PanLITHOPROBE Workshop IV:

Intra-Orogen Correlations and Comparative Orogenic Anatomy

J.A. Percival[1], W. Bleeker[1], F.A. Cook[2], T. Rivers[3], G. Ross[4], C. van Staal[1]

[1]Geological Survey of Canada
601 Booth St.
Ottawa ON K1A 0E8

[2]Dept. of Geology and Geophysics
University of Calgary
Calgary, AB, T2N 1N4

[3]Dept. of Earth Sciences
Memorial University of Newfoundland
St. John's, NF A1BB 3X5

[4]Geological Survey of Canada, 3303 - 33rd Street N.W., Calgary, AB T2L 2A7
present address: Box 458, Kula HI 96790

Geoscience Canada, September 2003.

INTRODUCTION

Canada's diverse continental landmass has long been recognized as a collage of distinct orogenic provinces (e.g. Price and Douglas 1972). Work over the past twenty years during the tenure of the LITHOPROBE program has revealed intriguing similarities and differences in orogens formed during the four billion year record of geological time. Armed with common geological, geophysical, geochemical and geochronological observations from each orogen, Earth scientists can now focus on key orogenic parameters to explore how crust- and mantle-forming processes may have changed over geological time. At a recent PanLITHOPROBE workshop, representatives working on the major orogenic provinces of Canada investigated by LITHOPROBE (Cordillera, Appalachians, Grenville, Paleoproterozoic, Superior, Slave orogens; Fig. 1) met to distill and synthesize information from their respective areas of expertise, and to compare orogenic evolution over large tracts of ground and a wide swath of geological time.

Participants were provided with a list of parameters considered to be significant in describing orogenic structure and history, and were asked to compile characteristics (in bold below) of their orogen of interest within this common template. Beginning with physical parameters, the list also included important aspects of orogenic and postorogenic evolution. ***Crustal thickness and its variation*** describe the end result of major crust-forming events, as well as evidence of "scars" produced during the process. ***Crustal structure, composition, seismic velocity and reflectivity*** define many first-order characteristics of the orogenic crust**.** ***Mantle lithospheric structure and composition*** incorporate information from geophysical and xenolith studies constraining the nature of the shallow orogenic mantle. The ***nature of orogen margins*** (e.g. continents) is important in assessing whether orogens had "rigid backstops" and conversely, the degree of orogenic reworking. The ***age and style of rifting*** describe the nature of the continental breakup phase preceding orogeny. The ***nature and age of accreted terranes*** provide insight into processes and paleogeography preceding terrane accretion. The ***nature and age of continental magmatic arcs*** give information on the character and longevity of subduction preceding collision. The ***location and nature of paleo-suture zones*** point to zones where oceanic crust has been consumed. The ***age and style of accretion*****,** including ***collisional geometry,*** explore the three-dimensional form (thin-skinned *vs* thick-skinned), kinematics and duration of collisional processes. ***Current or paleotopography and evolution of P-T conditions through time*** describe vertical crustal movements during orogenesis as well as the movement of heat through the crust. The ***age and style of post-collisional processes*** provide insight into the final processes that have shaped orogenic crust. Variation in the development and/or preservation of these parameters explains many of the differences among Canada's orogenic provinces.

Each working group compiled background material in advance of the meeting then spent 1-2 days preparing a short synthesis (Intra-orogen correlations) presented in a plenary session. The six presentations and accompanying discussions occupied most of a day and led to a list of about 50 discussion topics. These were assembled and digested by a panel (Chris Beaumont, Jeremy Hall, Karl Karlstrom, Ray Price), who then led a discussion on comparative orogenic anatomy on the final day of the workshop.

CORDILLERA

F.A. Cook on behalf of the Cordillera working group (S. Carr, R. Clowes, D. Francis, L. Hollister, R. Hyndman, A. Jones, R. Price, G. Ross, D. Symons, D. Thorkelson)

The Canadian portion of the Cordillera in western North America is one of the classic orogens of the world. It is bounded on the east by a stable craton that was extended during Proterozoic and Paleozoic rifting events and on the west by the actively deforming convergent/transform margin of the eastern Pacific Ocean (Gabrielse and Yorath, 1991). The Cordillera is thus the youngest orogen in which LITHOPROBE worked and portions of two major transects have been devoted to studying it (Southern Canadian Cordillera Transect; 1984-1995 (Cook, 1995), and Slave NORthern Cordillera Lithospheric Evolution, or SNORCLE, transect; 1995-2003; Fig. 1), thus providing a basis for comparisons along strike. Geomorphologic belts are used for simplicity in referencing the descriptions (Fig. 2).

In the southern Cordillera (Price, 1981), the ***crustal thickness*** varies from >40 km in the Foreland Belt to 33-35 km beneath the Omineca Belt. The transition occurs in the vicinity of the southern Rocky Mountain Trench (Fig. 2), west of which the thickness remains uniform to the Coast Belt, where it thickens again by a few kilometres. The northern Cordillera exhibits the same gross crustal structure, except that the thickest crust occurs ~100-150 km east of the deformation front. The 33-35 km crustal thickness of the interior southern Cordillera is commonly explained as a consequence of Paleocene-Eocene extension and associated uplift of mid-crustal rocks. The explanation for the thin crust in the northern Cordillera is more problematic as regional late extension has not been recognized there and the regional metamorphic grades of surface rocks do not indicate similar large uplifts. Estimates of ***lithospheric thickness*** range from 50-60 km in the Intermontane Belt, where high heat flow is interpreted to represent high temperatures at depth, to >100 km in the Foreland Belt and east of the Cordillera.

The oldest rocks in the Cordillera (~2.1 Ga) are present in uplifts that were exposed as a result of post-contractional extension and provide a temporal link with the sub-Phanerozoic rocks of the western Canadian Shield. These are generally interpreted as remnants of the cratonic crust that was rifted during Mesoproterozoic extension, the eastern limit of which may be reflected in a prominent series of west-facing crustal-scale homoclines beneath the Foreland Belt. The ***nature and style of*** the earliest ***rifting*** is preserved in thick strata of the Wernecke Supergroup (*ca.*1.8-1.7 Ga) in the north and the Belt-Purcell Supergroup (*ca.* 1.5- 1.4 Ga) in the south and may have been diachronous from north to south. Whether these rocks were deposited in deep, intracratonic basins, or whether they were open to large oceans is still debated. There is evidence for periods of pre-Cordilleran contractional deformation within these and other Precambrian strata throughout the Cordillera, but the regional extent and paleogeographic significance of such deformation are uncertain. Neoproterozoic - Cambrian rifting initiated the development of the westward thickening Cordilleran miogeocline.

Continental basement and cover rocks are traced in the crust beneath much of the Cordillera. In the north, the SNORCLE reflection data have been interpreted as having images of the thick supracrustal strata and their basement projecting as far west as the BC-Alaska border (Cook et al., in press). In the south, some basement rocks that were metamorphosed to amphibolite grade are now exposed as a result of post-contractional extension (e.g., Parrish et al., 1988). Seismic reflection data from the southern Cordillera have been interpreted to indicate that North American basement tapers westward as far as the Fraser fault (Cook, 1995).

For the most part, therefore, ***accreted terranes*** appear to be thin and confined to the crust. In some areas of the northern Cordillera, the surface geology and seismic profiles indicate terrane flakes that are only a few kilometres thick; other terranes may comprise much of the crust. In contrast to many other orogens, however (e.g., Newfoundland Appalachians), ophiolites are either non-existent or only fragmentary throughout the Cordillera. Terranes are thus defined by distinct paleontological, stratigraphic, structural, metamorphic, and igneous histories, but ***suture zones*** are often manifested solely as faults. In some regions, the stratigraphic relationships between the North American miogeoclinal rocks (Neoproterozoic-Early Mesozoic) and adjacent accreted terranes are ambiguous. If strata are correlative from one to the other, such relationships may indicate there was no major terrane; if they are not correlative, the accretion boundaries are cryptic.

Magmatic activity has punctuated the development of the Cordillera since the Paleoproterozoic. Evidence of early magmatic episodes is a key tool for regional correlations of Proterozoic stratigraphic sequences because both the igneous rocks and their detritus provide age constraints. Paleozoic magmatism was sparse along the North American margin, but many of the accreted terranes have distinct magmatic signatures. Regionally extensive magmatic activity accompanied two major accretionary episodes, in the Jurassic-Early Cretaceous and the Late Cretaceous-Paleocene, during which widespread arc magmas and granites intruded through both accreted rocks and underlying North American rocks (e.g., Guichon Creek, Cassiar, etc.). Postcontraction regional extension in the south during the Eocene was accompanied by the last phase of orogen-scale magmatism.

Distinct differences in geological evolution between the northern Cordillera and the southern Cordillera date back to the Mesoproterozoic record of diachronous extension. They are, however, emphasized by ***post-collisional features*** such as variations in structural evolution, magmatism, level of exposure, and neotectonics. For example, strike-slip faults, such as the Tintina-Northern Rocky Mountain Trench, were associated with transcurrent displacement following accretion in the north. This motion was probably transformed southward into coeval contractional structures of the Foreland Belt. In contrast, regional lithospheric extension (Paleocene-Eocene) in the south was partly coeval with, and/or followed by, limited strike slip faulting. Throughout the Cordillera, therefore, the magnitude of orogen-parallel terrane displacement (e.g., "Baja BC") is at present unresolved with large estimates (1000-3000 km) determined from paleomagnetic measurements, and considerably more modest estimates determined from visible structures.

Post-collisional Late Tertiary to Holocene mafic magmatism occurs in several localities throughout the Canadian Cordillera. The largest centres, which may be associated with back-arc extension, are located in northern British Columbia and the Yukon. The widespread small centres are more likely related to fractures. Significantly, ***mantle*** xenoliths throughout the Cordillera have Proterozoic Rb/Sr and Re/Os ages indicating that whatever has happened to the crust during accretion and contraction, the underlying old mantle is still present.

Along-strike differences between north and south are also apparent in some geophysical signatures such as the electrical conductivity of the crust (more resistive along the SNORCLE transect profiles than along the southern Cordillera profiles), heat flow (generally higher in the north), and Neogene tectonism (more earthquakes in the north). Some of these differences may be due to variations in the initial state of the Proterozoic margin; some may be due to variations in convergence during orogenesis, and some may be due to variations in convergence today. A challenge for continuing analyses of the LITHOPROBE and other data sets will be to determine the relative importance of each.

NORTHERN APPALACHIANS

C. R. van Staal on behalf of the Appalachian working Group: C. Beaumont, S. Castonguay, J. Hall, R. Jamieson, G. Jenner, S. Lin, B. Murphy and A. van der Velden.

The Canadian Appalachians (Maritimes and Newfoundland) are an example of a long-lived (*ca.* 250 m.y.) Paleozoic accretionary orogen, punctuated by accretion of small oceanic terranes and four major oblique collisional events: Taconic, Salinic, Acadian and Alleghenian. The first three orogenic events are mainly the result of the successive arrival of four microcontinents (Dashwoods, Ganderia, Avalonia and Meguma) at the Laurentian margin (Fig. 3), which was thus expanding oceanwards with time (van Staal et al., 1998; Waldron and van Staal, 2001 and references therein), whereas the Alleghenian orogeny was due to continent collision during final closure of the Rheic Ocean. Alleghenian deformation in Newfoundland is mainly concentrated along major strike-slip faults (e.g. Cabot Fault) and to a first approximation can be ignored elsewhere on the island.

The Canadian Appalachians (Fig. 3) are imaged with deep seismic reflection lines acquired along several marine transects and two major on-land profiles across Newfoundland (Fig. 1), the results of which were earlier discussed by Marillier et al. (1989), Quinlan et al. (1992) and Hall et al. (1998). The two on-land transects (Fig. 4) were reprocessed by van der Velden and Cook (2002a).

The Canadian Appalachians are bounded to the west by the ***Laurentian craton***, where little or undeformed Paleozoic sediments overlie a dominantly Grenville-age basement. The Humber Zone (Williams, 1979) represents the peripheral part of the Laurentian craton that was involved in Appalachian orogenesis.

Crustal thickness in the Canadian Appalachians varies from 45 km beneath the Laurentian craton to 30-35 km beneath the Central Mobile Belt (Dunnage and Gander zones), to 40 km beneath the Avalon Zone. Thus the crust is the thinnest beneath the CMB, which was most affected by deformation, metamorphism and magmatism. Since evidence for syn-or post-accretion extension in the CMB is sparse, this feature may be due to the pre-accretion, thin nature of the crust of the oceanic terranes and microcontinents amalgamated in the CMB (Ellis et al., 1998). The Meguma Zone, absent in Newfoundland, has a thickness of about 30-35 km in Nova Scotia. The Moho beneath the Newfoundland CMB displays both across- and along-strike relief. Beneath the Gander zone the Moho shallows and reflective upper mantle layers appear to thin along strike towards the northeast, coinciding with an offshore Carboniferous basin in Notre

Dame Bay (Chian et al., 1998). In addition, there is a marked lateral increase in seismic velocity in the lower crust along the same section, suggesting the presence of mafic rocks below this basin. These structures suggest a relationship between localized Carboniferous extension and mafic underplating. Hence, if correct, the seismic Moho beneath the CMB is largely a deformed, pre-Carboniferous structure. Other high-velocity layers possibly related to underplating occur at the edge of the Laurentian craton and beneath the Magdalen Basin southwest of Newfoundland. Prominent, west-dipping reflections of Gander Zone lower crust continue from the southeastern end of the transect at least as far west as the Red Indian line (Fig. 3) and project into the mantle (Fig. 4). The mantle reflections have been interpreted as subduction scars formed during Siluro-Devonian, west-directed underthrusting of Ganderia and Avalonia beneath Laurentia (van der Velden and Cook, 2002a). This is consistent with geometrical and relative age relationships between the reflection fabrics and known Siluro-Devonian faults. Interpretations of the origin and age of the prominent lower crustal reflectivity fabric beneath Ganderia range from largely due to syn-collisional shearing (e.g. Ellis et al., 1998) to an inherited, pre-collisional layering (van der Velden and Cook, 2002a).

Evidence of a major ***rifting and opening of an ocean*** is well preserved in the Humber Zone. Rift-related clastic sediments thicken toward the east, and associated rift-related magmatism took place intermittently between 615 and 550 Ma. A transgressive sequence overlying the rift clastics indicates a rift-drift transition near the base of the Cambrian (*ca.* 540 Ma). The rift-drift event relates to the departure of the peri-Laurentian Dashwoods microcontinent rather than creation of the Iapetus Ocean, which is purported to have opened earlier (Waldron and van Staal, 2001). Evidence related to the age and style of rifting of Ganderia, Avalonia and Meguma from Gondwana is poorly preserved in the sedimentary record, although an independent drift across the ocean(s) is suggested by geological, fossil and paleomagnetic data.

The nature and age of accreted oceanic terranes. The Dunnage Zone of the Northern Appalachians, and Newfoundland in particular, contains the remnants of several unrelated, thin, allochthonous, Iapetan oceanic terranes. Paleomagnetic and fossil data suggest they can be separated into peri-Laurentian (Notre Dame Subzone) and peri-Gondwanan (Exploits Subzone) terranes, which formed on opposite sides of Iapetus and are separated by the Red Indian Line. The 507-489 Ma Baie Verte oceanic tract and the 480-460 Ma Annieopsquotch accretionary tract

(AAT) (van Staal et al., 1998) comprise oceanic terranes preserved in the Notre Dame Subzone. The peri-Gondwanan oceanic terranes of the Exploits Subzone have a similar age range (513-460 Ma). The accreted oceanic terranes invariably consist of suprasubduction zone rocks (i.e. forearc, arc and back-arc). True MORB-type oceanic crust is not preserved anywhere. Accretion of the oceanic terranes to continental crust was mainly characterized by mélanges and localized deformation. Accretion of the Dashwoods microcontinent to Laurentia produced the Taconic Orogeny (*ca.* 475-465 Ma), which caused significant shortening and metamorphism of the magmatic rocks of the Notre Dame arc built on the Dashwoods. Accretion of the Dashwoods microcontinent was followed rapidly along its eastern margin by 470-460 Ma accretion of the AAT, and the 455-450 Ma arrival of the Victoria-Exploits arc, which was built on the leading edge of Ganderia. This latter collision produced the Red Indian Line ***suture zone,*** characterized by duplex-style thrust complexes, oblique reverse ductile shear zones, local folding and mélanges, and continued deformation and metamorphism of the Dashwoods and Humber zones. After accretion of the Victoria-Exploits arc, deformation related to closure of the Exploits back-arc basin to the east juxtaposed both sides of the basin along the Dog Bay Line (Figs. 3, 4) during the *ca.* 430 Ma Salinic Orogeny. This collision produced both high-level structures (e.g. mélanges) and metamorphic tectonites, and coincides with termination of the last phase of arc magmatism (*ca.* 440-435 Ma) in the Notre Dame arc to the west (Fig. 4). Arc magmatism was followed by *ca.* 430-425 Ma, bimodal, within-plate magmatism in the Notre Dame and Dashwoods subzones (Fig. 3).

While the western part of Ganderia was colliding with Laurentia, oceanic crust was subducting beneath it from the Avalon side. This produced Early to Late Silurian arc - back-arc magmatism along its southern and eastern edge, cryptic evidence of which is preserved in Newfoundland (e.g. La Poile Basin and Burgeo granite, Kerr et al., 1994), but much better in the Maritimes (e.g. Barr et al., 2002). Termination of the Silurian arc, inversion of the La Poile Basin (O'Brien et al., 1991), pervasive Early Devonian deformation and low- to high-grade metamorphism, and voluminous, largely granitoid magmatism throughout the Gander Zone and immediately adjacent Exploits Subzone, is probably due to the docking of Avalonia (the onset of the Acadian Orogeny). Acadian structures near the Gander-Avalon boundary (Figs. 3, 4) generally have a southeasterly vergence (e.g.Colman-Sadd, 1980). However, a large west-directed hot nappe (Fig. 4, Meelpaeg allochthon) exposed in southwestern and central Newfoundland (Fig. 3) may form part of a retro-wedge.

The predominance of low-grade metamorphism and preservation of large tracts of Siluro-Devonian marine and terrestrial sedimentary and volcanic rocks throughout the CMB, locally in nearly pristine condition, indicate that the core of the Canadian Appalachians, with the exception of some restricted areas with exposed high-grade metamorphic rocks near the external boundaries of the CMB, generally experienced moderate to low amounts of denudation. Furthermore, since evidence for extension is rare or absent in the CMB, this suggests that thickening of the Appalachian core generally was limited and the ***paleotopography*** low. The Meguma zone, the furthest outboard terrane in the Northern Appalachians, is absent on the island of Newfoundland, but its accretion to composite Laurentia was probably responsible for Middle to Late Devonian orogenesis (Neoacadian) and voluminous granitoid magmatism in Nova Scotia.

Post-collisional processes mainly involved localized Middle to Late Devonian granitoid magmatism in the CMB and orogen-wide Late Devonian-Carboniferous strike-slip faulting associated with transtension and/or transpression, and basin formation.

THE GRENVILLE PROVINCE

Toby Rivers on behalf of the Grenville working group (Sharon Carr, Louise Corriveau, Nicholas Culshaw, Tony Davidson, Michael Easton, Charles Gower, Andrew Hynes, Aphrodite Indares, Rebecca Jamieson, Jacques Martignole).

The Grenville Province comprises the exposed part of the late Mesoproterozoic Grenville orogen, which extends in the subsurface and in isolated outliers southwest as far as Texas (Fig. 5). The Grenvillian orogeny, which took place between ~1190 and 990 Ma, is interpreted to be the result of collision between Laurentia and another continent, possibly South America, to the southeast. The Himalayan-scale collision was preceded by about 300 m.y. of northwest-dipping subduction that produced an Andean arc – back-arc system (1500-1200 Ma) on the southeastern margin of Laurentia (e.g., Hanmer et al., 2000; Rivers and Corrigan, 2000).

Present crustal thickness ranges between 42 and 47 km under much of the Grenville Province, on average a few kilometres thicker than under the adjacent Archean and Paleoproterozoic orogens. The ***orogenic crustal thickness*** may have been up to 70 km locally, based on metamorphic pressure estimates. Relief on the Moho appears low in most LITHOPROBE soundings, as imaged in the GLIMPCE, Abitibi-Grenville and ECSOOT transects, compatible with a hot lower crust and thermal relaxation following orogenic thickening. However, crust-penetrating normal faults offset the Moho by a few kilometres in the western Quebec transect (C, Figs. 6, 7), and in Labrador, the Grenville Front gravity low is caused by crust up to 5 km thicker than elsewhere. ***Seismic velocities*** in Grenville crust are generally slightly greater than those in adjacent orogens at similar depths, compatible with the higher grades of metamorphism. Reflectivity is weak to absent in the ***upper lithospheric mantle***, the thickness of which is poorly constrained.

At the scale of the orogen, the Grenville's ***tectonic architecture*** is doubly vergent, although most of the exposed part verges to the northwest. A marginal parautochthonous belt in the northwest can be readily linked with the adjacent foreland, despite the effects of Grenvillian metamorphism and polyphase deformation (Fig. 6; Rivers et al., 1989; 2002). The Parautochthonous belt is structurally overlain by the High Pressure belt, characterized by eclogite- and/or granulite-facies rocks, which is in turn overlain by the Low Pressure belt in the orogenic hinterland. Throughout much of the province, the southeast-dipping crustal architecture has been exceptionally imaged in LITHOPROBE seismic profiles, which show gently to moderately dipping reflectors flattening into the mid to lower crust (Fig. 7; Ludden and Hynes, 2000a). Major reflectors can be correlated with both thrust- and normal-sense shear zones that mark contractional and extensional structures, respectively (e.g., Martignole et al., 2000). A wedge of Superior Province crust can be traced up to 350 km beneath the central Grenville Province (transects C and D, Fig. 7), where it appears to have behaved as a relatively competent ramp above which ductily deformed Proterozoic crust was imbricated.

Most of the Grenville Province is formed from ***reworked Laurentian crust*** of Archean to Mesoproterozoic age. ***Rift*** deposits have not been identified and the earliest Mesoproterozoic activity relevant to the ensuing Grenvillian orogenesis was the construction of a ***continental magmatic arc*** between *ca.* 1500 and 1200 Ma. The arc, which comprises a suite of calc-alkaline and A-type volcanic and plutonic rocks, along with coeval back-arc mafic dyke swarms, anorthosite complexes and clastic sedimentary deposits, extends along the Laurentian margin for over 5000 km of strike length.

Juvenile terranes that were accreted to the Laurentian margin immediately prior to the Grenvillian orogeny include the Composite Arc belt (*ca.* 1300-1250 Ma) and the metasedimentary Frontenac-Adirondack Lowland terrane of the southwestern Grenville Province, as well as the Coal Creek domain (1325-1275 Ma) of the Llano Uplift in Texas (Fig. 5; Mosher, 1988; Carr et al., 2000). Depositional environments of the Composite Arc belt and Coal Creek domain include arc and rifted arc oceanic settings; MORB-like compositions are rare. Where mapped, ***sutures*** separating the ***accreted terranes*** from the reworked Laurentian margin are ductile shear zones up to several kilometres wide. No suture with the putative southeastern continent has been identified, implying that with the exception of the accreted terranes, all parts of the orogen in North America have Laurentian affinities.

Grenvillian ***metamorphic grade*** in the Grenville Province is generally high, in the upper amphibolite and granulite facies. Metamorphic events also vary spatially and temporally, and have been dated at ~1190-1160 Ma, ~1080-1020 Ma and ~1010-990 Ma in different parts of the province (e.g., Rivers, 1997). Grenvillian ***P-T-t paths*** display wide variations depending on crustal level. The deep crustal rocks in the High Pressure belt evolved along very steep *P-T-t* paths, compatible with rapid exhumation by tectonic extrusion, whereas coeval high-*T*, medium-*P* rocks in the Low Pressure belt show evidence for more gradual exhumation (Indares et al., 2000; Rivers et al., 2000). The Parautochthonous belt followed intermediate *P-T-t* trajectories. Peak temperatures in excess of 800˚C in the lower and middle crust, which led to anatexis and widespread emplacement of granitoid plutons during and immediately following the metamorphic peak, are unlikely to have been achieved by crustal thickening alone. It has been surmised that magmatism associated with the *ca.* 1.1 Ga mid-continental Keweenawan Rift system (Fig. 5) may have contributed 'excess' heat in the western Grenville Province (Culshaw et al., 1997). Elsewhere, evidence for widespread syn-orogenic mafic magmatism in the form of mafic dykes and gabbronorite-anorthosite intrusions has been interpreted as due to extensional thinning of the lithospheric mantle following collisional thickening (Corrigan and Hanmer, 1997). Several isolated blocks lack evidence of penetrative Grenvillian metamorphism, implying development at shallow crustal levels prior to down-faulting during late-stage orogenic collapse.

In addition to late extensional structures, ***late- to post-collisional features*** include two widespread suites of late-tectonic and post-tectonic granitoid plutons in the eastern Grenville Province (Gower and Krogh, 2002). Their geographic distribution suggests a unique lower crustal and/or mantle evolution in this region, which is not well understood. Throughout the Grenville, hornblende and muscovite $^{40}Ar/^{39}Ar$ cooling ages of ~950-905 Ma indicate locally divergent uplift and cooling paths for adjacent structural domains, implying that brittle fault activity continued during uplift and exhumation.

In summary, the Grenville Province was part of a hot wide orogen that developed on the site of a long-lived Mesoproterozoic continental arc on the southeastern Laurentian margin, in response to collision of a putative outboard continent. Some aspects of the Grenville orogen, such as its scale, the presence of eclogites, and the inference of tectonic extrusion of high-grade rocks, invite comparisons with the Himalayan and Variscan belts. Coeval high-temperature, medium-pressure metamorphic terranes in the hanging wall above the High Pressure belt may have developed under an uplifted plateau region. Numerical modelling of tectonic extrusion suggests that hot wide orogens are the sites of massive crustal-scale horizontal displacements and shortening along gently dipping shear zones, compatible with the LITHOPROBE images of the Grenville orogen.

PALEOPROTEROZOIC (2.0-1.8 Ga) OROGENS OF CANADA

G.M. Ross (on behalf of the participants of the PanLITHOPROBE IV meeting working group; Kevin Ansdell, Zoli Hajnal, Dick Wardle, Jeremy Hall, David Eaton, Ray Price, Carolyn Relf, Bill Davis, David Snyder, Ken Ashton, John Ketchum, Nick Culshaw)

Paleoproterozoic orogenic belts of Canada comprise nearly 6000 kilometres of strike-length orogenic material that record the formation of the core of the Laurentian craton between 2.0 and 1.8 Ga (Fig. 8; Hoffman, 1989). Older orogens (*ca.* 1.98-1.90 Ga) are restricted to northwest Canada from central Alberta to the Arctic coast (Thelon-Taltson and Wopmay orogens). Widespread Paleoproterozoic collisional orogenesis occurred between *ca.* 1860 and 1800 Ma, including the circum-Superior Trans-Hudson orogen (THO) and collisional zones in central Alberta (East Alberta orogen)(Wardle and Hall, 2002; Ross, 2002) and western Northwest Territories (western Wopmay orogen). Paleoproterozoic orogenic belts include both accretionary and collisional orogens. The former involve outward-younging belts of material added to the growing orogen (e.g. Makkovik, Wopmay). In contrast, collisional orogens involved significant pre-existing crustal material (Archean and older Proterozoic in Paleoproterozoic orogens). Accretionary orogens may evolve to collisional orogens with time (Trans-Hudson orogen, for example) or this change may occur as an along-strike variation reflecting the nature (size, age and strength) of material arriving at the consuming plate margin.

The ***crustal thickness*** of Paleoproterozoic orogens ranges from about 35 km (East Alberta) to over 50 km (Torngat orogen). The crust-mantle boundary (Moho) invariably displays relief, which is inferred to date back to the time of orogeny**.** The origins of the Moho relief may be composite and can reflect simple crustal thickening, subcrustal accretion (Sask craton; THO), magmatic underplating, and late stage fault juxtaposition of crustal elements of contrasting thickness. Virtually all LITHOPROBE lines across Paleoproterozoic orogens (SNORCLE, Alberta basement, THO and ECSOOT transects; Fig. 1) have revealed substantial seismic reflectivity throughout the entire crust. As a result of the excellent observed reflectivity, a number of major reflection styles and geometries can be discerned, and compare favorably with orogenic geometries seen in Phanerozoic orogens (Beaumont and Quinlan, 1994). ***Structure in the mantle lithosphere*** has been imaged on both reflection and refraction surveys within Paleoproterozoic orogens and includes the "frozen subduction" of the SNORCLE program (Cook et al., 1999), the Deep Probe/SAREX refraction profile (Gorman et al., 2002), and local short segments of dipping reflectivity in the shallow subcrustal mantle, which are interpreted as subduction scars (Eaton and Cassidy, 1996; White et al., 2002).

Crustal levels preserved in Paleoproterozoic orogens range from shallow levels of exhumation, typified by the Flin-Flon assemblage of THO (300-400 MPa; 10-12 km), to the deepest levels which are implied by 1.0-1.2 GPa rocks of the core zone of Torngat Orogen. An intriguing observation is that *ca.* 1.9 Ga orogens of northwest Canada have well-preserved foreland basins whereas *ca.* 1.8 Ga orogens lack coeval forelands. One of the key findings of the intraorogenic comparison approach is that evidence for synorogenic (or even late orogenic) extension, which normally assists exhumation, is lacking in Paleoproterozoic orogens. This includes seismic evidence as well as field relationships and kinematic analysis of shear zones. Further work defining ***P-T-t loops*** for Paleoproterozoic orogens will help constrain exhumation paths.

Paleoproterozoic orogens involved the assembly of ***pre-existing crustal fragments and microcontinents*** of both Archean and older Proterozoic age and thus the shape and strength of the collided elements played a key role in orogenic style and evolution. The ***age and style of rifting*** sets the collisional template, defining the shape of the rifted margin (salient-reentrant geometries) and the thermal age (strength) of the margin, similar to younger orogens. The time interval between the age of rifting and the onset of convergence exerts a first-order control on the thermal state and elastic thickness of the lithosphere loaded during contraction and may explain the variable development and preservation of foreland sequences between Proterozoic orogens.

Paleoproterozoic orogens have ***accreted oceanic material*** comparable in diversity to Phanerozoic rocks although the ophiolite components are less prevalent. Circum-Superior orogens have a relatively young (*ca.* 1.88 Ga) magmatic-oceanic component related to rifting that seems to be concentrated along the continental margin of the Superior craton and may have been related to a plume impinging on the underside of the rifted Superior lithosphere. ***Continental magmatic arcs*** form the magmatic glue that welded constituent cratonic elements during consumption of oceanic lithosphere, ocean closure and eventual collision. A range of different erosional levels within these arcs is preserved, from deep structural levels in the Thelon-Taltson, to shallow levels in Great Bear Magmatic Zone. The duration of arc magmatism is comparable to that in Phanerozoic arcs, ranging from about 70 to 10 m.y., although the volume of some arcs, such as the Wathaman batholith, is remarkable given its short duration. One lesson learned from reflection profiles in Paleoproterozoic orogens (and elsewhere in LITHOPROBE surveys) is that the ascent of magmatic material and emplacement in the mid to upper crust has done little to modify highly reflective crust, through which the magmas must have traversed during emplacement. This observation suggests that magmas rose along transient conduits that may subsequently have closed. However, post-magmatic deformation and metamorphism during terminal phases of continental collision and assembly may also have overprinted the magmatic conduit systems.

With the exception of the Torngat orogen, which underlies the highest peaks in eastern North America, Paleoproterozoic orogens in Canada have little contemporary topographic relief. Reconstructing ***paleotopography*** is a difficult proposition especially if the synorogenic foreland basin is not preserved. In Paleoproterozoic orogens of western Canada, sedimentary basins that are demonstrably post-orogenic, such as the cratonic sheet sandstones of the Athabasca, Thelon, and Hornby Bay basins, all approximately 1700 Ma, should provide a measure of remnant orogenic topography. On the basis of facies patterns and paleocurrents, none of these basins seem to show an influence by orogenic topography suggesting that it was essentially removed by the time of deposition of these basins. On average that rate would correspond to 100 – 200 m.y.

for removal of orogenic topography. This contrasts with Phanerozoic orogens such as the Appalachians, which still have strong modern day topographic expression more than 300 m.y. after cessation of orogeny.

Paleoproterozoic orogens were variably affected by ***post-collisional magmatism***, i.e. magmatism that is less than 50 m.y. younger than the age of collision, as distinct from magmatism that is separated from orogenic activity by more than 200 m.y. (e.g. transcontinental magmatism 1490-1350 Ma that affected New Quebec and Makkovik orogens more than 300 m.y. after orogenesis). In Alberta, post-collisional magmatism is inferred from seismic images, which are interpreted to show the presence of the intrusive equivalents of large igneous provinces (LIPs) in the form of underplated material and midcrustal sills, the latter covering a region of at least 120,000 km^2. Post-collisional granitic magmatism is common in some Paleoproterozoic orogens (e.g. Rae/Hearne hinterland), whereas it appears to be absent in others (e.g. Torngat, New Quebec). This may be due in part to the state of the lower crust, considering that dehydrated, refractory, Archean lower crust, a common basement to Paleoproterozoic orogens, would be less fertile than accreted Proterozoic crust which may not have undergone previous melting.

SUPERIOR PROVINCE

J.A. Percival and PanLITHOPROBE IV working group: K. Bethune, A. Calvert, T. Corkery, J. Craven, D. Davis, H. Helmstaedt, A. Leclair, S. Lin, J. Parks, M. Sanborn-Barrie, T. Skulski, G. Stott, P. Thurston, K. Tomlinson, G. West, D. White

Although not traditionally viewed as an orogenic belt, the Superior Province has many features interpreted to record mountain-building processes on a 2000-km length scale, including arc magmatic rocks, orogenic flysch deposits, regionally extensive strain fabrics and medium to high metamorphic grades. Recent LITHOPROBE reflection profiles, from the Western Superior, Kapuskasing and Abitibi-Grenville transects (Fig. 1), interpreted in light of new geological mapping and a robust geochronological framework, have revealed a crustal architecture that invites comparisons to modern collisional orogenic belts (Williams et al., 1992; Calvert and Ludden, 1999; Ludden and Hynes, 2000b; Fig. 9).

Where measured, the ***crustal thickness*** of the Superior Province ranges between 38 and 45 km, apparently peneplaned from the maximum 44-70 km thickness at the orogenic climax inferred from metamorphic assemblages. Anomalies associated with Proterozoic structures include thicker crust (53 km) beneath the Kapuskasing uplift, a Paleoproterozoic intracratonic thrust (e.g., Percival, 1994), and thinner crust (35 km) beneath the Nipigon plate, a Mesoproterozoic aulacogen developed on Superior Province basement. Estimates of ***lithospheric thickness*** range up to 300 km, and shear wave analyses indicate east-west seismic anisotropy (Musacchio et al., in press). Shallow mantle sampled in refraction experiments also displays marked anisotropy (8.3-8.8 km/s), suggestive of depleted harzburgitic compositions. Magnetotelluric experiments indicate strong east-west anisotropy at mantle depths below the *ca.* 2.7 Ga southwestern Superior Province, in contrast to a distinctly isotropic mantle domain beneath the *ca.* 3.0 Ga North Caribou terrane of the northwestern Superior Province (Craven et al., 2001).

Domains of old (>2.8 Ga) ***continental crust*** within the Superior Province (Fig. 10) are separated by belts of younger oceanic material. In the north, the Northern Superior superterrane (Skulski et al., 2000)("superterrane" implies a collage of terranes assembled prior to incorporation into the Superior Province) records an ancestry back to *ca.* 3.82 Ga. The North Caribou-La Grande-Goudalie superterrane (Stott, 1997), dominated by juvenile 3.0 Ga crust, extends through northern Manitoba, Ontario and Quebec and appears to reflect a craton-scale swing in structural grain (e.g. Percival et al., 1994), although tectonic discordance between older NW trends in the north and younger east-west trends in the south may also explain this pattern. Smaller domains of old continental crust to the south include the Winnipeg River (up to 3.4 Ga), Marmion (3.0 Ga) and Opatica (2.81 Ga) terranes. At the southern margin of the Superior, the Minnesota River Valley terrane (3.6 Ga)(Fig. 8) may be part of a bounding craton, although the continental fragments were variably reworked by Neoarchean (2.75-2.65 Ga) magmatic and metamorphic activity, such that the extent of orogen-bounding continents is uncertain.

Scant evidence is available on the ***nature, style and timing of early rifting*** within the Superior Province. Thin rift sequences are locally associated with old cratonic fragments, along with distal platformal equivalents (Thurston and Chivers, 1990). These sequences generally comprise lower clastic (fuchsitic quartz arenite, grit, conglomerate) and chemical (carbonate, iron formation) sedimentary layers deposited in intertidal, shallow marine, platformal and submarine fan environments, overlain by volcanic (komatiite, basalt, rhyolite) sequences. Age constraints for two clastic sequences near the southern edge of the North Caribou superterrane suggest deposition prior to 2.93 Ga at the margin of an ocean that closed after 2.72 Ga. Generally less than 500 m thick, these apparent rift sequences resemble those at volcanic passive margins such as in East Greenland.

Isotopically ***juvenile rocks*** ($\varepsilon Nd^{2.7\ Ga}$ =+5 to +2) occur in greenstone belts separating continental domains. Dominated by tholeiitic and komatiitic magmatism derived from depleted mantle sources, these juvenile belts are interpreted to have formed in oceanic settings, possibly analogous to oceanic plateaus. Relatively rare but widespread (Fig. 10) associated basalts characterized by Th and LREE depletion bear resemblance to mid-ocean ridge basalt (N-MORB). Calc-alkaline volcanic rocks akin to island arc edifices typically overlie lower mafic sequences in many juvenile greenstone belts. Rare adakite, Nb-enriched basalt and komatiite point to a considerable range of arc/plume processes, particularly well illustrated in the Abitibi subprovince. Subvolcanic intrusions of dominantly tonalitic composition make up large volumes of juvenile crust and were generated by recycling of oceanic crust through melting and fractionation processes. Oceanic rocks formed between 2.77 and 2.70 Ga are widespread throughout the southern Superior Province, and *ca.* 2.84 Ga examples are present in the Oxford-Stull Lake terrane, northwestern Superior Province.

Continental arcs are well developed in the northeastern Superior Province, where hydrous to charnockitic granodiorite and tonalite crystallized as massive vertical sheets between 2.78 and 2.70 Ga (Percival et al., 2001). Erosional levels (avg. 15 km) are slightly deeper than in the northwestern Superior where magmatic rocks of similar composition and age (2.74-2.71 Ga) form horizontal sheets at *ca.* 12 km emplacement levels (Stone, 2000). Pre-arc continental basement ages are reflected in enriched isotopic signatures and inherited zircon populations.

Sutures are inferred at several interfaces between continental and oceanic domains (Fig. 10), although flysch deposits and younger structures invariably obscure their character. Subduction polarity is deduced from the presence of calc-alkaline arc magmatic belts that were active up to a few million years prior to collision, as well as from subduction scars: dipping upper mantle reflections presumed to image ancient subducted slabs (e.g. Calvert and Ludden, 1999). Suture zones are characterized by regionally extensive belts of greywacke flysch deposited early during the collisional process and subsequently deformed and metamorphosed during continued convergence. Their depositional ages constrain the time of docking events across the Superior Province (Davis, 1998; Figure 11): 1) Northern Superior - North Caribou collision *ca.* 2.72 Ga, forming the initial northern portion of the composite Superior superterrane (CSS) during the Northern Superior orogeny; 2) accretion of the Winnipeg River - Wabigoon to CSS *ca.* 2.71-2.70 Ga (Uchian orogeny; Stott, 1997); 3) accretion of the Abitibi – Wawa to CSS *ca.* 2.69 Ga (Shebandowanian orogeny); and 4) terminal collision of the Minnesota River Valley to CSS *ca.* 2.68 Ga (Minnesotan orogeny).

Pressure-temperature-time (PTt) paths are best documented in flysch sequences deposited just prior to burial and metamorphism. For example, the English River flysch sequence, deposited in the North Caribou – Winnipeg River suture zone between 2.704 and 2.698 Ga, reached peak P-T conditions (650 MPa; 800^{o}C) by 2.69 Ga. Sustained high temperatures and thick crust are indicated by continued metamorphism and emplacement of crust-derived granites until 2.65 Ga. Peak Shebandowanian conditions (600 MPa; 800^{o}C) were attained in the <2.698 Ga Quetico flysch sequence at *ca.* 2.66 Ga, and declined southward in the Abitibi belt (220 MPa; 260^{o}C).

Post-collisional features include development of dextral transpressive zones, linked temporally and spatially to emplacement of mantle-derived magmas such as sanukitoid-suite rocks (high-Mg granodiorite, monzodiorite), rare carbonatite and associated alkaline rocks. These events occurred 1-5 m.y. after the inferred time of accretion, with progressively younger ages toward the south (2.71-2.68 Ga). Molasse deposits (“Timiskaming” conglomerates) show similar age distribution. Post-tectonic granites and pegmatites crystallized between 2.68 and 2.64 Ga throughout the Superior Province; their emplacement may relate to fluid circulation responsible for growth of late monazite and titanite (2.69-2.61 Ga). Deep crustal extension and high-grade metamorphism between 2.66 and 2.62 Ga are further indications of persistent high temperatures and ductile conditions following assembly of the province. Together, these phenomena point to a process of mantle magma generation, followed by deep-crustal melting and associated thermotectonic activity. The ultimate cause may relate to slab breakoff or more widespread lithospheric delamination.

SLAVE CRATON

W. Bleeker on behalf of the Slave craton working group: B. Davis, R. Ernst, B. Griffin, A. Jones, J. Ketchum, C. Relf, D. Snyder, A. van der Velden.

The Slave craton, one of *ca.* 35 principal Archean crustal fragments scattered around the globe (Bleeker, 2003), is a small to moderate size craton (*ca.* 500 km E-W by >700 km N-S) in the northwestern Canadian Shield (Fig. 12). Its key features include a high proportion of ancient crust, a craton-scale stratigraphy, high-amplitude mantled granitoid-gneiss domes, voluminous late granites, and widespread high-T, low-P metamorphism (Bleeker and Davis, 1999; Bleeker, 2002). It has been imaged in the eastern SNORCLE transect (Fig. 1).

The ***present topography*** of the Slave is dominated by a broad dome or arch rising to 550 m above sea level. The ***present crustal thickness*** averages 38-40 km, increasing to *ca.* 45 km near Paleoproterozoic bounding structures, and thinning to *ca.* 35 km beneath in the north-central part of the craton below parts of the Paleoproterozoic Kilihigok basin (KB, Fig. 12)(Bank et al., 2000). A crude estimate of average ***orogenic crustal thickness*** of 52 km at *ca.* 2.58 Ga is suggested by widespread andalusite-grade metamorphism (<360 MPa), indicating an average of *ca.* 10-12 km of syn- and post-orogenic exhumation. This exhumation was essentially complete by *ca.* 2.0 Ga, the age of onlapping cover sequences.

The nature of the ***subcontinental lithospheric mantle*** *(SCLM)* of the Slave is particularly well defined through geophysical and xenolith data. Slave lithosphere extends to a depth of about 180-220 km, with local maxima to 250 km (Bostock, 1998; Cook et al., 1999). Ancient crust of the Central Slave Basement Complex (CSBC, Fig. 12; Bleeker et al., 1999a,b) is underlain by seismically fast mantle lithosphere (e.g., Bank et al., 2000), xenoliths of which have Re-Os ages reflecting crustal ages (Aulbach et al., 2001; Irvine et al., 2001). Mantle xenoliths and xenocrysts, brought to the surface by diamondiferous kimberlite pipes, provide a complex picture of distinct and stratified mantle domains (Kopylova et al., 1998; Griffin et al., 1999; Grütter et al., 1999; Kopylova and Russel, 2000; Carbno and Canil, 2002). A key feature of the central Slave SCLM, including that of the Lac de Gras kimberlite field, is a *ca.* 150 km thick, conductive (Jones et al., 2001), ultra-depleted harzburgite layer above more fertile lherzolite (Griffin et al., 1999). A relative abundance of diamondiferous eclogite xenoliths in some pipes may hint at a role for subduction and subcretion of oceanic crust at the base of the Slave lithosphere (Kopylova et al., 1998; Heaman et al., 2002; see also Bostock, 1998).

The ***crustal architecture*** of the Slave craton is dominated by the CSBC and its thin, widespread Central Slave Cover Group (2850-2800 Ma; Bleeker et al., 1999a,b; Sircombe et al., 2001; Fig. 13). This is overlain by voluminous tholeiitic basalt and minor komatiite (2740-2700

Ma), probably indicating ***rifting and/or plume*** activity, at a scale comparable to that of modern large igneous provinces. Neither geochemical nor field data have yet provided indications of this ancient crust and its cover stratigraphy in the eastern Slave, with the possible exception of the Hope Bay Block in the northeast (HB, Fig. 12), which remains insufficiently tested.

The east-west dichotomy has been explained in terms of collision of an ***exotic eastern arc terrane*** with an ancient crustal block (e.g., Kusky, 1989). However, because the <2690 Ma volcanic and sedimentary rocks of the eastern Slave are continuous or can be correlated with the upper part of the western Slave stratigraphy, any terrane collision would have to have occurred between *ca.* 2700 and 2690 Ma, a time interval considered too short for a full Wilson cycle. Progressive rifting, accompanied by voluminous volcanism and plutonism (back-arc setting?) may be an alternative to terrane collision to explain the lack of an ancient basement signature in the eastern Slave.

After 2690 Ma, the structural grain changed from N-S to NE-SW, on the basis of: 1) facies boundaries (i.e. distribution of banded iron formation (BIF) and gold deposits) in *ca.* 2680-2660 Ma Burwash Formation turbidites; 2) a chain of *ca.* 2661 Ma felsic volcanic centers (***continental volcanic arc***?); 3) the NE-SW trend of *ca.* 2642-2635 Ma F_1 folds in Burwash turbidites; 4) a ***magmatic arc*** of *ca.* 2635-2620 Ma Defeat Suite plutons; and 5) speculative boundaries between contrasting mantle lithosphere domains (Grütter et al., 1999; Davis et al., 2003). Collectively, these features suggest a supra-subduction zone setting (arc and back-arc?), possibly with a trench to the southeast of the present Slave. Significantly, all post-Burwash volcanic rocks occur in the northwestern Slave (Fig. 12), suggesting that after D_1 collision (folding of the Burwash Basin) and Defeat magmatism, a subduction flip may have occurred, moving the active margin to the northwest of the present Slave craton. These features were overprinted by F_2 folds and subsequent strike-slip faults along dominantly NNW-SSE to N-S trends between 2600 and 2590 Ma, leading to interference and partial masking of earlier trends (e.g., Davis and Bleeker, 1999).

Peak-metamorphic conditions generally were attained syn- to post-D_2, near the time of voluminous granitoid magmatism, including a craton-wide “granite bloom” at about 2590-2580 Ma (Davis and Bleeker, 1999). This intracrustal depletion event extracted aqueous fluids, minimum melt fractions and most of the heat producing elements from the lower crust. Large-scale advection of granitic melts into the upper crust is thought to have contributed to the crustal-scale amplitude (*ca.* 10-15 km) of composite granite-gneiss domes, many of which are cored by young granites (Bleeker, 2002). This irreversible transfer of heat producing elements to upper crustal levels allowed the lower crust to cool and stiffen, setting the stage for "cratonization" of the Slave crust. Although not easily ruled out, there is no direct evidence for mafic magmatic input from the mantle during the granite bloom. In rare sections of Slave crust exposing 700-900 MPa metamorphic levels, these younger events are manifested by a subhorizontal migmatitic layering and intercalated granite sheets, which may be the principal cause for strong lower crustal reflectivity. SNORCLE images of offsets and imbrication of this reflectivity and the Moho (Fig. 13) may be subduction scars (Cook et al., 1999; van der Velden and Cook, 2002b), or younger (e.g., Wopmay orogen) structures.

Following the 2590-2580 Ma thermal peak, the upper crust underwent rapid cooling (e.g., Bethune et al., 1999). However, zircon growth events in lower crustal xenoliths record a number of younger events at 2560 and 2520 Ma (Davis et al., 2003), indicating that metamorphic activity in the lower crust continued for up to 60 m.y. after the metamorphic peak, similar to the pattern observed in the Kapuskasing uplift of the Superior craton (Moser and Heaman, 1997). Post-Archean thermal events recorded in accessory minerals of some xenoliths (zircon, titanite, rutile) indicate that transient heating of the lower crust, and possibly magmatic addition, occurred repeatedly, accompanying intrusion of Proterozoic dyke swarms at 2.2 and 1.27 Ga (Davis et al., 1997). Rutile ages from lower crustal xenoliths provide a minimum age for establishment of a cratonic geotherm at *ca.* 1.8 Ga.

DISCUSSION

Summary by J.A. Percival from discussion organized by C. Beaumont, J. Hall, K. Karlstrom and R. Price, facilitated by notes from A. Calvert and K. Tomlinson.

An early discussion point considered whether Precambrian terranes, particularly those of Archean age, should be considered as orogens. The original definition of orogeny relates to the construction of mountain belts, although other characteristics (collisions, presence of sutures, metamorphic zonation, fold-thrust belts, etc.) have become engrained in our common understanding of the term. It was argued for the Superior Province that belts of 800-900 MPa metamorphic rocks with Archean cooling ages and normal crustal thickness must have had major topographic expression during the orogenic climax, and therefore qualify as *bona fide* orogenic belts.

A theme that pervaded the discussion concerned secular variation of orogenic processes. At the extremes, are Archean orogens fundamentally different than Cenozoic ones? In order to answer this question, individual parameters need to be isolated, considered and compared. For example, low-P, high-T metamorphism is not a uniquely Archean feature; thermal and tectonic controls must be defined before appealing to generally hotter Archean conditions. Owing to higher concentrations of heat-producing elements, the Earth must have generated more heat during the Archean, but many believe that once stabilized, continental keels were not subjected to thermal erosion. Consequently, proportionally more heat must have been dissipated through the oceans.

Orogen classification

A scheme was proposed to classify orogens according to their accretion history. This concept is expressed graphically in terms of three end-members: A) subduction with accretion; B) subduction without accretion; and C) collision (Fig. 14). A fourth end member, such as rifting, could be added, and “plume” was suggested to describe one possible non-subduction-related process. The purpose of the diagram is to display the evolution of individual orogens as simplified pathways, with the six orogens displayed on Fig. 14. Most began near the B apex, and material was accreted on the way to a terminal collision (C), although the Cordillera has not reached that stage. The dimension of time is not quantified, but a cladogram (e.g., Fig. 11) can be added to elucidate the age of oceanic and continental fragments, as well as the timing of assembly of the orogen.

Is the diagram useful for describing Precambrian orogens? Although most participants found the concept easy to apply, some argued that large continents and continental margins did not yet exist during most of the Archean. This feature can be accommodated by considering an intermediate point on the A-C join to describe thermally immature arc crust. Material of this character is considered important in the history of the Superior Province, but also figures prominently in Cordilleran accreted terranes and recent island arc collisions in the southwestern Pacific Ocean. Alternatively, plume-driven processes may have been relatively important in some Archean terranes.

What influences orogenic style?

A second theme considered “what influences orogenic style”, under several categories:

1) The role of inheritance is significant in many orogens. In the Appalachians, for example, reentrant/promontory geometry has controlled rifting, deformation and preservation patterns. Similar underlying variations may have influenced the development of the northern *vs* southern Cordillera. The observation that passive margins characterize 1.9 Ga orogens and active rift margins are prevalent in 1.8 Ga orogens may also relate to the strength (strong, weak respectively) of preexisting crust. In the central Superior Province the relatively large size and thickness of the North Caribou cratonic fragment determined its behaviour as the upper plate during plate convergence.

2) The rift/convergence time gap may be difficult to constrain, particularly in non-fossiliferous sequences. It influences the thickness of rift sediments, which in turn plays a role in the thick *vs* thin-skinned nature of deformation. Similarly, the time gap determines temperature and hence elastic thickness of the plate, which in turn influences orogenic topography and character of the foreland basin. Other factors include the amount of continental freeboard at the time of rifting, and the active *vs* passive nature of the rift margin. The length of the gap also determines the time available for production of oceanic terranes (arcs, plateaux, seamounts), and controls the potential longevity of subduction regimes and consequent continental arc magmatism. It may also determine the style of magmatism; if plates are < *ca.* 20 m.y. old at the time of subduction then adakitic magmatism is possible.

3) Conditioning of margins during subduction influences orogenic style considerably. In particular, the polarity of subduction determines whether an arc develops in the upper or lower plate, which can dominate the thermal structure. For example, many Superior Province arcs were active just prior to collision, resulting in mechanically weak plates with consequent limited overthickening, and widespread high-T, low-P metamorphism. Similarly, preconditioning by arc magmatism has influenced parts of the Appalachian and Grenville orogens. A second consideration is the roughness of the downgoing plate, which partly determines whether consuming margins are accretionary and grow outwards, or migrate arcward in response to forearc erosion. The taper of a relatively stiff margin may be reflected in the internal geometry of the orogen, as exemplified by the eastern Grenville.

4) Accretion prior to collision has had variable influence on tectonic style. Where best constrained, in the northern Cordillera, accreted terranes appear as thin, transported flakes that may have behaved passively. Alternatively, accretion of hot arc material in the central Newfoundland Appalachians resulted in extrusion of hot nappes.

5) Continent-continent collisions are generally not entirely constrained. In both the Appalachian and Grenville examples, the outer continents were subsequently rifted away. Nevertheless, the Grenville records intense shortening, uplift and channel flow thought to be due to a full-scale continental collision resembling the Himalaya in magnitude. In Paleoproterozoic orogens, the Archean Superior and Slave provinces acted as orogen-bounding continents, whereas the Archean Hearne and Rae provinces underwent significant reworking within the orogenic internides.

6) Reworking of continents during collision apparently increases in intensity with geologic age, but could also be a function of deeper erosion levels in older terranes. Basement reworking is not prominent in the Cordillera except in the Omineca belt in the south. It is widespread within the Rae and Hearne provinces, which appear to have been orogenic hinterlands at several times during the Paleoproterozoic, housing variably cryptic evidence for thermal and structural overprints between *ca.* 2.5 and 1.7 Ga. Mesoarchean microcontinents within the Superior Province were variably digested by arc magmatism prior to thorough structural reworking during collisions.

Other factors that may have influenced style but are difficult to quantify include convergence obliquity, the distribution and concentration of heat-producing elements, differing atmospheric conditions, delamination, plume activity, and intracratonic orogenesis. Full accounting of these attributes is required in the understanding of tectonic style.

Orogenic Climax

A third theme described the orogenic climax in different orogens, from the point of view of maximum crustal thickness, topographic relief, material flow, and the progress of deformation and metamorphism in space and time. Opinions differed as to what event(s) define the climax. In the Cordillera, high-grade metamorphism and possibly maximum crustal thickness occurred in the Mesozoic as a result of terrane accretion, and may have persisted until extensional collapse in the Eocene. The climax of Appalachian orogenesis (continent-continent collision) took place in the Devonian, and is characterized by a change from calc-alkaline to S-type plutonism, along with transcurrent deformation. Maximum inferred crustal thickness, high-P, T metamorphism and tectonic extrusion represent the peak of Grenvillian orogenesis between *ca.* 1.1 and 1.0 Ga, thought to relate to continent-continent collision and subsequent extensional collapse. Paleoproterozoic orogenies occurred at *ca.* 1.9 and 1.8 Ga, marked by both head-on and oblique collisions, leading to production of syn-collisional granites. The lack of extensional structures and low metamorphic grade in some orogen segments suggests modest degrees of tectonic overthickening or rapid erosional exhumation. Several distinct orogenies can be recognized within the Superior Province between 2.72 and 2.68 Ga, each represented by suturing of continental and oceanic domains that involved crustal thickening followed by low-P metamorphism and transpressional deformation. In the Slave Province the climax is represented by widespread granite emplacement between 2.60 and 2.58 Ga, accompanied by low-P metamorphism and deformation.

Orogenic pathways leading to the orogenic climax can be illustrated on a Hertzsprung-Russell – type diagram (designed for star classification, as modified by Susan Ellis and Chris Beaumont, pers. comm.). Using “excess temperature” (peak metamorphic conditions, above stable geotherm) and “magnitude of orogen” (cross-strike width) as axes, Earth’s familiar active mountain ranges (Andes, New Zealand Alps, Himalaya) are plotted as examples (Fig. 15), along with paths for the six Canadian orogens as proposed by Gerry Ross. There was general agreement on the diagram’s utility in describing orogenic evolution and understanding one of its fundamental parameters, temperature, and the consequent degree of crust-mantle coupling. For example, the diagram underlines the importance of magmatic heat input in developing weak crust and wide orogens with subdued topography. High, wide mountain ranges are produced in orogens with moderate excess temperature.

Orogenic anticlimax; what’s it like now?

The final theme that received attention was late orogenic effects, leading up to the present lithospheric configuration. Considerations addressed were the scale and timescale of orogenesis, strike variations, across-orogen variations, nature and age of the Moho and crustal thickness, and presence of subduction scars and mantle reflections.

Orogenesis occurred in the Cordillera between the mid-Mesozoic and present, although the focus and style have changed regionally, encompassing convergence, strike-slip and extension. Moho relief is relatively low owing to ductile lower crustal conditions. Thin crust and high surface topography are dynamically supported by shallow asthenosphere.

Many events affected the Appalachian orogen in the 60 m.y. following the orogenic climax, including granitoid magmatism, strike-slip faulting, basin development and opening of the Atlantic Ocean. Two subduction scars have been imaged beneath Newfoundland.

The 600 km wide Grenville orogen extends from Scandinavia to Texas and developed over a 200 m.y. time span. Metamorphism occurred earlier in the southwest, and is zoned from foreland to hinterland. The Moho is generally flat and was probably established at the orogenic climax, with a late bulge beneath the Grenville Front.

Paleoproterozoic orogens include the Trans-Hudson, which extends over 6000 km and many other shorter segments. Their width exceeds 1000 km if Rae/Hearne basement structural reworking and magmatism are included. Foreland-hinterland zonation is well developed during orogenies that lasted *ca.* 80 to 120 m.y.

Tectonic features of the Superior Province can be traced up to 2000 km along strike, over a width scale of *ca.* 800 km, which comprises four orogenic systems. Each 200-300 km wide belt took 20-30 m.y. to achieve peak metamorphic conditions, which decayed over the subsequent 50-60 m.y. Several short-wavelength Moho features, including subduction scars, are thought to record collisional events.

In the Slave Province, orogenesis had ceased by 2580 Ma (massive late granite event) and the erosion surface cooled to *ca.* 400°C by 2550 Ma. The present Moho may have been established during events in the Proterozoic, and scar-like features may relate to late delamination rather than subduction.

ACKNOWLEDGMENTS

Thanks are due to members of the Pan-LITHOPROBE subcommittee who contributed to the formulation and running of the workshop, as well as to Ron Clowes for his advice and enthusiasm. Invited participants Sue Mahlburg Kay, Bill Griffin and Karl Karlstrom contributed perspectives from other parts of the world. Rapporteurs Andrew Calvert and Kirsty Tomlinson provided timely summaries of the discussion sessions. Gwen Mason is thanked for efficient logistics and the staff of Sam Jakes Inn for helpful and unobtrusive service. Deborah Lemkow produced blended geological-geophysical maps. Sally Pehrsson and Tom Skulski made helpful suggestions on early versions of the manuscript and Glen Stockmal gave a thoughtful review. Geological Survey of Canada contribution no. 2003089; Lithoprobe contribution no. 1343.

REFERENCES

Armstrong, R.L., 1988, Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, *in* Clark, S.P., Burchfiel, B.C. and Suppe, J., eds., Processes in continental lithospheric deformation: Geological Society of America, Special Paper 218, p. 55-91.

Aulbach, W., Griffin, W.L., Pearson, N.J., O'Reilly, S.Y., Doyle, B.J. and Kivi, K., 2001, Re-Os isotope evidence for Mesoarchean mantle beneath 2.7 Ga Contwoyto terrane, Slave craton, Canada: implications for the tectonic history of the Slave craton, *in* Slave-Kaapvaal Workshop, September 5-9, 2001, Merrickville, Ontario.

Bank, C.G., Bostock, M.G., Ellis, R.M. and Cassidy, J.F., 2000, A reconnaissance teleseismic study of the upper mantle and transition zone beneath the Archean Slave Craton in NW Canada: Tectonophysics, v. 319, p. 151-166.

Barr, S M., White, C.E. and Miller, B.V., 2002, The Kingston terrane, southern New Brunswick, Canada: Evidence for an Early Silurian volcanic arc; Geological Society America Bulletin, v. 114, p. 964-982.

Beaumont, C. and Quinlan, G., 1994, A geodynamic framework for interpreting crustal-scale seismic reflectivity patterns in compressional orogens: Geophysical Journal International, v. 116, p. 754-783.

Bethune, K.M., Villeneuve, M.E. and Bleeker, W., 1999, Laser $^{40}Ar/^{39}Ar$ thermochronology of Archean rocks in Yellowknife Domain, southwestern Slave Province: insights into the cooling history of an Archean granite-greenstone terrane: Canadian Journal of Earth Sciences, v. 36, p. 1189-1206.

Bleeker, W., 2002, Archaean tectonics: a review, with illustrations from the Slave craton: Geological Society of London, Special Paper 199, p. 151-181.

Bleeker, W., 2003, The late Archean record: a puzzle in ca. 35 pieces: Lithos, in press.

Bleeker, W. and Davis, W.J., eds., 1999, NATMAP Slave Province Project: Canadian Journal of

Earth Sciences, v. 36, p. 1033-1238.

Bleeker, W., Ketchum, J.W.F., Jackson, V.A. and Villeneuve, M.E., 1999a, The Central Slave Basement Complex, Part I: Its structural topology and autochthonous cover: Canadian Journal of Earth Sciences, v. 36, p. 1083-1109.

Bleeker, W., Ketchum, J.W.F. and Davis, W.J., 1999b, The Central Slave Basement Complex, Part II: Age and tectonic significance of high-strain zones along the basement-cover contact: Canadian Journal of Earth Sciences, v. 36, p. 1111-1130.

Bostock, M.G., 1998, Mantle stratigraphy and evolution of the Slave Province: Journal of Geophysical Research, v. 103, p. 21,183-21,200.

Calvert, A. and Ludden, J.N., 1999, Archean continental assembly in the southeastern Superior Province of Canada: Tectonics, v. 18, p. 412-429.

Carbno, G.B. and Canil, D., 2002, Mantle structure beneath the SW Slave Craton, Canada; constraints from garnet geochemistry in the Drybones Bay Kimberlite: Journal of Petrology, v. 43, p. 129-142.

Carr, S.D., Easton, R.M., Jamieson, R.A. and Culshaw, N.G., 2000, Geologic transect across the Grenville Orogen of Ontario and New York. Canadian Journal of Earth Sciences, v. 37, p. 193-216.

Chian, D., Marillier, M., Hall, J. and Quinlan, G., 1998, An improved velocity model for the crust and upper mantle along the central mobile belt of the Newfoundland Appalachian orogen and its offshore extension: Canadian Journal of Earth Sciences, v. 35, p. 1238-1251.

Colman-Sadd, S.P., 1980, Geology of south-central Newfoundland and evolution of the eastern margin of Iapetus: American Journal of Science, v. 280, p. 991-1017.

Colman-Sadd, S.P., Hayes, J.P. and Knight, I. 1990, Geology of the Island of Newfoundland. Newfoundland Department of Mines and Energy, Map 90-01.

Cook, F., ed., 1995, The Southern Canadian Cordillera Transect of Lithoprobe: Canadian Journal of Earth Sciences, v. 32, p. 1483-1824.

Cook, F.A., van der Velden, A.J., Hall, K.W. and Roberts, B.J., 1999, Frozen subduction in Canada's Northwest Territories; Lithoprobe deep lithospheric reflection profiling of the western Canadian Shield: Tectonics, v. 18, p. 1-24.

Cook, F.A., Clowes, R.M., Snyder, D.B., van der Velden, A.J., Hall, K W., Erdmer, P. and Evenchick, C.A., Precambrian crust beneath the Mesozoic Northern Canadian Cordillera discovered by LITHOPROBE seismic reflection profiling: Tectonics, accepted pending revision.

Corrigan, D. and Hanmer, S., 1997, Anorthosites and related granitoids in the Grenville orogen: a product of convective thinning of the lithosphere?: Geology, v. 25, p. 61-64.

Craven, J.A., Kurtz, R.D., Boerner, D.E., Skulski, T., Spratt, J., Ferguson, I.J., Wu, X. and Bailey, R.C., 2001, Conductivity of western Superior Province upper mantle in northwestern Ontario: Geological Survey of Canada, Current Research 2001-E6, 6 p.

Culshaw, N.G., Jamieson, R., Ketchum, J.W.F., Wodicka, Corrigan, D. and Reynolds, P.H. 1997, Transect across the northwestern Grenville orogen, Georgian Bay, Ontario: polystage convergence and extension in lower orogenic crust: Tectonics, v. 16, p. 966-982.

Davis, D.W., 1998, Speculations on the formation and crustal structure of the Superior province from U-Pb geochronology, *in* Harrap, R.M., Helmstaedt, H., eds., Western Superior Transect Second Annual Workshop. Lithoprobe Report 65, p. 21-28.

Davis, W.J., 1997, U-Pb zircon and rutile ages from granulite xenoliths in the Slave Province; evidence for mafic magmatism in the lower crust coincident with Proterozoic dike swarms: Geology, v. 25, p. 343-346.

Davis, W.J. and Bleeker, W., 1999, Timing of plutonism, deformation, and metamorphism in the Yellowknife Domain, Slave Province, Canada: Canadian Journal of Earth Sciences, v. 36, p. 1169-1187.

Davis, W.J., Canil, D., MacKenzie, J.M. and Carbno, G.M., 2003, Petrology and U-Pb geochronology of lower crustal xenoliths and the development of a craton, Slave province, Canada: Lithos, in press.

Eaton, D.W. and Cassidy, J., 1996, Relic Proterozoic subduction zone in western Canada: evidence from seismic reflection and receiver function data: Geophysical Research Letters, v. 23, p. 3791-3794.

Ellis, S., Beaumont, C., Jamieson, R. A. and Quinlan, G., 1998, Continental collision including a weak zone: the vise model and its application to the Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 35, p. 1323-1346.

Gabrielse, H. and Yorath, C.J., 1991, Geology of the Cordilleran Orogen in Canada, Geological Survey of Canada, Geology of Canada, no. 4, 844 p.

Gorman, A.R. and 12 others, 2002, Deep Probe: Imaging the roots of western North America. Canadian Journal of Earth Sciences: v. 39, p. 375-398.

Gower, C.G. and Krogh, T.E., 2002, A U-Pb geochronological review of the Proterozoic history of the eastern Grenville Province; Canadian Journal of Earth Sciences, v. 39, p. 795-829.

Griffin, W.L., Doyle, B.J., Ryan, C.G., Pearson, N.J., O'Reilly, S.Y., Davies, R., Kivi, K., van Achterbergh, E. and Natapov, L.M., 1999, Layered mantle lithosphere in the Lac de Gras area, Slave Craton; composition, structure and origin: Journal of Petrology, v. 40, p. 705-727.

Grütter, H.S., Apter, D.B. and Kong, J., 1999, Crust-mantle coupling; evidence from mantle-derived xenocrystic garnets, *in* Gurney, J.J., Gurney, J.L., Pascoe, M.D. and Richardson, S.H., eds., The J. B. Dawson volume; proceedings of the VIIth international kimberlite conference: v. 1, p. 307-313.

Hall, J., Marillier, F. and Dehler, S. 1998, Geophysical studies of the structure of the Appalachian orogen in the Atlantic borderlands of Canada: Canadian Journal of Earth Sciences, v. 35, p. 1205-1221.

Hanmer, S., Corrigan, D., Pehrsson, S. and Nadeau, L., 2000, SW Grenville Province, Canada: the case against post-1.4 Ga accretionary tectonics: Tectonophysics, v. 319, p. 33-51.

Heaman, L.M., Creaser, R.A. and Cookenboo, H.O., 2002, Extreme enrichment of high field strength elements in Jericho eclogite xenoliths; a cryptic record of Paleoproterozoic subduction, partial melting, and metasomatism beneath the Slave Craton, Canada: Geology, v. 30, p. 507-510.

Hoffman, P.F. 1989, Precambrian geology and tectonic history of North America, i*n* Bally, A.W. and Palmer, A.R., eds., The geology of North America-an overview: Geological Society of America, The Geology of North America, A, p. 447-512.

Indares, A., Dunning, G. and Cox, R. 2000, Tectono-thermal evolution of deep crust in a Mesoproterozoic continental setting: the Manicouagan example: Canadian Journal of Earth Sciences, v. 37, p. 325-340.

Irvine, G.J., Pearson, D.G., Kopylova, M.G., Carlson, R.W., Kjarsgaard, B.A. and Dreibus, G., 2001, The age of two cratons: a PGE and Os-isotopic study of peridotite xenoliths from the Jericho kimberlite (Slave craton) and Somerset Island kimberlite field (Churchill Province, *in* Slave-Kaapvaal Workshop, September 5-9, 2001, Merrickville, Ontario.

Jones, A.G., Ferguson, I.J., Chave, A.D., Evans, R.L. and McNeice, G.W., 2001, Electric lithosphere of the Slave Craton: Geology, v. 29, p. 423-426.

Kerr, A., Jenner, G.A. and Fryer, B. J., 1994, Sm-Nd isotopic geochemistry of Precambrian to Paleozoic granitoid suites and the deep-crustal structure of the southeast margin of the Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 32, p. 224-245.

Kopylova, M.G. and Russell, J.K., 2000, Chemical stratification of cratonic lithosphere; constraints from the northern Slave Craton, Canada: Earth and Planetary Science Letters, v. 181, p. 71-87.

Kopylova, M.G., Russell, J.K. and Cookenboo, H., 1998, Upper-mantle stratigraphy of the Slave Craton, Canada; insights into a new kimberlite province: Geology, v. 26, p. 315-318.

Kusky, T.M., 1989, Accretion of the Archean Slave Province: Geology, v. 17, p. 63-67.

Ludden, J, and Hynes, A. 2000a, The Lithoprobe Abitibi-Grenville transect: two billion years of crust formation and recycling in the Precambrian Shield of Canada: Canadian Journal of Earth Sciences, v. 37, p. 459-476.

Ludden, J., and Hynes, A., eds., 2000b, The Lithoprobe Abitibi-Grenville Transect: Canadian Journal of Earth Sciences, v. 37, p. 115-516.

Marillier, F., Keen, C.E., Stockmal, G.S., Quinlan, G., Williams, H., Colman-Sadd, S.P. and O'Brien, S.P., 1989, Crustal structure and surface zonation of the Canadian Appalachians: implications of deep seismic reflection data: Canadian Journal of Earth Sciences, v. 26, p. 305-321.

Martignole, J., Calvert, A.J., Friedman, R. and Reynolds, P., 2000, Crustal evolution along a seismic section across the Grenville Province (Quebec): Canadian Journal of Earth Sciences, v. 37, p. 291-306.

Moser, D. and Heaman, L.M., 1997, Proterozoic zircon growth in Archean lower crustal xenoliths – a consequence of Matachewan ocean opening: Contributions to Mineralogy and Petrology, v. 128, p. 164-175.

Mosher, S., 1998, Tectonic evolution of the southern Laurentian Grenville orogenic belt. Geological Society of America Bulletin: v. 110, p. 1357-1375.

Musacchio, G., White, D.J., Asudeh, I, and Thomson, C.J., Lithospheric structure of the Archean western Superior Province from seismic refraction/wide-angle reflection profiling: Journal of Geophysical Research, submitted

O'Brien, B.H., O'Brien, S.J. and Dunning, G.R., 1991, Silurian cover, Late Precambrian-Early Ordovician basement, and the chronology of Silurian orogenesis in the Hermitage flexure (Newfoundland Appalachians): American Journal of Science, v. 291, p. 760-799.

Parrish, R.R., Carr, S.D. and Parkinson, D.L., 1988, Eocene extensional tectonics and geochronology of the southern Omineca belt, British Columbia and Washington: Tectonics, v. 7, p. 181-212.

Percival, J.A., ed., 1994, The Kapuskasing transect of Lithoprobe: Canadian Journal of Earth Sciences, v. 31, p. 1013-1286.

Percival, J.A., Stern, R.A., Skulski, T., Card, K.D., Mortensen, J.K. and Bégin, N.J., 1994, Minto block, Superior Province: Missing link in deciphering assembly of the craton at 2.7 Ga: Geology, v. 22, p. 839-842.

Percival, J.A., Stern, R.A., Skulski, T., 2001, Crustal growth through successive arc magmatism: Reconnaissance U-Pb SHRIMP data from the northeastern Superior Province, Canada: Precambrian Research, v. 109, p. 203-238.

Price, R.A., 1981, The Cordilleran foreland thrust and fold belt in the southern Canadian Rocky Mountains: Geological Society of London, Special Publication 9, p. 427-448.

Price, R.A. and Douglas, R.J.W., eds., 1972, Variations in Tectonic Styles in Canada: Geological Association of Canada Special Paper 11, 688 p.

Quinlan, G.M., Hall, J., Williams, H., Wright, J.A., Colman-Sadd, S.P., O'Brien, S.J., Stockmal, G.S. and Marillier, F., 1992, Lithoprobe onshore seismic reflection transect across the Newfoundland Appalachians: Canadian Journal of Earth Sciences, v. 29, p.1865-1877.

Rivers, T. 1997, Lithotectonic elements of the Grenville Province: Precambrian Research, v. 86, p. 117-154.

Rivers, T. and Corrigan, D., 2000, Convergent margin on southeastern Laurentia during the Mesoproterozoic: tectonic implications: Canadian Journal of Earth Sciences, v. 37, p. 359-383.

Rivers, T., Martignole, J., Gower, C.F. and Davidson, A., 1989, New tectonic divisions of the Grenville Province, southeast Canadian Shield. Tectonics, v. 8, p. 63-84.

Rivers, T., Ketchum, J., Indares, A. and Hynes, A., 2002, The High Pressure belt in the Grenville Province: architecture, timing and exhumation: Canadian Journal of Earth Sciences, v. 39, p. 867-893.

Ross, G.M., ed., 2002, The Lithoprobe Alberta basement transect: Canadian Journal of Earth Sciences, v. 39, p. 287-437.

Sircombe, K.N., Bleeker, W. and Stern, R.A., 2001, Detrital zircon geochronology and grain-size analysis of ~2800 Ma Mesoarchean proto-cratonic cover succession, Slave Province, Canada: Earth and Planetary Science Letters, v. 189, p. 207-220.

Skulski, T., Corkery, M.T., Stone, D., Whalen, J.B. and Stern, R.A., 2000, Geological and geochronological investigations in the Stull Lake - Edmund Lake greenstone belt and granitoid rocks of the northwestern Superior Province, *in* Report of Activities 2000, Manitoba Industry, Trade and Mines, Manitoba Geological Survey, p. 117-128.

Stone, D., 2000, Temperature and pressure variations in suites of Archean felsic plutonic rocks, Berens River area, northwestern Superior Province, Ontario, Canada: Canadian Mineralogist, v. 38, p. 455-470.

Stott, G.M., 1997, The Superior Province, Canada, *in* de Wit, M.J. and Ashwal, L.D., eds., Greenstone Belts, Oxford Monograph on Geology and Geophysics: 35, Oxford Clarendon, pp. 480-507.

Swinden, H.S., Jenner, G.A. and Szybinski, Z.A., 1997, Magmatic and tectonic evolution of the Cambro-Ordovician Laurentian margins of Iapetus: Geochemical and isotopic constraints from the Notre Dame subzone, Newfoundland, *in* Sinha, A.K., Whalen, J.B. and Hogan, J.P., eds., The nature of magmatism in the Appalachian Orogen: Geological Society of America Memoir 191, p. 337-365.

Thurston, P.C. and Chivers, K.M., 1990, Secular variation in greenstone sequence development emphasising Superior Province, Canada: Precambrian Research, v. 46, p. 21-58.

Van Staal, C.R., Dewey, J.F., MacNiocaill, C. and McKerrow, S., 1998, The Cambrian-Silurian tectonic evolution of the northern Appalachians: history of a complex, southwest Pacific-type segment of Iapetus, *in* Blundell, D. J. and Scott, A. C., eds., Lyell: the Past is the Key to the Present: Geological Society Special Publication 143, pp. 199-242.

van der Velden, A.J. and Cook, F.A., 2002a, Attempted subduction of the Gondwanan continental margin beneath Laurentia: new images from reprocessed Lithoprobe seismic reflection data across the Newfoundland Appalachians, *in* Abstract with Programs, Geological Society of America, Annual Meeting, p. 264.

van der Velden, A.J. and Cook, F.A., 2002b, Products of 2.65-2.58 Ga orogenesis in the Slave Province correlated with Slave-Northern Cordillera lithospheric evolution (SNORCLE) seismic reflection patterns: Canadian Journal of Earth Sciences, v. 39, p. 1189-1200.

van der Velden, A.J., van Staal, C.R. and Cook, F.A., in prep, Attempted subduction of the Gondwanan margin beneath Laurentia revealed: Lithoprobe seismic reflection images of the Newfoundland Appalachians

Waldron, J.W.F. and van Staal, C.R., 2001, Taconic Orogeny and the accretion of the Dashwoods block: a peri-Laurentian microcontinent in the Iapetus Ocean: Geology, v. 29, p. 811-814.

Wardle, R.J. and Hall, J., 2002, Proterozoic evolution of the northeastern Canadian Shield: Lithoprobe Eastern Canadian Shield onshore-offshore transect: Canadian Journal of Earth Sciences, v. 39, p. 563-897.

Wheeler, J.O., Hoffman, P.F., Card, K.D., Davidson, A., Sanford, B.V., Okulitch, A.V. and Roest, W.R., 1996, Geological Map of Canada: Geological Survey of Canada, Map 1860 A, CD-ROM.

Wheeler, J.O. and McFeely, P., 1991, Tectonic assemblage map of the Canadian Cordillera and adjacent parts of the United States of America: Geological Survey of Canada, Map 1712A, scale 1:2,000,000.

White, D.J., Musacchio, G., Helmstaedt, H., Harrap, R, Thomson, C., Sol, S. and Thurston, P., 2001, Remnants of Archean subduction in the western Superior Province: Results from combined Lithoprobe deep seismic studies, *in* Harrap, R.M. and Helmstaedt, H.H., eds., 2001 Western Superior Transect Seventh Annual Workshop. Lithoprobe Report 80, Lithoprobe Secretariat, University of British Columbia, pp. 163-164.

White, D.J., Lucas, S.B., Bleeker, W., Hajnal, Z., Lewry, J.F. and Zwanzig, H.V., 2002, Suture-zone geometry along an irregular Paleoproterozoic margin: The Superior boundary zone, Manitoba, Canada: Geology, v. 30, p. 735-738.

White, D.J., Musacchio, G., Helmstaedt, H., Harrap, R.M., Thurston, P.C., van der Velden, A. and Hall, K., Images of a lower-crustal oceanic slab: Direct evidence for tectonic accretion in the Archean western Superior Province: submitted to Geology

Williams, H., 1979, Appalachian orogen in Canada: Canadian Journal of Earth Sciences, v. 16, p. 530-536.

Williams, H.R., Stott, G.M., Thurston, P.C., Sutcliffe, R.H., Bennett, G., Easton, R.M. and Armstrong, D.K., 1992, Tectonic evolution of Ontario: Summary and synthesis, *in* Thurston, P.C., Williams, H.R., Sutcliffe, R.H., Stott, G.M., eds., Geology of Ontario, Ontario Geological Survey Special Volume 4, Part 2, pp. 1255-1332.

Figure Captions

Fig. 1: Precambrian tectonic domains for North America classified using U-Pb ages and Nd signature. The Sri (initial $^{87}Sr/^{86}Sr$) line in the Cordillera marks the western edge of thick Precambrian crust (from Armstrong, 1988). EAO: East Alberta orogen; MRV: Minnesota River valley gneiss; Mak-Ket: Makkovik-Ketilidean. Modified from Hoffman (1989). Detailed legend for Paleoproterozoic units is given in figure 8. LITHOPROBE transects: AB: Alberta basement; AG: Abitibi-Grenville; ECSOOT: Eastern Canadian Shield onshore-offshore transect; KSZ: Kapuskasing structural zone; LE: Lithoprobe east; SNORCLE: Slave-Northern Cordillera Lithospheric evolution; SC: Southern Cordillera; WS: Western Superior; THO: Trans-Hudson orogen.

Fig. 2: Geological map of the Canadian Cordillera (after Wheeler and McFeely, 1991; Wheeler et al., 1996) with the five major morphogeological belts and the two LITHOPROBE transects indicated.

Fig. 3: Geology of Newfoundland after Colman-Sadd et al., 1990 with modifications by van Staal et al., 1998 and unpublished data. Meelpaeg seismic transect, the basis of the geological section of Figure 4, is outlined by the line segments with numbers (see also Hall et al., 1998). RIL – Red Indian Line; MP – Meelpaeg allochthon; PB – Port aux Basques extension of Meelpaeg allochthon.

Figure 4: Interpreted seismic reflection profile of Meelpaeg transect (from van der Velden et al., in prep). Migrated reflection data is plotted at 1:1 assuming a velocity of 6000 m/s.

Colour scheme is similar to that of Fig. 3. The Meelpaeg allochthon is bounded at its hanging wall by a low-angle normal fault (GBLF). BOI – Bay of Island ophiolite; HRF – Humber River fault; BVL – Baie Verte Line; CF – Cabot fault; NDA – Notre Dame arc; HMT – Hungry Mountain thrust; AAT – Annieopsquotch accretionary tract; SC – subduction complex of underplated material; VARC – Victoria arc; RIL – Red Indian Line; DBL – Dog Bay Line; DLB – Deer Lake basin; VRT – Victoria River thrust; GBLF - Great Burnt Lake fault; SRF – Salmon River fault; DCT – Day Cove thrust; HBF-Hermitage Bay fault; WHF – White Horse fault.

Fig. 5: Sketch map of North America (modified from Rivers, 1997) showing the location of the Grenville Province and its extension to the southwest in the subsurface and outliers (LU - Llano Uplift). Mesoproterozoic arc rocks (red dots) occur within the Grenville Province and in the buried foreland, where they are known as the Southern and Eastern Granite -Rhyolite belts (SGR and EGR). Accreted late Mesoproterozoic terranes: Composite Arc belt (CAb), Frontenac-Adirondack Lowland belt (F-ALb), Coal Creek domain (CCd). Mesoproterozoic continental back-arc deposits include the Seal Lake Group (SLG) (red beds and mafic sills), anorthosites and mafic dyke swarms.

Figure 6: Sketch map of the Grenville Province showing the distribution of orogen-scale belts (after Rivers et al., 2002). Thick lines labeled A to G are the locations of seismic transects. ABT - Allochthon boundary thrust, CAb - Composite Arc belt, F-ALb - Frontenac-Adirondack Lowland belt, HP belt - High Pressure belt.

Figure 7: Interpretations of LITHOPROBE seismic transects showing the stacked crustal structure of the Grenville orogen (after Ludden and Hynes, 2000a; Rivers et al., 2002). Locations of transects A-E are shown on Fig. 6. Thick black arrows in transect C show locations of crustal-scale normal-faults interpreted to be due to orogenic collapse. Cab - Composite Arc belt, FALb - Frontenac-Adirondack Lowland belt

Fig. 8: Paleoproterozoic tectonic elements of North America (modified after Hoffman, 1989). CB: Cumberland batholith; EAO: East Alberta Orogen; GF: Great Falls Tectonic Zone; GS: Great Slave Lake shear zone; MRV: Minnesota River Valley; NA: Narsajuaq arc; NQ: New

Quebec orogen; STZ: Snowbird Tectonic zone; THO: Trans-Hudson Orogen; TO: Torngat orogen; TS: Trans-Scandinavian belt.

Fig. 9: Composite N-S cross section of Superior Province. Segment B-C is based on Western Superior LITHOPROBE line 1 seismic reflection (modified after White et al., submitted) and refraction (Mussachio et al., submitted) constraints (QF: Quetico fault; SLF: Sydney Lake - Lake St. Joseph fault; M1, M2, M3 are distinctive Moho segments). Line segment C'-D from Calvert and Ludden is a composite of Abitibi-Grenville lines. A-B is speculative, based on surface geology and subduction polarity inferred from distribution of arc magmatic rocks. Abbreviations as in Fig. 10.

Fig. 10: Tectonic elements of the Superior Province, showing old cratons and other features: NSS: Northern Superior superterrane; NCLGGS: North Caribou- La Grande- Goudalie superterrane; WR: Winnipeg River terrane; KU: Kapuskasing uplift; NP: Nipigon plate. Features of tectonic significance are indicated in the legend.

Fig. 11: Cladogram (*cf.* Hoffman, 1989) illustrating timing of assembly of the Superior Province from continental and oceanic fragments. Note successive merging of terranes between 2720 and 2680 Ma.

Fig. 12: a) Geological map of the Slave craton. Transparent overlay (light purple) outlines probable and possible (Hope Bay block) distribution of ancient basement. Line "A" outlines an arc of 2661 Ma felsic volcanic centers; line "B" outlines an approximate northwestern boundary to the "Burwash Basin"; all post-Burwash volcanic and turbiditic rocks occur to the northwest of the line.

Fig. 13: Cross-section through the Slave craton; for section line, see Fig. 12.

Fig. 14: Orogenic classification diagram developed at the workshop to describe the development of orogens in terms of subduction, accretion and collision. Additional end-members may be necessary in some orogens to describe non-plate tectonic processes.

Fig. 15: Orogenic pathways illustrated on a Hertzsprung-Russell diagram, as modified by S. Ellis and C. Beaumont. Type orogens are shown for comparison to Archean, Proterozoic and Phanerozoic orogens of Canada.

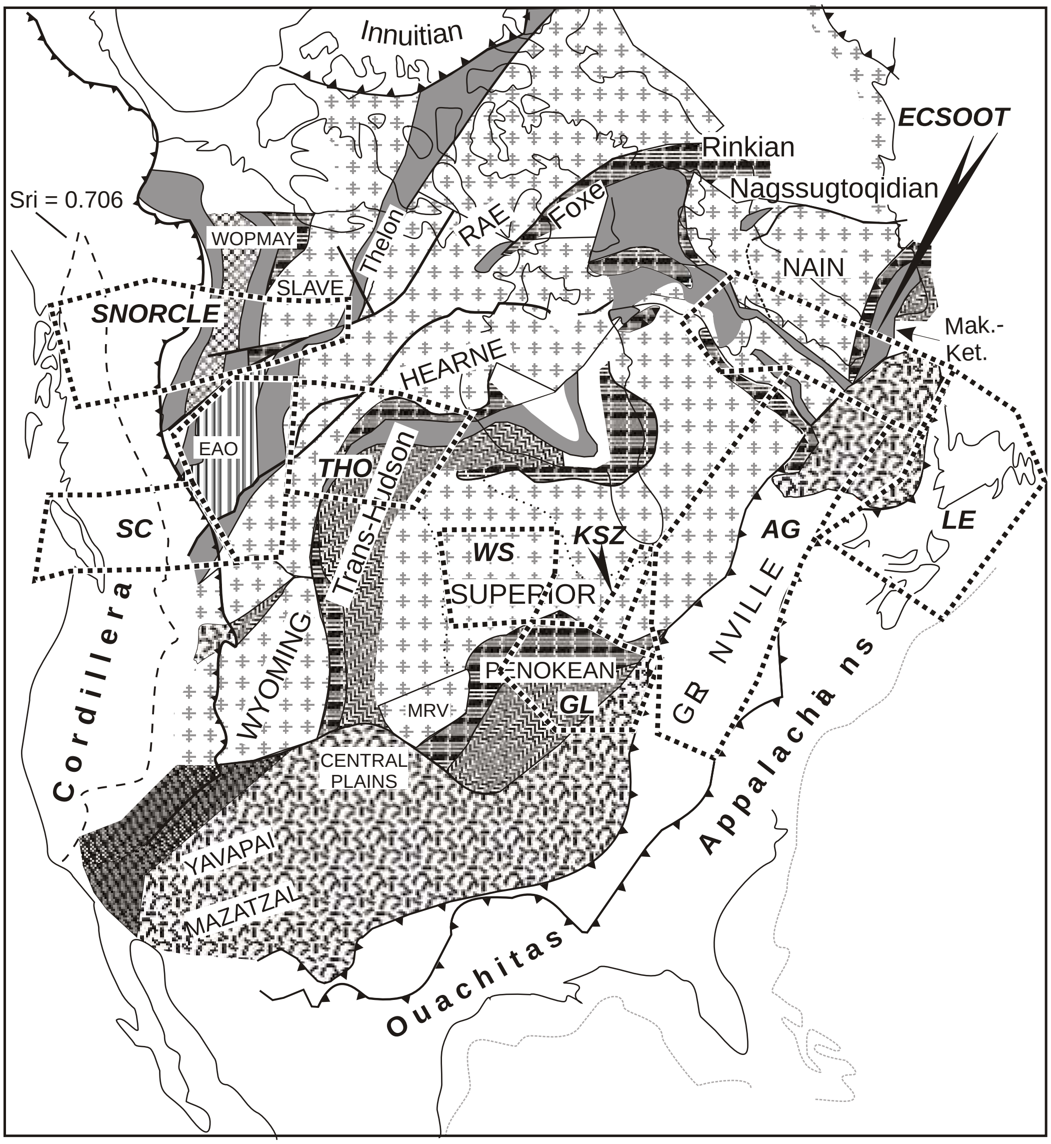

Fig. 1: Precambrian tectonic domains for North America classified using U-Pb ages and Nd signature. The Sri (initial $^{87}Sr/^{86}Sr$) line in the Cordillera marks the western edge of thick Precambrian crust (from Armstrong, 1988). EAO: East Alberta orogen; MRV: Minnesota River valley gneiss; Mak-Ket: Makkovik-Ketilidean. Modified from Hoffman (1989). Detailed legend for Paleoproterozoic units is given in figure 8. LITHOPROBE transects: AB: Alberta basement; AG: Abitibi-Grenville; ECSOOT: Eastern Canadian Shield onshore-offshore transect; KSZ: Kapuskasing structural zone; LE: Lithoprobe east; SNORCLE: Slave-Northern Cordillera Lithospheric evolution; SC: Southern Cordillera; WS: Western Superior; THO: Trans-Hudson orogen.

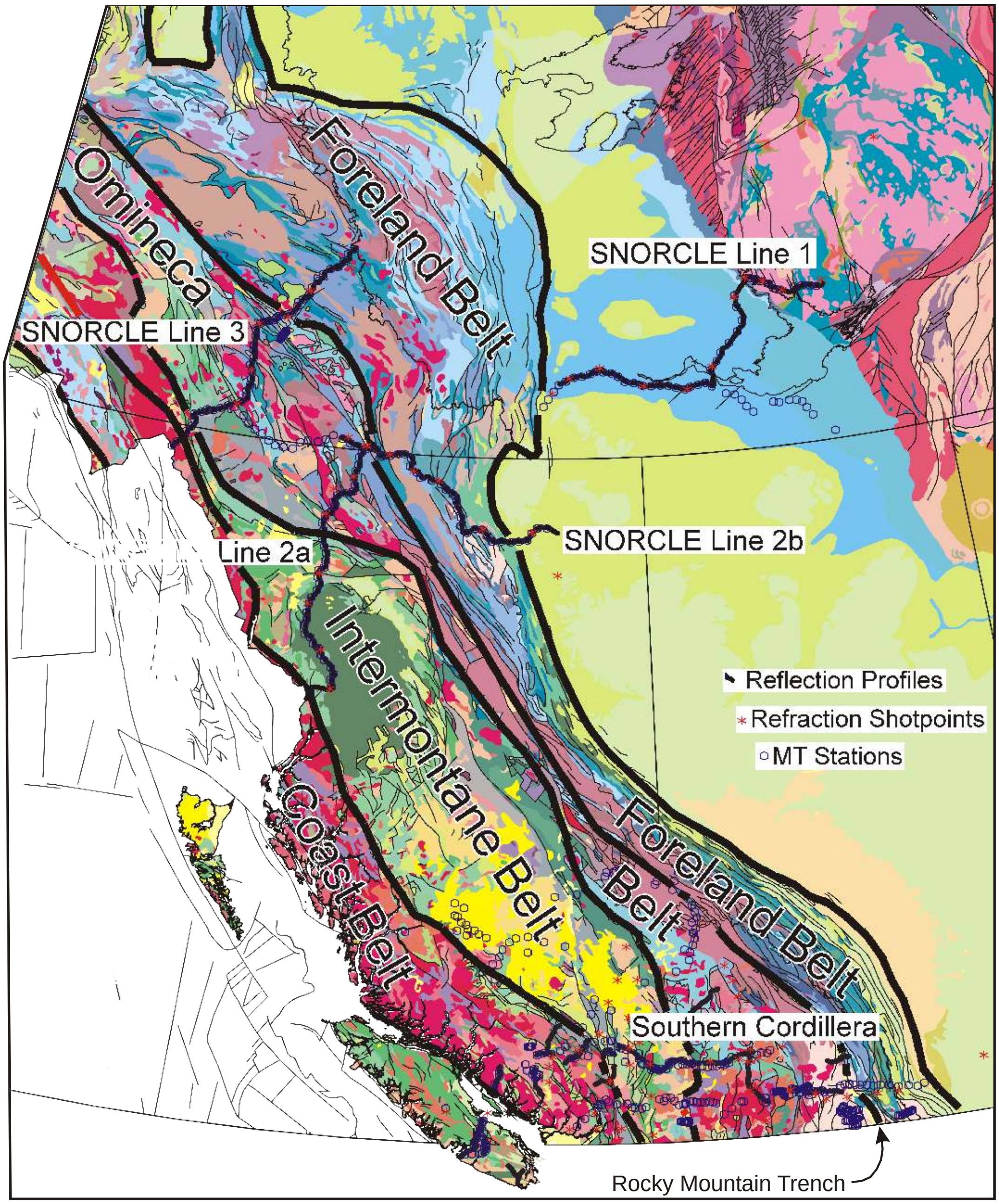

Fig. 2: Geological map of the Canadian Cordillera (after Wheeler and McFeely, 1991; Wheeler et al., 1996) with the five major morphogeological belts and the two LITHOPROBE transects indicated.

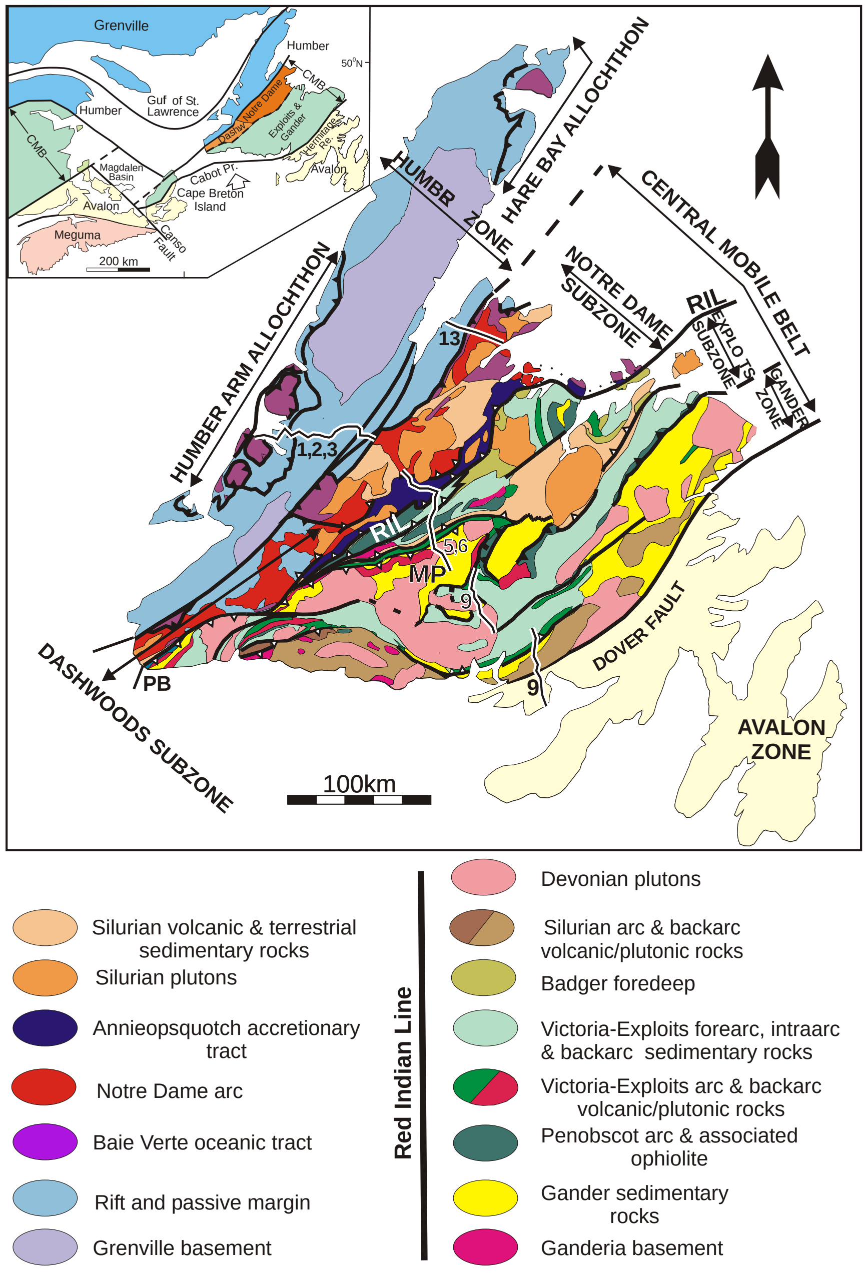

Fig. 3: Geology of Newfoundland after Colman-Sadd et al., 1990 with modifications by van Staal et al., 1998 and unpublished data. Meelpaeg seismic transect, the basis of the geological section of Figure 4, is outlined by the line segments with numbers (see also Hall et al., 1998). RIL Red Indian Line; MP Meelpaeg allochthon; PB Port aux Basques extension of Meelpaeg allochthon.

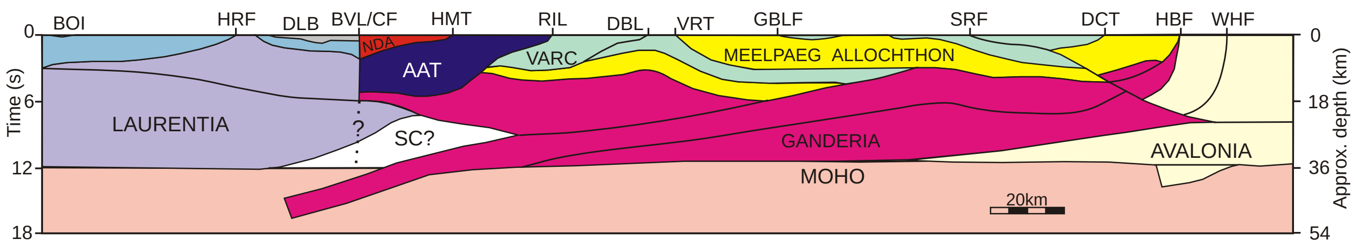

Figure 4: Interpreted seismic reflection profile of Meelpaeg transect (from van der Velden et al., in prep). Migrated reflection data is plotted at 1:1 assuming a velocity of 6000 m/s.
Colour scheme is similar to that of Fig. 3. The Meelpaeg allochthon is bounded at its hanging wall by a low-angle normal fault (GBLF). BOI Bay of Island ophiolite; HRF Humber River fault; BVL Baie Verte Line; CF Cabot fault; NDA Notre Dame arc; HMT Hungry Mountain thrust; AAT Annieopsquotch accretionary tract; SC subduction complex of underplated material; VARC Victoria arc; RIL Red Indian Line; DBL Dog Bay Line; DLB Deer Lake basin; VRT Victoria River thrust; GBLF - Great Burnt Lake fault; SRF Salmon River fault; DCT Day Cove thrust; HBF-Hermitage Bay fault; WHF White Horse fault.

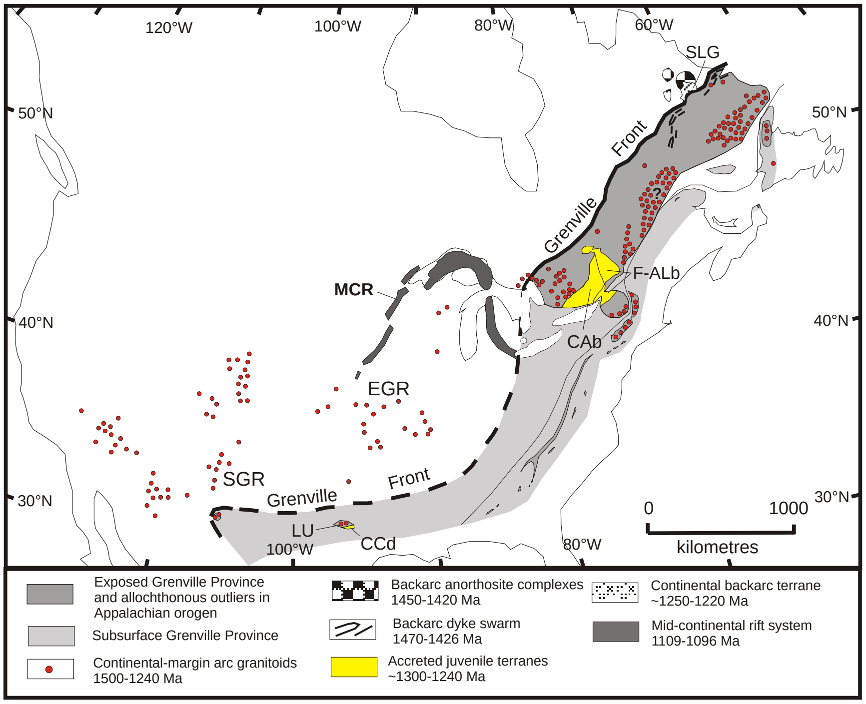

Fig. 5: Sketch map of North America (modified from Rivers, 1997) showing the location of the Grenville Province and its extension to the southwest in the subsurface and outliers (LU - Llano Uplift). Mesoproterozoic arc rocks (red dots) occur within the Grenville Province and in the buried foreland (Southern and Eastern Granite-Rhyolite belts: SGR and EGR). Accreted late Mesoproterozoic terranes: Composite Arc belt (CAb), Frontenac-Adirondack Lowland belt (F-ALb), Coal Creek domain (CCd). Mesoproterozoic continental back-arc deposits include the Mid-continent rift (MCR), Seal Lake Group (SLG) (red beds and mafic sills), anorthosites and mafic dyke swarms.

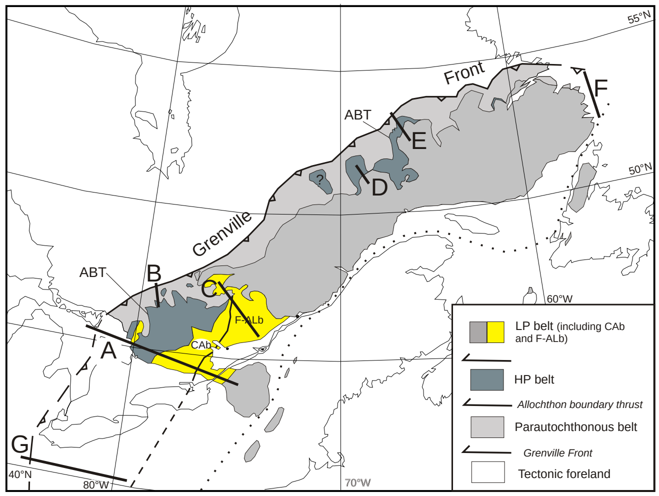

Figure 6: Sketch map of the Grenville Province showing the distribution of orogen-scale belts (after Rivers et al., 2002). Thick lines labeled A to G are the locations of seismic transects. ABT - Allochthon boundary thrust, CAb - Composite Arc belt, F-ALb - Frontenac-Adirondack Lowland belt, HP belt - High Pressure belt.

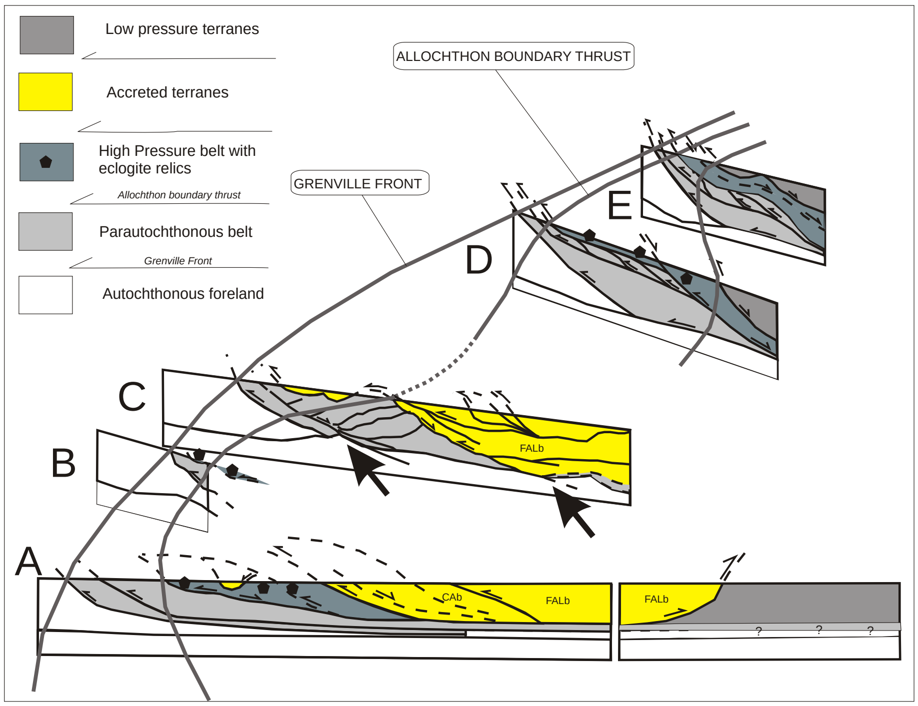

Figure 7: Interpretations of LITHOPROBE seismic transects showing the stacked crustal structure of the Grenville orogen (after Ludden and Hynes, 2000a; Rivers et al., 2002). Locations of transects A-E are shown on Fig. 6. Thick black arrows in transect C show locations of crustal-scale normal-faults interpreted to be due to orogenic collapse. Cab - Composite Arc belt, FALb - Frontenac-Adirondack Lowland belt

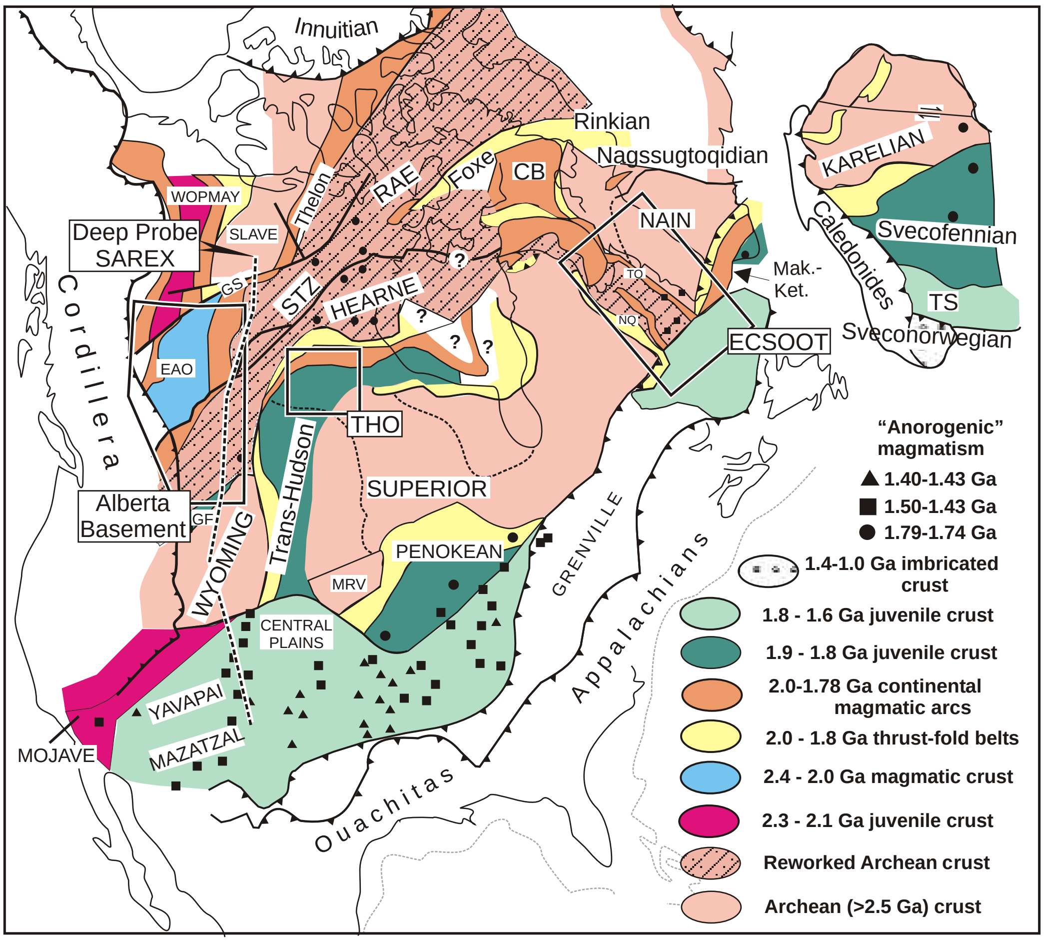

Fig. 8: Paleoproterozoic tectonic elements of North America (modified after Hoffman, 1989). CB: Cumberland batholith; GF: Great Falls Tectonic Zone; GS: Great Slave Lake shear zone; NA: Narsajuaq arc; NQ: New Quebec orogen; STZ: Snowbird Tectonic zone; TO: Torngat orogen.

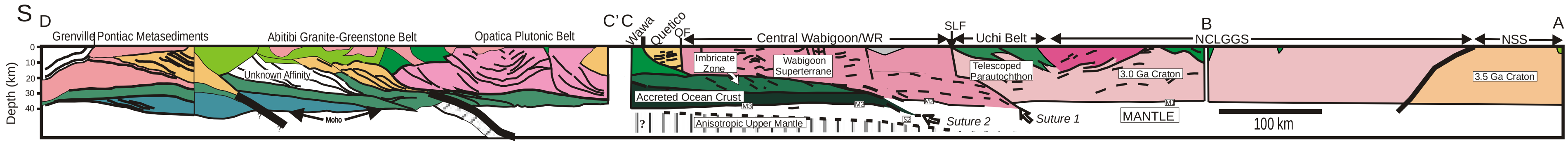

Fig. 9: Composite N-S cross section of Superior Province. Segment B-C is based on Western Superior LITHOPROBE

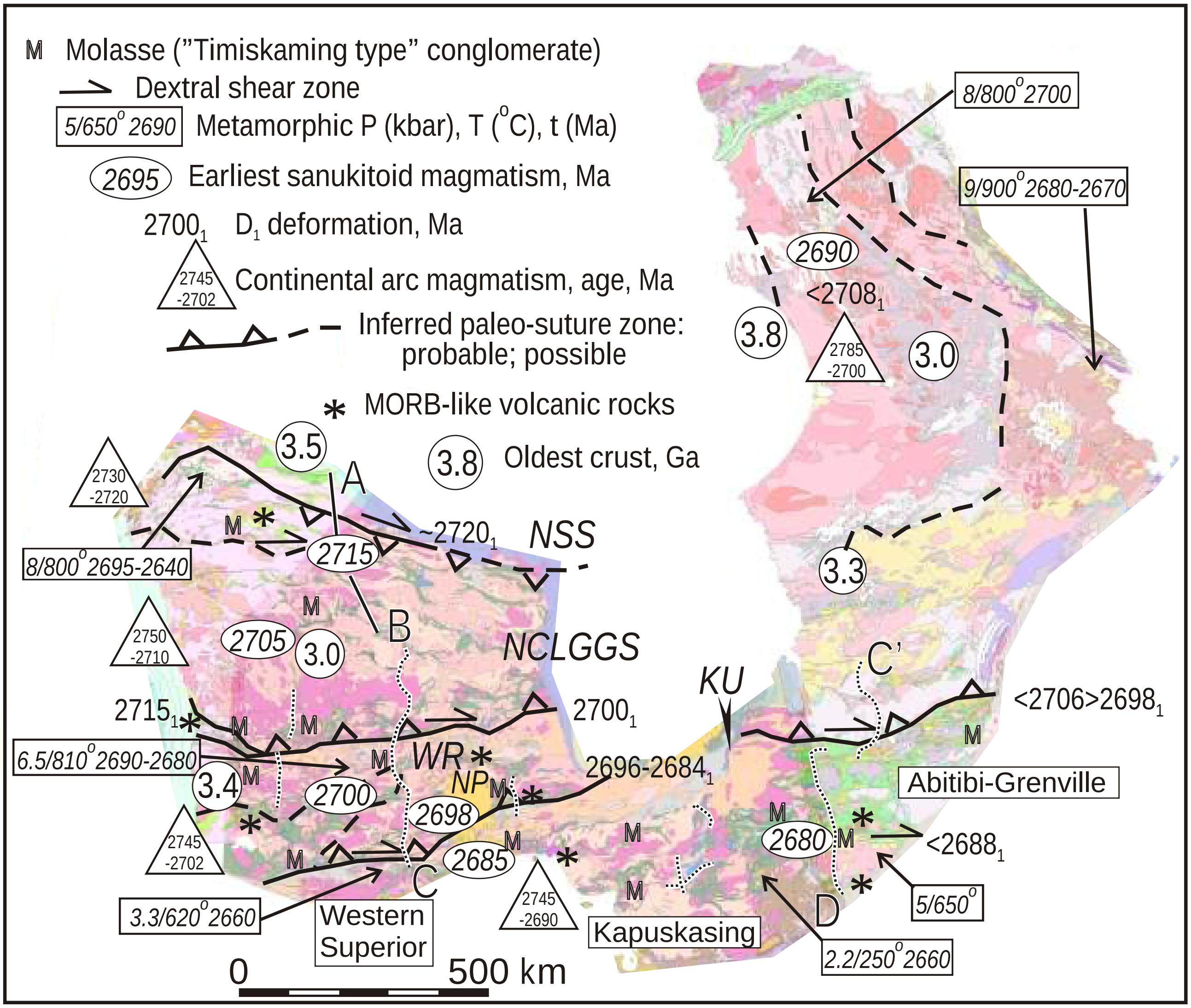

Fig. 10: Tectonic elements of the Superior Province, showing old cratons and other features: NSS: Northern Superior superterrane; NCLGGS: North Caribou-La Grande- Goudalie superterrane; WR: Winnipeg River terrane; KU: Kapuskasing uplift; NP: Nipigon plate. Features of tectonic significance are indicated in the legend.

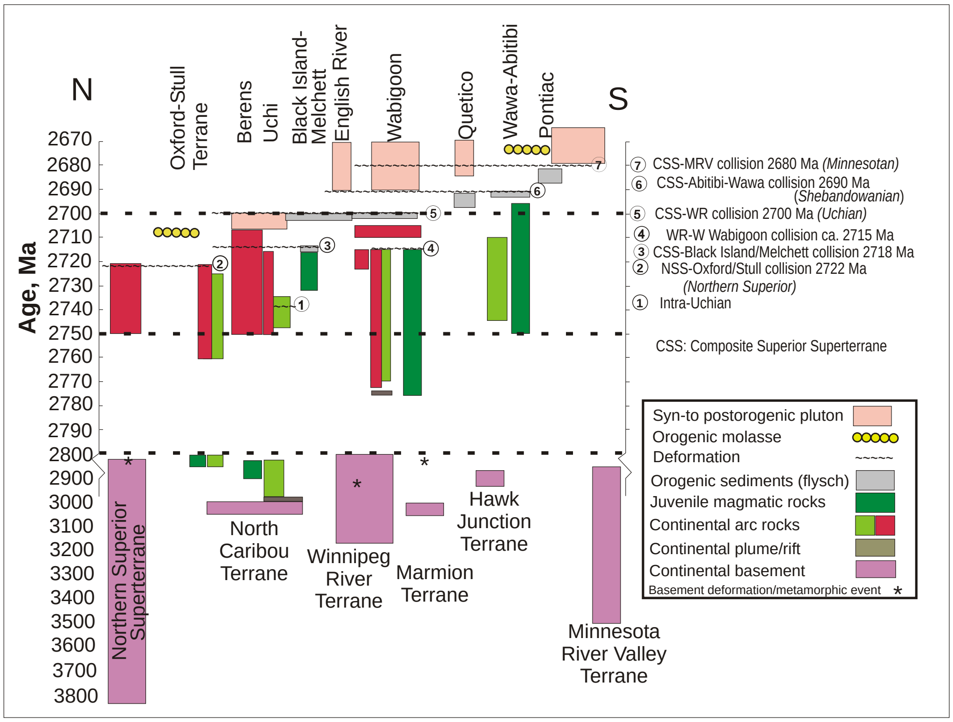

Fig. 11: Cladogram (*cf.* Hoffman, 1989) illustrating timing of assembly of the Superior Province from continental and oceanic fragments. Note successive merging of terranes between 2720 and 2680 Ma.

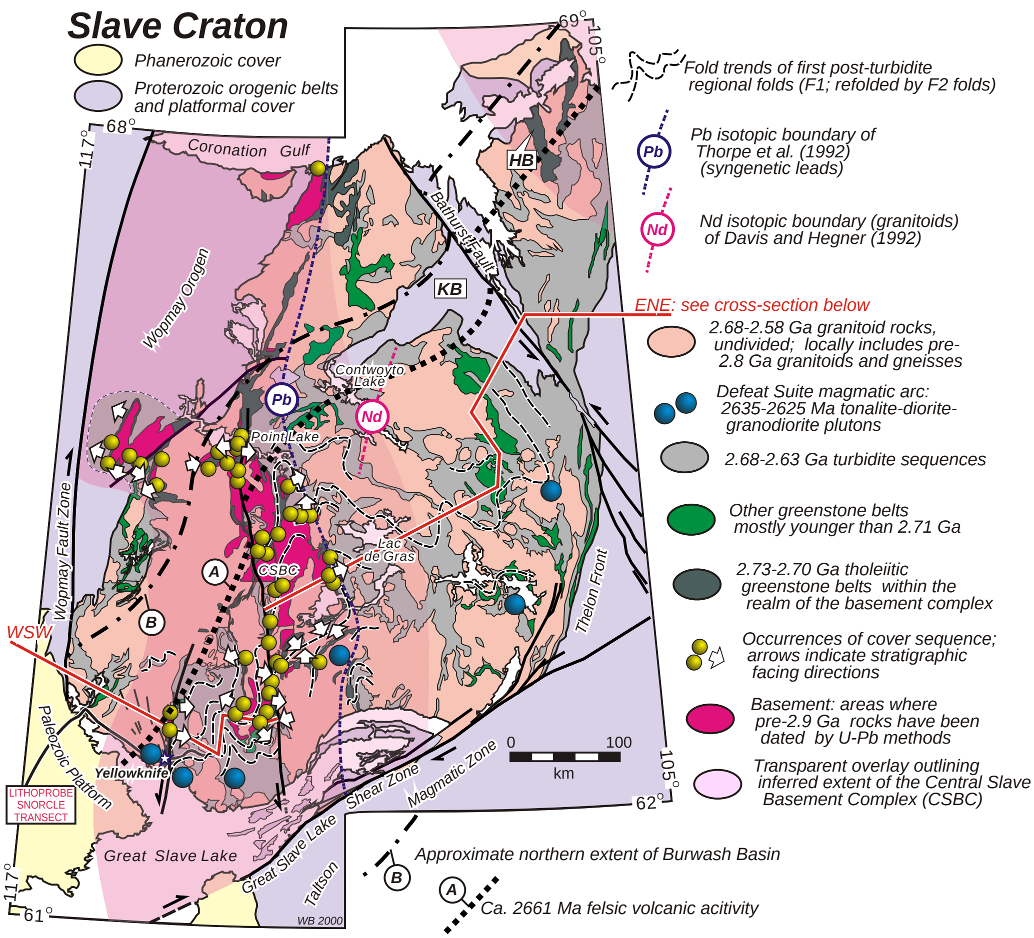

Fig. 12: Geological map of the Slave craton. Transparent overlay (light purple) outlines probable and possible (Hope Bay block) distribution of ancient basement. Line “A” outlines an arc of 2661 Ma felsic volcanic centers; line “B” outlines an approximate northwestern boundary to the “Burwash Basin”; all post-Burwash volcanic and turbiditic rocks occur to the northwest of the line.

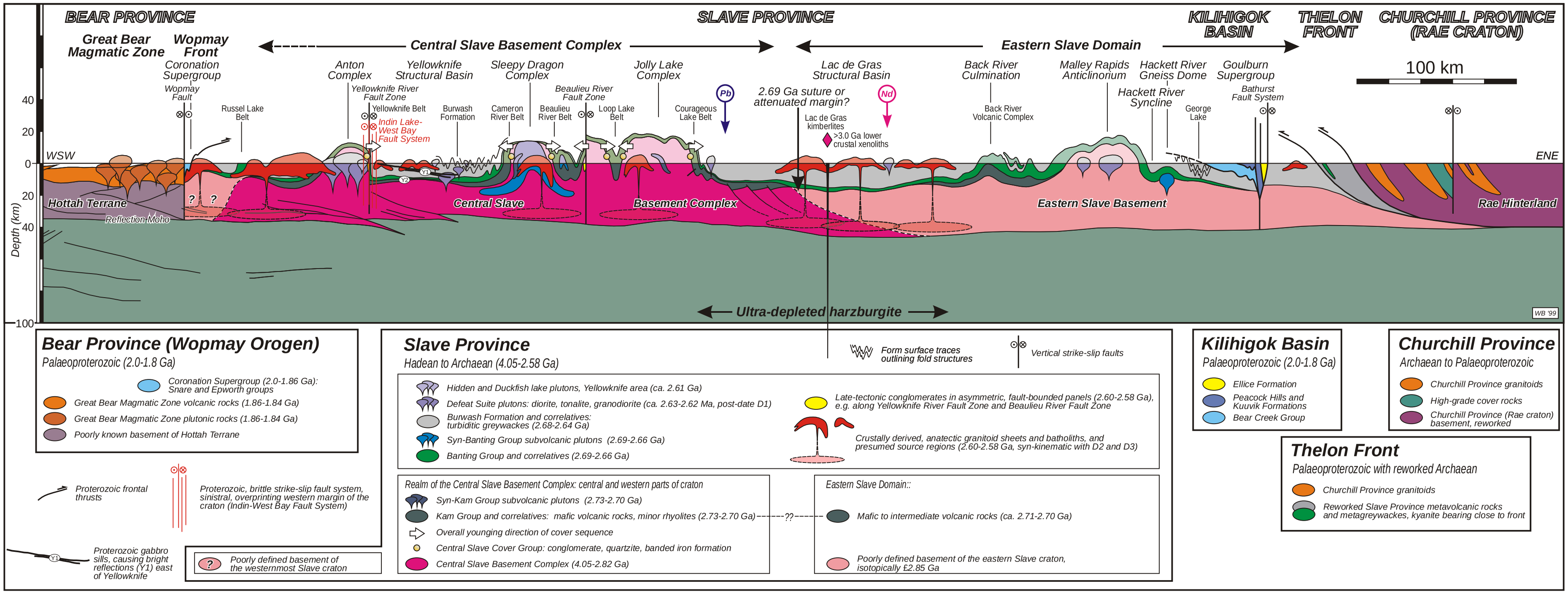

Fig. 13: Cross-section through the Slave craton; for section line, see Fig.

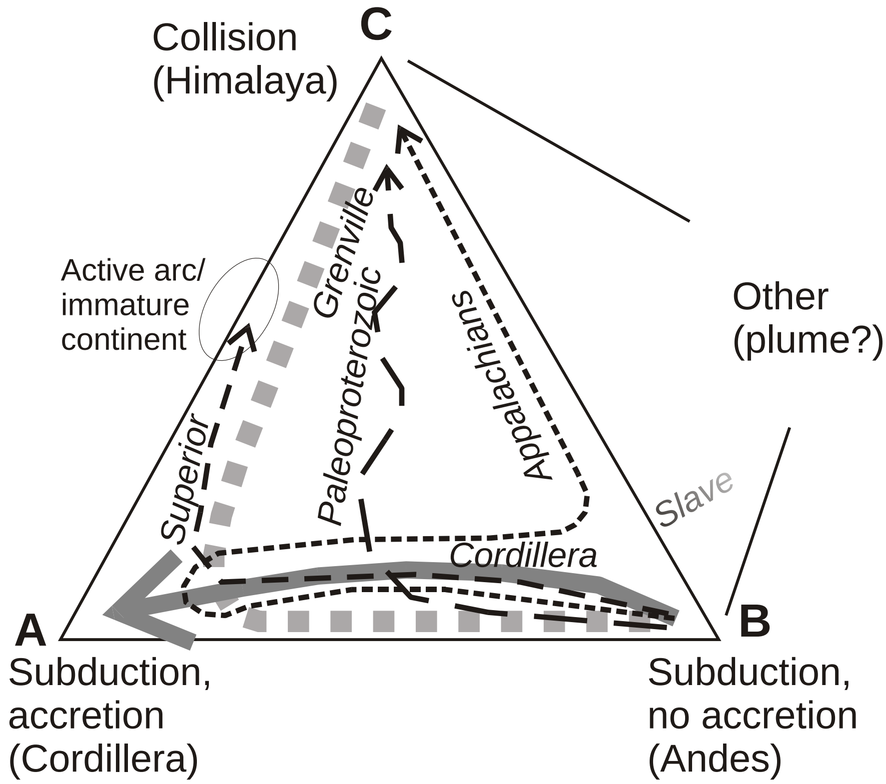

Fig. 14: Orogenic classification diagram developed at the workshop to describe the development of orogens in terms of subduction, accretion and collision. Additional end-members may be necessary in some orogens to describe non-plate tectonic processes.

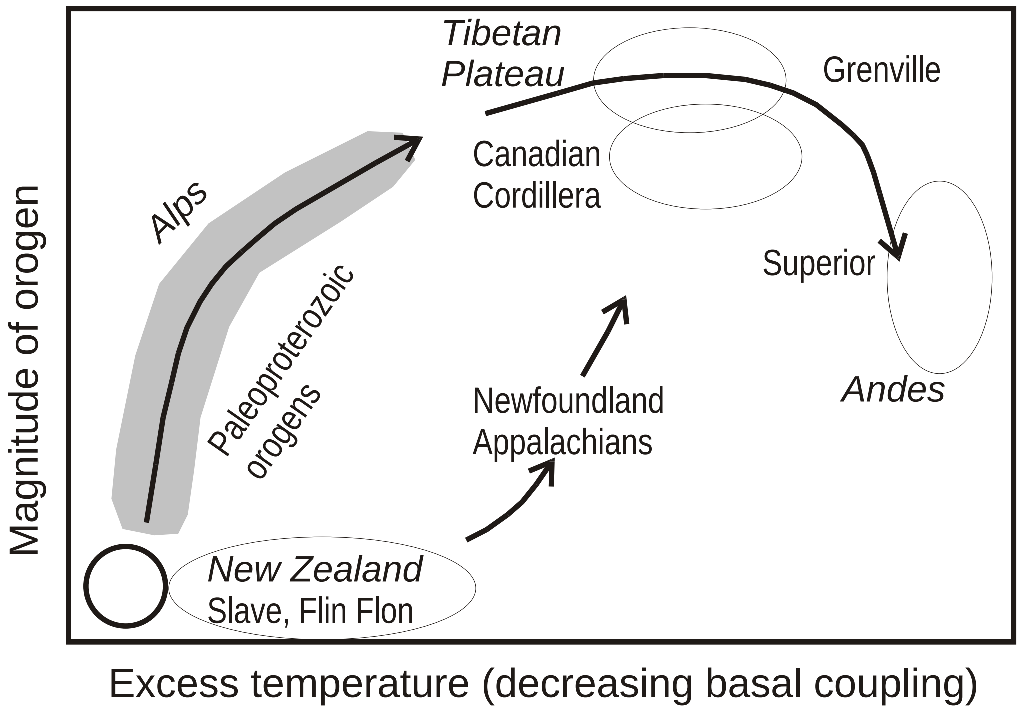

Fig. 15: Orogenic pathways illustrated on a Hertzsprung-Russell diagram, as modified by S. Ellis and C. Beaumont. Type orogens are shown for comparison to Archean, Proterozoic and Phanerozoic orogens of Canada.