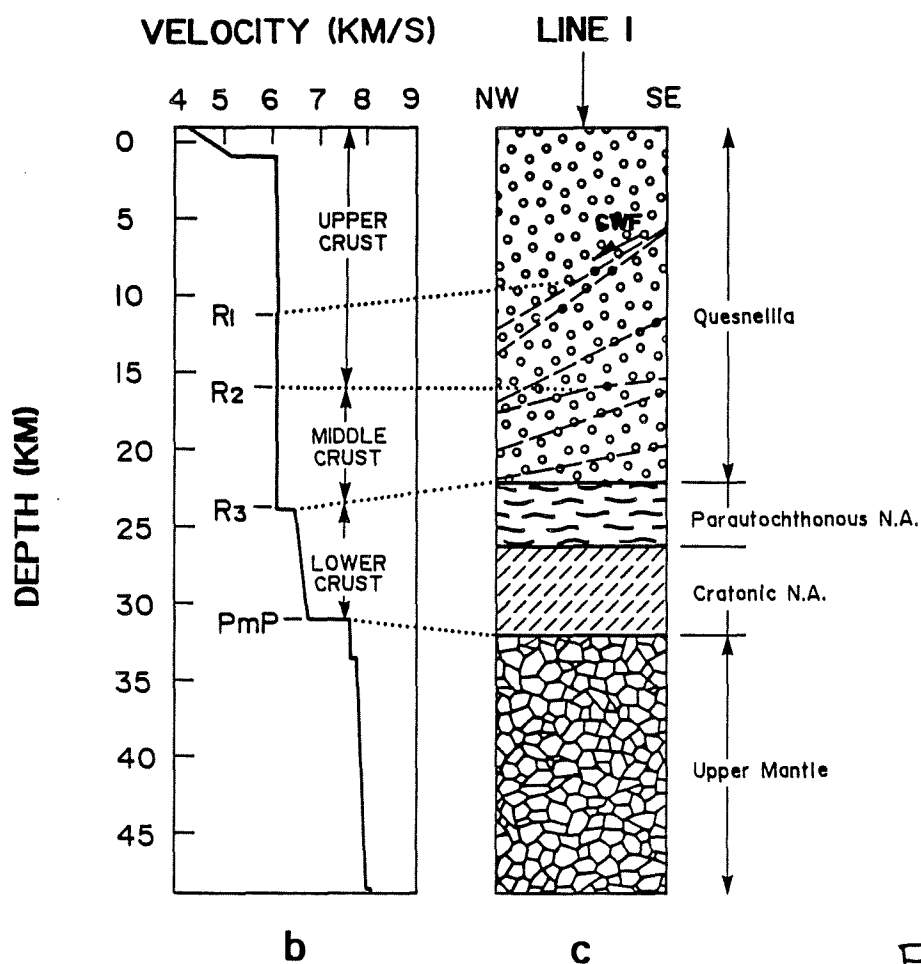
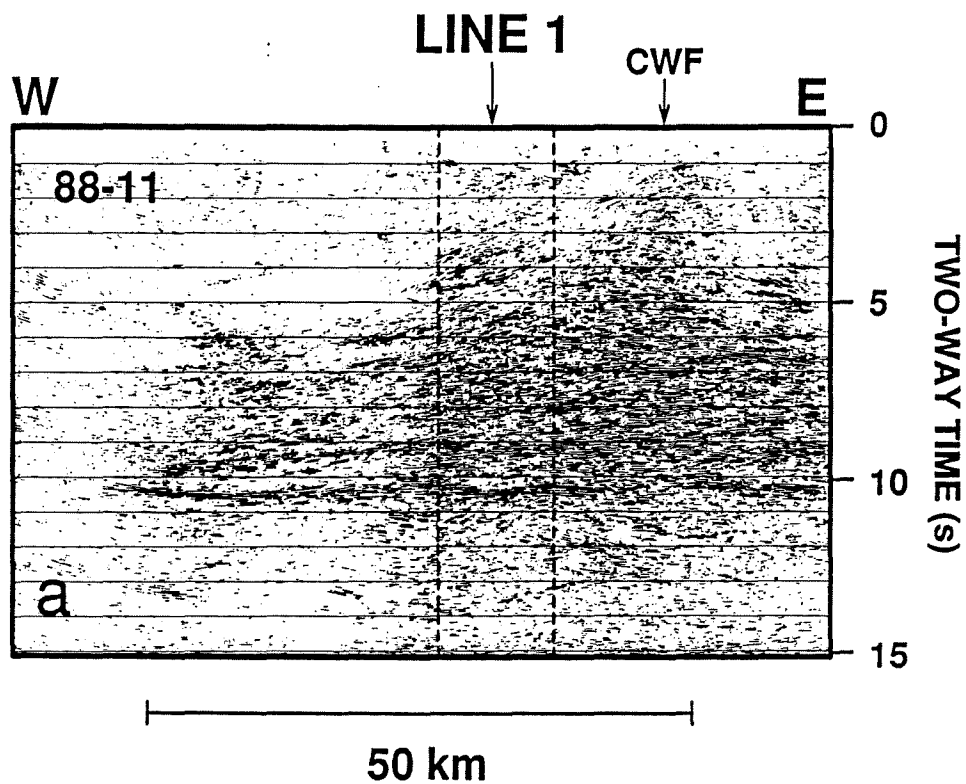


Fig. 6