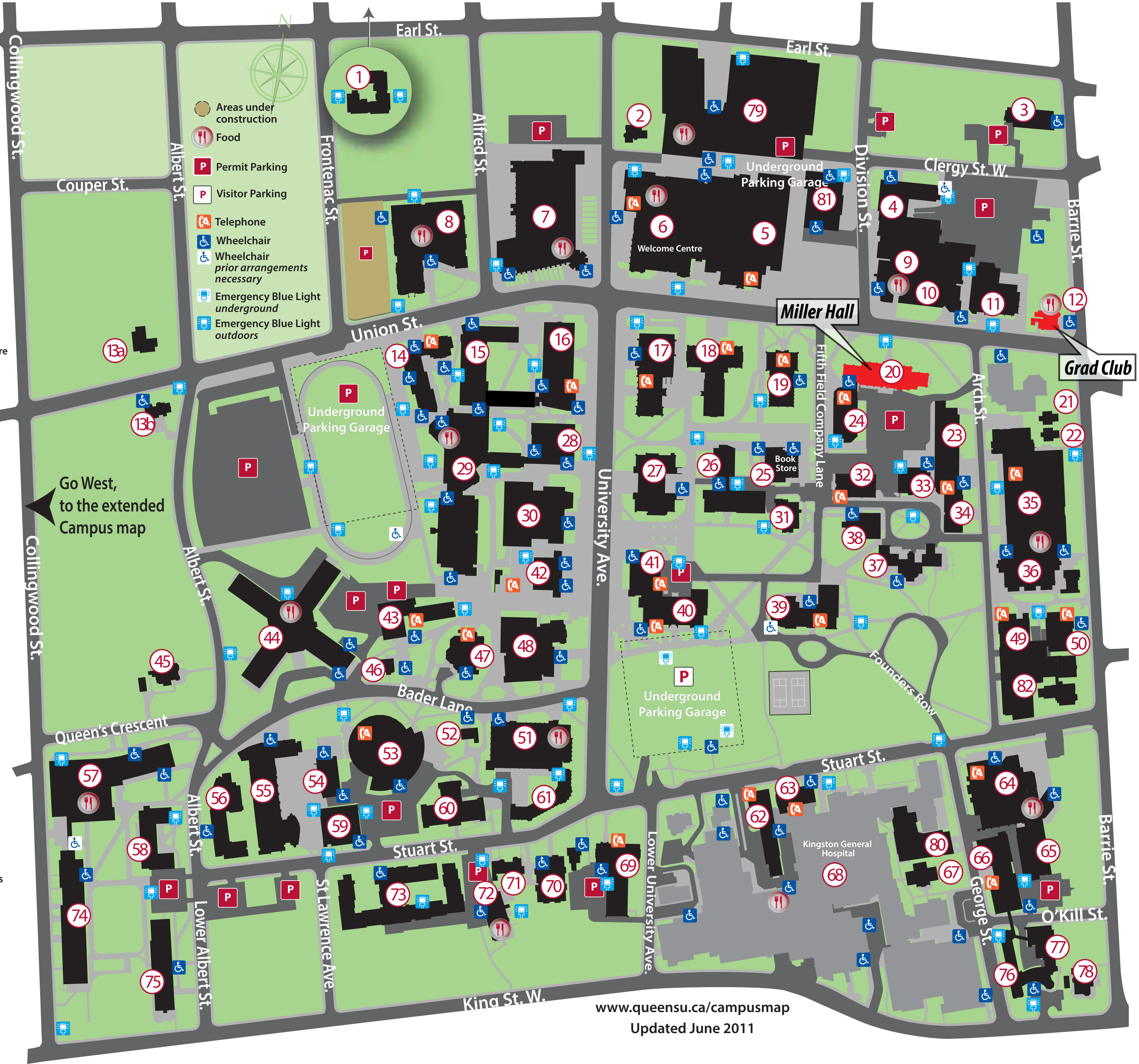
2013 Cordilleran Tectonics Workshop

February 16-17, 2013
Queen's University
Kingston, ON

49	Abramsky Hall
61	Adelaide Hall
48	Agnes Etherington Art Centre
2	Apartments and Housing
52	Ban Righ Centre
51	Ban Righ Hall
9	Beamish-Munro Hall
36	Biosciences Complex
64	Botterell Hall
24	Bruce Wing
65	Cancer Research Institute
50	Cataraqui Building
31	Carruthers Hall
54	Chernoff Auditorium
55	Chernoff Hall
60	Chown Hall
25	Clark Hall
34	Craine Building
17	Douglas Library
16	Dunning Hall
4	Dupuis Hall
35	Earl Hall
30	Ellis Hall
62	Etherington Hall
71	Film and Media
26	Fleming Hall
21	Four Directions Aboriginal Student Centre
80	GIDRU Wing
8	Goodes Hall
10	Goodwin Hall
74	Gordon-Brockington Hall
18	Gordon Hall
12	Grad Club
41	Grant Hall
46	Grey House
1	Harkness International Hall
47	Harrison-LeCaine Hall
23	Humphrey Hall
32	Jackson Hall
42	Jeffery Hall
6	John Deutsch University Centre
33	Kathleen Ryan Hall
40	Kingston Hall
68	Kingston General Hospital
70	LaSalle Building
57	Leonard Hall
73	Leggett Hall
66	Louise D Acton Building
3	MacGillivray Brown Hall
29	Mackintosh-Corry Hall
78	Macklem House
69	McLaughlin Hall
58	McNeill House
20	Miller Hall
75	Morris Hall
67	Museum of Health Care
19	Nicol Hall
38	Old Medical Building
27	Ontario Hall
5	Physical Education Centre
14	Policy Studies Building
79	Queen's Centre
13	Queen's Daycare (13a, 13b)
22	Queen's Quarterly/McGill-Queen's Press
77	Quinte Thousand Island Lodge
59	Rideau Building
28	Richardson Hall
63	Richardson Laboratory
45	School of English
81	School of Kinesiology and Health Studies
82	School of Medicine
15	Sir John A Macdonald Hall
53	Stirling Hall
7	Stauffer Library
37	Summerhill
39	Theological Hall
72	University Club
44	Victoria Hall
76	Waldron Tower
11	Walter Light Hall
43	Watson Hall
56	Watts Hall



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2013 Cordilleran Tectonics Workshop

Queen's University, Kingston, Ontario

Friday, Feb. 15			
7:00 PM 9:00 PM	***Ice breaker + Registration + Poster setup*** ***(cash bar + munchies)***	*Miller Museum* *36 Union St. (opposite Division St.)*	
Saturday, Feb. 16		***Speaker***	***Abstract (p.)***
	Technical session - *Miller 105*; **Posters** - *Miller 102*; **Coffee & lunch** - *Miller Museum*		
7:30 AM	***Registration + Posters*** ***coffee + muffins***		
8:30 AM	Testing the oroclinal entrapment hypothesis in BC and Yukon	*Alex Zagorevsky*	***67***
	Reviving Ray Price's conceptual model of continuous ductile extrusion/intrusion of "hot tongues" in orogenic belts	*Félix Gervais*	***23***
	The development of thrust belts and the influence of fluid pressure	*Paul MacKay*	***32***
10:00 AM	***coffee + discussion + posters***		
10:30 AM	Stratigraphic uncertainty and errors in shortening from balanced sections in the Cordillera	*Rick Allmendiger*	***4***
(40 min.)	The influence of conceptual models and geo-poetry in tectonics and structural geology	*Ray Price*	***41***
11:40 AM	***posters + discussion*** ***lunch*** ***posters + discussion***		
1:30 PM	Structural and metamorphic contrasts in the southern Kootenay Arc and Purcell Anticlinorium, southeastern British Columbia	*Ewan Webster*	***66***
	Belts of Cretaceous, Paleocene and Eocene suprastructure or infrastructure in polydeformed metamorphic rocks in the Thor-Odin – Pinnacles area of southern BC	*Deanne van Rooyen*	***58***
	The Mesozoic evolution of a transient, distributed high-grade transposing shear zone at the base of a critically tapered orogenic wedge	*Reid Staples*	***56***
3:00 PM	***coffee + discussion + posters***		
3:30 PM	Tectonic interpretation of eclogites in the St. Cyr area, Yukon-Tanana terrane	*Meredith Petrie*	***34***
	Eocene Tectonic and Magmatic Evolution of Central British Columbia	*Esther Bordet*	***7***
4:30 PM	***posters + discussion***		
7:00 PM	***Dinner on your own*** ***Social gathering at Queen's Grad club (upstairs)***	*162 Barrie St.* *(NW corner of Barrie & Union;* *1 block E of Miller Hall)*	
Sunday, Feb. 17 (morning)			
7:30 AM	***coffee + muffins + Posters***		
8:30 AM	Constraints on the original setting of the flysch of the Chugach and Prince William terranes in Alaska using detrital zircon	*John Garver*	***21***
	Along-strike variation in detrital zircon hafnium isotope compositions from the Chugach-Prince William terrane, Alaska	*Nicolas Roberts*	***50***
	Tectonic implications of Devonian to Early Mississippian rifting in the Alexander terrane and Wrangellia, northern Cordillera	*Steve Israel*	***26***
10:00 AM	***coffee + discussion + posters***		
10:30 AM	The "British Columbia Caledonides": Mid-Paleozoic orogeny in the southern Alexander terrane	*JoAnne Nelson*	***33***
(30 min.)	Pre-ice age 'Bell super-river' of northern Canada and the Early Miocene (22-17 Ma) beginning of the Grand Canyon	*Jim Sears*	***54***
11:40 AM	***posters + discussion*** ***lunch*** ***posters + discussion***		

Sunday, Feb. 17 (afternoon)

1:00 PM	Mount Harper Volcanic Complex, Ogilvie Mountains : A far-flung occurrence of the Franklin Igneous Event?	*Grant Cox*	***17***
	Detrital zircon (U-Th)/He and muscovite 40Ar/39Ar thermochronometry from the Mackenzie Mountains & Corridor, NWT: Insights into burial and exhumation of the Northern Cordillera	*Jeremy Powell*	***39***
	Overview of U-Pb Geochronology for the GEM Minerals - Multiple Metals Northwest Canadian Cordillera Project, Stevenson Ridge Area, Yukon	*Nancy Joyce*	***27***
2:30 PM	***Where to next year ??***		
	coffee		
4:00 PM	***posters + discussion***		

Posters

		Lead Author	***Abstract (p.)***
1	Microstructural analysis and 40Ar/39Ar thermochronology of the Okanagan Valley Fault System, British Columbia	*Nicole Allen*	***3***
2	Cache Creek terrane, Stikinia and overlap assemblages of eastern Whitehorse (NTS 105D) and western Teslin (NTS 105C) map areas	*Luke Bickerton*	***6***
3	Propagation of shear zones in the southern Canadian Cordillera	*Sharon Carr*	***12***
4	Geology of the Rackla belt, central Yukon	*Maurice Colpron*	***14***
5	Neogene exhumation of the Bhutan Himalaya: new insights from the inversion of low-temperature thermochronologic data	*Isabelle Coutand*	***15***
6	The Southeast Zone (Cu-Mo) and Deerhorn (Cu-Au) porphyries; a possible genetic relationship between a calc-alkalic and an alkalic deposit, Woodjam Property, central British Columbia	*Irene Del Real*	***18***
7	Early Neoproterozoic stratigraphy in Yukon: Correlation and basin development	*Galen Halverson*	***24***
8	Miocene-Present shortening in the Himalayan foreland belt	*John Hirschmiller*	***25***
9	Late Neogene Kinematics of the Sikkim Himalaya using ZHe Thermochronology and 3-D Thermokinematic Modelling	*Kyle Landry*	***28***
10	Age and provenance of cover strata to the Paleocene Resurrection Peninsula ophiolite, Seward, Alaska	*Rose Pettiette*	***36***
11	40Ar/39Ar Dating and Characterization of Hornblende from the Nelson Plutonic Suite, Southern Kootenay Arc, SE B.C.	*Jessica Pickett*	***38***
12	Provenance and thermal history of the Upper Cretaceous Shumagin Formation, Nagai Island, southern Alaska	*Carly Roe*	***51***
13	Geology of the Dawson Range – White Gold district, western Yukon: improved constraints on Yukon Tanana terrane architecture	*Jim Ryan*	***52***
14	Cretaceous tectonism, mineralization and hydrocarbon trap formation of the northern Canadian Cordillera: results from zircon (U-Th)/He thermochronology	*David Schneider*	***53***
15	Three Dimensional Variations of Non-coaxial Shear Strain and Flow within the Okanagan Valley Shear Zone, Okanagan Mountain Provincial Park, BC	*Vincent Twomey*	***57***
16	The missing terrane Bonnetia preserved as clasts in 1.60 Ga Wernecke Breccia	*Jaap Verbaas*	***61***
17	Low-temperature cooling and exhumation of the Olympus-Ossa massif (Continental Hellenides, NE Greece): new insights from zircon and apatite (U-Th)/He thermochronology and thermal modelling	*Mike Walsh*	***62***

Microstructural analysis and 40Ar/39Ar thermochronology of the Okanagan Valley Fault System, British Columbia

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This study focuses on the thermo-structural evolution and exhumation of the high-grade metamorphic infrastructure of the southeastern Canadian Cordillera that is exposed in a crustal section between Sicamous and Revelstoke, British Columbia. Of particular interest is the Okanagan Valley fault system (OVfs) in the area surrounding Sicamous. The OVfs formed due to a change from transpression to transtension on the western margin of North America in Early Cenozoic time which put part of the southern Canadian Cordilleran orogen into a state of extensional collapse. The OVfs represents the top boundary of extension-accommodated exhumation of the southern Shuswap metamorphic complex [1, 2]. At the latitude of this study, the OVfs has been proposed to have up to 30 km of horizontal displacement [2]. The OVfs exhibits a penetrative solid state fabric in a >1km-thick shear zone within sillimanite-grade footwall gneisses, partially overprinted by brittle deformation textures. We utilize a multi-faceted approach combining microstructural analysis and ^{40}Ar/^{39}Ar thermochronology to critically examine two possible modes of exhumation in the OVfs: normal ductile and channel flow systems. Structural measurements and samples were collected along a sixty kilometer ENE-WSW oriented profile across the fault system and the footwall gneisses within the Shuswap complex to the east. Microstructure analysis of brittle and ductile fabrics in high and low temperature regimes, together with crystallographic-preferred orientation (CPO) analysis, is being conducted using standard microscope and Fabric Analyser (FA) techniques. FA is used to determine the c-axis orientations of quartz crystals in the footwall gneisses. Coupled with microstructural textural mapping, FA techniques will identify the dominant slip systems, temperature of deformation, and ductile flow style of the OVfs, and will assist in unravelling potential ductile overprinting events [3]. These new insights into strain partitioning and temperature of deformation associated with the OVfs will be useful when interpreting the thermochronological results. The ^{40}Ar/^{39}Ar thermochronology involves dating muscovite, biotite, and hornblende crystals from twelve samples across the OVfs, which have been strategically selected from both the low grade meta-sedimentary hanging-wall rocks and high grade granodioritic gneiss of the footwall [1, 2]. The new cooling ages and microprobe geochemistry analysis combined with previously published ^{40}Ar/^{39}Ar ages [4] and the aforementioned petrofabric analyses will help unravel the temperature-deformation-time history of these rocks, and provide a better understanding of the exhumation processes linked to the OVfs.

[1] Brown, S., Gibson, H.D., Andrews, G., Thorkelson, D., Marshall, D., Vervoort, J., and Rayner, N., 2012. New constraints on Eocene extension within the Canadian Cordillera and identification of Phanerozoic protoliths for footwall gneiss of the Okanagan Valley shear zone. Lithosphere, 4, 354-377.
[2] Johnson, B. J., and Brown, R. 1996. Crustal structure and early Tertiary extensional tectonics of the Omineca Belt at 51°N latitude, southern Canadian Cordillera. Canadian Journal of Earth Sciences, 33, 1596-1611.
[3] Peternell, M., Hasalova, P., Wilson, C. J. L., Piazolo, S., and Schulmann, K., 2010. Evaluating quartz crystallographic preferred orientations and the role of deformation partitioning using EBSD and fabric analyzer techniques. Journal of Structural Geology, 32, 803-817.
[4] Grevais, F., and Brown, R. 2010. Testing modes of exhumation in collisional orogens: Synconvergent channel flow in the southeastern Canadian Cordillera. Lithosphere, 3, 55-75.

Stratigraphic uncertainty and errors in shortening from balanced sections in the Cordillera

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Shortening from balanced cross sections is typically cited as a minimum estimate because of the uncertainty in the position of eroded hanging wall cutoffs. We show here using area balancing that the single most significant source of error is that associated with the shape and thickness of the initial stratigraphic wedge involved in the deformation. New methods and software are introduced that, in combination with freely available of scans of virtually all geologic maps published by the USGS and GSC, allow one to make hundreds of map thickness measurements in just a few hours. These methods are applied to geologic maps and cross sections from the western North American Cordillera to determine the uncertainty of shortening in iconic cross sections by Price and Fermor (1985), and Royse (1993). 1 sigma stratigraphic thickness uncertainty, measured in homoclinal dip packages of prominent Paleozoic units within single thrust plates (and single quadrangles; Price, 1970a, b; Ollerenshaw & Price, 1971; Price & Mountjoy, 1972a, b, c) ranges from 20-30% of average thickness in the Costigan and Sulphur Mtn. plates in southern Canada and can be as high as 37% in the Darby and Absaroka plates of the Idaho Wyoming thrust belt (mapping by Rubey, 1973). Assuming that all individual Paleozoic units in the cross sections have similar errors, the entire Paleozoic section used in the area balancing would have 8-11% uncertainty, assuming a normal or Gaussian distribution. Because the stratigraphic wedges in southern Canada and Idaho-Wyoming do not have a uniform taper, our basic area balance underestimates shortening. By balancing the non-uniform taper back to a uniform taper, we can account for this discrepancy. Total shortening determined in this way is ~104 ±17 km, which is identical to that obtained by Price and Fermor (1985). The Idaho-Wyoming section of Royse (1993; with map by Rubey, 1973) yields similarly large errors in

shortening magnitude: 56 ± 10 km for the three frontal thrust faults. Of those errors, uncertainty in the shape and thickness of the initial stratigraphic wedge accounts for 56% and 70% of the total in southern Canada and western Wyoming, respectively. Eroded hanging wall cutoffs account for just 15% in both areas, with the remainder coming from uncertainty in the subsurface geometry, including the position of the decollement. It is likely that deformation beneath that resolvable on GSC and USGS quadrangle maps accounts for a significant part of the stratigraphic variation documented here (e.g., Price, 1967; Mitra, 1994; Chester 2003, Yonkee and Weil, 2010; Cooley et al., 2011).

References Cited

Chester, J. S., 2003, Mechanical stratigraphy and fault--fold interaction, Absaroka thrust sheet, Salt River Range, Wyoming: Journal of structural geology, v. 25, no. 7, p. 1171-1192.

Cooley, M. A., Price, R. A., Dixon, J. M., and Kyser, T. K., 2011, Along-strike variations and internal details of chevron-style, flexural-slip thrust-propagation folds within the southern Livingstone Range anticlinorium, a paleohydrocarbon reservoir in southern Alberta Foothills, Canada: AAPG Bulletin, v. 95, no. 11, p. 1821-1849, doi: 10.1306/01271107097.

Ollerenshaw, N. C., and Price, R. A., 1971, Geology, Lake Minnewanka (west half), west of fifth meridian, Alberta: Geological Survey of Canada "A" Series Map 1272A, scale 1:50000.

Mitra, G., 1994, Strain variation in thrust sheets across the Sevier fold-and-thrust belt (Idaho-Utah-Wyoming): Implications for section restoration and wedge taper evolution: Journal of Structural Geology, v. 16, no. 4, p. 585-602.

Price, R. A., 1967, The tectonic significance of mesoscopic subfabrics in the Southern Rocky Mountains of Alberta and British Columbia: Canadian Journal Earth Sciences, v. 4, p. 39-70.

Price, R. A., 1970a, Geology, Canmore (east half), west of Fifth Meridian, Alberta: Geological Survey of Canada "A" Series Map 1265A, scale 1:50000.

Price, R. A., 1970b, Geology, Canmore (west half), west of Fifth Meridian, Alberta: Geological Survey of Canada "A" Series Map 1266A, scale 1:50000.

Price, R. A., and Fermor, P. R., 1985, Structure section of the Cordilleran foreland thrust and fold belt west of Calgary, Alberta: Geological Survey of Canada Paper 84-14.

Price, R. A., and Mountjoy, E. W., 1972a, Geology, Banff (east half), west of Fifth Meridian, Alberta-British Columbia: Geological Survey of Canada "A" Series Map 1294A, scale 1:50000.

Price, R. A., and Mountjoy, E. W., 1972b, Geology, Mount Eisenhower (east half), west of fifth meridian, Alberta: Geological Survey of Canada "A" Series Map 1296A, scale 1:50000.

Price, R. A., and Mountjoy, E. W., 1972c, Geology, Mount Eisenhower (west half), west of fifth meridian, Alberta: Geological Survey of Canada "A" Series Map 1297A, scale 1:50000.

Royse, F., 1993, An overview of the geologic structure of the thrust belt in Wyoming, northern Utah, and eastern Idaho, in Snoke, A. W. and others, eds., Geology of Wyoming: Laramie, Wyoming, Geological Survey of Wyoming, Memoir, p. 273-311.

Rubey, W. W., 1973, Geologic map of the Afton quadrangle and part of the Big Piney quadrangle, Lincoln and Sublette Counties, Wyoming: U. S. Geological Survey Miscellaneous Geologic Investigations Map I-686scale 1:62,500.

Yonkee, A., and Weil, A. B., 2010, Reconstructing the kinematic evolution of curved mountain belts: Internal strain patterns in the Wyoming salient, Sevier thrust belt, U.S.A: Geological Society of America bulletin, v. 122, no. 1-2, p. 24-49, doi: 10.1130/B26484.1.

Insight into geological relationships and the polyphase structural imbrication of Cache Creek terrane, Stikinia and overlap assemblages of eastern Whitehorse (NTS 105D) and western Teslin (NTS 105C) map areas, Yukon

Luke Bickerton[1], Maurice Colpron[2] and Dan Gibson[1]
[1]Simon Fraser University, Burnaby, BC; [2]Yukon Geological Survey, Whitehorse, YT

This project examines the relationships between the Whitehorse trough and the Intermontane terranes of Stikinia and Cache Creek near its northern termination in southern Yukon. In the Canadian Cordillera, Stikinia and Quesnellia represent early Mesozoic terranes of peri-Laurentian affinity that developed as allochthonous, low-latitude island arcs partially built upon the mid- to late Paleozoic Yukon-Tanana terrane (and correlatives). These arc terranes bound pelagic sedimentary rocks, oceanic seamount and ophiolite assemblages of the exotic Cache Creek terrane, which locally contains distinctive Early Permian Tethyan fusulinid fauna. This contrasts with the less exotic McCloud fauna found in Quesnellia and Stikinia. In south-central Yukon the exposure of Cache Creek terrane terminates where it is enveloped by Stikina and Quesnellia. In this region, these terranes are overlapped and imbricated with syn-orogenic Lower to Middle Jurassic basinal sedimentary rocks of the Whitehorse trough (Laberge Group).

Bedrock mapping at a scale of 1:50 000 within parts of the Whitehorse and Teslin map areas in the summer of 2012 has refined our understanding of the relationships between Cache Creek terrane and rocks of Stikinia and Whitehorse trough. For instance, in addition to the typical oceanic lithologies within Cache Creek terrane, we have identified a previously unknown siliciclastic package, informally named the Michie formation, and more fully characterized a calc-alkalic gabbroic intrusive complex, which we refer to as the

Marsh Lake intrusive complex. This mapping also helps refine the structural history of the area which complexly imbricated and interleaved Cache Creek terrane with rocks of Stikinia and Whitehorse trough. We have identified two main phases of compressional deformation: 1) an initial phase of west-verging thrusting, emplacing Cache Creek terrane rocks above rocks of Stikinia and the Whitehorse trough along the Judas Mountain thrust, a northern equivalent to the Nahlin fault; and 2) a subsequent, second phase of thrusting which reshuffles Stikinia and Whitehorse trough rocks onto the Cache Creek terrane along the east-verging Mount Michie thrust.

Eocene Tectonic and Magmatic Evolution of Central British Columbia

Esther Bordet, Craig Hart & Mitch Mihalynuk

A spectacular, 3000km long felsic magmatic belt dominated the Cordilleran landscape in the Early Eocene. Between 150 and 1000km in width, it extended from eastern Alaska to Idaho, blanketing an area estimated at 90,000 km^2. Its origins are controversial. We review geological, geochronological, structural and geochemical evidence from Eocene volcanic rocks in central BC (ECBC; Figure 1) to help constrain the range of tectonic mechanisms that could have produced this Silicic Large Igneous Province.

ECBC are predominantly dacitic and rhyolitic lavas and breccias, minor basalt and andesite flows, and interbedded volcaniclastic rocks, together generally more than 1000m thick (e.g. this study; Read, 2000). Our analyses consistently show a high-K calc-alkaline suite affiliation, although intraplate tholeiitic compositions have been documented (Thorkelson, 1989; Dostal et al., 2005). ECBC were extruded between 55 and 45 Ma as repeatedly shown by both U-Pb and $^{39}Ar/^{40}Ar$ geochronology (Figure 2; e.g. this study; Beitsprecher and Mortensen, 2004). ECBC is well represented by volcanic rocks of the Intermontane belt, and is additionally represented by plutonic activity along the Coast Belt and in the southern Omineca Belt (Figure 2). General east-west directed extensional deformation and transtension was coeval with Eocene magmatism in central BC as indicated by north-northeast-oriented fault-bounded extensional grabens filled with Eocene volcanic rocks in southern BC (e.g. Read, 2000). In addition northwest- to north-trending dextral strike-slip faults such as the Yalakom (57-34 Ma) and the Fraser fault (43-36 Ma) are structurally aligned with a belt of metamorphic core complexes (Struik, 1993).

Possible sources for the ECBC magmagenesis include: a) primary supra-subduction zone magmas (e.g. Pearce and Peate, 1995); b) decompression melting during extension (e.g. Conder et al., 2002); c) anatexis via slab window or other heat source (e.g. Beitsprecher et al., 2003). Although selected trace and rare earth elements could indicate a mantle source for Eocene magmas, the major, trace and REE profiles of Eocene rocks dominantly reflects the contribution of a composite, laterally and vertically homogeneous crust during magma ascent. Eocene extensional deformation in central BC took place in a crust estimated at 45-50 km thick and produced a thinning of 10-20 km (Mihalynuk and Friedman, 2009). This thinning may have triggered adiabatic rising of the mantle and generation of melts through decompression melting processes. Since Eocene elevations were up to 2 km higher than present (e.g. Mulch et al., 2007; Wolfe et al., 1998), thermal subsidence following extension probably reduced Interior Plateau elevations to those at present. Finally, the slab window model explains some anomalous geochemical compositions measured along the Eocene volcanic province in BC and the NW US, and provides a convenient mechanical explanation to the presence of a thermal anomaly in the Eocene.

Silicic Large Igneous Provinces (SLIP; Bryan, 2007) are huge accumulations of felsic volcanic rocks, generally as large caldera complexes in active continental margin settings. In terms of volume and extent ECBC are like a SLIP, although caldera complexes are rare and poorly defined (Metcalfe et al., 1997; Mihalynuk and Harker, 2007).

Breitsprecher, K., Thorkelson, D.J., Groome, W.G. and Dostal, J. (2003) Geochemical confirmation of the Kula-Farallon slab window in the Pacific Northwest, Data Repository Item 2003042. Geology, vol.31, no.4, p.351–354.

Breitsprecher, K. and Mortensen, J.K., (2004) BCAge 2004 A-1–a database of isotopic age determinations for rock units from British Columbia; BC Ministry of Forests, Mines and Lands, Open File 2004-3 (release 3.0), 9.3 Mb.

Bryan, S. (2007) Silicic Large Igneous Provinces. Episodes, v. 30, no. 1, p. 20-31.

Conder, J.A., Wiens, D.A. and Morris, J. (2002) On the decompression melting structure at volcanic arcs and back-arc spreading centers. Geophysical Research Letters, v. 29, no. 15, 4 p.

Dostal, J., Owen, J., Church, B. and Hamilton, T. (2005) Episodic Volcanism in the Buck Creek Complex (Central British Columbia, Canada): A History of Magmatism and Mantle Evolution from the Jurassic to the Early Tertiary. International Geology Review, vol, 47, no.6, p. 551-572

Metcalfe, P., Richards, T.A., Villeneuve, M.E., White, J.M and Hickson, C.J. (1997) Physical and chemical volcanology of the Eocene Mount Clisbako volcano, central British Columbia. Geological Survey of Canada Paper 1997-2, Open File 3448, 32 p.

Mihalynuk, M.G. and Friedman, R.M. (2009) First Isotopic Age Constraints for the Dean River Metamorphic Belt, Anahim Lake area: Implications for Crustal Extension and Resource Evaluation in West-Central British Columbia; *in* Geological Fieldwork 2008, Paper 2009-1, pages 101-108.

Mihalynuk, M.G. and Harker, L.L. (2007) Riske Creek Geology (NTS 92O/16W); B.C. Ministry of Energy and Mines, Open File 2007-6, 1:50 000 scale map.

Mulch, A., Teyssier, C., Cosca, M.A. and Chamberlain, C.P. (2007) Stable isotope paleoaltimetry of Eocene core complexes in the North American Cordillera. Tectonics, v. 26, 13 p.

Pearce, J.A. and Peate, D.W. (1995) Tectonic implications of the composition of volcanic arc magmas. Annu. Rev. Earth Planet. Sci., v. 23, p. 251-285.

Read, P.B. (2000) Geology and Industrial Minerals of the Tertiary Basins, South-central British Columbia. Ministry of Energy and Mines, Geological Survey Branch, Geofile 2000-3, 109 p.

Struik, L.C. (1993) Intersecting intracontinental Tertiary transform fault systems in the North American Cordillera. Canadian Journal of Earth Sciences, v. 30, p. 1262–1274.

Thorkelson, D.J. and Taylor, R.P. (1989) Cordilleran Slab Windows. Geology, vol. 17, p.833-836.

Wolfe J.A., Forest, C.E. and Molnar, P. (1998) Paleobotanical evidence of Eocene and Oligocene paleolatitudes in midlatitude western North America. GSA Bulletin, v. 110, no. 5, p. 664-678.

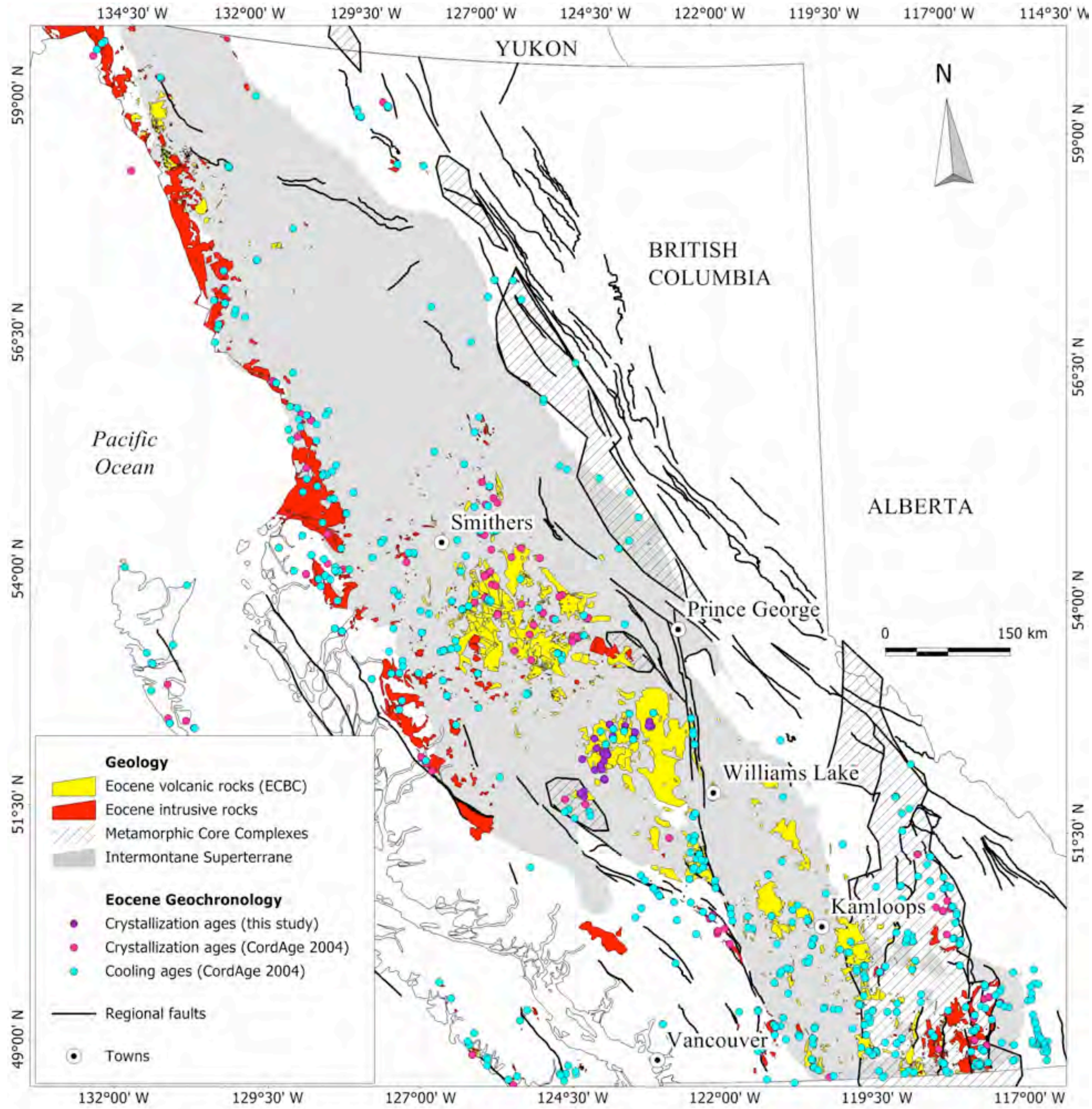

***Figure 1**: Distribution of Eocene magmatic rocks with respect to regional faults and metamorphic core complexes (after Massey et al., 2005; Struik et al., 1993). Eocene isotopic ages are selected from Beitsprecher and Mortensen (CordAge 2004).*

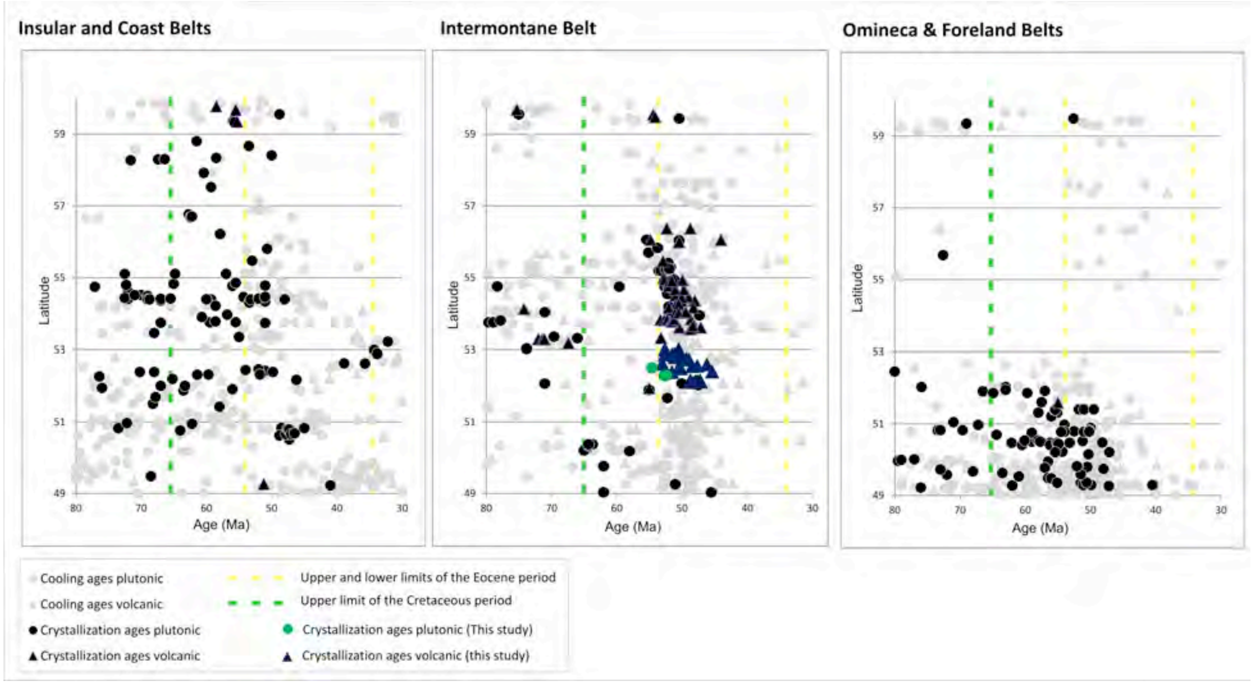

***Figure 2**: Late Cretaceous to the Late Paleogene crystallization and cooling ages for the Insular-Coast, Intermontane and Omineca-Foreland belts (Compiled after Beitsprecher and Mortensen, 1994 and recent data from this study)*

Propagation of shear zones in the southern Canadian Cordillera

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The Internal zone of the southeastern Canadian Cordillera is exposed in the Omineca belt of southern British Columbia. The rocks of the Western Internal zone were deformed and metamorphosed in the mid-crust during Cretaceous to Eocene orogenesis. They were predominantly exhumed in the Late Cretaceous to Eocene, and are exposed as tracts of metamorphic rocks and metamorphic core complexes (e.g. Kettle, Okanagan, Priest River and Valhalla), some of which are basement-cored domes (e.g. Frenchman Cap, Thor-Odin, and Spokane). The strongly deformed rocks can largely be ascribed to a set of compressional and extensional, ductile shear zones with thicknesses of 500 to 7000 m. There are also brittle-ductile extensional fault zones. We focus on the ductile compressional shear zones. The shear zones are composite and heterogeneous, and include mylonite zones, gneiss with thin mylonite layers, recumbent transposed folds and lenses of less deformed rocks bounded by mylonite zones. The composite nature is, in part, related to reactivation or overprinting of one shear zone by another. Mapping, overprinting relationships and geochronology give consistent results demonstrating the shear zones to be in downward younging order. An Early Cretaceous shear zone is the structurally highest and is locally preserved in the core of the Valhalla complex, whereas the structurally deepest, an Eocene shear zone is exposed at the deepest level of the Western Internal zone in the core of Frenchman Cap dome. There, the youngest, deepest shear zone passes downward into undeformed autochthonous or parautochthonous basement. Mapped geometry, metamorphic geochronological relationships and seismic reflectors suggest the presence of large frontal and lateral ramps where hotter rocks were sheared over cooler rocks. In the Valhalla complex, the Gwillim Creek shear zone rises eastward and southward through an edifice of sheet intrusions. The Monashee décollement exhibits a large, low-angle south-facing lateral ramp across the Frenchman Cap dome. This is suggested by the way its trace progressively cuts down southward across axial surfaces of large folds in its footwall. This geometry suggests that the décollement continues southward under the exposed folded rocks of the Thor-Odin dome rather than wrapping around and over the dome. The mapped geometry and ages of shear zones suggest that the shear zones are continuous with the Rocky Mountain Basal Décollement, and that each, in turn, when active, was the Rocky Mountain Basal Décollement. Taken together, linkage of shear zones to the Rocky Mountain Basal Décollement, shear zone and ramp geometry, and the downward younging of shear zones suggest a model for the progressive heating, weakening, localization and propagation of shear zones at the base of the Internal zone, and linkage with the Foreland Thrust and Fold belt via the Rocky

Mountain Basal Décollement (RMBD). The hot internal zone was bounded on the east by a cool stiff indenter that was progressively underthrusting the base of the Internal zone, and progressively heated and weakened to deform in turn. Thus, the development of a basal shear zone was coupled with flow of the hot mass of the internal zone up and over an indentor, strain softening of it, and incorporation of it into the wedge in successive stages. The base of the exposed Gwillim Creek shear zone serves as an example of the basal shear zone and décollement that was active in the Late Cretaceous to Paleocene; it was refrigerated from below, prior to that of overlying rocks in its hanging wall, as a result of overthrusting of hot rocks over cold footwall rocks. Our general model is consistent with those of Beaumont et al. (2011) demonstrating the lateral transition from stiff cool crust to hotter weaker crust where the stiff cool crust acted as an indentor, with development of a ramp at the edge of the indentor, and flow up and over the ramp. The overprinting of the stack of compressional shear zones by young extensional shear zones that merge obliquely with the stack leads to complex, confusing relationships.

A current interpretation is that the undeformed, deepest level of Frenchman Cap dome is autochthonous and lies below the deepest décollement. Should it be demonstrated that the 'cover sequence' included a thin Neoproterozoic and Early Cambrian succession, then the very reasonable reconstruction that restores the Bourgeau thrust, with its hanging wall of thick Neoproterozoic and Cambrian strata, to near the Frenchman Cap dome, presents a stratigraphic problem. We suggest a possible solution; a décollement (EBAD= Eocene Basal Décollement), linked in the Eocene to the Rocky Mountain Basal Décollement, lies below the undeformed Frenchman Cap level, and on palinspastic restoration, it is a belt that lies between the Porcupine Creek Anticlinorium and the Selkirk Fan Axis and contains a number of 'Highs' with thinned stratigraphy, that restores to the Frenchmen Cap complex.

Geology of the Rackla belt, central Yukon

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The Rackla belt of east-central Yukon straddles the northern edge of Selwyn basin, where Neoproterozoic to Permian rocks of the basin are juxtaposed against Paleozoic and older slope and shelf rocks of the Ogilvie platform along the Dawson thrust zone. The area is host to a variety of mineral occurrences, including significant recent discoveries of Carlin-type gold mineralization. Mapping by the Yukon Geological Survey helps refine the regional stratigraphic and structural context of gold, silver and base metal mineralization along the ~100 km-long Rackla belt.

The hangingwall of the Dawson thrust is underlain by typical Selwyn basin stratigraphy. The oldest units belong to the Neoproterozoic to Lower Cambrian Hyland Group, including thick sections of coarse sandstone and shale, and locally abundant carbonate turbidite, local debrite, and maroon shale. These rocks are unconformably overlain by shale, chert and sandstone of the Earn Group, which are in turn overlain by Carboniferous to Triassic rocks. In the western part of the Rackla belt, strata of the Earn Group locally contain significant occurrences of volcanic rocks, including host rocks to the Marg deposit (Cu-Pb-Zn-Ag-Au VMS, 3.96 MT; Redtails Metals Corp.). In the same region, Earn Group strata are locally extensively intruded by Triassic gabbro sills.

Stratigraphy in the footwall (north) of the Dawson thrust zone is for the most part correlative with that of Selwyn basin to the south, but generally of very different facies. Neoproterozoic rocks are predominant in the eastern part of the Rackla belt, near the headwater of the Nadaleen River, and host most of the Carlin-type gold mineralization discovered to date (Osiris, Isis, Conrad and Pharoah zones; ATAC Resources Ltd.). They generally consist of fine-grained siliciclastic and carbonate rocks, including two prominent carbonate marker horizons and locally abundant debris flow deposits. Occurrences of Ediacaran fossils in this sequence confirms its late Neoproterozoic age and suggest correlation with the upper part of the Windermere Supergroup in the Mackenzie Mountains (Sheepbed-Gametrail-Blueflower-Risky?). The upper carbonate marker is overlain by maroon shale; this carbonate/shale sequence is identical to the upper part of the Hyland Group (Algae and Narchilla formations), thereby providing a stratigraphic tie across the Dawson thrust, and broad correlations between Windermere and Hyland strata.

Paleozoic rocks north of the Dawson thrust are generally divided in shelf and offshelf facies by the Kathleen Lakes fault, an enigmatic structure that parallels the Dawson thrust to the north along the length of the Rackla belt. North of the Kathleen Lakes fault, predominantly well-bedded carbonate shelf rocks of Cambrian to Devonian age overlie the Neoproterozoic stratigraphy of the Nadaleen area. Paleozoic rocks between the Kathleen Lakes and Dawson faults consist predominantly of offshelf carbonate and shale of Cambrian to Permian age; they commonly include mixed siliciclastic, bioclastic and debris flow deposits.

This offshelf belt of Paleozoic rocks terminates abruptly to the east across a series of north-trending faults that bound stratigraphic and structural panels in the vicinity of known Carlin-type mineralization. Recent discovery of high-grade gold mineralization at the Anubis zone (ATAC Resources Ltd.) occurs in Middle Devonian carbonate near the east end of the Paleozoic offshelf belt.

Significant changes in thickness of Neoproterozoic strata across north-trending faults in the Nadaleen area suggest that these structures are in part syn-sedimentary faults that were likely reactivated in Paleozoic and younger time. Similarly, changes in Neoproterozoic-Paleozoic stratigraphy across the Dawson and Kathleen Lakes faults indicate a compound history for these structures possibly beginning in the Neoproterozoic, with reactivation during the Paleozoic and again during development of Mesozoic (Cretaceous?) fold-and-thrust structures along the Rackla belt. Displacement along both the Kathleen Lakes and Dawson faults appears to decrease eastward.

Neogene exhumation of the Bhutan Himalaya: new insights from the inversion of low-temperature thermochronologic data

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The processes driving Himalayan exhumation at a million-year scale since the latest Miocene, and the timing and rates at which they operate have been and are still disputed. Three distinct tectonic models prevail to account for the Latest Miocene-Pleistocene upper-crustal kinematics of the central Himalaya and include (1) out-of-sequence thrusting and possible reactivation of the Main Central Thrust driven by climatically enhanced exhumation of the Himalayan front (e.g. (Hodges et al., 2004; Wobus et al., 2003)), (2) steady slip on the Main Himalayan Thrust and growth of the Himalayan wedge due to underplating by the development of a duplex at mid-crustal depth (e.g. (Avouac, 2003; Bollinger et al., 2006)) and (3) overthrusting of a major crustal ramp with changing geometry (e.g. (Gansser, 1964; Robert et al., 2011)). There is also an ongoing debate as to whether or not climatically induced erosion plays a significant role in exhuming the wedge (e.g. (Whipple, 2009)). Finally, while certain studies suggest changing exhumation rates at various time since 10 Ma (e.g. (Grujic et al., 2006; Huntington et al., 2006; Wobus et al.,

2008) others advocate for steady exhumation rates since 12 Ma (Galy and France-Lanord, 2010).

Thermochronological data acquisition and modelling studies have primarily focused on relatively narrow segments of the western and central Himalaya, and the inferred crustal deformation, exhumation, and resulting thermal structure, have been extrapolated to the rest of the orogen (e.g. (Herman et al., 2010; Robert et al., 2011; 2009)). However, the Eastern Himalaya of Bhutan are difficult to link to existing kinematic models, due to unique features including: (1) the exposure of shallower structural level indicating a lower exhumation magnitude, (2) apatite fission-track (FT) ages markedly older than further west in Nepal and India (3) a steep, convex topographic front restricting modern orographic precipitation to foothill elevations of <2000 m, and (4) uplift of a foreland plateau producing tectono-climatic perturbations along the range front since the Late Miocene.

We use densely distributed apatite and zircon (U-Th)/He and fission-track *in situ* bedrock data acquired along two North-South oriented transects running from south of the Main Frontal Thrust (26.5°N), to north of the Southern Tibetan Detachment System (28.5°N), in western (89.2-89.8°E) and eastern (91.1-91.6°E) Bhutan ((Grujic et al., 2006); Long et al., 2012; this study) as input into a modified version of the thermo-kinematic model PECUBE (Braun, 2003; Braun et al., 2012) to perform non-linear inversions using the Neighbourhood Algorithm (Braun, 2003; Braun et al., 2012; Sambridge, 1999). This approach enables us to extract constraints on the geometry and the kinematics of the Main Central Thrust, the thermal structure of the middle to upper crust beneath Bhutan and the space-time distribution of exhumation along this segment of the Eastern Himalaya during the last 12 myr.

References

Avouac, J.-P., 2003. Mountain building, erosion, and the seismic cycle in the Nepal Himalaya. Advances in Geophysics 46, 1-80.

Bollinger, L., Henry, P., Avouac, J., 2006. Mountain building in the Nepal Himalaya: Thermal and kinematic model. Earth Planet. Sci. Lett. 244, 58-71

Braun, J., 2003. Pecube: a new finite-element code to solve the 3D heat transport equation including the effects of a time-varying, finite amplitude surface topography. Computers & Geosciences 29, 787-794.

Braun, J., Van Der Beek, P., Valla, P., Robert, X., Herman, F., Glotzbach, C., Pedersen, V., Perry, C., Simon-Labric, T., Prigent, C., 2012. Quantifying rates of landscape evolution and tectonic processes by thermochronology and numerical modeling of crustal heat transport using PECUBE. Tectonophysics 524-525, 1–28.

Galy, V., France-Lanord, C., 2010. Sr-Nd-Os evidence for a stable erosion regime in the Himalaya during the past 12 Myr. Earth Planet. Sci. Lett. 290, 474-480.

Gansser, A., 1964. Geology of the Himalayas. Intersci. Pub. (John Wiley & Sons), pp. 289.

Grujic, D., Coutand, I., Bookhagen, B., Bonnet, S., 2006. Climatic forcing of erosion, landscape, and tectonics in the Bhutan Himalayas. Geology 34, 801-804.

Herman, F., Copeland, P., Avouac, J.-P., Bollinger, L., Mahéo, G., Le Fort, P., Rai, S., Foster, D., Pêcher, A., Stüwe, K., Henry, P., 2010. Exhumation, crustal deformation, and thermal structure of the Nepal Himalaya derived from the inversion of thermochronological and thermobarometric data and modeling of the topography. J. Geophys. Res. 115, B06407.

Hodges, K., Wobus, C., Ruhl, K., Schildgen, T., Whipple, K., 2004. Quaternary deformation, river steepening, and heavy precipitation at the front of the Higher …. Earth Planet. Sci. Lett. 220, 379-389.

Huntington, K., Blythe, A., Hodges, K., 2006. Climate change and Late Pliocene acceleration of erosion in the Himalaya. Earth Planet. Sci. Lett. 252, 107-118.

Long, S.P., McQuarrie, N., Tobgay, T., Coutand, I., Coper, F.J., Reiners, P.W., Wartho, J-A., Hodges, K., 2012. Variable shortening rates in the eastern Himalayan thrust belt, Bhutan: Insights from multiple thermochronologic and geochronologic data sets tied to kinematic reconstructions. Tectonics, DOI: 10.1029/2012TC003155.

Robert, X., van der Beek, P., Braun, J., Perry, C., Dubille, M., Mugnier, J.-L., 2009. Assessing Quaternary reactivation of the Main Central thrust zone (central Nepal Himalaya): New thermochronologic data and numerical modeling. Geology 37, 731–734.

Robert, X., Van Der Beek, P., Braun, J., Perry, C., Mugnier, J.-L., 2011. Control of detachment geometry on lateral variations in exhumation rates in the Himalaya: Insights from low-temperature thermochronology and numerical modeling. J. Geophys. Res 116, B05202.

Sambridge, M., 1999. Geophysical inversion with a neighbourhood algorithm—II. Appraising the ensemble 138, 727–746.

Whipple, K.X., 2009. The influence of climate on the tectonic evolution of mountain belts. Nature Geosci. 2, 97–104.

Wobus, C., Hodges, K., Whipple, K., 2003. Has focused denudation sustained active thrusting at the Himalayan topographic front? Geology 31, 861-864.

Wobus, C., Pringle, M., Whipple, K., Hodges, K., 2008. A Late Miocene acceleration of exhumation in the Himalayan crystalline core. Earth Planet. Sci. Lett. 269, 1-10.

Mount Harper Volcanic Complex, Ogilvie Mountains : A far-flung occurrence of the Franklin Igneous Event?

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The middle Neoproterozoic (717 Ma) Mount Harper Volcanic Complex (MHVC) is a calc-alkaline magmatic suite developed within a rift system on the northwestern margin of Laurentia. Based on its low Al_2O_3, Na_2O and TiO_2 contents, the primary melt was derived from a harzburgitic source, was most likely picritic in composition and required mantle

potential temperatures above those recognized for the ambient mantle. Constraints on mantle melting place the mantle at ~ 6 km, a depth that that would require significant crustal attenuation. Although the volcanic rocks at Mount Harper are the same age as the Franklin large igneous province, the geochemical trends are distinct. Apart from their age, the only plausible link would be to consider the MHVC as the product of a partial melt at the margin of a dispersed mantle plume.

The Southeast Zone (Cu-Mo) and Deerhorn (Cu-Au) porphyries; a possible genetic relationship between a calc-alkalic and an alkalic deposit, Woodjam Property, central British Columbia

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Porphyry deposits of the Canadian Cordillera have been divided into pre- to syn-accretion and post-accretion class. The pre- to syn-accretion porphyry deposits correspond to a Late Triassic to Middle Jurassic age (216 to 183 Ma) and occur in the Quesnel and Stikine terranes in British Columbia. They are sub-divided into calc-alkalic and alkalic types on the basis of their host rock chemistry and alteration-mineralization styles (McMillan et al., 1995; Lang et al., 1995). The formation of some of theses deposits may have been controlled by specific tectonic events, probably genetically linked to subduction-related tectonics processes in discrete island arcs (McMillan et al., 1995). Although the precise tectonic environment is uncertain in many cases, porphyry mineralization appears to have been directly associated with specific phases of distinctive intrusive suites that may have been emplaced during brief time intervals. The post-accretion deposits (porphyry molybdenum, tin and tungsten deposits) were emplaced during Cretaceous and Tertiary time and are hosted by several of the older terranes (McMillan et al., 1995)

The Woodjam district consists of a cluster of porphyry deposits of Late Triassic to Middle Jurassic age in the Quesnel Terrane in central British Columbia. The district hosts several discrete porphyry deposits including the Megabuck (Cu-Au), Deerhorn (Cu-Au), Takom (Cu-Au), Southeast Zone (Cu-Mo) and the recently discovered Three Firs (Cu-Au). These deposits display various styles and assemblages of alteration and mineralization. Whereas the Southeast Zone is comparable to calc-alkalic porphyry deposits, the nearby Deerhorn is mainly associated with alkalic porphyry intrusions.

The Southeast Zone (SEZ) deposit is hosted in texturally variable quartz monzonite intrusions that are inferred to be part of the Takomkane batholith, a large composite calc-alkalic, of largely granitoid composition with a surface expression of approximately 40 × 50km (Schiarizza et al., 2009). This Batholith has been correlated with the Guichon

Batholith, that hosts the Highland Valley porphyry Cu-Mo deposit, and the Granite Mountain Batholith, that hosts the Gibraltar deposit. All quartz monzonite intrusions that host the SEZ are largely equigranular, white-grey to pink coloured and comprise interlocking crystals of plagioclase, potassium feldspar and quartz. Mafic minerals are typically hornblende and less abundant fine-grained biotite. A primary K-feldspar + biotite + magnetite alteration (K-silicate) was overprinted by a chlorite ± epidote ± pyrite, illite and hematite alteration. Mineralization is zoned from a chalcopyrite-bornite anomalous in gold (~0.2 ppm) to pyrite-dominated at the margins of the deposit.

The Deerhorn deposit is hosted in a series of narrow (<100m) monzonite bodies that have "pencil" geometries and intrude the volcano-sedimentary rocks of the Nicola Group.
The Nicola Group stratigraphy in the property consists of volcaniclastic sandstone, overlain by a plagioclase-phyric andesite with local clast breccia facies (Gold Fields pers. comm., 2012). At least two different monzonites intrude the Nicola stratigraphy; "Monzonite A" and "Monzonite D". "Monzonite A" displays an intense alteration that obliterated much of the primary texture but remnants of plagioclase and biotite phenocrysts are locally preserved. "Monzonite D" is characterized by plagioclase and hornblende phenocrysts and occurs as dikes with sharp contact that cross-cut Monzonite A and the Nicola Group stratigraphy (Gold Fields pers. comm., 2012).
K-feldspar + biotite + magnetite alteration occurred intensely in Monzonite A and adjacent volcanics. However, it occurs more weakly in Monzonite D. Chlorite + epidote + hematite + pyrite alteration, and a later white illite alteration that occurs as a halo to tourmaline veins overprint all lithology. Main mineralization occurs as laminated and sheeted network of quartz-magnetite-hematite-chalcopyrite veins that are commonly developed in Monzonite A and the adjacent volcanic host-rocks.

The SEZ deposit has host rock and alteration characteristics that are similar to calc-alkalic porphyry deposits, except for the lack of abundant quartz veins. The "pencil" shape intrusive host rock lacking modal quartz observed in the host rocks at Deerhorn is consistent with characteristics of Cu-Au alkalic porphyry systems (Holliday et al., 2002). But the occurrence of mineralized banded quartz veins and illite + tourmaline alteration, as well as weak Mo mineralization resemble calc-alkalic porphyry deposits. Therefore, the porphyry copper environment at Woodjam might have been transitional between alkalic to calc alkalic suggesting that SEZ and Deerhorn deposits are genetically related.

Lang et al., 1995 proposed that alkalic magmatism in Quesnelia and Stikinia terranes can be attributed to arc (or interarc) collision events and the cessation or active subduction. This style of magmatism associated with most copper-gold porphyry deposits in the Canadian Cordillera fall in the age range of 210 Ma to 200 Ma, spanning the Triassic/Jurassic boundary (Mortensen et al., 1995). Although calc-alkalic and alkalic porphyry intrusives are petrographically distinct, the evidence at Woodjam suggests a petrogenetic association based on their spatial coincidence and similarities in their tectonic environment. Future work in the emplacement settings of the Takomkane Batholith will help understand the relationship between the SEZ and Deerhorn deposits.

References

Holliday, J.R., Wilson, A.J., Blevin, P.L., Tedder, I.J., Dunham, P.D., and Pfitzner, M. (2002): Porphyry gold-copper mineralization in the Cadia district, eastern Lachlan fold belt, New South Wales and its relationship to shoshonitic magmatism: Mineralium Deposita, v.37, p. 100-116.

Lang, J.R., Lueck, B., Mortensen, J.K., Russell, J.K., Stanley, C.R. and Thompson, J.M. (1995): Triassic-Jurassic silica undersaturated and silica-saturated alkali intrusions in the Cordillera of British Columbia: implications for arc magmatism: Geology, v. 23, p. 451-454.

McMillan, W.J., Thompson, J.F.H., Hart, C.J.R. and Johnston, S.T. (1995): Regional geological and tectonic setting of porphyry deposits in British Columbia and Yukon Territory: *in* Porphyry deposits of the Northwestern Cordillera of North America. T.G. Schroeter (editor): Canadian Institute of Mining, Metalurgy and Petroleum. Special Volume 46, p. 40-57.

Mortensen, J.K., Ghosh, D.K., Ferri, F. (1995): U-Pb geochronology of intrusive rocks associated with copper-gold porphyry deposits in the Canadian Cordillera: *in* Porphyry deposits of the Northwestern Cordillera of North America. T.G. Schroeter (editor): Canadian Institute of Mining, Metalurgy and Petroleum. Special Volume 46, p. 142-158

Schiarizza, P., Bell, K. and Bayliss, S. (2009): Geology and mineral occurrences of the Murphy Lake area, southcentral British Columbia (93A/03); *in* Geological Fieldwork 2008, BC Ministry of Energy, Mines and Petroleum Resources, Paper 2009-1, p. 169-188.

Constraints on the original setting of the flysch of the Chugach and Prince William terranes in Alaska using detrital zircon

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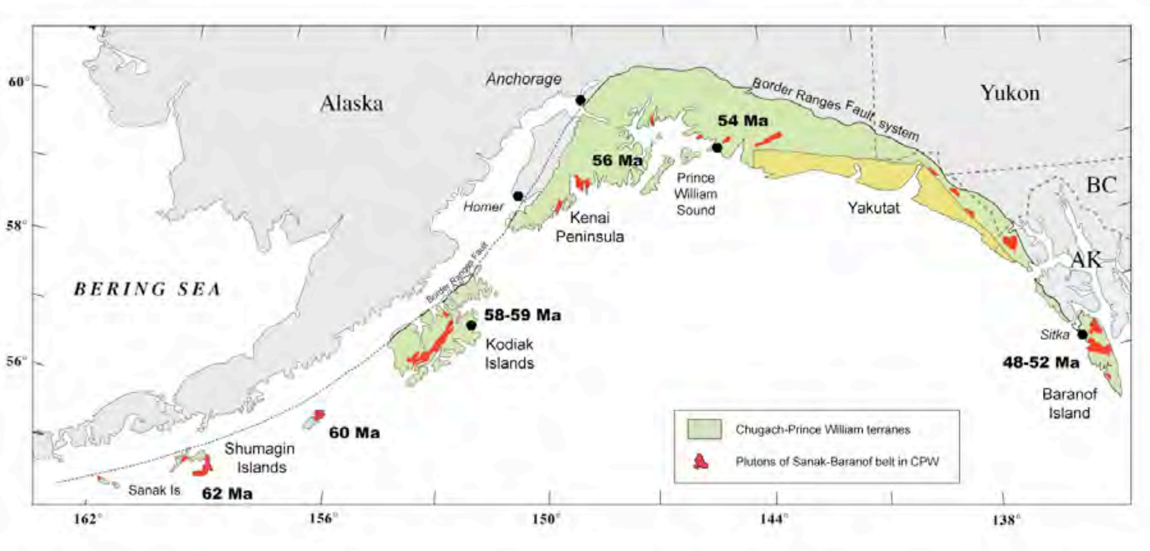
Flysch of the Chugach-Prince William (CPW) terrane in southern Alaska represents an enormously thick Maastrichtian to Eocene accretionary complex that formed adjacent to an active volcanic arc. Several thousand detrital zircon grains from sandstone samples across the belt indicate the source of sediment was an active Cretaceous to early Tertiary arc built primarily on a metaplutonic basement that was Upper Paleozoic to Lower Cretaceous in age. The Campanian-Maastrichtian to Eocene flysch is remarkably uniform in composition and grain-age distribution along the margin from Baranof Island in the east to the Shumagin Islands in the west. Temporal variation in sandstone composition and grain-age distribution from the Maastrichtian to the Eocene is minor, but there is an increase in the fraction of grains attributed to the active (or near active) volcanic arc. We have focused on U/Pb and fission track (ZFT) dating zircon from the flysch in four areas along the continental margin, and at this point in our evaluation, a primary requirement of the source terrane is that it must be comprised of a relatively homogeneous assemblage of Mesozoic rocks that have been deeply and continuously exhumed from the Late Cretaceous to the Eocene.



The thickest and most continuous section of the accretionary complex is in the central part of the CPW belt from Turnagain Arm (near Anchorage) through western Prince William Sound (southeast of Anchorage). Here, the detrital zircon record in the flysch is remarkable in that it shows the progressive evolution of an exhuming volcanic arc (from c. 75 to 55 Ma, and younger) that was superimposed on a Jura-Cretaceous metaplutonic basement complex that changed little in character through progressive exhumation. Paleocene ophiolites in the Prince William terrane (Knight Island and Resurrection Peninsula) have pillow basalts that are interbedded with, and overlain by, clastic strata of the Orca Group, and our new data indicate that we can tie these ophiolitic rocks to continentally derived strata (Pettiette et al., this volume). Paleomagnetic data from the Paleocene Resurrection Peninsula Ophiolite (~57 Ma) indicate translation of ~13°± 9° (Bol et al., 1992) and data from the slightly older Ghost Rocks Formation on Kodiak Island (>61 Ma) indicate translation of ~23° ± 6° (Gallen, 2008; Housen et al., 2009). Both of these data sets need to be considered in tectonic reconstructions of the CPW.

The least exposed and perhaps thinnest part of the terrane occurs far to the west in the Sanak and Shumagin Islands, where CPW rocks are barely emergent in the modern forearc. On Nagai Island (in the Shumagins), our new data indicate that the Maastrichtian Shumagin Formation was derived from a similar source as correlative units on Kodiak and in Prince William Sound: an active volcanic arc (70-75 Ma) and underlying metaplutonic complex (150-175 Ma). Deposition was followed by folding and imbrication, burial in the subduction wedge, and intrusion by the Sanak-Baranof Belt of plutons (here at ~62 Ma), which are inferred to be evidence of near trench plutonism related to the slab window of an adjacent TRT triple junction. Zircon fission track (ZFT) cooling ages between 58 and 54 Ma provides information about the original maximum burial depth (Roe et al., this volume).

In all detrital samples analyzed across the entire 2000 km long belt by our group and others, there is a small but significant fraction of Precambrian grains that vary in abundance (generally ~1 to 10%) and age distribution. These Precambrian zircons provide an important clue about the nature of basement terranes that were likely supplying zircons in the source regions. The Precambrian grains fall into two distinct cohorts: (1) zircons from the Shumagin, Kodiak, and PWS areas have a wide range of Precambrian ages with modes at 1810-1870 Ma and 2520-2680 Ma, similar to a northern Laurentian source. Raman spectra show that these grains have considerable internal disorder due to accumulated radiation damage for hundreds of Myr and are likely from a Paleozoic-cooled source; (2) Precambrian zircons of the Yakutat Group have modes at c. 1380-1450 and 1710-1740 Ma, which are similar to the Yavapai-Mazatzal province of southern Laurentia. Despite being Precambrian, this latter group of zircons have little internal disorder and appear to have cooled (started accumulating radiation damage) in the late Mesozoic (c. 100 Ma).

Our data are compatible with previous interpretations that the CPW is the accretionary complex to the Coast Mountains batholith. Paleomagnetic data from the volcanic rocks on Kodiak Island and on Resurrection Peninsula indicate latitudinal displacement that could be as much as 13° to 23°, which would put deposition and accretion of much of the CPW in the central or southern North American Cordillera. Ages, radiation damage, and hafnium isotopes (Roberts et al., this volume) of detrital zircon also appear to limit possible source terranes for some of the CPW to terranes that are presently far to the south.

Bol, A.J., Coe, R.S., Grommé, C.S., and Hillhouse, J.W., 1992, Paleomagnetism of the Resurrection Peninsula, Alaska: Implications for the tectonics of southern Alaska and the Kula Farallon Ridge: Journal of Geophysical Research, v. 97, p. 17,213-17,232.

Gallen, S.F., 2008. An investigation into the magnetic fabrics and paleomagnetism of the Ghost Rocks Formation, Kodiak Islands, Alaska; MSc. Thesis, Western Washington University, 119 p.

Housen, B. A., S. M. Roeske, S. Gallen, and K. O'Connell (2008), Paleomagnetism of the Paleocene Ghost Rocks, Kodiak Islands, Alaska: Implications for Paleocene Pacific-Basin/North America Plate Configurations, Eos Trans. AGU, 89(53), Fall Meet. Suppl., Abstract GP44A-02.

Reviving Ray Price's conceptual model of continuous ductile extrusion/intrusion of "hot tongues" in orogenic belts

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In the early 70's, Raymond A. Price proposed a tectonic model for the Canadian Cordillera involving buoyant upwelling of the infrastructure driving thrusting in the foreland-belt. Although we now know that the driving force was mainly horizontal and linked to the movement of tectonic plates, several aspects of the model are being rediscovered as potentially fundamental processes in orogenic systems. According to Larson et al., 2010 (rephrased from Price (1972): *"The deep hinterland is characterized by extending flow and the lateral extrusion of hot ductile rock, while the shallow foreland is characterized by compressing flow and the intrusion of formerly hot cooling rock.".* Furthermore, referring to the hot ductile rocks as "hot tongues", Price and Mountjoy (1970, p. 18) stated that this would be a "… *continuing process, in which earlier tongues are eventually uplifted and domed above later tongues that moved in and spread out beneath them*."

In this contribution, we will present stratigraphic, structural, metamorphic and geochronological data from the Canadian Cordillera and the Himalayas supporting Price's conceptual model. This model differs from the channel flow model derived from numerical modeling in that the exhumation of hot ductile rocks is not controlled by intense erosion at the mountain front, but by a combination of their intrusion into colder and shallower rocks, tectonic unroofing following their incorporation into the foreland wedge, and post-orogenic extension. Price's conceptual model, therefore, reconciles the false dichotomy between lateral mid-crustal flow and critical taper, which has plagued recent research.

It is noteworthy that several supporting evidences were obtained through highly advanced analytic tools such as precise isotopic analyses of µm spots in chronometer minerals and as rock-specific thermodynamic forward modeling of complex chemical systems (i.e., pseudosections). It is remarkable that more than 40 years of scientific advancement was required to arrive at a point that we can now provide strong analytical-based support for a model conceived through basic geological fieldwork, observation and intuition.

References:

Larson, K., Godin, L., Price, R.A., 2010. Relationships between displacement and distortion in orogens: Linking the Himalayan foreland and hinterland in central Nepal. Geol. Soc. Am. Bull. 122, 1116–1134.

Price, R.A., 1972. The distinction between displacement and distortion in flow, and the origin of diachronism in tectonic overprinting in orogenic belts, in Gill, J.E. (Ed.), International Geological Congress Section 3, v. 24, pp. 545-551.

Price, R.A., Mountjoy, E.W., 1970. Geologic structure of the Canadian Rocky Mountains between Bow and Athabasca Rivers–a progress report. Structure of the southern Canadian Cordillera: Geological Association of Canada, Special Publication 6, 7–25.

Early Neoproterozoic stratigraphy in Yukon: Correlation and basin development

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Recent integrated mapping, physical and chemical stratigraphy, and radiometric dating of early Neoproterozoic strata in Yukon have permitted us to produce a more robust stratigraphic framework for the rocks deposited in northwestern Laurentia during the early stages of break-out from the supercontinent Rodinia. Detailed mapping and sequence stratigraphic analysis in the Coal Creek inlier (central Ogilvie Mountains) has revealed that the lower Fifteenmile Group (Gibben and Chandindu formations) was deposited during an episode of continental extension, which initiated Neoproterozoic basin development at c. 850 Ma across northern Canada (onset of Sequence B deposition). In the overlying upper

Fifteenmile Group, the Reefal assemblage (upper Fifteenmile Group) marks the onset of a phase of thermal subsidence, and the Craggy dolostone records the expansion of a broad carbonate platform over central-western Yukon. The Fifteenmile Group is truncated beneath a low angle unconformity in the Hart River inlier (eastern Ogilvie Mountains) reflecting regional tilting and renewed extension, perhaps associated with the 780 Ma Gunbarrel mafic event. The lower Fifteenmile Group correlates with the Hematite Creek Group in the Wernecke Mountains, and the Reefal Assemblage with a relatively thin section of Basinal assemblage (lower Little Dal Group), that is truncated on an angular unconformity that developed during the Cryogenian Corn Creek orogeny. The Callison Lake Dolostone, which overlies the Fifteenmile Group in the Ogilvie Mountains, is absent in the Wernecke Mountains, but likely broadly correlates with the Coates Lake Group in the Mackenzie Mountains to the east. This new stratigraphic synthesis for early Neoproterozoic strata in Yukon presents a unique opportunity to calibrate this fascinating chapter in Earth history and inform ongoing debates over the timing and geometry of Rodinia break-up, tempo of Proterozoic biospheric evolution, and trigger of the Cryogenian glacial epoch.

Miocene-Present shortening in the Himalayan foreland belt

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The 2500 km long Himalayan orogen is characterized by continuity of the principal lithotectonic units. There is evidence for different convergence rates between the western and eastern parts of the orogen; in addition, present-day precipitation rates and Late Miocene erosion rates indicate an east to west gradient. Further complications are induced by the Shillong plateau, which is a basement pop-up structure in front of the eastern Himalaya, and the only active structure in the Himalayan foreland that could accommodate or partition 4-7 mm/yr of plate convergence. This study aims to test whether these differences are reflected in the rates of tectonic activity and shortening along the range. To do so we have constructed balanced cross sections for 11 transects across the Siwalik Group.

The Siwalik Group comprises the deformed part of the Neogene foreland basin along the southern orogen margin. The group consists of synorogenic sediments, which date back to ~18.5 Ma and form the youngest and frontal parts of the Himalayan fold-and-thrust belt. Thrust faults in the Sub Himalaya are splays of a major décollement (the Main Himalayan Thrust), which spans the entire Himalaya thrust belt. Several south-verging thrusts define the deformation and shortening in the Siwalik Group: (1) the Main Boundary Thrust is the backstop of the Siwalik group against the Lesser Himalaya, (2) the Main Dun Thrusts form a succession of duplexes within the Sub Himalaya, and (3) the Main Frontal Thrust is the frontal deformed toe.

During the last 11 myr, convergence rates of the Indian plate colliding with the Eurasian plate were constant, but varied laterally from ~34 mm/yr in the northwest to ~44 mm/yr in the northeast of India. Current GPS velocities are consistent with plate convergence velocities, since rates are ~10 mm/yr greater in the east than the west.

By constructing internally consistent cross sections, the shortening rates obtained will help determine if there are differences in shortening along the Himalaya. Factors that influence shortening will be examined, such as: sedimentation and/or erosion rates, partitioning of convergence, changes in overthrust vs. underthrust rates, changes in erosion rates, and changes in basal friction.

Tectonic implications of Devonian to Early Mississippian rifting in the Alexander terrane and Wrangellia, northern Cordillera

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High-precision U-Pb zircon ages and geochemical data indicate an episode of latest Devonian to Early Mississippian rifting within Wrangellia and the Alexander terrane, in southwest Yukon, Canada. A large gabbro complex in each of the Alexander terrane and Wrangellia were dated at ~363 Ma and found to have non-arc geochemical signatures. Spatially associated sills and dikes in the Alexander terrane are interpreted as being coeval with the gabbros and also have non-arc geochemical affinities. The Station Creek Formation, the lowest stratigraphically exposed rocks in Wrangellia, was deposited at 352 Ma and has back-arc to N-MORB geochemical signatures. These rocks are overlain by voluminous arc volcanic and volcaniclastic rocks (Skolai arc). Similar-aged arc, back-arc and sedimentary rocks are found on Vancouver Island within the Sicker arc, which we believe is the southern extension of the Skolai arc.

We propose that the non-arc 363 Ma gabbros and sills represent the initiation of extension through an arc located at the margin of the Alexander terrane (the Skolai/Sicker arc system). Extension progressed far enough to deposit non-arc basalts within a back-arc tectonic setting. Subduction reversal led to the closure of the back-arc and rejuvenation of the arc in the latest Mississippian. Collision of the arc with margin of the Alexander terrane led to exhumation and the deposition of conglomerates unconformably on top of the gabbro complexes. The collision subsequently shut down the arc and subsidence occurred.

The latest Devonian to Mississippian rifting in the Alexander terrane and Wrangellia is similar to other rifting events at the Laurentian margin and has important implications for global plate reconstructions.

Overview of U-Pb Geochronology for the GEM Minerals - Multiple Metals Northwest Canadian Cordillera Project, Stevenson Ridge Area, Yukon

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The Yukon-Tanana pericratonic terrane (YTT) in the northern Stevenson Ridge (NSR) area comprises a complex tectonic collage of Paleozoic and older metamorphosed volcanic, sedimentary and plutonic rocks that are intruded by Mesozoic to Cenozoic plutonic suites. Mineral exploration in YTT has increased significantly in recent years due to discoveries made in the White Gold District (gold hosted within Permian and older schists), Jurassic intrusive-hosted Cu-Au deposits (ex. Minto) and orogenic and intrusive-related gold deposits associated with the Mid- and Late-Cretaceous plutonic and volcanic rocks (ex. Casino, Coffee Creek); however, poor exposure and uncertain field relationships between geological units commonly complicate understanding of the YTT magmatic and tectonic history. Additionally, conventional ID-TIMS zircon U-Pb dating of rocks from this area has been plagued by discordant data and sometimes inconclusive results due to abundant inheritance and lead loss. Over the course of the GEM Multiple Metals Northwest Canadian Cordillera Project, huge strides have been made in our understanding of the tectonostratigraphy in central and west-central Yukon. Some 20 U-Pb ages from a broad range of metasedimentary, metaplutonic and metavolcanic suites were collected for dating from the NSR area.. All samples were dated using the SHRIMP (Sensitive High Resolution Ion Microprobe) at the Geological Survey of Canada, Ottawa. The SHRIMP has been an extremely powerful tool throughout the project, enabling us to accurately date YTT samples, by discriminating domains within complex grains.

Pre-Devonian metasedimentary rocks, which consist predominantly of interlayered muscovite-biotite±garnet schist and quartzite, yielded dominant Paleoproterozoic zircon populations (ca. 1700-1900 Ma), lesser Archean peaks (ca. 2500-2600 Ma), and minor Meso- and Neoproterozoic zircon grains. The youngest zircon grains were ~489 and 718 Ma. Late Devonian orthogneiss, metarhyolite and epiclastic tuffs, restricted to the western Stevenson Ridge area, gave zircon ages between 365 and 375 Ma, distinctly older than typical YTT igneous rocks. Petrographically similar Simpson Range suite orthogneiss, restricted to the northeast part of the Stevenson Ridge area, yielded distinctly younger

Mississippian ages ranging between 344 and 348 Ma. Trondhjemite, which intrudes Harzburgite Peak gabbro, yielded an igneous crystallization age of ca. 283 Ma. Sulphur Creek suite K-feldspar augen granites, that predominantly intrude metavolcanic Permian Klondike schist and Snowcap assemblage rocks, yielded Permian ages of 261-262 Ma. Two samples of porphyritic felsic tuff breccia of the Klondike schist gave ca. 256 and 259 Ma ages. Jurasssic Aishihik suite hornblende-porphyritic granite, which intrudes the Simpson Range suite, yielded ca. 197 Ma crystallization age and Mississippian inheritance. Cretaceous Dawson Range and Coffee phases of the Whitehorse plutonic suite yielded ca. 101 to 103 Ma ages. The youngest intrusive rocks yielded ca. 78 and 58 Ma ages. Geochronology results from the northern Stevenson Ridge project constrains the tectono-stratigraphy of this portion of the YTT terrane by establishing chronology of magmatism and defining distinct geochronologic domains. These data have greatly augmented our understanding of the magmatic and tectonic history of the area, and may help delineate gold- or base metal-prospective properties that have previously been underexplored.

Late Neogene Kinematics of the Sikkim Himalaya using ZHe Thermochronology and 3-D Thermokinematic Modelling

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The kinematics of Late Miocene crustal deformation across the Himalayan Orogen has seen substantial debate over the past decade. Exhumation of material within the Himalayas is controlled by the interactions between tectonic and climatic processes, both of which control the erosion of crustal material at the surface. However, the degree to which each of these processes has contributed to observed exhumation rates is not well understood. Data acquisition and modelling studies have primarily focused on the western and central Himalayas, where findings about crustal deformation, exhumation, and the resulting thermal structure have been extrapolated to elsewhere in the orogen (e.g. Herman et al., 2010). However, the applicability of previous studies to the Sikkim Himalaya is limited because this part of the range is located in a transition zone between Nepal to the west (e.g. Whipp et al., 2007, Herman et al., 2010) and Bhutan to the east (e.g. Grujic et al., 2006; Coutand et al., in prep.) (Figure 1), which have different structural, climatic and morphological characteristics. The orogen is characterized by a series of continuous lithotectonic units and their bounding structures found along strike of the range (Figure 1); from North to South, the major fault zones are the South Tibetan Detachment Zone (STDZ), the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Main Frontal Thrust (MFT). The MCT, MBT and MFT apparently all branch at depth from a major basal

shear zone known as the Main Himalayan Thrust (MHT) (e.g. Nelson et al., 1996). When focusing on the Sikkim Himalayas, two additional salient tectonomorphic features are observed (Figure 2): (1) the hanging wall of the MCT has been eroded such that the trace of the thrust has migrated northward forming the Teesta half-window and exposing the underlying units and (2) the Rangit window, located within the Teesta window, is surrounded by the folded Ramgarh Thrust and may be structured as a duplex at depth (Bhattacharyya and Mitra, 2009).

In order to quantify the geometry and kinematics of deformation in Sikkim during the last ~10 Ma, we use (U-Th)/He thermochronology on zircon (ZHe) coupled with 3-D thermokinematic modelling (PECUBE software, Braun, 2003; Braun et al., 2012). The (U-Th)/He technique produces cooling ages which represent the amount of time a sample has spent cooling from its closure temperature, ~180 °C for zircon (Reiners, 2005), to the surface, which provides us information about the thermal field and rate of cooling within the upper 5-7 km of the crust. PECUBE is a numerical code that solves a 3-D equation for heat transfer through a series of time-steps and predicts both the subsurface thermal field and the surface distribution of cooling ages for specific thermochronometers (Braun et al, 2012) allowing for testing of different tectono-morphic scenarios. 18 bedrock samples collected along a NNW-SSE transect across the Rangit Window (Figure 2), resulted in cooling ages ranging from 1.38 ± 0.05 Ma to 13.65 ± 0.4 Ma. This distribution of cooling ages is used as an input in the numerical models to test three tectonic scenarios based on published structural, geological and geophysical data: 1) Varying geometry and kinematics along the MHT, 2) duplexing beneath the Rangit window, and 3) a combination of both. For each scenario, inversions will be run to test thermal, geometrical, and kinematic parameters. From each inversion, the forward model yielding the best-fit will be used to calculate probability density functions to assess the significance of each tested parameter. If the models are not able to reproduce the observed ZHe cooling age pattern, this will suggest that tectonic processes alone cannot account for the late Neogene exhumation pattern documented along the Sikkim range front and that climatic processes need to be taken into consideration.

References

Bhattacharyya, K. and Mitra, G. (2009) A new kinematic evolutionary model for the growth of a duplex - an example from the Rangit duplex, Sikkim Himalaya, India. Gondwana Research, 16, 697–715.

Braun J. (2003) Pecube: a new finite-element code to solve the 3D heat transport equation including the effects of a time-varying, finite amplitude surface topography. Computers and Geosciences, 29, 787–794.

Braun, J., van der Beek, P., Valla, P., Robert, X., Herman, F., Glotzbach, C., Pedersen, V., Perry, C., Simon-Labric, T., Prigent, C. (2012) Quantifying rates of landscape evolution and tectonic processes by thermochronology and numerical modeling of crustal heat transport using PECUBE. Tectonophysics, 524–525, 1–28

Coutand I., D.M. Whipp Jr., D. Grujic, M. Bernet, M.G. Fellin, K.R. Landry, and N. McQuarrie, Geometry and kinematics of the Main Himalayam Thrust and upper crustal exhumation history of the Bhutan Himalaya: new insights from the inversion of low-temperature thermochronologic data, in prep. For J. Geophys. Res. Solid Earth.

Herman, F., Copeland, P., Avouac, J-P., Bollinger, L., Mahéo, G., Le Fort,P., Rai, S.M., Foster, D., Pêcher, A., Stüwe, K. and P. Henry. (2010) Exhumation, crustal deformation and thermal structure of the Nepal Himalaya derived from the inversion of thermochronological and thermobarometric data and modeling of the topography. J. Geophys. Res., Solid Earth, 115.

Grujic, D., Warren, C., and Wooden, J. (2011) Rapid synconvergent exhumation of Miocene-aged lower orogenic crust in the eastern Himalaya. Lithosphere 3, 5, 346–366.

Grujic D., Coutand I., Bookhagen B., Bonnet S., Blythe A. and Duncan C. (2006). Climatic forcing of erosion, landscape, and tectonics in the Bhutan Himalayas; Geology, 34, 801–804.

McQuarrie, N., Robinson, D., Long S., Tobgay, T., Grujic, D., Gehrels, G., Ducea, M. (2008) Preliminary stratigraphic and structural architecture of Bhutan: Implications for the along strike architecture of the Himalayan system. Earth and Planetary Science Letters, 272, 105–117.

Nelson, K. D., Zhao, W., Brown, L. D., Kuo, J., Che, J., Liu, X., Klemperer, S., Makovsky Y., Meissner R., Mechie, J., Kind., R, Wenzel, F., Ni, J., Nabelek, J., Leshou, C., Tan, H., Wei, W., Jones, A., Booker, J., Unsworth, M., Kidd, W., Hauck, M., Alsdorf, D., Ross, A., Cogan, M., Wu, C., Sandvol, E, and Edwards, M. (1996) Partially Molten Middle Crust Beneath Southern Tibet: Synthesis of Project INDEPTH Results. Science, 274 1684-1688

Reiners, P.W. (2005) Zircon (U-Th)/He Thermochronometry. Reviews in Mineralogy & Geochemistry, 58, 151-179.

Whipp, D. M., Ehlers, T. A., Blythe, A. E., Huntington, K. W., Hodges, K. V., & Burbank, D. W (2007). Plio-Quaternary exhumation history of the central Nepalese Himalaya: 2. Thermokinematic and thermochronometer age prediction model. Tectonics, 26 (3).

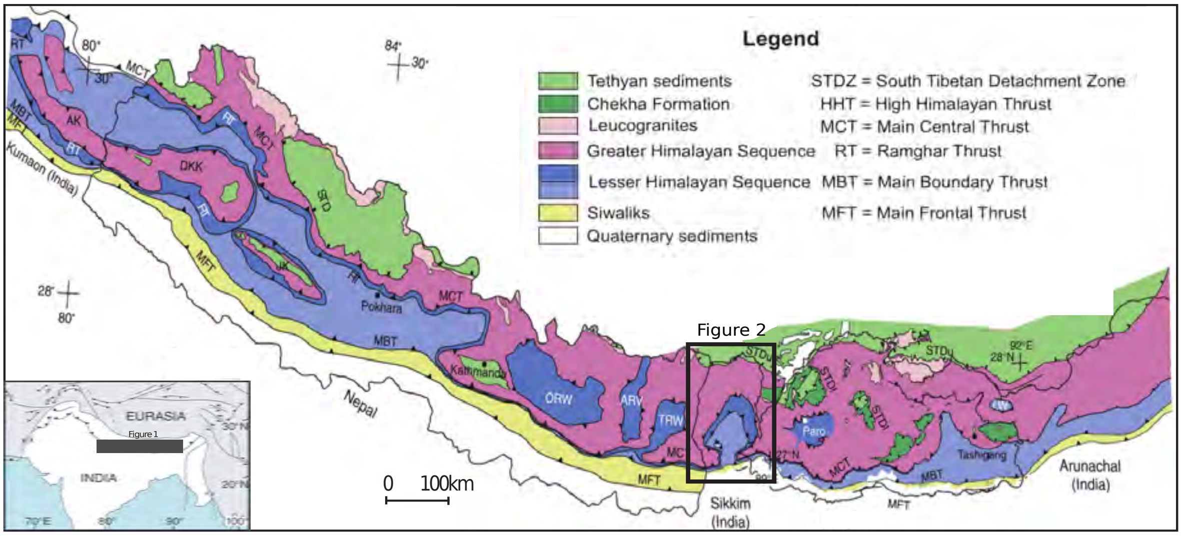

Figure 1: A simplified geological map of the Himalayas showing Bhutan, Nepal and Northern India. The black outlined box shows the location of figure 2 and the study area, Sikkim India. Inset map from Grujic et al, 2011. Overall map modified from McQuarrie et al, 2008.

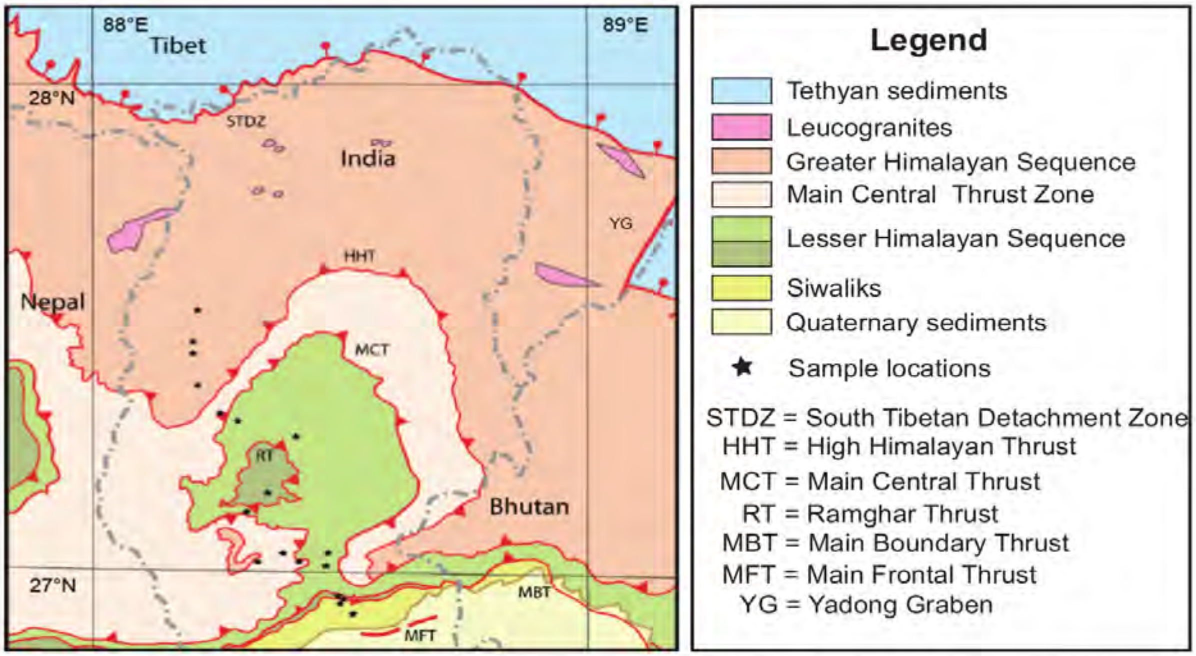

Figure 2: Simplified geologic map centered on Sikkim, India showing the major geologic units and structures. Zircon (U-Th)/He sample locations are denoted by black stars. Modified from Grujic et al., 2011.

The development of thrust belts and the influence of fluid pressure

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Fold and Thrust belts are contractional systems created by plate collisions. These collisions create stress conditions where the maximum and intermediate principal stresses are horizontal and the minimum principal stress is vertical. The stress orientation favours the development of low angle reverse faults consistent with Anderson's rules. Though the stress orientation is important in the determination of the fault orientation, the shape of the thrust system is also dependent on a wide variety of semi-related rates. Rates of uplift, erosion, deposition all play a role in the shape of the thrust belt. Spatial variations in sedimentary thickness, rock properties, and the relief on crystalline basement also have a profound effect on the development of the thrust belt.

Another fundamental influence on thrust belts is the presence of fluids within the geologic section and the role these fluids play as a trigger mechanism for seismic failure of faults. Failure occurs in the crust when the differential stress conditions within the crust (the difference between the maximum and minimum principal stresses) exceeds the strength of the crustal material. The effect of increased fluid pressure is to reduce the effective stresses within the system but maintain a consistent differential stress. Thus increasing fluid pressure is an effective trigger mechanism to create failure conditions in the section and allow faults to slip. As faults slip the fluids have an escape route and leave the system thus reducing the fluid pressure and re-establishing stability conditions effectively arresting the slip on the fault. Motion on the fault ceases until the fluid pressure elevates and recreates the failure condition thus repeating the process.

Within the sedimentary section the principal fluids available are water and hydrocarbons. Water is an effective mechanism to increase fluid pressure in relatively young unconsolidated sediments as those sediments compact; but in older more consolidated strata there is little water available to sustain prolonged deformation periods. The generation of hydrocarbons appears to be a more effective mechanism to create sustained elevated fluid pressure and to maintain that fluid pressure within a leaky system. Organic material goes through a volume increase when heated and converted to hydrocarbons. This volume increase creates substantial over-pressure fluid conditions within the rock as a greater volume must be confined within a restricted pore volume. The generation of hydrocarbons are a sustained source of fluids that is used to create episodic elevated fluid pressures and failure within a thrust belt.

The flush of hydrocarbons during deformation results in abundant petroleum traps where the structural development and hydrocarbon charge are simultaneous. There are several nuances which add to the complexity of the system. Erosion has a greater effect where it both lightens the weight of the overburden on the active thrust belt but in some cases also compromises the top seal no longer allowing fluid pressures to build up and likely retarding the continuity of deformation. Another implication to this system is that the migration pathways become predominantly horizontal rather than vertical. The flush of hydrocarbons will migrate beyond the thrust belt into the adjoining foreland basin forming massive hydrocarbon resource deposits within the undeformed strata. In the case of the Canadian Rockies the lateral migration of hydrocarbons is hundreds of kilometres in distance to the point where the flush of hydrocarbons coming from the thrust belt has migrated to the other side of the foreland basin to form the massive oilsands bitumen deposits at the Alberta/ Saskatchewan border.

The “British Columbia Caledonides”: Mid-Paleozoic orogeny in the southern Alexander terrane

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The Alexander terrane (AT) in southeastern Alaska is a Neoproterozoic –Early Devonian primitive arc terrane with faunal and geochronological affinities to western Baltica / Polar Urals. Permian faunas place it in the northern Pacific, and it was accreted to the western Cordillera by the mid-Jurassic. Bedrock mapping and geochronology in the lesser-known AT of coastal NW British Columbia provide constraints on its mid-Paleozoic tectonics. The lowest stratigraphic unit is the Cambrian-Ordovician Descon Formation (Moira Sound unit?) (ca. 460-520 Ma) – arc-related andesitic breccia, tuff, felsic volcanics, volcanogenic sediments and hypabyssal rocks. It is unconformably overlain by a Devonian clastic succession of mixed Paleozoic arc and pericratonic provenance, the Mathieson Channel unit (MCU). MCU includes lithic feldspathic sandstone, local plutonic-volcanic clast conglomerate, abundant carbonate, basalt and minor rhyolite. Detrital zircon populations from eastern MCU near Grenville and Mathieson channels are ca 400-460 Ma, with a peak at 423 Ma, sourced primarily from Late Ordovician-Silurian plutonic rocks like those of AT in southeastern Alaska. Farther west towards and on Banks Island, detrital zircon spectra show both mid-Paleozoic peaks like eastern MCU, and a set of peaks between 2.0 to 1.0 Ga, including populations in the NAMG. Rare quartzite-clast conglomerates contain exclusively Precambrian signatures. MCU was derived from two source terranes: mid-Paleozoic AT arc granitoids to the east, and a pericratonic (Baltican?) source to the west (present coordinates).

The Ogden Channel plutonic-metamorphic complex occurs as a fault-bounded panel on Porcher Island, near the western limit of typical Alexander stratified rocks, and east of the pericratonic Banks Island outcrop belt. Evidence for Early Devonian tectonism is shown by epidote amphibolite-facies metamorphism and synplutonic ductile deformation affecting both Descon-age strata and plutonic bodies as young as ca 413 Ma, cut by post-tectonic tonalite (ca. 410 Ma). Synmagmatic shear zones preserve evidence for sinistral and/or oblique sinistral-reverse motion. It may represent a mid-Paleozoic accretionary boundary between the AT and a pericratonic fragment, while MCU represents the associated clastic overlap. In southeastern Alaska, this Late Silurian-Early Devonian event is termed the Klakas orogeny. Observed features of the Klakas orogeny in NW BC - widespread shallow-water clastic-carbonate deposits of the MCU, restricted occurrence of coeval ductilely-deformed plutonic rocks, and sinistral strain indicators – highlight the significance of oblique motions. This mechanism is consistent with evidence for Silurian-Devonian sinistal transport of terranes of the northernmost Caledonides (e.g. Pearya) westward towards the Pacific realm.

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Note: in this version we refer to Mathieson Channel unit, because of ban on new stratigraphic names in GAC abstracts.

Tectonic interpretation of eclogites in the St. Cyr area, Yukon-Tanana terrane

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The St. Cyr area of the Yukon-Tanana terrane consists of well preserved to heterogeneously retrogressed eclogite boudins meter- to tens-of-meters in size hosted within a coherent slab of quartzofeldspathic tectonites. The slab is approximately 30 km long by 6 km thick and is thrust to the northeast upon a unit consisting of low-grade shales, slates, psammites, and carbonates. To the west and southwest the slab sits in tectonic contact with a metavolcaniclastic unit and a sliver of garnet-mica schists correlated with the Snowcap Assemblage. Meter- to tens of meter-scale slices of serpentinized ultramafics and associated leucogabbros and amphibolites are tectonically interleaved within the eclogite-bearing quartzofeldspathic slab. The host quartzofeldspathic tectonites consist of intercalated metasedimentary and metaigneous rocks that display a continuous, steep to shallowly dipping, northwest-striking foliation. Metasedimentary rocks include garnet- and kyanite-bearing quartzites, garnet-mica schists and feldspar-quartz-mica schists, while felsic meta-igneous rocks include garnet-bearing metatonalites and metatrondhjemites.

These assemblages suggest that the quartzofeldspathic host rocks achieved similar high-pressure (HP) conditions as those of the mafic boudins.

In order to characterize the age and tectonic affinity of the igneous protoliths, detrital provenance of the metasediments, and timing of high-pressure metamorphism in the St. Cyr area, we applied bulk rock geochemistry and *in situ* SHRIMP-RG and LA-ICP-MS U-Pb zircon geochronology. Eclogite and their retrogressed counterparts have predominantly N-MORB and island arc tholeiite protoliths. Eclogite yields protolith ages of 379 ± 4 and 369 ± 3 Ma, while felsic intrusive rocks give magmatic ages between 346 ± 4 and 333 ± 3 Ma. Provenance ages of metasedimentary rocks range from ca. 1.8 Ga to 370 Ma. Metamorphic zircons from both eclogites and their host quartzofeldspathic schists display sector zoning, depleted heavy rare earth element patterns, and lack Eu anomalies, characteristic of their growth during eclogite-facies metamorphism (Corfu et al., 2003; Rubatto, 2002). These metamorphic zircons give HP metamorphic ages between 274 ± 4 and 266 ± 3 Ma.

The protolith ages for the eclogites suggest that the mafic rocks intruded rocks of Laurentian provenance coeval with the approximate opening of the Slide Mountain Ocean. Following the rifting (or coeval with prolonged rifting) of the proto Yukon-Tanana terrane from the Laurentian margin, the felsic intrusives of the St. Cyr area were added to the arc system built upon Yukon-Tanana, as their protolith ages are coeval with the Little Salmon magmatic cycle of the Yukon-Tanana terrane. Provenance ages of metasedimentary rocks are consistent with their derivation, at least in part, from the oldest exposed rocks in the Yukon-Tanana terrane, the Snowcap Assemblage. The eclogites and surrounding quartzofeldspathic metasediments and felsic intrusive rocks represent a coherent slice of the Yukon-Tanana arc. The HP-slice formed by subduction erosion/ablation of material of the overriding plate by the downgoing Slide Mountain Ocean. The juxtaposition of eclogites within felsic intrusives and arc-derived metasediments that record the same age of HP metamorphism is consistent with their origin within the arc-trench gap of the Yukon-Tanana terrane. This interpretation is in contrast to previous studies that concluded that the eclogite in the St. Cyr area are part of an oceanic mélange associated with the Slide Mountain Ocean (e.g. Erdmer, 1992; Erdmer et al., 1998). The slices of serpentinized ultramafic and lower grade metabasic rocks now spatially associated with the eclogite-bearing HP unit do not show the same evidence of HP metamorphism. This suggests that these slices represent imbrication of Yukon-Tanana and possibly Slide Mountain terrane material during exhumation of the high-pressure crust.

References:

Corfu, F., Hanchar, J. M., Hoskin, P. W. O., and Kinny, P., 2003, Atlas of zircon textures, *in* Hanchar, J. M., and Hoskin, P. W. O., eds., Zircon, Volume 53, p. 469-500.

Erdmer, P., 1992, Eclogitic rocks in the St. Cyr klippe, and their tectonic significance: Canadian Journal of Earth Sciences, v.29, p. 1296-1304.

Erdmer, P., Ghent, E.D., Archibald, D.A., and Stout, M.Z., 1998, Paleozoic and Mesozoic high-pressure metamorphism at the margin of ancestral North America in central Yukon: Geological Society of America Bulletin, v. 110, p. 615-629.

Rubatto, D., 2002, Zircon trace element geochemistry: partitioning with garnet and the link between U-Pb ages and metamorphism: Chemical Geology, v. 184, no. 1-2, p. 123-138.

Age and provenance of cover strata to the Paleocene Resurrection Peninsula ophiolite, Seward, Alaska

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The southern margin of Alaska is defined by a late Mesozoic to Cenozoic accretionary complex that comprises the Upper Cretaceous to Eocene Chugach-Prince William (CPW) terrane. The Upper Cretaceous Valdez Group and the Paleocene to Eocene Orca Group define the bulk of the Chugach-Prince William terrane in the Kenai Peninsula and western Prince William Sound area. Sandstones of the Campaniam-Maastrichtian Valdez Group and the Paleocene Orca Group consist of lithologically similar feldspathic and volcanic-lithic sandstones. During the Paleocene to early Eocene, ridge subduction led to the formation and emplacement of the Resurrection and Knight Island ophiolites and subsequent intrusion of the Sanak-Baranof belt (SBB) plutons along the 2200 km length of the CPW accretionary complex.

Controversy surrounds the age of the ophiolites and the age and stratigraphic relationship of adjacent clastic strata (see Bradley and Miller, 2006). Original mapping of the Resurrection Ophiolite indicated it was associated with the Cretaceous Valdez Group, and hence was thought to be Cretaceous in age (Tysdal and Case, 1979). A U/Pb zircon date from an intrusive plagiogranite from Killer Bay on the east side of the Resurrection Peninsula constrains the age of the ophiolite at 57 ± 1 Ma; the Knight island Ophiolite (in Prince William Sound) is undated but assumed to be the same age (Nelson et al., 1989). On the northeastern side of Resurrection Peninsula, a thrust fault is mapped between the ophiolite and Upper Cretaceous Valdez Group. However, on the western side, there is controversy about the stratigraphic affinity of clastic strata (cf. Bradley and Miller, 2006; Kusky and Young, 2004), with the crux of the issue as to whether the strata are Cretaceous Valdez Group and fault bounded, or whether they are Paleocene and essentially in stratigraphic continuity with the ophiolite.

To determine the age, provenance and stratigraphic affinity of the clastic rocks interbedded with (and stratigraphically above) the Resurrection Peninsula Ophiolite, we collected U/Pb detrital zircon dates from four samples (n=404) from Thumb Cove, Humpy Cove, and Nash Road, across the bay from Seward. One sample (RB12-04), collected at the end of Humpy Cove, is from a thin-bedded, medium-grained sandstone interbedded with (and cross-cut by) basaltic rocks and thus this sample provides a key tie to the ophiolite. The maximum depositional age of this sample is 57 Ma given by a robust mode formed from the youngest four zircons. The grain-age distribution includes modes at 73, 109, 159, and 188 Ma, and is essentially identical to the other three samples.

Because of the similar grain age distributions of the four samples from Resurrection Bay, we group them together and compare them to strata of the Orca Group 70-80 km to the NE in Prince William Sound: 1) All samples from Resurrection Bay, and those of the Orca Group in western Prince William Sound (inboard of Montague Island), are dominated by a young population of grain ages between 57 and 75 Ma. 2) All samples have a minor fraction of grain ages dispersed between 100 - 225 Ma, and these grain ages occur in two primary populations. One between 100 - 115 Ma, and the other 155 - 225 Ma. 3) Comparing the Resurrection Bay samples directly to samples from different tectonostratigraphic belts in the Western PWS defined by Kveton (1989), they most closely resemble those of the Whale Bay Belt.

A Kuiper's statistical test shows that the Resurrection Bay samples and Orca Group in the Whale Bay Belt, and correlative units along strike, are identical (i.e., the null hypothesis that they are the same cannot be disproved with 95% confidence). Thus we conclude that the sandstones interbedded with the Resurrection Peninsula Ophiolite are stratigraphically correlative to the Orca Group. Because the clastic strata of the Orca Group are definitively tied to the ophiolite, these results breath new life into the paleomagnetic data obtained from the Resurrection Peninsula ophiolite that indicate a paleolatitude 13 ± 9° south of the present location to near present day northern Washington (Bol et al., 1992). Together, these results support large coast parallel transport of the CPW terrane since the Paleocene and the search for the original source of the clastic rocks may include terrains now far to the south.

REFERENCES

Bradley, D.C., and Miller, M.L., 2006, Field guide to south-central Alaska's accretionary complex Anchorage to Seward: Anchorage, Alaska Geological Society, 32 p.

Bol, A.J., Coe, R.S., Grommé, C.S., and Hillhouse, J.W., 1992, Paleomagnetism of the Resurrection Peninsula, Alaska: Implications for the tectonics of southern Alaska and the Kula Farallon Ridge: Journal of Geophysical Research, v. 97, p. 17,213-17,232.

Dumoulin, J.A., 1987, Sandstone composition of the Valdez and Orca Groups, Prince William Sound, Alaska: U.S. Geological Survey Bulletin 1774, 37 p.

Kusky, T.M., and Young, C.P., 1999, Emplacement of the Resurrection Peninsula ophiolite in the southern Alaska forearc during a ridge-trench encounter: Journal of Geophysical Research, v. 104, no. B12, p. 29,025-29,054.

Nelson, S.W., Miller, M.L., and Dumoulin, J.A., 1989, The Resurrection Peninsula ophiolite, in Nelson, S.W., and Hamilton, T.D., eds., Guide to the geology of the Resurrection Bay-Eastern Kenai Fjords area: Anchorage, Geological Society of Alaska, Guidebook, p. 10-20.

Tysdal, R.G., and Case, J.E., 1979, Geologic map of the Seward and Blying Sound quadrangles, Alaska: U.S. Geological Survey Miscellaneous Investigations Map I-1150, 12 p., scale 1:250,000.

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^{40}Ar/^{39}Ar Dating and Characterization of Hornblende from the Nelson Plutonic Suite, Southern Kootenay Arc, SE B.C.

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The Kootenay Arc located in SE B.C. has experienced more than one episode of tectonism, metamorphism and plutonism. The Mid-Jurassic to Eocene thermal history of the area has been investigated using K-Ar and 40/39 dating of biotite and muscovite, however there are no reliable hornblende dates from this area. This study will investigate the two most easterly stocks of the Nelson Plutonic Suite in the area. The Mine and Wall stocks have U-Pb zircon ages between 171 and 168 Ma but record a wide range of mica cooling and overprinting dates between 166 Ma in the west and 67 Ma in the east. 40Ar/39Ar age spectra for hornblende from 11 rocks in these stocks comprising a transect of the area, will aid in defining the higher temperature part of the thermal history.

Previous attempts to prepare bulk hornblende separates were unsuccessful due to overgrowths and intergrowths of biotite, chlorite, plagioclase and K-feldspar. Part of this study involves testing the efficiency of SELFRAG disaggregation. The SELFRAG uses pulses of electrostatic power to break apart the rock along mineral cleavage planes and grain boundaries and should lead to higher purity mineral separates and better dates. Scanning Electron Microscopy (SEM) confirms that the separates sent for irradiation are free of K-rich inclusions and that hornblendes from the two plutons show little variation in chemistry. Ca/K ratios are typical of igneous amphibole. Electron microprobe analyses are planned.

Combined with previous published and unpublished K-Ar and 40/39 results for micas these hornblende dates should provide some insight into the history of the enigmatic Next Creek fault. This is a zone of low-temperature alteration and brittle faults near the eastern margin of the Mine stock that has not yet been mapped into the country rock, but marks a major change in K-Ar and 40/39 mica dates. East of the fault, Late Cretaceous-to-Eocene dates predominate; west of the zone, mid-Jurassic to early-Cretaceous dates with no evidence of Eocene overprinting are typical. Petrography reveals that part of the "Jersey Creek Phase" of the Mine stock is a biotite granodiorite in marked contrast to the biotite-hornblende-epidote granodiorite of the Mine and Wall stocks.

Detrital zircon (U-Th)/He and muscovite ^{40}Ar/^{39}Ar thermochronometry from the Mackenzie Mountains & Corridor, NWT: Insights into burial and exhumation of the Northern Cordillera

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The Mackenzie River corridor of the Northwest Territories has experienced a protracted burial and unroofing history throughout the Phanerozoic with little quantitative constraints on the amount of deposition or erosion occurring during the Carboniferous through Early Cretaceous. We are using innovative and complementary approaches to resolve the timing of maximum burial and onset of hydrocarbon generation, and its relationship with the formation of structural traps. Detrital thermochronometry provides a powerful tool to aid in our understanding of hydrocarbon formation and migration, as these isotopic systems detail the temperature-time histories of sedimentary basins and provide critical insight into the magnitude and extent of major thermal events.

Samples for detrital zircon (U-Th)/He and detrital muscovite ^{40}Ar/^{39}Ar thermochronology were collected along a transect extending approximately 150 km from the northern Mackenzie fold-thrust belt into the adjacent Mackenzie River corridor. Sampling targeted strata that would help resolve the timing of maximum burial and subsequent unroofing. Rocks include clastic Neoproterozoic strata exposed in the core of anticlines and from the hanging wall and footwall of the Plateau Fault, the eastern-most crustal-scale Laramide thrust fault that places Neoproterozoic strata on top of Paleozoic rocks. Younger clastic strata through the Cretaceous were also collected. Since radiogenic helium and argon are only retained in the crystal structure of zircon and muscovite at temperatures lower than ~180°C and ~350°C, respectively, ages recorded by these thermochronometers indicate when the sample cooled through these conditions. The challenge will be to resolve the tectonic implications (basin deepening, thrusting, hydrothermal fluids) for our cooling age pattern.

Single grain zircon (U-Th)/He and muscovite ^{40}Ar/^{39}Ar thermochronometry has been performed on Neoproterozoic quartzites, Cambrian and Cretaceous sandstones, and Devonian siltstones. The He systematics of zircon from the Neoproterozoic units have been thermally reset since deposition and consequently record Late Cretaceous cooling. Moreover, a subset of these samples serves to resolve the timing of movement on the Plateau Fault to be post-Cenomanian. In the Cambrian and Cretaceous samples, zircon preserve cooling ages older than the stratigraphic age of the units, indicating that burial has not been significant enough to achieve the temperatures necessary to reset the thermochronometer. Instead, the zircon (U-Th)/He ages for these samples document cooling in their source regions. Cooling ages recorded in the Cretaceous samples vary between Triassic, Permian and Carboniferous, supporting the hypothesis of variable provenance throughout the Cretaceous. None of the eight muscovite samples selected for detrital ^{40}Ar/^{39}Ar analyses have been reset since deposition. Instead, some of the Devonian Imperial Formation samples consistently yield peak detrital ages between 400-600 Ma, indicative of Baltica-derived material through the Arctic. Detrital muscovite ^{40}Ar/^{39}Ar ages for the four Neoproterozoic units detail Grenvillian-aged cooling in their source terrane.

Our preliminary dataset of zircon (U-Th)/He cooling ages provide insight into the timing of regional tectonics within the Mackenzie Corridor and appear to correspond with the Late Albian-Early Cenomanian erosional event modeled through borehole AFT by Issler et al. (2005). While the remainder of our samples have not been heated sufficiently >180°C to reset the helium and argon systematics, these data do help constrain the upper boundary of temperatures reached during burial(s) and detail the timing of unroofing in varying Neoproterozoic, Cambro-Devonian and Cretaceous source terranes. Ultimately, the increased risks and costs associated with hydrocarbon exploration in frontier regions necessitate the synthesis of a variety of geological data. Our project aims to aid in this endeavor by modernizing the ways in which thermochronological methods are applied to sedimentary basin analysis.

The influence of conceptual models and geo-poetry in tectonics and structural geology

2012 Penrose Gold Medal Lecture *(as revised 04 Jan. 2013)*

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My fascination with the nature, origin, and evolution of mountains began during the summer of 1952, when, after only one course in geology, I had the good fortune to be employed on Geoffrey B. Leech's GSC (Geological Survey of Canada) field party in the Purcell Mountains of southeastern British Columbia. Having never before been in the mountains, I was enthralled and intrigued by their majesty, formidable beauty, and mystery. Fortunately for me, Geoff Leech was a superb mentor and role model. He nurtured my fascination with the mountains and my latent interest in geology, with the result that my scientific focus shifted from physics and chemistry to geology. My principal scientific quest became: "Whence the Mountains?" particularly the mountains of the southeastern Canadian Cordillera. Geoff arranged for me to acquire diverse GSC field experience during following summers in the southwestern Canadian Rockies, the Precambrian Shield north of Lake Athabasca, and the southern Alberta Foothills. Thanks to Geoff and to R.J.W. ("Bob") Douglas, my GSC thesis supervisor and prime mentor, I was able to obtain a GSC PhD thesis project that straddled the Lewis thrust sheet and the Flathead Valley graben at North Kootenay Pass. Then, between 1958 and 1968, with Bob's support, I was given two GSC mapping projects that spanned the Rockies; one along the U.S.A. border in the Fernie area; and the other, Operation Bow-Athabasca, a large helicopter-supported project to map the region between Banff and Jasper, which included my esteemed colleague and close friend Eric Mountjoy and eight other GSC geologists. Besides these exceptional opportunities for a hands-on regional overview of the southern Canadian Rockies, I was also authorized to spend several summers studying thrust-related folding and the tectonic significance of meso-scale faulting and fracturing within this region. As one of many individual scientists who benefitted immeasurably from serving my country by conducting scientific research for the Geological Survey of Canada, it was my honour, duty, and privilege to interrupt my research from 1981 to 1988 to assume responsibility for management of the GSC during an interval of fundamental change.

Since becoming a member of the faculty of Queen's University in 1968, I have been inspired and enlightened by working with many gifted graduate students and research associates; and also by collaborating with stimulating colleagues like Dugald Carmichael, John Dixon and Herb Helmstaedt. Co-supervision of eight graduate students with Dugald enhanced my appreciation of metamorphic petrology and its utility in elucidating tectonic processes. My fruitful collaboration with Jim Monger on the evolution of the Canadian Cordillera began after I first moved from the GSC to Queen's and is still flourishing 35 years later. Sixty years after shifting from chemistry and physics into geology, I am now equipped with a wealth of new information and many new conceptual models, (some of my own making), and I now can comfortably offer credible explanations for the nature, origin, and evolution of the southeastern Canadian Cordillera, and thereby for some other mountain belts elsewhere.

S. Warren Carey, Harry H. Hess, and Walter H. Bucher, three of my mid-twentieth century geotectonics heroes, have inspired me in my quest for insight on mountain building. In 1952 **S. Warren Carey**[1] provided an elegant exposition on how **our thinking in tectonics and structural geology is done with models**, and how some of these models are empirical but not readily applicable very far beyond the scale of time and the scale of length of the observations with which they were formulated. In his geo-poetical "expanding earth" conceptual model for the origin of the ocean basins, Carey[2] focused on structural evidence of continental rifting and divergence between conjugate continental fragments, and on conceptual models such as "megashears" that, like transform faults, linked "sphenochasms" and "rhombochasms" to explain the opening of ocean basins and the apparent "drift" between continents. **Harry H. Hess** presented a different more comprehensive, insightful and elegant conceptual model for "The History of the Ocean Basins" in his classic 1962 paper[3], which he himself called an **"essay in geo-poetry". In this paper, which is arguably the most insightful and influential global tectonics article of the 20th century, Hess suggested that *thermal convection within the mantle drives the continuous creation and destruction of the ocean floor via the symmetrical generation of new ocean floor above divergent, gravity-driven buoyant upwelling of hot mantle, and via the reciprocal asymmetrical gravity-driven sinking and consumption of solid, older, colder, negatively buoyant ocean floor***. In this conceptual model, ocean basins are ephemeral; they open as divergent upwelling currents cause continents to split apart and carry the pieces away from each other; and they close with convergent flow where sinking oceanic lithosphere gives rise to oceanic trenches, magmatic arcs, the deformation of continental margins, terrane accretion, and continental "collisions". **Walter H. Bucher**'s GSA presidential address[4], titled "Role of Gravity in Orogensis", was published in the October 1956 issue of the GSA Bulletin. This was the first issue of the GSA Bulletin that I received as a new GSA member! Bucher's paper was particularly inspirational for me because his analog models elaborated and elucidated **conceptual models of gravitational lateral spreading in foreland thrust-and-fold belts and of intrusive fold-nappes that flow almost horizontally within the metamorphic core zones of orogenic belts**, thus guiding my quest for understanding of mountain building processes within my small corner of the world --- the southeastern Canadian Cordillera.

The southern part of the Canadian Cordilleran foreland thrust-and-fold belt, which comprises the Southern Canadian Rockies and adjacent parts of the Purcell and Cariboo Mountains, consists of thrust slices of supracrustal that have been detached from the under-riding edge and margin of Laurentia by an over-riding tectonic collage of allochthonous terranes that originated mainly as oceanic magmatic arcs. The detached sedimentary strata came from four different superimposed sedimentary basins: (1.) the Mesoproterozoic Belt-Purcell intracontinental rift basin, (2.) the late Neoproterozoic Windermere intracontinental rift basin, (3.) the Cambrian to Middle Jurassic Cordilleran miogeocline (a passive-margin, continental terrace-wedge basin), and (4.) the syn-orogenic Upper Jurassic to Paleocene Cordilleran foreland basin. This complex composite wedge of sedimentary strata was compressed horizontally and thickened (i.e. extended vertically) by imbricate listric thrust faulting and related folding, as it was being detached and displaced up to more than 200 km northeastward. Seismic reflection imaging and aeromagnetic anomaly maps show that the Paleoproterozoic crystalline basement of the Interior Plains extends under the Canadian Rockies without disruption. The deformation was 'thin-skinned'. The concept of tectonic heredity, as exemplified by the different configurations and locations of the margins of these different basins, and expressed by tectonic inversion of the structural relief of the basins as their contents were detached and displaced on to the flat surface of the craton, is important for the elucidation of mountain building.

Bucher's gravitational spreading analog model involved pervasive flow from regions of higher elevation and higher lithostatic pressure toward regions of lower elevation and lower thickened pressure. In the area with higher surface elevations the deformation in the model involves vertical compression (surface subsidence) and horizontal extension; but in the area with lower surface elevations it involves horizontal compression and vertical extension (surface uplift), but how does this happen and what happens in between?

Simple shear (laminar flow with no stretching or shortening in the direction of flow) **is the most popular geological conceptual model for flow in rocks**. Although it has commonly been used to illustrate and analyze gravity-driven lateral flow in mountain belts, it is an inappropriate conceptual model because **simple shear is a special condition that marks the boundary between two quite different flow regimes[5]: extending flow (extension in the direction of flow) and compressing flow (compression in the direction of flow).** The application of this more comprehensive conceptual model for gravity-driven flow in orogenic belts provides important tectonic insights that are not available with the simple shear model. The characteristics of extending flow in lateral gravitational spreading are: horizontal stretching (stretching in the direction of flow), thinning (vertical compression), boudinage and excision of less ductile layers, converging flow lines, and increasing displacement in the direction of flow. The characteristics of compressing flow in lateral gravitational spreading are: horizontal shortening (compression in the direction of flow), thickening (vertical extension), diverging flow lines, and decreasing displacement in the direction of flow. **Deformation in the Cordilleran foreland thrust-and-fold belts bears the earmarks of compressing flow; whereas, the deformation within mid-crustal metamorphic rocks that were exhumed as crustal-scale boudins in the interior of the southern Canadian Cordillera bear the earmarks of extending flow** that occurred before as well as during their tectonic exhumation by Eocene regional dextral transtension.

What we perceive of the deformation within the Cordilleran foreland thrust and fold belt depends upon the scale at which we observe it. Our conceptual models of the nature and evolution of the deformation must be adapted to meet the changes in our perceptions between one scale of observation and another. In the external part of the Southern Canadian Rockies foreland thrust-and-fold belt, slabs of rock that have undergone horizontal displacements of many tens of km as well as associated large rotations generally provide little or no evidence of internal deformation at the scale of a thin section or of a hand specimen. Delicate intricate details of sedimentary and fossil structures are preserved without distortion. However, at the scale of an outcrop, or a larger scale, the supracrustal strata comprise stratified 3-D mosaics of meter-scale to centimeter-scale blocks of rock that are bounded by fractures. The 'fractures' are mainly parallel or perpendicular to the bedding. Some of the 'bedding-perpendicular' fractures are extension fractures that may or may not be filled or coated with carbonate minerals or quartz; some are stylolites that mark 'planes' along which there has been 'pressure solution'; some are polished or slicken-lined shear surfaces on which slicken lines commonly are parallel with bedding. Bedding surfaces may be stylolitic, but they commonly are polished or slicken-lined shear surfaces on which slicken lines are perpendicular to the hinge lines of adjacent folds. Some of the fractures are small faults that are commonly polished or slicken-lined shear surfaces. These small faults are inclined to the bedding, generally at $\sim 30^0$, if they are 'contraction faults', which produce bedding-parallel shortening, or at $>60^0$ if they are 'extension faults', which produce bedding-parallel stretching. At the outcrop scale and beyond, the fracture-controlled rheology of the deformed stratified rock mass can be geo-poetically described as "**cataclastic ductility**". Distortion of formation boundaries, and of individual beds, has been accomplished by the integrated opening and closing across, and slip along, networks of discrete fractures, some of which are small faults that offset the bedding. **These small faults show preferred orientations with respect to the bedding surfaces, but not to gravity. Apparently because the bedding surfaces were surfaces of low shear strength, and slip along the bedding reduced the shear stress parallel with the bedding, thus making the local orientation of the principal stresses within the stratified rock mass parallel and/or perpendicular to the bedding**.

On the scale of a mountainside, **compressing flow deformation within these un-metamorphosed supracrustal strata is expressed as listric, concave-upward, thrust faults and thrust-related, flexural-slip, chevron-style and concentric-style folds**. It is noteworthy that **tip lines of blind thrust faults that have propagated along the axial zones of kinematically elegant chevron folds terminate at tip lines that form centre-lines for the curvature within overlying concentric folds.**

On a regional scale the thrust faults all 'die out' along strike. The northeastward-tapering wedge-shaped mass of supracrustal strata as been shortened, thickened, and displaced northeastward by thrust-fault displacements that are distributed over a myriad array of discrete displacement discontinuities, all of which are embedded within an otherwise coherent mass of rock. These listric (concave upward) displacement discontinuities (faults) are mostly linked downward to a basal detachment zone close to the top of the underlying Paleoproterozoic basement. When viewed at a scale that is much larger than the largest thrust fault, the deformation within the foreland thrust-and-fold wedge involves large distortion without loss of overall cohesion: and therefore, it is a type of flow.

The mapped lengths of the larger thrust faults range from 10's of km to about 100 km; and there are high lateral gradients in the amount of displacement on the individual thrust faults. I**ndividual incremental displacements on the thrust faults evidently propagated as "smeared out" dislocations. The maximum velocity of propagation of a displacement on a large fault must have been small compared to the total area of the fault that was affected by that incremental displacement; and thus only part of the**

total area affected by the incremental displacement was undergoing displacement at any one time. Therefore, the so-called "mechanical paradox of large overthrusts" arises from an unrecognized fallacious assumption in the conceptual model that was used to analyze the mechanics of overthrusting, namely that displacements on thrust faults occur simultaneously over the entire fault.

Viewed at the proper scale, the **flow within the Cordilleran foreland thrust-and-fold belt was analogous to the flow of the Pleistocene ice sheets** that covered most of the interior of Canada. However, because of the much greater specific gravity and thickness of the deformed and displaced rocks, **the Cordilleran foreland thrust-and-fold belt induced a much larger isostatic flexure in the continental lithosphere than that which was caused by the ice sheets. This flexure created a foreland basin that subsided and trapped the Cordilleran detrital outwash, but only at times when the thrust-and-fold belt was thickening and spreading laterally**. When the thrust-and-fold belt was not rising and spreading laterally there was no subsidence to trap sediment within foreland basin, and consequently the sediment eroded from the mountains by-passed the foreland basin, as it does today. According to this conceptual model, gaps in the sedimentary record in the foreland basin deposits are associated with times when thrusting and related folding were not occurring. This is contrary to previous conceptual models, which did not recognize isostatically induced subsidence, and therefore interpreted times of erosion as times of uplift and mountain building.

My **balanced (retro-deformable) structure sections are based on the concept that whatever occurs on one side of a fault must have a compatible counterpart on the other side**. Thus, what is discernible along the hanging wall of the thrust fault has been used to predict what exists out of view along the footwall; and likewise what is discernible along the footwall of a thrust fault has been used to reconstruct what has been eroded from the hanging wall. These retro-deformable structure sections have been used to construct **palinspastically restored structure sections** that portray the configuration of the remaining (i.e. uneroded) deformed strata, and the locations where they existed prior to thrusting. Sets of palinspastically restored retro-deformable structure sections have been used to construct **palinspastically restored maps** that portray the locations, configurations (isopachs), and structural relationships of the Belt-Purcell, Windermere, and Cordilleran miogeocline sedimentary basins as they existed prior to the thrusting and folding.

Tectonic heredity - reactivation of pre-existing structures during ensuing unrelated episodes of deformation – is best illustrated in the southern Canadian Rockies by the sequential reactivation of faults related to the Paleoproterozoic Vulcan structure, a major northeast-trending crustal suture that marks the northwest side of the Archean Medicine Hat block under southern Alberta. Reactivation of part of the Vulcan structure is responsible for a 225 km dextral offset in the eastern margin of the Cordilleran miogeocline from southeastern British Columbia to northeastern Washington. It also influenced the configuration of the eastern margin of the late Neoproterozoic Windermere basin, and the evolution of the Mesoproterozoic Belt-Purcell basin. Tectonic inversion of sedimentary-basin structural relief occurred when the supracrustal strata in the Belt-Purcell, Windermere, and Cordilleran miogeocline basins were being detached and displaced upward and northeastward across basin-margin ramps and over the flat surface of the craton. The thick (5 – 20 km) sedimentary sequences filling the basins were transformed into very large tectonic culminations. **The orientations of the flanks of these culminations, which were inherited from the orientations of the basin margins from whence the displaced supracrustal strata came, controlled topographic gradients, and thus the directions of lateral gravitational spreading within the foreland thrust-and-fold belt.** The northwest trend of the thrust-and-fold belt in northern Montana and southern Canada is inherited from the orientation of the Belt-Purcell basin. The north-south trend of the thrust-and-fold belt in southern Alberta and British Columbia is inherited from this part of the margin of the Cordilleran miogeocline, and the local northeast-trending, southeast-verging thrust-and-fold structures in southeastern British Columbia are inherited from the orientation of the dextral offset in the margin of the Cordilleran miogeocline that was, in turn, inherited from the Paleoproterozoic Vulcan structure.

Most of the northeastward tectonic displacement across the foreland thrust-and-fold belt of the southern Canadian Cordillera occurred during **a Late Cretaceous to Late Paleocene interval of dextral transpression between Laurentia and the Cordilleran accreted terranes. During this interval much of the convergence and tectonic shortening across the southern part of the Canadian Rockies was transformed northward into dextral strike-slip along the Northern Rocky Mountain trench fault zone and related faults** to the west of it, as the amount of tectonic shortening across the southern Canadian Rockies decreased substantially northwestward beyond Yellowhead Pass (~53^0 N). This decrease in tectonic shortening is accompanied by a matching northwestward decrease in the thickness and extent of the Late Cretaceous-Paleocene sediment in the Cordilleran foreland basin.

A regional transition from dextral transpression to dextral transtension that occurred near the end of the Paleocene terminated thrust faulting and related folding within the Canadian Rockies while initiating an episode of early Eocene oblique regional extension and crustal-scale boudinage in the southern Canadian Cordillera. Dextral transtension was transferred southwestward, via oblique, en echelon, crustal-scale boudinage within the south central Cordillera, from the southern end of Tintina-Northern Rocky Mountain trench fault system in the north to the Yalakom-Ross Lake fault zone in the southern Coast Mountains and the northern Cascade Mountains in the south. During the Late Paleocene-Early Eocene episode of crustal-scale boudinage, the basal detachment zone of the foreland thrust-and-fold belt was exhumed isostatically (in response to eastward extensional removal of overlying supracrustal strata) from depths of >30 km (8 – 10 kb) within three, en echelon, 35 km thick, crustal-scale boudins (the Monashee complex, the Valhalla complex, and the Priest River complex) in which it now occurs just above and/or just below the present bedrock surface. The detached supracrustal strata were tectonically juxtaposed over an adjacent zone of ductile necking in which the Paleoproterozoic/Archean crust is only ~ 15 km thick. This zone of crustal necking is gradational eastward into the adjacent ~35 km thick undeformed Paleoproterozoic/Archean crust that underlies the basal detachment of the foreland thrust-and fold belt beneath the southern Canadian Rockies.

Lithoprobe geophysical imaging has demonstrated that under south-central British Columbia the Moho is relatively flat and at a depth of 30-35 km between the zone of crustal necking adjacent to the Rockies in the east and the southern Coast Mountains and northern Cascade Mountains in the west; whereas there are variations in structural relief of up to 20 km or more along the top of the Paleoproterozoic/Archean crystalline basement between the tops of the crustal boudins (the tectonically exhumed metamorphic core complexes) and the tops of adjacent zones of crustal necking which are overlain by up to 20 km of supracrustal strata. **The present-day relatively uniform total crustal thickness (depth to the Moho) of 30-35 km under south-central British Columbia evidently is an expression of reciprocal crustal stretching. Crustal boudins of Paleoproterozoic and Archean continental crust were exhumed isostatically by severe horizontal stretching and extensional removal of overlying supracrustal strata, whereas in the adjacent zones crustal necking it is the lower continental crust that is severely stretched and thinned to about 15 km while the overlying supracrustal strata that were not subjected to strong horizontal stretching.** Metamorphic mineral assemblages that are now preserved near the top of the crustal boudins, 35 km above the Moho, formed at depths of up to 20 km or more beneath supracrustal rocks that now reside within adjacent zones of crustal necking. Accordingly, **at the end of the Paleocene, prior to the episode of Early Eocene dextral transpression, the crust under south-central British Columbia was 55 – 60 km thick.**

Although the dextral transtension, crustal boudinage, and reciprocal crustal stretching ended about 35 – 40 Ma ago, this part of south-central British Columbia, which now lies within the back-arc region of the Cascadia subduction system, is still a region of abnormally high heat flow and shallow asthenosphere. **The sustained high heat flow in the back-arc region of the Cascade subduction system has been attributed to retrograde thermal convective upwelling in the back-arc asthenosphere that is coupled, by mantle corner flow, to the downward flow of subducting oceanic lithosphere in the Cascadia subduction zone**. This conceptual model of supra-subduction zone retrograde asthenospheric flow coupled to the downward flow in the subduction zone provides a simple explanation for several aspects of the Mesozoic-Cenozoic evolution of the southeastern Canadian Cordillera, including the initial stages of Mesozoic terrane accretion along the western margin of Laurentia, which involved the closure of the Slide Mountain back-arc basin and ensuing the obduction of Slide Mountain terrane over the margin of the Cordilleran miogeocline, both of which occurred behind the active Quesnellia magmatic arc; and then the juxtaposition of Quesnellia, as a tectonic flake, over the outboard margin of Laurentia. The model also provides a simple explanation for the convergence between the North American craton and the magmatic and core of the Cordilleran orogen that gave rise to the Late Jurassic to Late Paleocene horizontal shortening across the foreland thrust-and fold belt. Asthenospheric upwelling in the eastern back-arc region, that is coupled to the retrograde corner flow over the Cascade subduction zone at the west side of the back-arc region may also provide dynamic uplift that accounts for the abnormally high topography in the southern Canadian Rockies and adjacent Columbia Mountains.

Balanced geological maps of both sides of fault surfaces are helpful in the analysis and elucidation of thrust faulting. A comparison of structure-contoured balanced geological maps of both the hanging wall and the footwall of the Hosmer thrust fault has been used to illustrate the changing three-dimensional relationships of fault displacements associated with changes in the direction of lateral gravitational spreading during the lifetime of the fault. **A geo-poetical conceptual model of the effects of superposition of early Eocene dextral transtension on late Cretaceous-Paleocene dextral transpression is illustrated using augen-shaped fault windows into the basement where major normal faults offset a structure-contoured regional geological map of the footwall of the basal detachment fault of the entire foreland thrust-and-fold belt.** The map extends northward from ~48^0 to 54^0, and westward beyond the culminations of three crustal boudins that locally expose rocks that are just below or very close to the basal detachment in the Monashee metamorphic complex, the Valhalla metamorphic complex, and the Priest River complex.

Tectonic wedging and delamination, which occurs at all scales from the microscopic to the lithospheric, is the compressing flow counterpart of the boudinage and excision that are associated with extending flow. It involves intrusive compressing flow and it occurs at various places in the Canadian Cordillera. At the ‘blind’ tip-line of the foreland thrust-and-fold belt, there is wedge-shaped thrust-duplex with a foreland-vergent floor thrust and a retro-vergent roof thrust, that is known locally as “the triangle zone”. Growth and propagation of the thrust-duplex wedge involves coordinated slip on the floor thrust, the roof thrust, and the imbricate thrusts that link one to the other as the wedge delaminates the stratigraphic succession within which it is propagating. **Tectonic wedging and delamination at a crustal- or lithospheric-scale, in combination the conceptual model of retrograde thermal convection in the asthenosphere that is linked to the mantle corner flow associated with the downward movement of the subducting oceanic lithosphere provides a simple explanation for the collapse of the Slide Mountain back-arc basin, the obduction of Slide Mountain terrane over the margin of the Cordilleran miogeocline, and the juxtaposition of Quesnellia, as a tectonic flake, over the outboard margin of Laurentia.**

It has been 56 years since I first read Walter H. Bucher inspiring paper on “Role of Gravity in Orogenesis”. My appreciation of the topic has evolved significantly in that time. Therefore, I will conclude with a brief summary of my current geopoetical view of the:

ROLE OF GRAVITY IN OROGENESIS

- **Planet earth is a gravity-drive heat engine.**
- **Gravity-driven thermal convection in the molten outer core generates the magnetic field and heats the base of the mantle.**
- **Because of gravity, buoyant hot rock rises vertically through the mantle.**
- **Because of gravity the buoyant mantle rock diverges symmetrically as it approaches the surface and then flows horizontally, forming new oceanic**

crust and oceanic lithosphere that is itself constrained by gravity to flow parallel with earth's spherical surface, as evolving tectonic plates.

- **Because of gravity, cooler, thicker, stiffer negatively buoyant spherical plates of oceanic lithosphere are bent and sink below the spherical surface of the earth, thus forming an oceanic trench and also a magmatic belt within the over-riding plate.**
- **Thickening of buoyant crust at convergent plate boundaries produces gravity-driven isostatic rock uplift and thus the topographical relief that drives lateral gravitational spreading, which includes both extending flow deep within cores mountain belts, and compressing flow along the margins of mountain belts.**

[1] Carey, S.W. (1962). "*Scale of geotectonic phenomena*", Journal of the Geological Society of India, v. 4, p. 97-105

[2] Carey, S.W. (1958). "*The tectonic approach to continental drift: Symposium*, University of Tasmania, Hobart, 1956, p. 177-358.

[3] Hess, H. H. (1962). "*History of Ocean Basins*": in *Petrologic studies: a volume in honor of A. F. Buddington*., A. E. J. Engel, Harold L. James, and B. F. Leonard (editors), Geological Society of America, Boulder CO., p. 599–620. (See also : Hess, H.H. (1960). "*Evolution of ocean basins"*: Report to U.S. Office of Naval Research. Contract No. 1858(10), NR 081-067. pp. 38.)

[4] Bucher, W.H. (1956). "*Role of gravity in orogenesis*", GSA Bulletin, v. 67,n. 10, p1295-1318.

[5] Price, R.A. (1972). "*The distinction between displacement and distortion in flow, and the origin of diachronism in tectonic overprinting in orogenic belts*"; Proceedings, 24th International Geological Congress, Montreal, Canada, Section 3, p. 545-551.

Along-strike variation in detrital zircon hafnium isotope compositions from the Chugach-Prince William terrane, Alaska

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The Chugach-Prince William Terrane (CPW) is a Late Cretaceous to Paleocene accretionary complex that spans ~2200 kilometers of the southern coast of Alaska, from Sanak Island in the west to Baranof Island in southeast Alaska. The flysch of the CPW is composed of turbidites that vary from conglomerate, quartzofeldspathic sandstone, volcanic-lithic sandstone and interbedded mudstone. As one of the most outboard terranes in Alaska, understanding the accretion history of the CPW and its subsequent coast-parallel translation should illuminate key elements of the final assembly of the North American Cordillera.

In this study we report 434 integrated U/Pb ages and Hf isotope compositions from four widely separated locations along the arcuate belt of the CPW. Together, the U/Pb ages range from 34 Ma to 2935 Ma with ε_{Hf}(t) values from +17.3 to -31.2; of the 434 zircons we measured, 230 are Precambrian, and 204 are Phanerozoic. We specifically targeted Precambrian zircons from a much larger detrital zircon U/Pb data set (n>2000, Garver et al., this volume), but also include Hf isotope compositions from important Phanerozoic populations present in all samples from the CPW. Zircons from 10 samples (n=1053) of the Shumagin Formation in the Shumagin Islands (our farthest west sampling area) yield U/Pb age populations with peaks at 74, 88, and 160 Ma with only 17 Precambrian grains (Roe et al., this volume). All but two Phanerozoic zircons from the Shumagin Formation yield positive ε_{Hf}(t) values consistent with partial melting of a relatively juvenile source region. This is in contrast to similar-aged zircons from the other three sampling areas (from west to east), Kodiak Island, Prince William Sound, and Yakutat, where ε_{Hf}(t) values range from +11.9 to -26.5 suggesting that Phanerozoic zircons from these areas are crystalizing from melts derived from a heterogeneous source region that includes juvenile and Precambrian crust.

Precambrian zircons from Kodiak and Prince William Sound (PWS) have U/Pb age distributions with major populations at 1810-1870 and 2520-2680 Ma and have ε_{Hf}(t) from +13.9 to –21.1. This is in contrast to the age distribution from Yakutat with modes at 1380-1450 and 1710-1740 Ma, and ε_{Hf}(t) from +11.7 to –3.4. Mesoproterozoic and late Paleoproterozoic (<1750 Ma) zircons from Yakutat, Kodiak, and PWS have ε_{Hf}(t) > -5 and all zircons between 1420 and 1750 Ma have positive ε_{Hf}(t) values suggesting a relatively juvenile source area for the origin of these zircons.

Taken together, the integrated U/Pb and Hf isotope data show that the origin and provenance of detrital zircons from the CPW varies systematically along strike. Phanerozoic U/Pb ages have a strong Coast Mountains batholith signature (Garver et al., this volume) with more juvenile crust in the magmatic source region in the Shumagin

Formation, compared to tectonostratigraphically equivalent rocks in Kodiak, PWS, and Yakutat. The dominance of Mesoproterozoic and Late Paleoproterozoic zircon with slightly negative to positive $\varepsilon_{Hf}(t)$ values in Yakutat appears to correlate well with zircon derived from a southern Laurentia source (i.e. the Mazatzal and Yavapai province) and associated Mesoproterozoic A-type granites.

Provenance and thermal history of the Upper Cretaceous Shumagin Formation, Nagai Island, southern Alaska

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The Chugach-Prince William (CPW) composite terrane is a Late Cretaceous to Eocene accretionary complex exposed for ~2200 km in southern Alaska. Principally composed of deep-water turbidites with abundant quartzofeldspathic and volcanic-lithic sandstones, shale, and basaltic rocks including the Resurrection and Knight Island ophiolite complexes, the CPW is also defined by Paleocene age granitic plutons of the Sanak-Baranof Belt that range in age from ~62 Ma on Sanak Island to 48 Ma on Baranof Island in SE Alaska. The eastern extent of the CPW is defined by the Upper Cretaceous Shumagin Formation exposed on Sanak and Shumagin Islands.

New detrital zircon U/Pb dates (n=1053) collected from ten samples of volcanic-lithic and arkosic sandstones from Nagai Island in the Shumagins confirm that the Shumagin Formation is Upper Cretaceous in age. The maximum depositional ages for ten samples are closely clustered and range from 73-77 Ma. The U/Pb zircon age of an interbedded tuff yields and age of 73.7 ± 1.2 Ma, further confirming the Late Cretaceous age of the Shumagin Formation and suggests that the ages of the youngest detrital zircons in most of the samples are close to the depositional age of these rocks. Collectively, samples from the Shumagin Formation have three main populations of zircon ages with modes at 74, 89, and 161 Ma with variation between samples mainly in the relative number of grains making up these populations. Only 17 out of 1053 grains are Precambrian and range from 1445 – 2760 Ma with all but four of the grains between 1750 - 2000 Ma.

The Phanerozoic age populations match well with those from correlative rocks on Kodiak Island, Prince William Sound, and Yakutat suggesting a source region with an active Late Cretaceous arc built on a mostly Mesozoic age meta-plutonic basement (Garver et al., this volume). The Precambrian ages are consistent with the Paleoproterozoic and Archean modes found in correlative units farther east, and the paucity of Precambrian grains in the Shumagin Formation might say something about along strike variations in the meta-plutonic basement of the Late Cretaceous arc source region. Hf isotopic data on U/Pb-dated Phanerozoic grains showof the Shumagin Formation are dominated by positive $\varepsilon_{Hf}(t)$ values showing that the source is juvenile (see Roberts et al., this volume).

Two new U/Pb dates from the Shumagin Batholith, part of the Sanak-Baranof Belt, are 61.7 ± 0.7 Ma and 62.6 ± 0.7 Ma, which we interpret as the crystallization age of these rocks. These dates confirm that the intrusion and crystallization of the Sanak-Baranof Belt, attributed to the passage of a trench-ridge-trench (TRT) triple junction, occurred in the early Paleocene in this part of the CPW. Detrital zircon fission track (ZFT) dates yield cooling ages of 58-54 Ma and appear to show variable amounts of overprinting related to intrusion of the Shumagin Batholith, and slab window heating associated with passage of the TRT triple junction.

Geology of the Dawson Range – White Gold district, western Yukon: improved constraints on Yukon Tanana terrane architecture

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The Dawson Range is underlain by the basement rocks of the Yukon-Tanana terrane (YTT), intruded and overlain by locally voluminous late Triassic to Tertiary plutonic and volcanic rocks. The central core of the map area is transacted by the mid-Cretaceous Whitehorse plutonic suite (hbl-granodiorite of the Dawson Range batholith (DRB) phase, and bt-monzogranite of the Coffee Creek granite (CCg) phase) and it masks a pre-mid Cretaceous, fundamental tectonic boundary in intermontane geology. On the northeast side of the DRB, typical YTT rocks are exposed, comprising a thoroughly deformed and metamorphosed pre-Devonian to Permian basement complex. Pre-Devonian quartzite, psammite, marble and amphibolite (Snowcap assemblage; SCA) form the oldest rocks. The SCA is locally in structural contact with amphibolite that is interpreted as the arc-related Devonian to Mississippian Finlayson assemblage. The SCA and Finlayson assemblage are intruded by Permian granites of the Sulphur Creek suite. Early Mississippian Simpson Range plutonic suite is restricted in the map area to the northwest extremity, and is in thrust contact on top of the Snowcap assemblage and Permian intrusions. Occurrences of the Late Triassic Pyroxene Mountain suite occur only in the hanging wall Simpson Range suite rocks, leading us to conclude that the thrust is post late Triassic. On the south side of the CCg, a different thrust of similar scale separates amphibolite facies schist and Permian augen granite from greenschist facies metavolcanic Klondike Schist, indicating that thrusting postdates peak metamorphism. Our work demonstrates that the Permian magmatic portion of YTT is much more widespread than previously known, and extends from the Alaska border in southwest Stewart River map sheet some 180 km to the east-southeast into Carmacks map sheet.

On the southwest side of the DRB, host rocks are dominated by amhibolite facies siliciclastic rocks of the Scottie Creek formation and derived partially melted migmatic paragneiss, that have similar compositional character as the SCA to the northeast. However, these rocks lack Permian intrusions, and are spatially associated with metaplutonic rocks (Baker orthogneiss) and metavolanic rocks (White River formation) that are latest Devonian, and distinctly older than the typical rocks of YTT to the northeast. The southeast domain is intruded by the Late Triassic Snag Creek gabbro suite that is distinct from the Pyroxene Mountain suite on the northeast side of the map area. Along the northern margin of DRB, we have mapped several lozenges of peridotites that we interpret as marking the thrust contact between the White River assemblage and typical YTT to the northeast. Snag Creek gabbro is restricted to the White River assemblage, leading us to interpret this thrust as a post-late Triassic fundamental terrane boundary. This boundary appears to have focussed the location of the Whitehorse plutonic suite, as well as the Late Cretaceous Casino suite and Prospector Mountain suite, and their associated intrusion related mineralization. The large scale structures were episodically reactivated and overprinted by mid to late Cretaceous structures that have long strike length, but not necessarily have significant offset (e.g., Big Creek Fault).

Cretaceous tectonism, mineralization and hydrocarbon trap formation of the northern Canadian Cordillera: results from zircon (U-Th)/He thermochronology

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The northern Intermontane terranes of the Canadian Cordillera are dissected by a series of diachronous dextral strike-slip faults, including the Cretaceous Teslin fault possessing moderate displacement (~100 km) and the major Tertiary Tintina fault with >400 km displacement. The Teslin can be traced down to 7-8 seconds (~20 km) in seismic profiles and likely originated as a SW-directed thrust fault during the Jurassic which has been reactivated as a strike-slip fault in the Cretaceous. Jurassic cooling and exhumation of the middle crust now exposed across the central Yukon Cordillera has been slowly coming to light. We suggest unroofing is likely more widespread and long-lived then previously documented. Thirty Paleozoic and Mesozoic granitoids from the northern termination of the Teslin fault were selected for (U-Th)/He zircon thermochronology and only samples that exhibited typical igneous zoning and lack metamorphic overgrowths were analyzed. Analyses yield robust and reliable ages for each sample, which can be divided into three fault-parallel corridors: 215-130 Ma, 115-90 Ma, and 70-55 Ma. No clear pattern emerges when comparing age versus elevation, grain size, or mineral chemistry. The Klondike Plateau and rocks directly west of the Tintina fault record Jurassic cooling. The youngest domainal ages are proximal to voluminous Early to Mid-Cretaceous plutons and fault splays of the Teslin system, where structures with overall small displacement are associated with gold and copper-gold deposits. The remaining structural-age corridor can be resolved into a SW-directed extrusion wedge geometry, exhuming a large portion of the Yukon-Tanana

terrane during Albian-Cenomanian tectonism. In the Cordilleran foreland front range of the Northwest Territories, 500 km to the northeast, detrital ZHe ages from ten Neoproterozoic units record contemporaneous cooling during the Late Cretaceous. Moreover, a subset of these samples serves to resolve the timing of movement on the eastern-most Cordilleran thrust fault, the Plateau Fault, to be Cenomanian. This appears to correspond with a significant Late Albian-Early Cenomanian erosional event modeled through basin borehole AFT data. Our new ZHe dataset across the northern Canadian Cordillera demonstrate a strong coupling between hinterland and foreland tectonism during the mid-Cretaceous. Protracted terrane accretion and transpression / transtension drove the exhumation between the Tintina and Teslin faults which also resulted in mineralization. Synchronous and far-field convergence and thrusting inboard caused basin inversion and provided the structural traps required for hydrocarbon reservoirs.

Pre-ice age 'Bell super-river' of northern Canada and the Early Miocene (22-17 Ma) beginning of the Grand Canyon

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Late Oligocene to Early Miocene rifting established the upper Colorado River basin. Uplift of the shoulders of the rifts warped the Paleogene land surface into a broad, southwest-plunging structural basin. The upper Colorado River followed the main axis of the structural basin while tributary rivers followed second-order structural troughs. Oligocene monadnocks that stand above broad, Middle Miocene paleovalleys show that vigorous Early Miocene erosion stripped 1-2 km from the upper Colorado River basin. The immense sediment flux from 22 to 17 Ma required a through-going river several times larger than the modern upper Colorado, as well as an appropriate sediment depocenter. A set of Middle Miocene paleovalleys that cross the Navajo Reservation merge with a broad bedrock terrace that transects the Grand Canyon about midway in elevation between the rim and the river; that terrace may represent the Middle Miocene floor of the Grand Canyon.

I propose that the Colorado River exited the Early Miocene Grand Canyon in the Grand Wash and flowed to the north through rift valleys in the Great Basin and Northern Rockies, where it joined the already well-established 'Bell River' basin in northern Montana. This pre-ice age river basin was first proposed by R. Bell in *Scottish Geographic Magazine* in 1895. It flowed through Hudson Bay and Hudson Strait to the Labrador Sea. Miocene paleovalleys along the reconstructed river basin contain fluvial deposits with provenances that indicate northward flow from the Colorado Plateau to the Great Basin, from the Great Basin to central Montana, from central Montana to Saskatchewan, and from Saskatchewan to the Saglek basin in the Labrador Sea. Balkwill et al. (1990) proposed that a 'super-river' of the scale of the Mississippi fed the Saglek basin, the largest Cenozoic depocenter along the eastern seaboard of North America. The scale of the Saglek basin can accommodate the sedimentary volume denuded from the Colorado Plateau during the Early Miocene. Late Cenozoic glaciation, volcanism, and tectonics segmented the 'super-river' into the modern drainage basins.

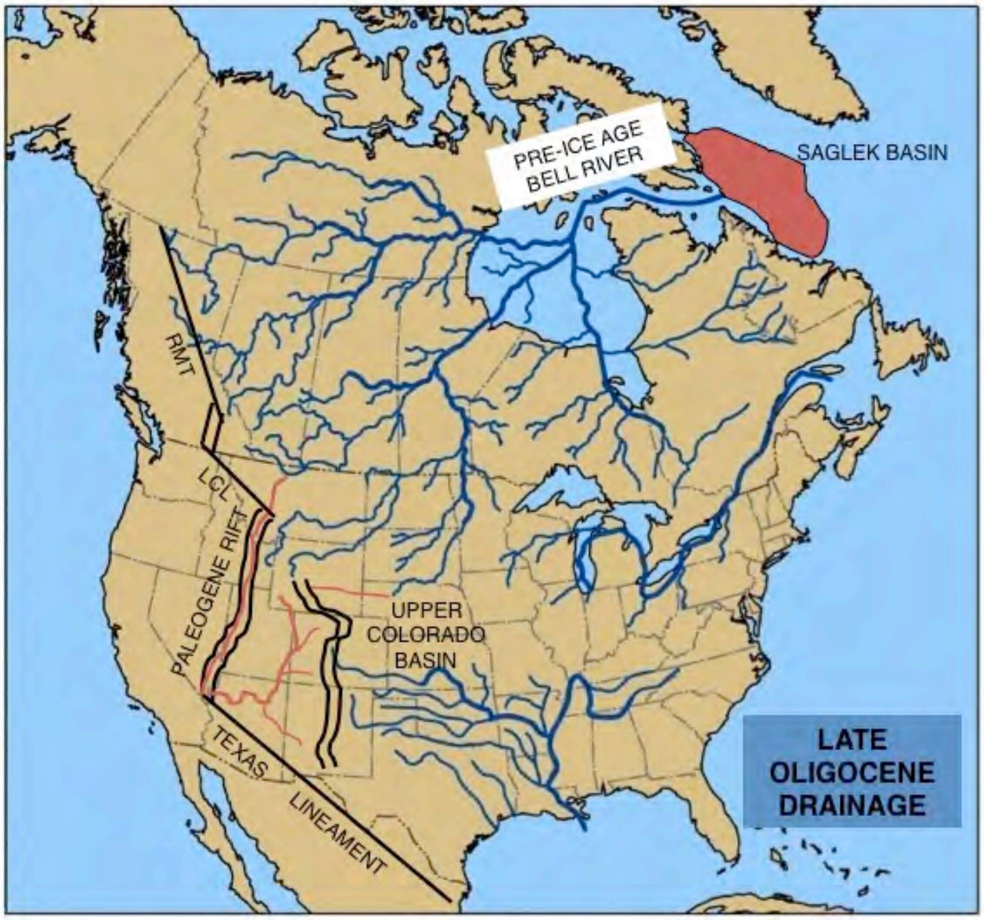

Figure caption: Upper Colorado River basin flows down structural trough between Rio Grande Rift and Paleogene rift. River enters rift and flows through Nevada, Utah, Idaho, and Montana. It joins pre-ice age Bell River system in Canada and flows to Saglek basin in Labrador Sea. US part of drainage was destroyed by tectonics, volcanism, and glaciation after 6 Ma.

The Mesozoic evolution of a transient, distributed high-grade transposing shear zone at the base of a critically tapered orogenic wedge

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In situ U-Pb monazite geochronology coupled with equilibrium assemblage modeling has revealed a pattern of both structurally downward and eastward younging metamorphism and transposition from the Late Permian to mid- Cretaceous within the basal metasedimentary assemblage (Snowcap) of Yukon-Tanana terrane, in the northern Canadian Cordillera. ^{40}Ar/^{39}Ar thermochronology reveals that rocks previously metamorphosed and transposed at approximately 600 °C and 9 kbar (~30 km's depth) in Permo-Triassic were exhumed to upper crustal levels in the Early Jurassic. This event proceeded metamorphism and transposition of rocks to the east within the Australia Mountain and the Finlayson areas under similar *P-T* conditions (7.5 – 9 kbar; 600 – 650 °C) in the Middle to Late Jurassic and Early Cretaceous. Extensional exhumation in the mid-Cretaceous juxtaposed these younger tectono-metamorphic domains against the Permo-Triassic domain that was previously exhumed in the Early Jurassic. These data, which also demonstrate a temporal overlap between deformation in the hinterland (Yukon-Tanana terrane) and the onset of deformation in the foreland fold and thrust belt to the east in the Late Jurassic, are reconciled by a model of ductile underthrusting beneath a propagating orogenic wedge at critical taper. The apparent absence of Late Permian metamorphism within Yukon-Tanana terrane rocks to the east at Australia Mountain and in the Finlayson area is attributed to their position within the colder forearc at this time, contrary to the Permian metamorphic domain that was located in the center of the Permian arc. The transposed nature of the rocks in the Finlayson area and at Australia Mountain, P-T data and monazite geochronology places these rocks at 600 – 650 °C and 25 to 30 km's depth in the Middle to Late Jurassic and Early Cretaceous, respectively. This is interpreted to record episodic underthrusting of these rocks within a distributed basal shear zone at 25 – 30 kilometers depth beneath an east-propagating orogenic wedge. This progressive underthrusting of new material beneath an orogenic wedge in critical taper will induce extension in the rear of the wedge in order regain a stable taper. As underthrusting progressed, rocks previously transposed and metamorphosed within the basal shear zone in the Permo-Triassic were exhumed upward into the upper structural levels of the wedge through structural reorganization within the wedge along compressional and extensional structures. This interpretation is consistent with the observation that different domains of Yukon-Tanana terrane occupied a zone in which a high-grade transposition fabric developed at approximately the same depth (25 – 30 km's), but at progressively younger times, demonstrating a repeated process through time. This explains how rocks previously metamorphosed and transposed in the Permo-Triassic were exhumed by extension immediately preceding compression (transposition) and metamorphism at depth in what is now the Australia Mountain and Finlayson areas.

Three Dimensional Variations of Non-coaxial Shear Strain and Flow within the Okanagan Valley Shear Zone, Okanagan Mountain Provincial Park, BC

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The north-south striking Okanagan Valley shear zone (OVSZ) is a fundamental structural boundary between the sub-greenschist facies hanging wall to the west typified by discrete brittle deformation and the high-grade, penetratively-deformed Shuswap metamorphic complex in the footwall to the east. It is characterised by a < 30° west-dipping, 1.5-2km-thick, strongly prolate, brittle to ductile shear zone consisting of mylonitic ortho- and paragneiss with syntectonic leucocratic intrusions. Previous detailed studies of the OVSZ have focused on constraining the pressure-temperature-time (P-T-t) path of the shear zone utilising U–Pb and $^{40}Ar/^{39}Ar$ age analysis and conventional geothermobarometry. To date, no rigorous quantitative three-dimensional strain analysis has been carried out within the shear zone; only qualitative kinematic indicators such as porphyroclast asymmetry have been utilised for assessing likely flow vorticity. This, in part, has led to discrepancies amongst the models proposed for the exhumation of the Shuswap metamorphic complex from mid-crustal depths during the Eocene. We present detailed 1:10 000 scale mapping of lithology and structures across the Okanagan Valley Shear Zone in and around the Okanagan Mountain Provincial Park, documenting the progressive development of finite strain markers. Oriented samples were collected in approximate vertical sections within the shear zone to identify variations in mineral assemblages, microstructures, and crystal fabric data with respect to structural depth. Using optical microscopy on these samples, we demonstrate the varying recrystallization regimes in deformed quartz minerals down the structural column that can be used to infer the varying temperatures and pressures of deformation across the shear zone.

In addition, complete crystallographic preferred orientation data from the quartz-rich units will be collected using Electron Backscatter Diffraction (EBSD) analysis in conjunction with data acquired using a Fabric Analyser (FA). This will provide quantitative data to characterize the distortional strain, deformation temperatures, and the relative proportion of pure shear versus simple shear across the shear zone. The significance of recording non-coaxial shear in the OVSZ with a significant pure shear component could indicate a degree of vertical thinning and flattening of the shear zone itself during exhumation. By not accounting for any syn-extensional sub-vertical thinning related to the pure shear component, previous studies may have overestimated the horizontal extension accommodated by the shear zone. In addition, the recorded deformation temperatures will be considered together with the predicted creep temperature regimes to create a thermal profile across the structural succession of the shear zone. The integration of these data with previous detailed studies in the flanking regions to the north and south will provide a more complete understanding of the thermo-kinematic evolution of the OVSZ and the exhumation of the Shuswap metamorphic complex from mid-crustal depths.

Belts of Cretaceous, Paleocene and Eocene suprastructure or infrastructure in polydeformed metamorphic rocks in the Thor-Odin – Pinnacles area of southern BC

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The Thor-Odin dome is a basement-cored tectonothermal culmination in the southern Canadian Cordillera containing high-grade metamorphic rocks that were polydeformed in the Late Cretaceous to Eocene (Hinchey et al. 2006, and references therein). There is a tract of rocks south of the Thor-Odin dome that extends, in map view, ~20 km southward to the Pinnacles culmination and Whatshan Batholith. It comprises a heterogeneous tract of polydeformed medium- to high-grade metamorphic rocks and hosts a concordant ~ 2 km thick sheet of Ladybird granite, the South Fosthall pluton near the base of the structural section overlying the dome. The aforementioned tract, along with the Thor-Odin dome, is exposed in the footwall of the Columbia River fault system. The Columbia River fault is a moderately east-dipping, ductile-brittle, normal fault, active periodically between ~55 Ma and 35 Ma (Lorencak et al. 2001), which juxtaposed upper crustal rocks with a generally pre-Middle Jurassic deformation and Late Jurassic to Early Cretaceous cooling history against the above-mentioned medium to high-grade rocks with Late Cretaceous to Eocene cooling histories. This tract of rocks that structurally overlies the Thor-Odin dome has been interpreted as a mid-crustal zone that was exhumed and cooled during Eocene extension (Carr 1991), orogenic infrastructure or a mid-crustal channel that was bounded at the top by the Columbia River fault and was active during the Late Cretaceous to Eocene (e.g. Vanderhaeghe et al. 1999; Glombick 2005; Teyssier et al. 2005; Lemieux 2006; Kuiper et al. 2006; Williams et al. 2006; Gervais and Brown 2011).

These rocks experienced protracted, but not necessarily continuous, deformation and metamorphism throughout the Cretaceous to Paleocene. The timing of tectonothermal events youngs downwards, and metamorphic grade generally increases downwards throughout the structural section into the dome. Based on a data compilation which includes timing of metamorphism, deformation, anatexis in basement rocks, intrusion of leucogranites, and ^{40}Ar/^{39}Ar hornblende cooling dates, there are at least four belts of rocks, or tectonothermal domains, that experienced regional metamorphism, deformation and high temperature cooling at different times.

This complex history can be understood by identifying the time at which belts of rocks were penetratively deforming in the infrastructure, and when they were deactivated, cooling, and being translated in the suprastructure. The structurally highest belt of rocks includes those of the Whatshan-Pinnacles area, which was polyfolded in the Late Cretaceous (pre ~75 Ma) and was located in the infrastructure of the orogen at that time. At ~73 - 64 Ma, the rocks of the central part of the tract (i.e. Plant Creek-South Fosthall area), structurally above the South Fosthall pluton, were penetratively deformed in the infrastructure, whereas the Whatshan-Pinnacles rocks were deactivated acting as suprastructure to the Plant Creek-South Fosthall area between. After ~64 Ma, deformation ended in the rocks of the Plant Creek – South Fosthall area whereas deformation continued in the structurally lowest part of the tract of rocks, beneath the South Fosthall pluton (i.e. Mount Symonds-Cariboo Alp area). After ~58 Ma, the Mount Symonds-Cariboo Alp area was no longer active and lay in suprastructure relative to the deforming rocks in the Thor-Odin dome, which remained in the infrastructure until ~52 Ma when they cooled through ~300^{0}C. It is significant to note that all the rocks from Plant Creek to the interior of the Thor-Odin dome cooled through ~300^{0}C at ~52 Ma. We interpret that as the major period of motion on the Columbia River Fault. The Columbia River fault has a history of periodic reactivation from ~55 Ma to 35 Ma, and this period around 52 Ma represents a major period of activity causing the lower temperature cooling (below ~300^{0}C as mentioned above) of the rocks discussed here.

The Columbia River Fault crosscuts the trace of these aforementioned belts of rocks and the fossil suprastructure-infrastructure boundaries. This includes rocks in the southern part of the region that had cooled below ~500^{0}C (closure T for argon in hornblende) before the Columbia River fault was activated at ~55 Ma. Therefore, the Columbia River fault is a younger, Eocene structure imposed on rocks with a variety of tectonothermal histories. Rocks thought to constitute a mid-crustal flow zone or channel, in fact, comprise several distinct tectonic belts that record Cretaceous metamorphism and cooling in the upper structural levels and three stages of infrastructural flow at progressively deeper crustal levels in the Late Cretaceous, Paleocene and Eocene, respectively, in the deeper part of the structural section.

References

Carr, S.D., 1991a. Three crustal zones in the Thor-Odin - Pinnacles area, southern Omineca Belt, British Columbia. Canadian Journal of Earth Sciences 28, 2003-2023.

Gervais, F., Brown, R.L., 2011. Testing modes of exhumation in collisional orogens: Synconvergent channel flow in the southeastern Canadian Cordillera. Lithosphere 3, 55-75.

Glombick, P.M., 2005. Mesozoic to Early Tertiary Tectonic Evolution of the Shuswap Metamorphic Complex in the Vernon Area, Southeastern Canadian Cordillera. University of Alberta, Edmonton. Ph.D. Thesis.

Hinchey, A.M., Carr, S.D., McNeill, P.D., Rayner, N., 2006. Paleocene-Eocene high-grade metamorphism, anatexis and deformation in the Thor-Odin dome, Monashee complex, southeastern Britich Columbia. Canadian Journal of Earth Sciences 43, 1341-1365.

Kuiper, Y.D., Williams, P.F., Kruse, S., 2006. Possibility of channel flow in the southern Canadian Cordillera; a new approach to explain existing data, in: Law, R.D., Searle, M.P., Godin, L. (Eds.), Channel Flow, Ductile Deformation and Exhumation in Continental Collision Zones. Geological Society of London, Special Publication 268, pp. 587–609.

Lemieux, Y., 2006. Structure, geochronology and thermobarometry of the eastern flank of the Shuswap metamorphic complex in the Upper Arrow Lake area, southeastern British Columbia. University of Alberta, Edmonton, Ph.D. Thesis.

Lorencak, M., Seward, D., Vanderhaeghe, O., Teyssier, C., Burg, J.-P., 2001. Low-temperature cooling history of the Shuswap metamorphic core complex, British Columbia; constraints from apatite and zircon fission-track ages. Canadian Journal of Earth Sciences = Journal Canadien des Sciences de la Terre 38, 1615-1625.

Teyssier, C., Ferré, E., Whitney, D.L., Norlander, B., Vanderhaeghe, O., Parkinson, D., 2005. Flow of partially molten crust and origin of detachments during collapse of the Cordilleran orogen., in: Bruhn, D., Burlini, L. (Eds.), High-Strain Zones: Structures and Physical Properties Geological Society Special Publications, pp. 39-64.

Vanderhaeghe, O., Burg, J.-P., Teyssier, C., 1999a. Exhumation of migmatites in two collapsed orogens: Canadian Cordillera and French Variscides. Geological Society, London, Special Publications 154, 181-204.

Williams, P.F., Jiang, D., Lin, S., 2006. Interpretation of deformation fabrics of infrastructure zone rocks in the context of channel flow and other tectonic models, in: Law, R.D., Searle, M.P., Godin, L. (Eds.), Channel flow, ductile extrusion and exhumation in continental collision zones. Geological Society. London. Special Publications. 268 pp. 221-235.

The missing terrane Bonnetia preserved as clasts in 1.60 Ga Wernecke Breccia

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The Wernecke Breccia is a set of hydrothermal breccias which crosscut the Wernecke Supergroup at 1.60 Ga. The Wernecke Supergroup consists of locally deformed and metamorphosed, fine grained siliciclastic and carbonate rocks. Clasts of the Wernecke Breccia are mainly sourced from the Wernecke Supergroup, however, some of the clasts are lithologically distinct and older than the Wernecke Supergroup and hence are considered exotic. These exotic clasts include igneous and sedimentary varieties and reach sizes of up to 900 x 300 x 30 m. The inferred source for these clasts is a hypothetical terrane called Bonnetia. Bonnetia is considered to have been thrust onto the Laurentian continental margin, shortly before brecciation as part of Racklan orogeny. Bonnetia was entirely eroded prior to deposition of the Pinguicula Group between 1.4 and 1.0 Ga, except for its clasts in the Wernecke Breccia.

Our understanding of Bonnetia is constrained by field relations, petrology, geochemistry and isotopic ages of the exotic clasts. Results show that Bonnetia contained 1) a widespread mafic to intermediate plutonic complex that was at least in part 1.71 Ga 2) mafic volcanic successions (undated); and 3) sedimentary strata, some of which were locally intercalated with the volcanic successions. Geochemical analyses on the igneous clasts indicate that Bonnetia formed in a volcanic arc environment possibly modified by a plume, rift or slab window, and was built in part on continental crust.

Our current research aims to characterize the composition and geological history of Bonnetia by examining the petrology, chemical composition, isotopic character and geochronology of the exotic clasts in Wernecke Breccia. An increased understanding of Bonnetia will clarify the nature and timing of late Paleoproterozoic events in northwestern Laurentia and its adjacent ocean basin, and lead to improvements in paleogeographic reconstructions.

Low-temperature cooling and exhumation of the Olympus-Ossa massif (Continental Hellenides, NE Greece): new insights from zircon and apatite (U-Th)/He thermochronology and thermal modelling

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The NW Aegean is a well-studied region experiencing N-S extension in the rear of the South Hellenic Subduction Zone (Fig.1) (Gautier et al., 1999). There is some consensus that Aegean extension is the result of a southward migration of the Hellenic arc from rollback of the subducting slab (Berckhemer, 1977; Lacassin et al., 2007; Jolivet and Brun, 2010). The migration of this subduction zone creates a free boundary allowing Aegean crust, already thickened from alpine collision, to gravitationally spread in a southward direction (Gauthier et al., 1999, Lacassin et al., 2007). Also impacting this region is the westward escape of Anatolia along the North Anatolian Fault caused by the Middle to Upper Miocene collision of Arabia and Eurasia (Gautier et al., 1999, Lacassin et al., 2007). Recent studies suggest kinematic and mechanical interactions between the Aegean extension and displacement along the right-lateral strike-slip North Anatolian Fault, which propagated westward into the Aegean around 5 Ma (Lacassin et al., 2007, Flerit et al., 2004).

The Olympus-Ossa range is composed of two tectonic windows located in the footwall of a NNW-SSE-trending normal fault (Fig. 1) located in the northwestern part of the Aegean domain and at the westward extent of the North Anatolian Fault (Fig. 2) (Jolivet and Brun, 2010). The Olympus-Ossa range basement belongs to the continental Hellenides, an orogen that was structured throughout the Cenozoic during the convergence between the Eurasian and Apulian plates (Jolivet and Brun, 2010). It is comprised of metamorphosed and deformed Triassic and Cretaceous-Eocene limestones of the southwestern Neotethys Ocean, representing the passive margin of the Apulian Plate (Schermer, 1990; Nance, 2010). During the Early Tertiary alpine collision, this passive margin was overridden by a series of thrust sheets including blueschist metamorphosed continental margin sediments, granitoid gneisses, schists, and ophiolites (Shermer, 1990; Nance, 2010). The core of the modern Olympus-Ossa tectonic windows have been exhumed through divergent low-angle extensional shear zones (Killias et al., 2002) initiated between 23-16 Ma in the Olympus region (Schermer, 1993) followed by high-angle normal faulting during the latest Tertiary-Quaternary (Schermer, 1993; Lacassin et al., 2007; Nance, 2010) at timing and rates that remain poorly constrained. In particular, some authors have suggested that the propagation of the North Anatolian Fault into the NW Aegean Domain around 5 Ma triggered a phase of rapid crustal exhumation in the study area (Lacassin et al., 2007).

To constrain the Late Tertiary-Quaternary upper crustal cooling and exhumation history of the Olympus-Ossa massif, we have analysed 16 bedrock samples collected across the tectonic windows and the Pelagonian domain, using apatite and zircon (U-Th)/He thermochronology. This low-temperature thermochronology method involves measurement of uranium, thorium, and helium to provide single-grain ages at which apatite and zircon crystals reached closure temperatures of 70°C (2.8 km crustal depth) and 180°C (7.2 km crustal depth), respectively (assuming a geothermal gradient of ~25°C/km) (Farley, 2002). Data are currently being processed at the University of California Santa Cruz. Obtained ages will be coupled with unpublished apatite fission-track data and used in the inverse thermal modelling software HeFTy (Ketcham, 2005) to provide a low-temperature cooling history for the region.

References

Berckhemer, H., (1977) Some aspects of the evolution of marginal seas deduced from observations in the Aegean region. In: Biju-Duval, B., Montadert, L. (Eds.), Int. Symp. Struc tural History of the Mediterranean Basins, Split, Yugosla via, 25–29 October 1976. Technip, Paris, 303–313.

Farley, K.A., (2002) (U-Th)/He Dating: Techniques, Calibrations, and Applications. Reviews in Mineralogy and Geochemistry. 47: 819-844

Flerit, F., Armijo, R., King, G., Meyer, B., The mechanical interaction between the propagating North Anatolian Fault and the back-arc extension in the Aegean. Earth and Planetary Science Letters. 224: 347-362

Gautier P., Brun J.P., Moriceau R., Sokoutis D., Martinod J., Jolivet L., (1999) Timing, kinematics and cause of Aegean extension: a scenario based on a comparison with simple analogue experiments. Tectonophysics 315: 31–72.

Ketcham, R.A., (2005) Forward and Inverse Modeling of Low-Temperature Thermochronometry Data. *Reviews in Mineralogy and Geochemistry* 58: 275-314

Kilias, A., Tranos, M.D., Orozco, M., AlonsoChaves, F.M. and Soto, J.I., (2002) Extensional collapse of the Hellenides: A review. Revista de la Sociedad Geologice de Espana. 15:129-139.

Jolivet, L., Brun, J.P., (2010) Cenozoic geodynamic evolution of the Aegean. Int Journal Earth Science. 99:109-138

Lacassin, R., Arnaud, N., Leloup, P.H., Armijo, R., Meyer, B., (2007) Syn- and post-orogenic exhumation of metamorphic rocks in North Aegean. eEarth Discuss. 2: 51-63

Nance, D., (2010) Neogene–Recent extension on the eastern flank of Mount Olympus, Greece. Tectonophysics. 488: 282-292

Schermer, E.R., Lux, D.R., Burchfiel B.C., (1990) Temperature-time history of subducted continental crust, Mount Olympos region, Greece. Tectonics 9:1165–1195.

Schermer, E.R., (1993) Geometry and kinematics of continental basement deformation during the Alpine orogeny, Mt. Olympos region, Greece. J Struct Geol 15:571–591.

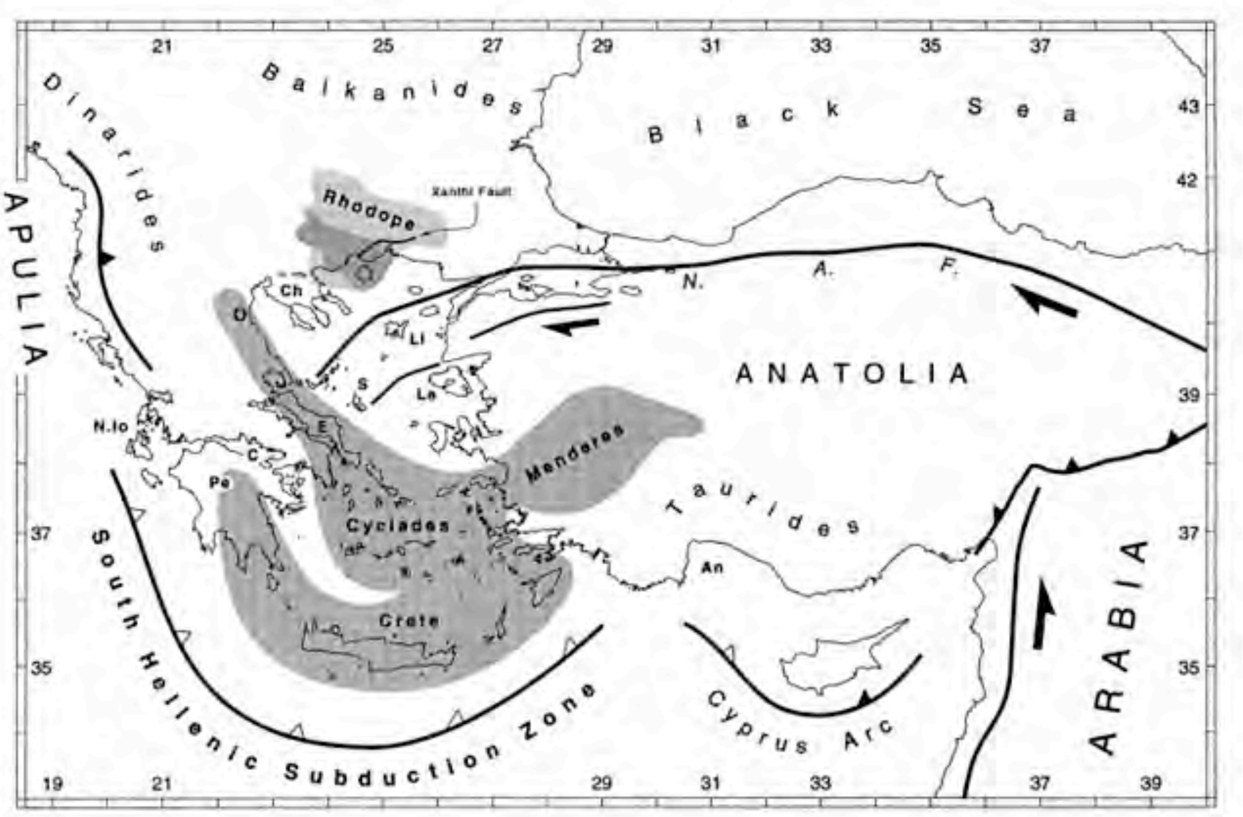

Figure 1: Tectonic setting of Aegean Extension (from Gautier et al, 1999). Abbreviations referenced in the text are as follows, O: Olympus Ossa-Range, N.A.F.: North Anatolian Fault.

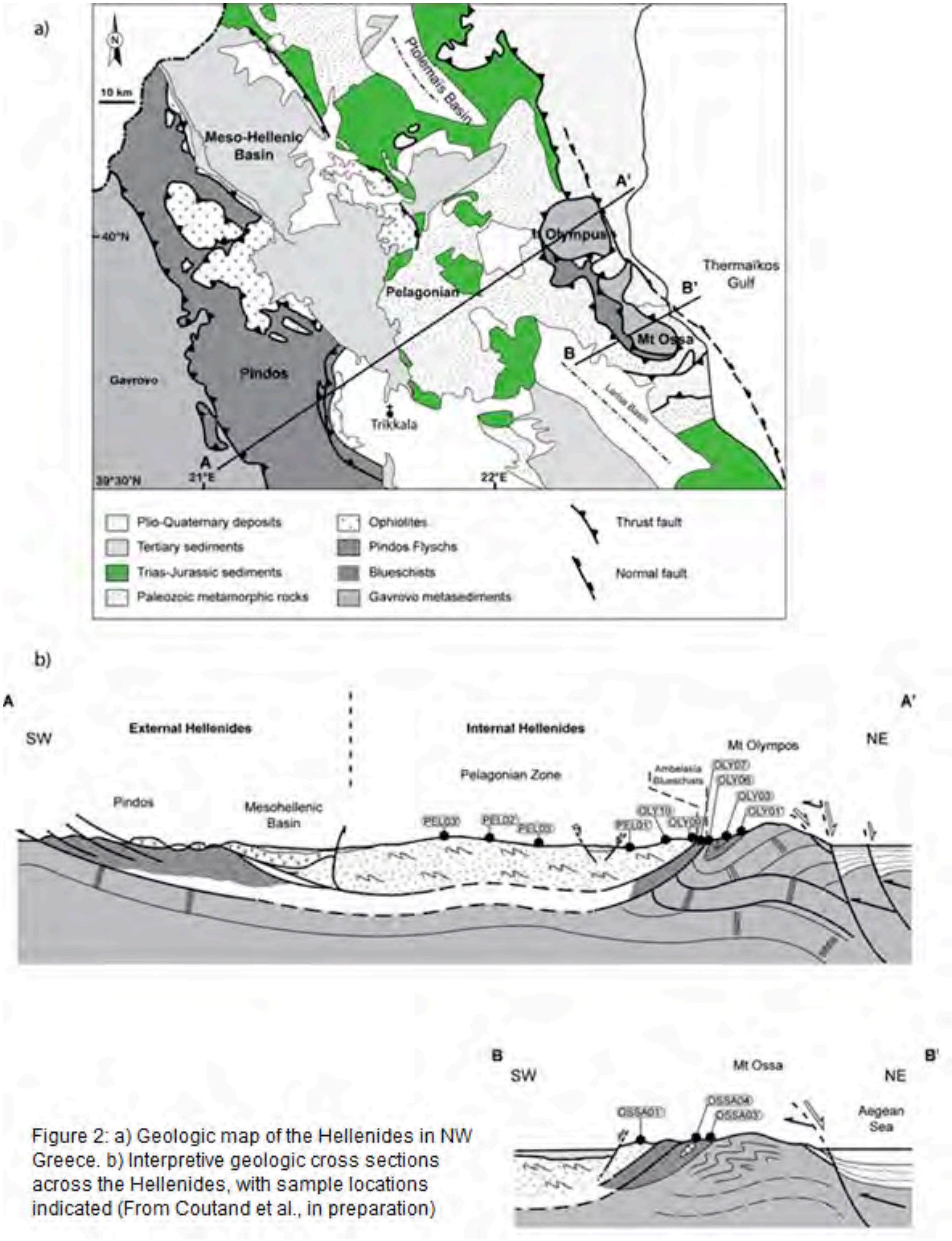

Figure 2: a) Geologic map of the Hellenides in NW Greece. b) Interpretive geologic cross sections across the Hellenides, with sample locations indicated (From Coutand et al., in preparation)

Structural and metamorphic contrasts in the southern Kootenay Arc and Purcell Anticlinorium, southeastern British Columbia.

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The geologically complex region of southeastern BC between Nelson, Salmo, Creston and the Canada–United States border straddles the tectonic interface between the pericratonic metasedimentary and volcanic rocks of Quesnellia to the west, and distal marginal rocks of the ancestral North American margin to the east. This tectonic juxtaposition, and subsequent episodes of magmatism, metamorphism and deformation, occurred during Cordilleran orogenesis in a time interval spanning the Jurassic to Eocene.

The primary structural-tectonic domains in the area are the Purcell Anticlinorium, Kootenay Arc and northernmost extension of the Priest River Complex. The nature of the interface between these three domains is complex, with spatial variations in the grade of metamorphism and intensity of deformation. Two large Eocene normal faults crosscut the study area: the Purcell Trench fault and Midge Creek fault, across which there are marked differences in structural style and metamorphic grade.

The structure of the rocks in the study area is dominated by three folding episodes, spanning the interval from mid-Mesozoic to Eocene. Broadly, there is an increase in structural complexity and intensity of deformation from the southwest to the east and north, corresponding to progressively deeper structural levels and younger structures. Exceptions to these gradational patterns are abrupt decreases in the intensity of deformation going from the footwall to hangingwall of both the Purcell Trench fault and Midge Creek fault.

The regional metamorphic grade in the study area is dominantly greenschist facies, apart from two discrete elongate domains of amphibolite-facies metamorphic rocks which generally correspond with the domains of younger and more intense deformation. In the northern part of the field area, the amphibolite-facies domains meet, forming a southward facing forked isograd pattern. The western domain is parallel to strike and is truncated by the Midge Creek fault. This domain is a continuation of the metamorphic high mapped north of the west arm of Kootenay Lake by Moynihan and Pattison (GSC Current Research, 2008). The eastern domain is approximately parallel to the Purcell Trench fault and transects the strike of the lithological units. This domain continues south into the United States and merges with amphibolite-facies metamorphism in the Priest River Complex. The metamorphism becomes younger from Jurassic in the west, to Late Cretaceous in the east, similar to the age progression of deformation. Thus, the apparently continuous isograd pattern represents an interplay of multiple periods of metamorphism from the Middle Jurassic to Late Cretaceous.

Testing the oroclinal entrapment hypothesis in BC and Yukon

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The distribution of Quesnellia, Stikinia, Yukon-Tanana (YTT) and Cache Creek (CCT) terranes has lead to several hypotheses regarding the emplacement of demonstrably exotic CCT between terranes that have closer affinities to North America. The hook-like map-view geometry of Stikinia, YTT and Quesnellia has been utilized as the principal support for entrapment of the CCT by oroclinal enclosure. Several modern analogues have been proposed to support this model including the Halmahera-Sangihe arc-arc collision in the Molucca Sea and the Banda Arc orocline. Testing the orocline hypothesis directly has been difficult. Identification of polarity of subduction under Triassic Stikinia has been, in part, unsuccessful due to overall poor geochronological coverage and lack of a regional variation in the composition of the arc magmatic rocks. Testing of rotation through paleomagnetism studies has been limited by the lack of undisturbed sites with reliable paleohorizontal indicators and primary magnetization tests.

In this presentation, the underlying assumptions of the oroclinal entrapment model are critically evaluated on basis of modern plate tectonic criteria. A simple tectonic model, consistent with recently published models, is constructed to evaluate plate velocities and subduction rates during formation of the hypothesized orocline. In this model, Quesnellia-YTT-Stikinia form a curvilinear chain during the Late Triassic to Early Jurassic with Stikinia and Quesnellia segments forming linear underformable limbs that rotate about an oroclinal hinge. The folding mechanism is one of tangential longitudinal folding: outer arc of hinge stretches, inner arc shortens, separated by a neutral surface. During the closure of the orocline, absolute velocity of the limbs increases linearly from the hinge to the limbs, requiring different rates of subduction and hence highly variably nature of magmatism over relatively short distances. The model also requires decreasing subduction rates over time and, as the orocline closes, predominantly oblique convergence along the limbs and a progressively decreasing driving force for closure. The absolute upper plate velocity of the limbs depends on their length, the initial angle between Stikinia and Quesnellia and time from orocline initiation to closure. On of the greatest difficulties in this test is defining the location of the rotational hinge as it constrains the length of the limbs. Placement of the hinge along the northwestern-most extent of Stikinia yields velocities that exceed typical modern upper plate velocities along the limb tips. In addition, the length of the limbs, and hence maximum plate velocities, may be underestimated by this hinge because Triassic arc cumulates (e.g., Pyroxene Mountain suite) and arc plutons (Taylor Mountain batholith) occur outside of the defined terrane boundaries. Constraining the rotational motion to Stikinia alone, as suggested by the extant models, greatly compounds this problem as it requires doubling of the absolute plate velocity along the Stikinia segment. The previously proposed modern analogues do not adequately explain the oroclinal entrapment. Recent reconstructions of the Molucca Sea arc-arc collision suggest that the Sangihe and Halmahera arcs evolved above separate subduction zones and did not form an initially straight arc chain. Comparison with other oroclines, such as Banda, does not support the entrapment either, as these oroclines formed by progressive bowing out of subduction zone that lies on the outer arc of the orocline. This configuration cannot lead to entrapment of exotic terranes as accretion would occur external to the orocline. A combination of Permian to Triassic strike-slip and Jurassic thrusting more realistically explains the present distribution of Stikinia-YTT-Quesnellia terranes and the entrapment of CCT.