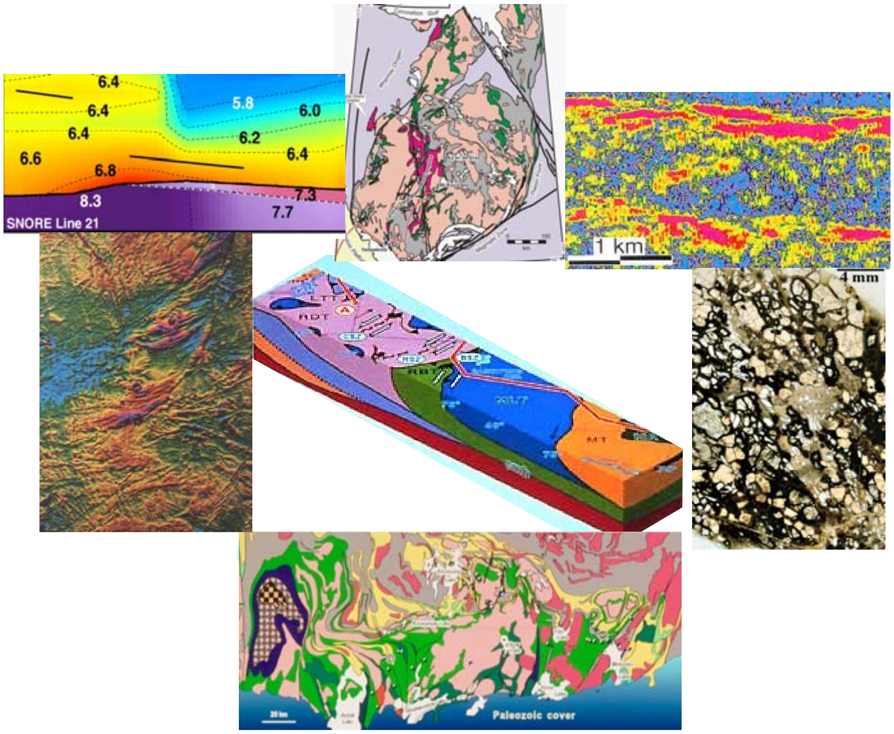
LITHOPROBE

Canada's National Geoscience Project
Le projet pancanadien en sciences de la Terre

THE CELEBRATORY CONFERENCE

From Parameters to Processes – Revealing the Evolution of a Continent
October 12 – 15, 2004 Toronto, Canada



Program and Abstracts

LITHOPROBE Report No. 86

LITHOPROBE
Canada's National Geoscience Project
Le projet pancanadien en sciences de la Terre

WELCOME TO

THE *LITHOPROBE* CELEBRATORY CONFERENCE

"From Parameters to Processes – Revealing the Evolution of a Continent"

I want to wish a very warm welcome to all participants at the LITHOPROBE Celebratory Conference. For 20 years, LITHOPROBE has been investigating key tectonic areas of Canada to determine their structure and complex geological evolution and to understand the processes that have shaped that evolution. Now the project is drawing to a conclusion and this conference demonstrates how well we have succeeded in achieving our objectives.

At such a point in time, it may be worthwhile reflecting on "from whence we came". To this end, I quote below from a summary in the Phase II proposal to NSERC and the GSC, which was submitted in May 1986 by the LITHOPROBE Steering Committee.

> LITHOPROBE is an exciting and enterprising concept which builds on Canadian expertise and addresses the next intellectual frontier in Earth Sciences. The investigation of the third dimension of the continental lithosphere requires "big science". It will take advantage of the technological developments, particularly in seismology, that now permit probing of the lithosphere as never before. Through LITHOPROBE, Canada, with its large share of the Earth's continental crust, will fulfill its responsibility to study the crust in concert with other developed nations.
>
> LITHOPROBE will involve a large cross-section of the Canadian Earth science community. By bringing together a mix of expertise, with its resulting synergism, it will achieve a better understanding of the continental lithosphere. Early grass roots support and commitment in response to the geographically widespread nature of the studies ensure the interest and participation of a large segment of the Earth science community, including the provincial and industrial sectors. LITHOPROBE will be a catalyst to revitalize the Earth sciences in Canada.

Through the efforts of literally hundreds of people like those attending this meeting, LITHOPROBE has unequivocally met, and I am certain, exceeded the expectations of that Steering Committee. To you and to all of the scientists who have participated in LITHOPROBE over the years, I express my sincere thanks for your contributions to this project.

I also want to take this opportunity to thank Cecilia Li, the LITHOPROBE Administrator for the past 10 years, and her predecessor, Lilian Beames. They kept the operation of the Secretariat running smoothly at all times, often under considerable pressure. Cecilia also has been the principal logistical organizer for this conference and deserves our thanks.

Ron M. Clowes

Ron Clowes

September 24, 2004

LITHOPROBE
Canada's National Geoscience Project
Le projet pancanadien en sciences de la Terre

THE *LITHOPROBE* CELEBRATORY CONFERENCE:

"From Parameters to Processes – Revealing the Evolution of a Continent"
October 12 - 15, 2004 Toronto, Ontario, Canada

Program and Associated Social Events:

Tuesday, October 12, 2004

19:00 – 22:00	**Welcoming Reception – Centennial Ballroom, Inn on the Park**

Wednesday, October 13, 2004

09:00 – 12:15	**MEDIA MORNING**
08:30 – 09:00	**Pressroom and conference area opens.** **Posters can be put up throughout morning**
09:00 – 09:20	**Introduction: LITHOPROBE, a national undertaking – the who, how, what and why of the project; the LITHOPROBE cross-Canada cross-section – a new view of our country** ***Ron Clowes, Director, LITHOPROBE, U. of British Columbia, Vancouver, BC***
09:20 – 09:40	**Official opening of conference on behalf of NSERC; the NSERC perspective on LITHOPROBE [speaker to be confirmed]** **The principal funding partner – Geological Survey of Canada (NRCan) and LITHOPROBE, a productive partnership [speaker to be confirmed]** ***Tom Brzustowski, Pres., NSERC*** ***Irwin Itzkovitch, ADM, ESS, NRCan***
09:40 – 09:55	**The Ancient Earth: Development of the Canadian Shield, the oldest parts of North America – building a continental foundation from 4000 to 2500 million years ago** ***John Percival, GSC Ottawa, Ottawa, ON***
09:55 – 10:10	**The Middle Earth I: Ancient oceanic crust in the middle of the Prairies and formation of the Canadian Shield 2000 to 1800 million years ago** ***David Corrigan, GSC Ottawa, Ottawa, ON***
10:10 – 10:25	**The Middle Earth II: A Himalayan-scale mountain range through southern Ontario and Quebec – colliding continents enlarge proto-North America from 1100 – 1000 Ma** ***Andrew Hynes, McGill U., Montreal, QC***
10:25 – 10:45	**BREAK**
10:45 – 11:00	**The Late Earth I: The story of the Appalachians – Opening and closure of ocean basins and the arrival of south American and African pieces in Atlantic Canada** ***Cees van Staal, GSC Ottawa, Ottawa, ON***
11:00 – 11:15	**The Late Earth II: The story of the Canadian Cordillera – British Columbia grows westward and the Rocky Mountains are formed during the period 200 – 50 Ma** ***Fred Cook, U. of Calgary, Calgary, AB***
11:15 – 11:30	**LITHOPROBE and the Mining Industry: Diamonds, Earth's mantle and the roots of continents** ***Herman Grutter, Mineral Services Canada, North Vancouver, BC***

11:30 – 11:45	**LITHOPROBE and the Petroleum Industry: New contributions to regional geological frameworks and exploration for oil and gas deposits** ***Gary Taylor, Past-president, Canadian Society of Exploration Geophysicists, Calgary, AB***
11:45 – 12:00	**LITHOPROBE and the International Community – a Canadian project, considered the best of its kind in the world, influences scientific approaches in other countries** ***Maarten J. de Wit, U. of Cape Town, South Africa***
12:00 – 12:15	**“The Big One!”: Megathrust earthquakes and LITHOPROBE on the west coast – contributions to understanding of seismic hazards** ***Roy Hyndman, GSC Pacific, Sidney, BC***
12:15 – 13:10	**LUNCH at Ontario Science Centre; POSTER viewing**
13:10 – 16:50	**THE EARLY EARTH – ESTABLISHING THE CRATONS**
13:10 – 13:50	**Recombining the fragmented structure and memory of cratons** ***Maarten J. de Wit, U. of Cape Town, South Africa***
13:50 – 14:20	**The Slave craton from on top: The crustal view** ***Wouter Bleeker, GSC Ottawa, Ottawa, ON***
14:20 – 14:50	**The Slave craton from underneath: The mantle view** ***Alan Jones, Dublin Inst. Adv. Studies & GSC Ottawa***
14:50 – 15:20	**BREAK**
15:20 – 15:50	**The Superior craton – What have we learned from geological, geochemical and geochronological studies? Lessons on the development of the Archean Earth and processes involved** ***Herb Helmstaedt, Queen’s U., Kingston, ON***
15:50 – 16:20	**The Superior craton – What have we learned from reflection, refraction, teleseismic, magnetotelluric and heat flow studies? Lessons on development of the Archean Earth and processes involved** ***Don White, GSC Ottawa, Ottawa, ON***
16:20 – 16:50	**Orogenic framework for the Superior Province: Dissection of the "Kenoran Orogeny"** ***John Percival, GSC Ottawa, Ottawa, ON***
16:50 – 18:20	**POSTER SESSION [with refreshments]**

Thursday, October 14, 2004

08:20 – 14:00	**THE MIDDLE EARTH – STITCHING THE CRATONS AND OTHER EVENTS**
08:20 – 09:00	**Progressive proterozoic growth of southern Laurentia by magmatic stabilization of lithosphere, and preservation of proterozoic suture scars in the modern-day lithosphere** ***Karl Karlstrom, U. of New Mexico, Albuquerque, NM***
09:00 – 09:30	**Probing the Lithosphere of the Wopmay orogen** ***Fred Cook, U. of Calgary, Calgary, AB***
09:30 – 10:00	**The Trans-Hudson and East Alberta orogens of western Canada – geophysical characteristics of complex collisional processes and delineation of the Sask craton** ***Zoli Hajnal, U. of Saskatchewan, Saskatoon, SK***
10:00 – 10:30	**BREAK**
10:30 – 11:00	**Evolutionary Tectonic Development of the Trans-Hudson orogen - a tale of three cratons, a large ocean, accretionary and collisional tectonics** ***David Corrigan, GSC Ottawa, Ottawa, ON***
11:00 – 11:30	**Evolution of the Southeastern Churchill Province and development of the Torngat orogen in northeastern Labrador – results from extensive geological and geophysical studies** ***Jeremy Hall, Memorial U., St. John's, NL***
11:30 – 12:00	**The ascendency of a late paleoproterozoic and mesoproterozoic tectonic dynasty: An eastern Laurentian perspective** ***Charlie Gower, Geological Survey Mines and Energy, St. John's, NL***
12:00 – 13:00	**LUNCH at Ontario Science Centre; POSTER viewing**
13:00 – 13:30	**Architecture and tectonic evolution of the Grenville Province: Part of a hot wide orogen that developed over 200 M.y. on the southeastern margin of Laurentia** ***Toby Rivers, Memorial U., St. John's, NL***
13:30 – 14:00	**The Grenville orogen of Ontario and New York – A Himalayan-Scale Mountain Belt: Significance of along-strike variations** ***Sharon Carr, Carleton U., Ottawa, ON***
14:00 – 16:40	**THE LATE EARTH – YOUNG OROGENIC BELTS (I)**
14:00 – 14:30	**The Northern Appalachian orogen – From rifting and ocean opening to accretion of oceanic terranes and collisional events** ***Cees van Staal, GSC Ottawa, Ottawa, ON***
14:30 15:00	**BREAK**
15:00 – 15:30	**The northern Canadian Cordillera - a synthesis of new geological and geophysical results for the Yukon and surrounding areas** ***Jim Mortensen, U. of British Columbia, Vancovuer, BC***
15:30 – 16:00	**The evolving Cordilleran lithosphere** ***Fred Cook, U. of Calgary, Calgary, AB***
16:00 – 16:40	**International presentation relating to one of the major Phanerozoic orogens that have been well studied — Himalayan orogen, Alpine orogen of Europe or the South American Cordilleran orogen** ***TBA***
16:40 – 18:10	**POSTER SESSION [with refreshments]**

19:00 – 23:00	***LITHOPROBE* Banquet – Centennial Ballroom, Inn on the Park**

Friday, October 15, 2004

08:30 – 09:30	THE LATE EARTH – YOUNG OROGENIC BELTS (II)
08:30 – 09:00	Probing the Cordilleran lithosphere with mafic lavas and mantle xenoliths *Don Francis, McGill U., Montreal, QC*
09:00 – 09:30	Some recurring themes in Cordilleran orogenic evolution: Tectonic heredity, tectonic wedging, and retrograde mantle flow *Ray Price, Queen's U., Kingston, ON*
09:30 – 12:00	PROCESSES IN EARTH – HOW THE PLANET WORKS (I)
09:30 – 10:00	An 1800-km cross section of the lithosphere through the northwestern North American plate: Lessons from 4.0 billion years of Earth's history *Fred Cook, U. Calgary, Calgary, AB*
10:00 – 10:30	BREAK
10:30 – 11:00	Geodynamical modeling of collisional orogens: from small-cold to large-hot orogens and applications to LITHOPROBE problems *Chris Beaumont, Dalhousie U. , Halifax, NS*
11:00 – 11:30	Coupled mantle-crust dynamics and its relevance for tectonic processes – Effect of mantle dynamics and properties on lithospheric structure *Russ Pysklywec, U. Toronto, Toronto, ON*
11:30 – 12:00	Metamorphic-tectonic interactions in large hot orogens: Lower crustal flow in the central Gneiss Belt, western Grenville Province *Becky Jamieson, Dalhousie U., Halilfax, NS*
12:00 – 13:00	LUNCH at Ontario Science Centre; POSTER viewing
13:00 – 14:00	PROCESSES IN EARTH – HOW THE PLANET WORKS (II)
13:00 – 13:30	Precambrian mafic magmatism: An overview *Larry Heaman, U. of Alberta, Edmonton, AB*
13:30 – 14:00	Secular changes in tectonic evolution and the growth of continental lithosphere *Tom Skulski, GSC Ottawa, Ottawa, ON*
14:00 – 16:00	THE RESOURCEFUL EARTH – SUSTAINING AND ENDANGERING LIFE ON THE PLANET
14:00 – 14:30	Enhancing base metal exploration through seismic reflection studies adapted for the crystalline rock environment *David Eaton, U. Western Ontario, London, ON*
14:30 – 15:00	BREAK
15:00 – 15:30	Diamonds and kimberlite intrusions – contributions from LITHOPROBE and related geophysical, geochemical and petrological studies *David Snyder, GSC Ottawa, Ottawa, ON*
15:30 – 16:00	Giant earthquakes beneath Canada's west coast *Roy Hyndman, GSC Pacific, Sidney, BC*
16:00 – 16:30	LITHOPROBE - A legacy of benefits to Canada *Ron Clowes, Director, LITHOPROBE* *U. of British Columbia, Vancouver, BC*
16:30 – 18:00	POSTER SESSION [with refreshments]

❧ End of Conference ❧

Abstracts of Oral Presentations

Geodynamical Modeling of Collisional Orogens: From Small-Cold to Large-Hot Orogens and Applications to Lithoprobe Problems
C. Beaumont, M.H. Nguyen, R.A. Jamieson and B.Lee

The Slave craton from on top: The crustal view
Wouter Bleeker, John Ketchum, Bill Davis, Keith Sircombe, Richard Stern and John Waldron

The Grenville orogen of Ontario and New York – A Himalayan-Scale Mountain Belt: Significance of along-strike variations
S.D. Carr, R.M. Easton, R.A. Jamieson, N.G. Culshaw and D.J. White

LITHOPROBE - A Legacy of Benefits to Canada
Ron M. Clowes

Probing the Lithosphere of the Wopmay Orogen
Frederick A. Cook

The Evolving Cordilleran Lithosphere
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An 1800-km cross section of the lithosphere through the northwestern North American plate: Lessons from 4.0 billion years of Earth's history
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Evolutionary Tectonic Development of the Trans-Hudson orogen - a tale of three cratons, a large ocean, accretionary and collisional tectonics
David Corrigan

The Middle Earth I: Ancient oceanic crust in the middle of the Prairies and formation of the Canadian Shield 2000 to 1800 million years ago
David Corrigan

Enhancing Base Metal Exploration Through Seismic Reflection Studies Adapted for the Crystalline Rock Environment
David W. Eaton, Bernd Milkereit and Matthew Salisbury

Probing the Cordilleran Lithosphere with Mafic Lavas and Mantle Xenoliths
Don Francis

The Ascendency of a Late Paleoproterozoic and Mesoproterozoic Tectonic Dynasty: an Eastern Laurentian Perspective
Charles F. Gower

The Trans-Hudson and East Alberta orogens of western Canada – geophysical characteristics of complex collisional processes and delineation of the Sask craton
Z. Hajnal, D.J. White, B. Nemeth, R.M. Clowes, A.G. Jones and M.D. Thomas

Evolution of the Southeastern Churchill Province and Development of the Torngat Orogen in Northeastern Labrador – Results from Extensive Geological and Geophysical Studies
Jeremy Hall and Richard J. Wardle

Precambrian Mafic Magmatism: An Overview
Larry M. Heaman

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The Superior Craton – What have we learned from geological, geochemical and geochronological studies? Lessons on the development of the Archean Earth and processes involved
H.H. Helmstaedt, R.M. Harrap and the Western Superior LITHOPROBE and NATMAP Working Groups

Giant Earthquakes Beneath Canada's West Coast
Roy D. Hyndman

The Middle Earth II: A Himalayan-scale mountain range through southern Ontario and Quebec – colliding continents enlarge proto-North America from 1100 – 1000 Ma
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Metamorphic-Tectonic Interactions in Large Hot Orogens: Lower Crustal Flow in the Central Gneiss Belt, Western Grenville Province
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The Slave craton from underneath: The mantle view
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Progressive proterozoic growth of southern Laurentia by magmatic stabilization of lithosphere, and preservation of proterozoic suture scars in the modern-day lithosphere
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The northern Canadian Cordillera - a synthesis of new geological and geophysical results for the Yukon and surrounding areas
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Orogenic framework for the Superior Province: Dissection of the “Kenoran Orogeny”
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Some Recurring Themes in Cordilleran Orogenic Evolution: Tectonic Heredity, Tectonic Wedging, and Retrograde Mantle Flow
Raymond A. Price

Coupled Mantle-Crust Dynamics and Its Relevance for Tectonic Processes Effect of Mantle Dynamics and Properties on Lithospheric Structure
Russell N. Pysklywec and Christopher Beaumont

Architecture and tectonic evolution of the Grenville Province: Part of a hot wide orogen that developed over 200 M.y. on the southeastern margin of Laurentia
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Secular Changes in Tectonic Evolution and the Growth of Continental Lithosphere
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Diamonds and kimberlite intrusions – contributions from LITHOPROBE and related geophysical, geochemical and petrological studies
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Cees van Staal, Johan Lissenberg, Neil Rogers, Alex Zagorevski, Jean Bédard, George Jenner, Vicky McNicoll, Pablo Valverde-Vaquero, Arie van der Velden, John Waldron and Joseph Whalen

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The Late Earth I: The story of the Appalachians – Opening and Closure of Ocean Basins and the Arrival of South American and African Pieces in Atlantic Canada
Cees van Staal, Conall MacNiocaill, Pablo Valverde-Vaquero and Vicki McNicoll

The Superior Craton – What have we learned from reflection, refraction, teleseismic, magnetotelluric and heat flow studies? Lessons on development of the Archean Earth and processes involved
D. J. White for the Western Superior LITHOPROBE and NATMAP Working Groups

Recombining the fragmented structure and memory of cratons
Maarten J. de Wit, AEON (Africa Earth Observatory Network)

Geodynamical Modeling of Collisional Orogens: From Small-Cold to Large-Hot Orogens and Applications to Lithoprobe Problems

C. Beaumont[1], M.H. Nguyen[1,2], R.A. Jamieson[2] and B. Lee[1]

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During the last decade we developed and used a range of finite element numerical models to gain insight into orogenesis. These models include: doubly (bi-) vergent, vise, accretionay wedge, Pyrenean and Alpine styles, and used both mechanical and thermomechanically coupled techniques applied to small-cold and large-hot orogens. Some of these model types have analogues in the orogens studied by Lithoprobe (e.g., Ellis and Beaumont, 1999).

Each of these orogen types occupies a characteristic position in an orogenic H-R diagram, just as star types plot in particular regions of the original stellar H-R diagram. The orogen H-R diagram, in which orogens are plotted according to their mass and temperature, provides a first-order classification and insight into the processes that occur in each orogen type. In addition, the evolution of orogens can be represented by paths in the H-R diagram.

Large-hot orogens are both massive and hot, leading to weak viscous regions of the crust that may contain partial melts and that may undergo gravitationally driven channel flows. Such flows can explain both the outward growth of the Tibetan plateau, as the channel tunnels outward, and the ductile extrusion of the Greater Himalayan Sequence.

Results from crustal-scale numerical models with self-generating mid-crustal channel flows and subduction-type kinematic basal boundary conditions (Beaumont et al., 2001, 2004, Jamieson et al., 2004) are certainly compatible with many first-order features of the Himalayan-Tibetan system. In these models radioactive self-heating of tectonically thickened crust leads to rheological 'melt-weakening', the development of a broad orogenic plateau, and efficient channel flows when the effective mid-crustal viscosity is 10^{19} Pa.s or less.

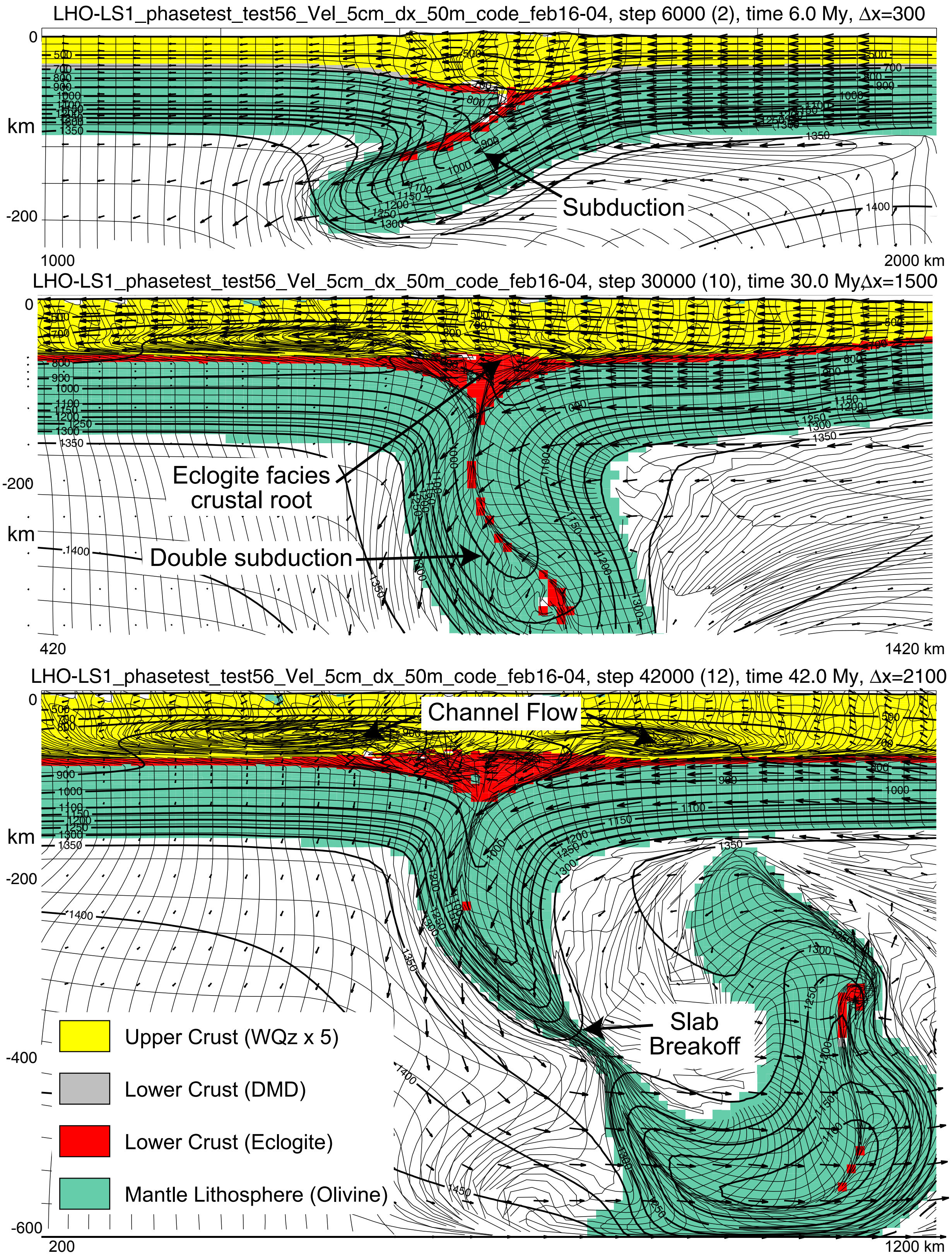
The focus of our recent research has been to broaden the investigation of large-hot orogens to models that include the lithosphere and upper mantle, thereby removing the need for the kinematic basal boundary conditions noted above. We also want to understand flow regimes in orogenic crust that is subcritical with respect to the ideal channel flows predicted by the numerical models in homogeneous melt-weakened crust. We regard the latter as an end member, which may only be possible beneath super-plateaus in giant collisional orogens, for example the Himalaya and Tibet. Such widespread channel flows may not be the best analogues for mid-crustal flows in more common situations such as cordilleran-type and other medium-sized collisional orogens.

In addition to: 1) the ideal homogeneous channel flow mode, we also recognize from the numerical model results; 2) the heterogenous channel flow mode, in which even relatively large scale blocks of refractory, non-fertile lower crust are detached and incorporated into the channel flow, and; 3) the hot fold-nappe mode, in which mid- and lower crust, which is forcibly expelled outward from the interior of the orogen, flows up and over stronger lower-crustal blocks that resist detachment and are therefore not incorporated into the flow. In the third flow regime the flow over stronger blocks creates large-scale highly ductile fold-nappes with overall strong flattening and extensional bulk strain and attenuated lower limbs. This last style of flow may be characteristic of crust that is subcritical in regard to ideal channel flow. That is, the crust fails to attain the necessary low bulk effective viscosity for efficient gravitationally-driven large-scale homogeneous channel flow. Under these circumstances the process that creates the hot fold-nappes is likely related to the tectonic boundary conditions. For example, the collision with the orogen of a relatively strong crustal block, which acts as a plunger or indentor, can initiate the outward flow over the block to form the expelled fold nappes. This process is particularly favoured when older cratonic, or oceanic, crust collides and cannot be assimilated by the orogen by the normal weakening processes (see Jamieson et al. abstract this volume).

There is also considerable debate concerning the mechanisms by which continental mantle lithosphere and perhaps lower crust are resorbed by the sublithospheric mantle during collisonal orogenesis, with subduction, ablative subduction, viscous dripping, delamination, and slab breakoff among the candidate mechanisms. The results of our recent upper mantle scale models exhibit a range of mantle-lithosphere interactions beneath large-hot orogens that depend on the mantle lithosphere rheology and temperature. The results (an example of which is shown in figure 1) are particularly sensitive to the bulk density contrast between the lithopheric mantle and the underlying mantle, with small variations leading to behaviours that range among advancing subduction with shortening and thickening of the retro-mantle lithosphere, advancing double subduction, normal asymmetric subduction, breakoff of the subucted slab, and delamination and rollback of the subducting mantle lithosphere. Combinations of these processes are also observed in the models with transient behaviours apparently related to the mass excess of the subducted lithophere and its strength. The sensitivity of the model behaviours to mantle density contrasts and other factors will be shown and the implications for the crustal flow regimes examined.

References: Beaumont, Jamieson, Nguyen & Lee (2001) Nature 414, 738-742; Beaumont, Jamieson, Nguyen & Medvedev (2004) J. Geophys. Res. 109, B06406,doi:1029/2003JB002809; Jamieson, Beaumont, Medvedev & Nguyen (2004) J. Geophys. Res. 109, B06407,doi:10.1029/2003/JB002811; Ellis & Beaumont (1999) Can. J. Earth Sci. 36, 1711-1741.

Figure 1: Three stages, 6, 30 and 42My, in the evolution of an upper mantle scale continental collision finite element model (2000x600km) for which convergence at 5cm/y equals 300, 1500 and 2100km. Arrows indicate velocity, fine lines are deformed Lagrangian mesh, and medium lines are isotherms (^{o}C). No surface erosion. A crustal channel develops above the eclogitic lower crust. Mantle lithosphere initially subducts then evolves to advancing double subduction and finally breaks off.



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The Slave Craton From On Top: The Crustal View

Wouter Bleeker[1], John Ketchum[2], Bill Davis[1], Keith Sircombe[1,3], Richard Stern[1,4], John Waldron[5]

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[2] Present at: GEMOC ARC National Key Centre, Department of Earth and Planetary Sciences, Macquarie University, New South Wales, 2109, Australia
[3] Presently at: Geoscience Australia, Curtin Geochronology Office, Room 039, Building 301, Dept. of Applied Physics, Curtin University of Technology, GPO Box U1987, Perth, WA 6845, Australia
[4] Present at: Centre for Microscopy and Microanalysis, M010, The University of Western Australia, 35 Stirling Highway, Crawley, Western Australia, 6009, Australia
[5] Department of Earth and Atmospheric Sciences, University of Alberta, Edmonton, Alberta, Canada T6G 2E3

The Archean Slave craton (Fig. 1) is a major building block of the Canadian Shield and one of ca. 35 Archean cratons preserved around the world (Bleeker, 2003). Its amalgamation with the Rae craton, starting at ca. 2 Ga, initiated the climactic 2-1.8 Ga growth of Laurentia (Hoffman, 1989), probably within the broader context of the formation of Earth’s first modern supercontinent, Nuna. Much of the Slave craton is old and, within the context of the Laurentian collage, it can be regarded, for all practical purposes, as an exotic fragment relative to other well-known cratons such as the Superior, Nain, and Rae.

As a mere fragment of ancient crust, surrounded by Paleoproterozoic rifted margins, it originated from the break-up of a much larger late Archean landmass, the supercraton Sclavia (Bleeker, 2003). The late Archean and earliest Proterozoic development of Slave crust should thus be viewed in the context of this larger supercraton, even though its shape and size are currently unknown. The critical point is that cratons like the Slave only preserve parts of much larger tectonic systems.

In agreement with this conceptual view, latest Archean events are remarkably homogeneous across the Slave craton and may be used to help identify neighbouring fragments of Sclavia from among the 35 extant cratons. One such event is a voluminous “granite bloom” between 2590-2580 Ma (Davis and Bleeker, 1999). This singular event in the craton’s evolution transferred, irreversibly, a significant fraction of heat-producing elements and lower crustal fluids to the upper crust, allowing cooling and stiffening of the lower crust and setting the stage for cratonization and long-term preservation (Bleeker, 2002).

Predating these latest events, the Slave crust preserves a complex and spatially heterogeneous record of crustal growth spanning nearly 1.5 billion years:

Basement complex

Much of the central and western parts of the craton are underlain by ancient and largely crystalline basement—the Central Slave Basement Complex (Bleeker et al., 1999a,b; Ketchum and Bleeker, 2001; Ketchum et al., 2004). Along the Acasta River, this basement complex consists of polymetamorphic gneisses of tonalitic and gabbroic composition that yield protolith ages of ca. 4.03 Ga (Stern and Bleeker, 1998; Bowring and Williams, 1999). Although essentially a chance discovery (Bowring et al., 1989), no other rocks of this age have been found. Apart from a central core with sporadic ages >3.5 Ga (Acasta to Point Lake), the Central Slave Basement Complex is mostly younger with important age modes, from detrital and protolith U-Pb zircon ages, around 3400 Ma, 3150 Ma, 2950 Ma and 2826 Ma (Sircombe et al., 2001).

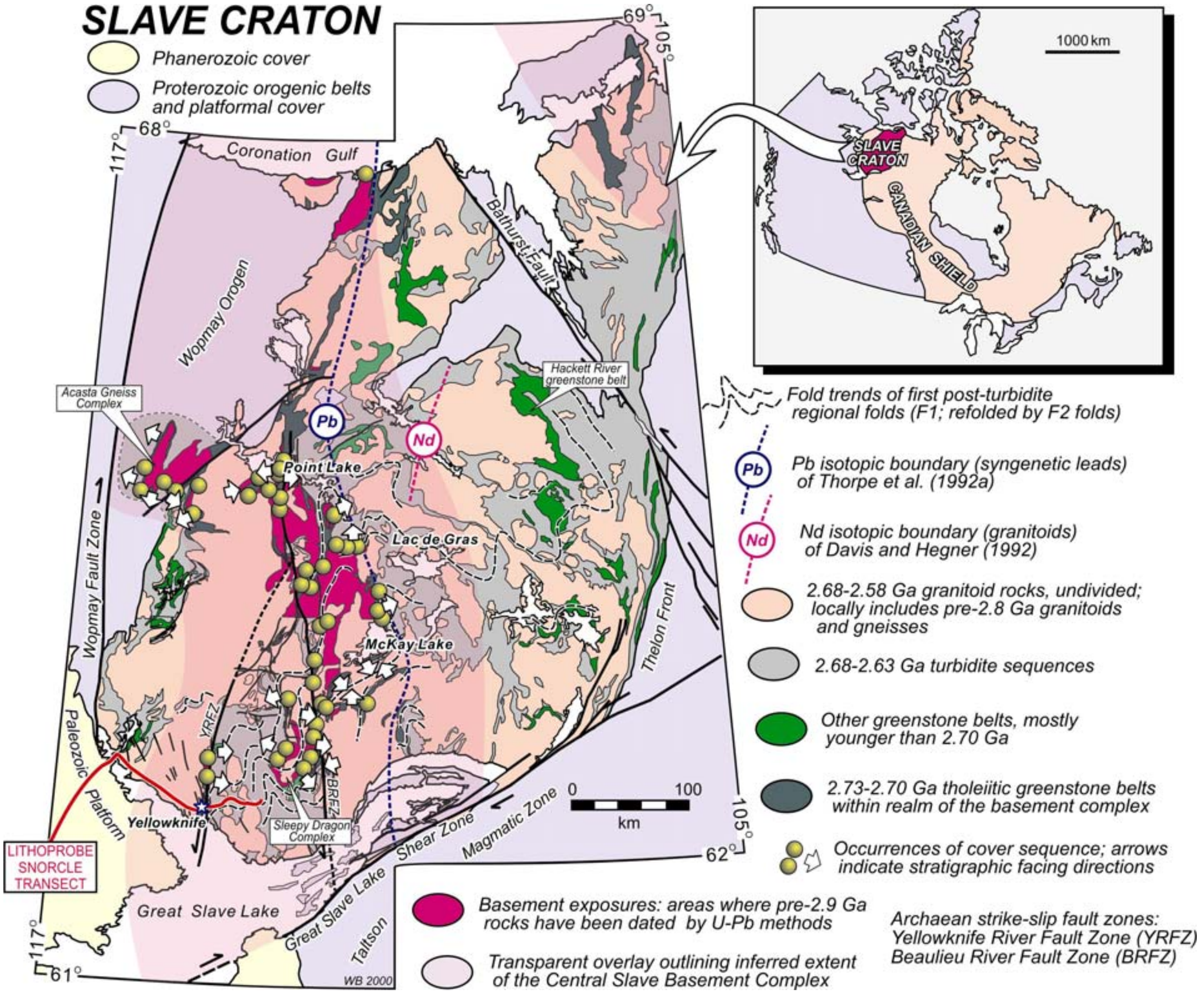

Figure 1. Geological map of the Slave craton. Inset shows location of the Slave craton in the Canadian Shield. Note SNORCLE transect line through Yellowknife.

Interestingly, complementary data from the mantle reveal that at least part of the lithospheric mantle below the central part of the craton is of similar antiquity (Aulbach et al., 2004). Although a crude age zonation can be recognized in the basement complex (Ketchum and Bleeker, 2001), no easily interpretable tectonic pattern has yet emerged. Pre-3.0 Ga supracrustal rocks have been found but form only a small component.

The cover sequence

The contiguous nature of the basement complex, by at least 2.9 Ga, is indicated by a thin but widespread, ca. 2.9-2.8 Ga (Ketchum and Bleeker, 2000) cover sequence of quartzite and banded iron formation (Fig. 2a,b), which marks the onset of the Neoarchean cycle of supracrustal development (Bleeker et al., 1999a). The supermature and commonly fuchsitic quartzites mark the emergence and erosional unroofing of the basement complex in what was probably an aggressive CO_2-rich atmosphere. Abundant detrital chromite may suggest contemporaneous komatiitic volcanism. Similar fuchsitic quartzite sequences occur in many other cratons worldwide, particularly between ca. 3.1 Ga and 2.8 Ga. After 2.4 Ga, mature quartzites are rarely fuchsitic.

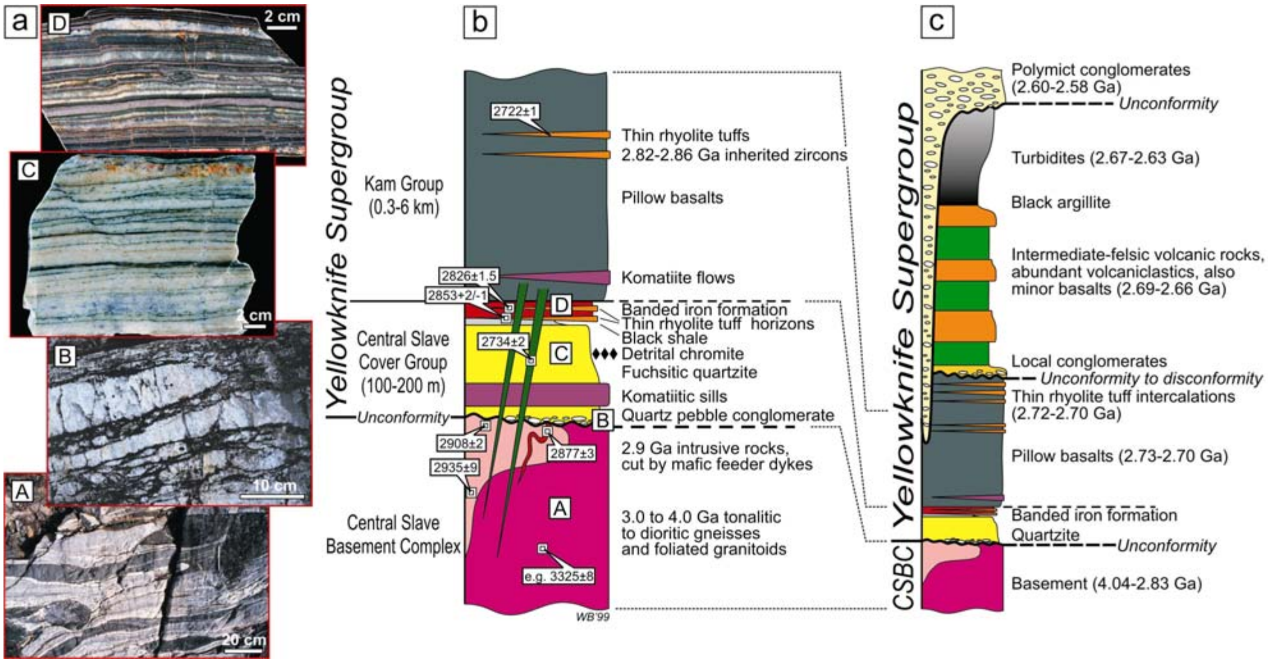

Figure 2. Generalized stratigraphy of the Slave craton. a) Photos (A...D, keyed to Fig. b) illustrating critical features of basement and cover. b) The basement complex and its cover sequence. c) Overall stratigraphy of the craton.

Ca. 2.73-2.70 Ga tholeiitic volcanism

The cover sequence is everywhere overlain by a thick and extensive sequence of tholeiitic basalts, with minor komatiite and rhyolite tuff intercalations (Fig. 2b). Although these lavas extruded in a subaqueous environment, regional correlations suggest a basalt sequence approaching LIP proportions (areal distribution >100,000 km^2, typical thickness 1-6 km). Stratigraphy, dense dyke swarms, and isotopic data link this basalt sequence to the basement (Bleeker, 2002 and references therein; Cousens, 2000). Well-dated components of this basalt-dominated sequence yield ages from 2734 Ma to 2697 Ma (Isachsen and Bowring, 1997; our unpublished data). The widespread basaltic volcanism probably accompanied rifting of the basement complex, possibly assisted by mantle plume activity.

Post-2.70 Ga volcanism

Ca. 2.7 Ga rifting and basaltic volcanism initiated a complex sequence of events including craton-wide, 2.69-2.66 Ga, typically calc-alkalic volcanism and sub-volcanic intrusive activity. These largely juvenile arc-like rocks dominate the eastern part of the craton, while in the central and western part they stratigraphically overlie basement and its basaltic cover (Fig. 2c). Hence, the most likely setting appears an arc- or back arc-like environment that was constructed on highly extended continental crust. The craton-scale stratigraphic relationships and lack of a suture do not easily support models that invoke collision of an exotic, juvenile arc terrane.

Ca. 2.68-2.66 Ga sedimentation

At ca. 2680 Ma, a broad turbidite basin—the Burwash Basin—developed across much of the craton and progressively buried the volcanic substrate (e.g., Ferguson et al., 2004). Late mafic sill complexes and other evidence suggest a volcanically active extensional setting, perhaps best compared with modern back-arcs. The minimum size of this basin was ca. 400x800 km, comparable to that of the Japan Sea, making it the largest and possibly best preserved Archean turbidite basin in the world. Like the Japan Sea, it was largely ensialic, in agreement with suggestions by many early workers (e.g., Henderson, 1985). The main axis of the basin and subsequent structural trends (Fig. 1a) are northeast-southwest, distinctly across the north-south isotopic boundaries that track the nature of deep basement. With more and better U-Pb zircon ages, a tentative volcanic line of 2661 Ma felsic volcanic complexes is recognized, parallel to the Burwash Basin.

Ca. 2.65-2.63 Ga closure of the Burwash Basin

Subsequent tectonic events record the closure and folding of the Burwash Basin (D1), prior to 2634 Ma, the age of a distinct and probably subduction-related magmatic suite (Defeat) across the southern Slave craton. Closure of the highly extended, but largely ensialic basin allowed considerable shortening and mobility but with a structural style dominated by fairly systematic, mostly upright, northeast-southwest trending fold trains. The folded Burwash strata do not represent an outboard accretionary prism and there is no “Contwoyto terrane” (cf. Kusky, 1989). The northeast-southwest D1 structural grain is also recognized in the lithospheric mantle. Shallow subduction (either from the SE or NW?) may have emplaced distinct mantle slabs (Davis et al., 2003).

Post-2.63 Ga turbidites

Along the northwestern margin of the craton, younger turbidites containing ca. 2630 Ma detrital zircons (e.g., Pehrsson and Villeneuve, 1999) record a migration of tectonic activity to the northwest. Deposition was coeval with uplift and erosional unroofing of Defeat plutons and tightly folded Burwash Formation strata. Shortly following their deposition, these younger turbidites were shortened and intruded by ca. 2615-2610 Ma tonalite-granodiorite plutons.

2.60-2.59 Ma: final orogenesis

Starting at ca. 2600 Ma, the entire craton was affected by cross-folding and significant further shortening (D2), characterized by broadly north-south structural trends, and probably in response to final collision along a distant active margin of Sclavia. Moderate overthickening of the crust led to HT-LP metamorphism, widespread anatexis, the appearance of S-type granites, and a hot and weak lower crust, culminating in ca. 2590 Ma extension and the regional “granite bloom”. The intrusion of carbonatites (Villeneuve and Relf, 1998) and involvement of other mantle-derived melts indicate a role for mantle processes (delamination?). While peak temperatures were attained in the lower crust, large basement-cored domes were amplified by buoyancy driven deformation; lower crustal devolatilization reactions mobilized gold-bearing fluids; and syn-orogenic clastic basins formed and were immediately infolded into tight synclines (Bleeker, 2002). At least one of these syn-orogenic clastic basins formed as late as ca. 2580 Ma (Sircombe and Bleeker, in prep.). Late strike-slip faulting overprinted and truncated the synclinally infolded clastic basins. The lower crust cooled (Bethune et al., 1999), finally coupled with the mantle, and the Slave (within Sclavia) became a craton.

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The Grenville Orogen Of Ontario And New York – A Himalayan-Scale Mountain Belt: Significance Of Along-Strike Variations

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In the western part of the Mesoproterozoic Grenville Province there are three tectonic elements: (1) pre-Grenvillian Laurentia and its margin, consisting of rocks of the Archean Superior and Paleoproterozoic Southern provinces as well as ca. 1800 - 1350 Ma supracrustal and continental arc rocks; (2) predominantly ~1300 - 1250 Ma allochthonous volcanic arcs and sedimentary rocks of the Composite Arc Belt that formed offshore, mainly on oceanic crust, and were likely amalgamated with each other by 1240 Ma; and (3) the Frontenac - Adirondack Belt composed of allochthonous terranes containing supracrustal rocks and orthogniess assemblages, including ca. 1130 anorthosite-mangerite-charnokite-granite (AMCG) suite granitoid rocks (Figs. 1 & 2, Carr et al. 2000). In this interpretation, the Frontenac - Adirondack and Composite Arc belts were amalgamated at ca. 1180 - 1160 Ma (cf. McLelland et al. 1996, Corriveau and van Breemen 2000, Hanmer et al. 2000). They were subsequently accreted to and translated toward the craton on underlying mid-crustal shear zone systems and/or zones of ductile penetrative strain which stacked and reworked rocks of the pre-Grenvillian Laurentian margin (Carr et al. 2000 and references therein, Jamieson et al. this volume). Deformation was intermittently active between ca. 1120 and 980 Ma, punctuated by periods of extension and exhumation, forming a Himalayan-scale collisional orogenic belt.

Crustal structure is interpreted from coincident near-vertical incidence seismic reflection and refraction - wide-angle reflection data, integrated with geologic information (White et al. 2000, Fig. 2). The 32-40 km-thick crust beneath the foreland adjacent to the Grenville Province is thin relative to the Grenville Front, tapers to the east and may be a relict feature that formed during Archean rifting at ca. 2480-2450 Ma. The crust beneath the Grenville Province is 42 - 46 km thick, and the craton appears to extend beneath the belt > 350 km southeast of the Grenville Front. Broad zones of southeast-dipping reflectors, including a zone of reflectors associated with the late strain adjacent to the foreland, appear to sole into the upper part of a high velocity lower crustal layer. This geometry is consistent with a model whereby allochthonous and parautochthonous crustal panels were deformed, transported towards the craton and stacked above reworked basement rocks of the pre-Grenvillian Laurentian margin. Despite the long-lived history of the pre-Grenvillian Laurentian margin and the complexity of the accreted rocks of the Composite Arc and Frontenac - Adirondack belts, the crustal architecture resulted primarily from Grenville orogenesis between ca. 1120 and 980 Ma. Migmatitic orthogneisses of the reworked Laurentian margin near the western end of the cross section (Muskoka domain, Fig. 1) may represent an exhumed Grenvillian hot nappe channel system (Jamieson et al. this volume).

The western Grenville Province shares many similarities with transects in the central and eastern Grenville Province (Rivers this volume); however there is much to be learned from the differences. Unlike cross-sections to the east, the Archean and Paleoproterozoic craton in the western Grenville appears to extend beneath the orogen for 100's of km with only a relatively narrow zone of reworking near the foreland (cf. sections A to D on Fig. 3). Grenvillian reworking of the craton appears to be penetrative as lower crustal reflections are generally concordant with the Grenville structural grain, in contrast to sections further east where basement structures and older metamorphic histories are preserved (cf. A with B & C, Fig 3). In the western Grenville, deformation occurred at 10-12 kb amphibolite- and granulite - facies conditions, and the structural style is dominated by penetrative flow in migmatitic rocks. In contrast, in the central Grenville Province (D, Fig. 3), 18 kb, high-pressure eclogite and granulite belts are interpreted to have been exhumed by tectonic extrusion; a footwall ramp is well preserved and the rheology is interpreted to have been relatively rigid (Rivers et al. 2002). These features suggest that the crust in the western Grenville was relatively weak compared to that of the central and eastern Grenville Province. We suggest the rheology in the western Grenville may have been influenced by the residual thermal effects of the magma-rich ca. 1100 Ma Mid-Continent Rift system centered near Lake Superior (Carr et al. 2000), thereby influencing orogenic processes and the structural style of the western Grenville Orogen. The along-strike variations are significant, and the Ontario - New York transect of the western Grenville cannot be considered as representative of the entire Grenville Province.

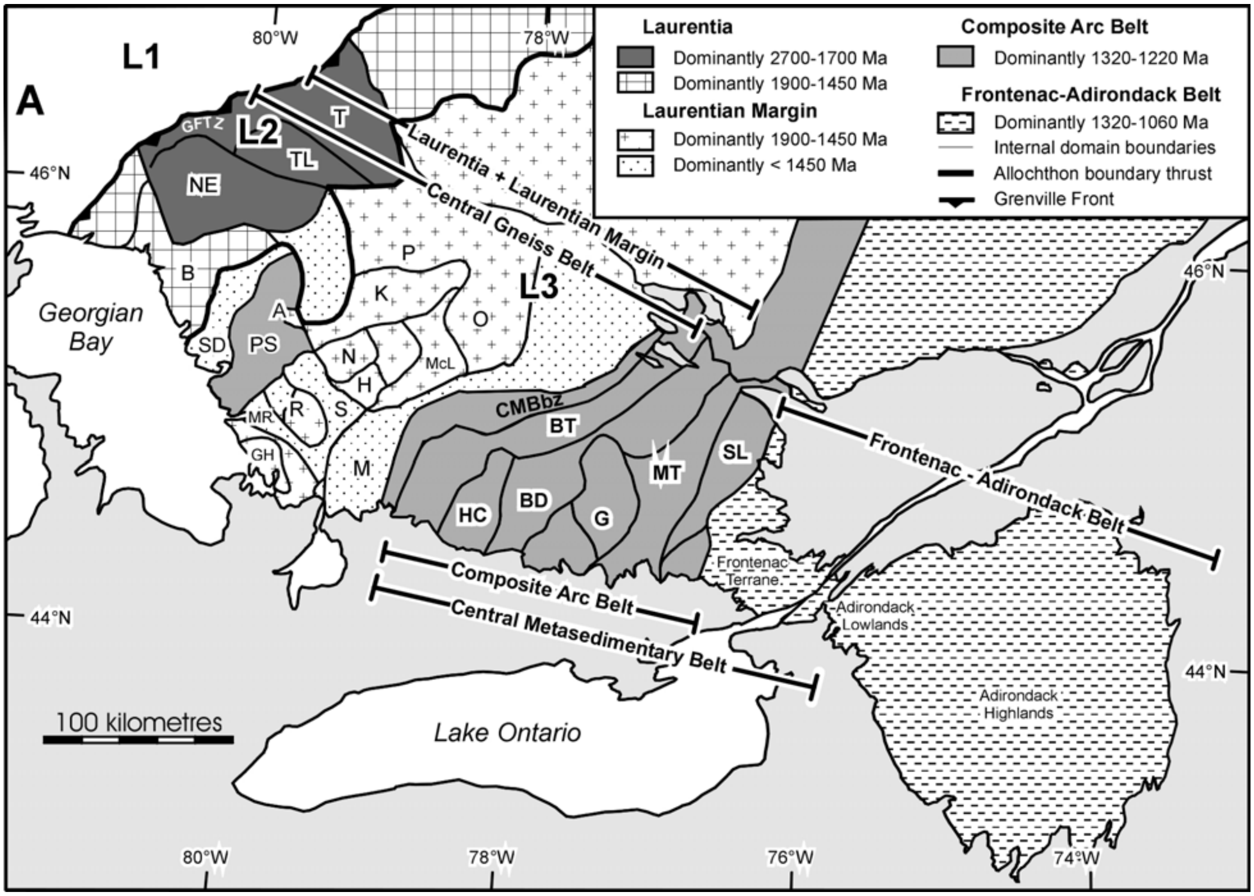

Figure 1. Major divisions and structures of the SW Grenville Province, including previous nomenclature (Wynne-Edwards, 1972) and nomenclature of Carr et al. (2000): (1) pre-Grenvillian Laurentia and its margin; L1, Laurentian foreland NW of the Grenville Front; L2, Archean crust with 1740 Ma and 1450 Ma plutons; and L3, 1800-1680 Ma supracrustal rocks with ca. 1450 Ma continental arc granitoids; (2) Composite Arc Belt; and (3) Frontenac – Adirondack Belt. Abbreviations: A, Ahmic domain; B, Britt domain; BD, Belmont domain; BT, Bancroft terrane; CMBbz, Central Metasedimentary Belt boundary zone; G, Grimsthorpe domain; GFTZ, Grenville Front tectonic zone; GH, Go Home domain; H, Huntsville domain; HC, Harvey Cardiff Arch; K, Kiosk domain; Mc, McCraney domain; McL, McLintock domain; MR, Moon River subdomain; MT, Mazinaw terrane; N, Novar domain; NE, Nepewassi domain; O, Opeongo domain; P, Powassan domain; PS, Parry Sound domain; R, Rosseau domain; S, Seguin subdomain; SD, Shawanaga domain; SL, Sharbot Lake domain; T, Tomiko domain; TL, Tilden Lake domain.

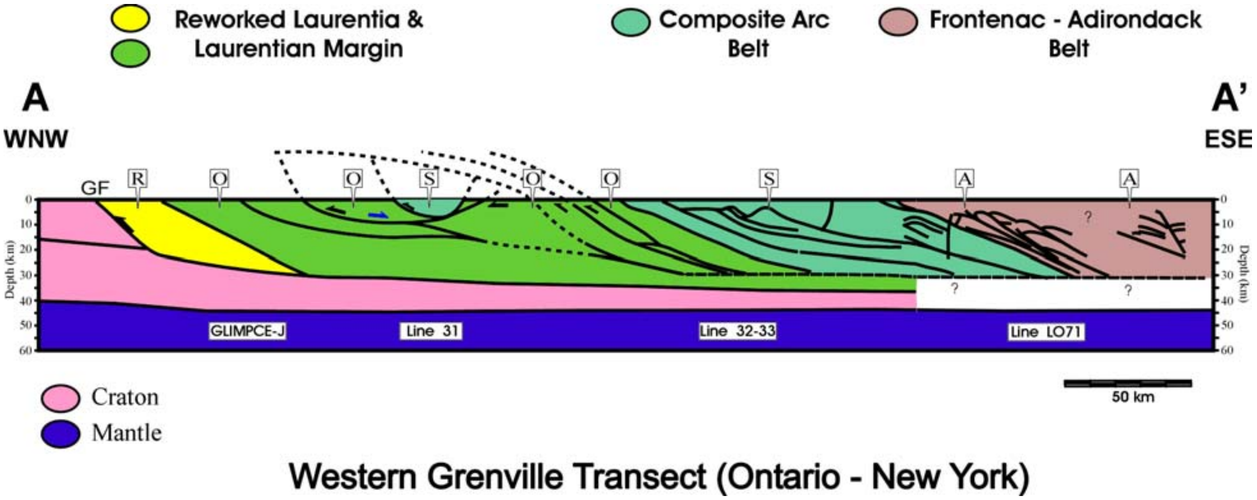

Figure 2. Cross section of the western Grenville based on refraction velocity models, near-vertical-incidence depth-migrated seismic reflection data and geological information (White et al. 2000). GF = Grenville Front. "S", "O" and "R" indicate metamorphism is predominantly of Shawinigan (1190-1140 Ma), Ottawan (1080-1020 Ma) and Rigolet (1000-980 Ma) pulses, respectively, of the Grenvillian orogen. All three events are preserved in different places in the Adirondack Highlands labelled "A".

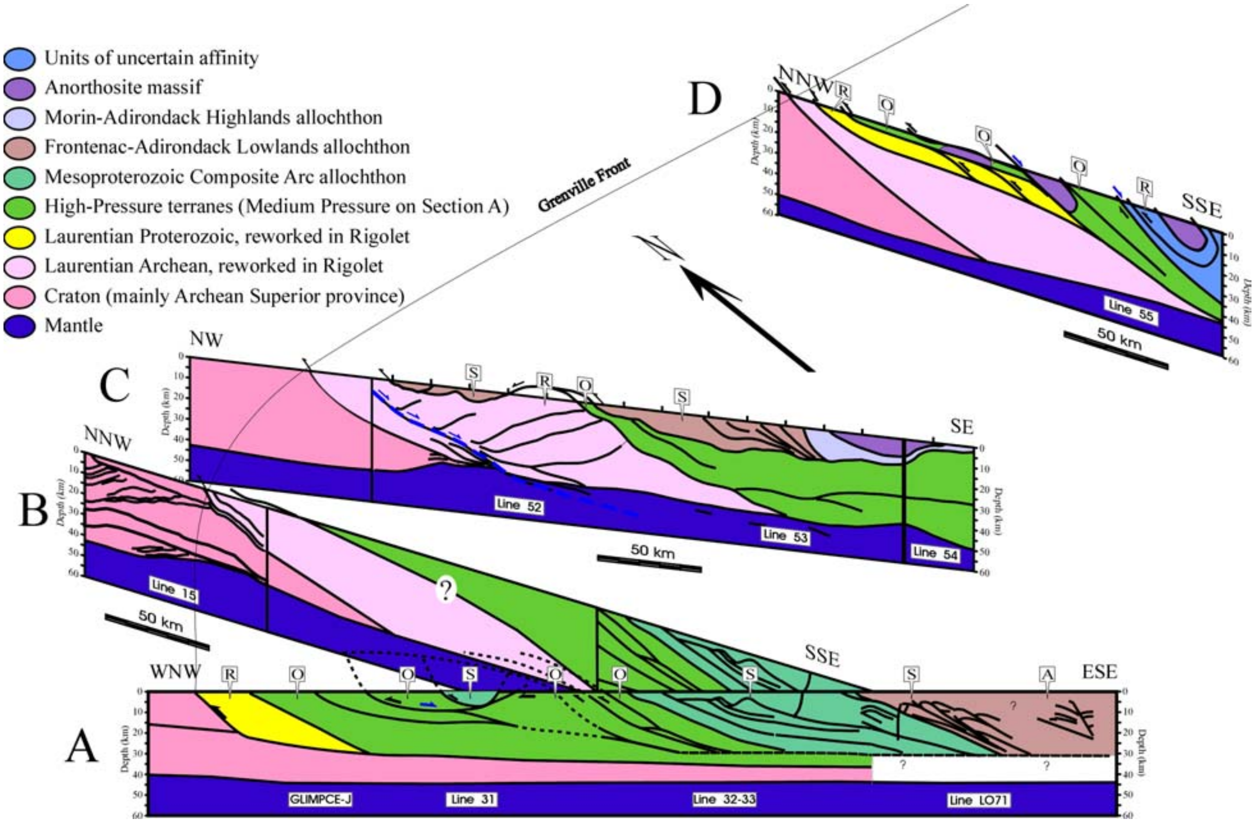

Figure 3. Four cross sections of the Grenville Province in Ontario and Quebec from Ludden and Hynes (2000); see Fig. 4 for location of cross sections and Fig. 2 caption for definitions of "S", "O", "R" and "A".

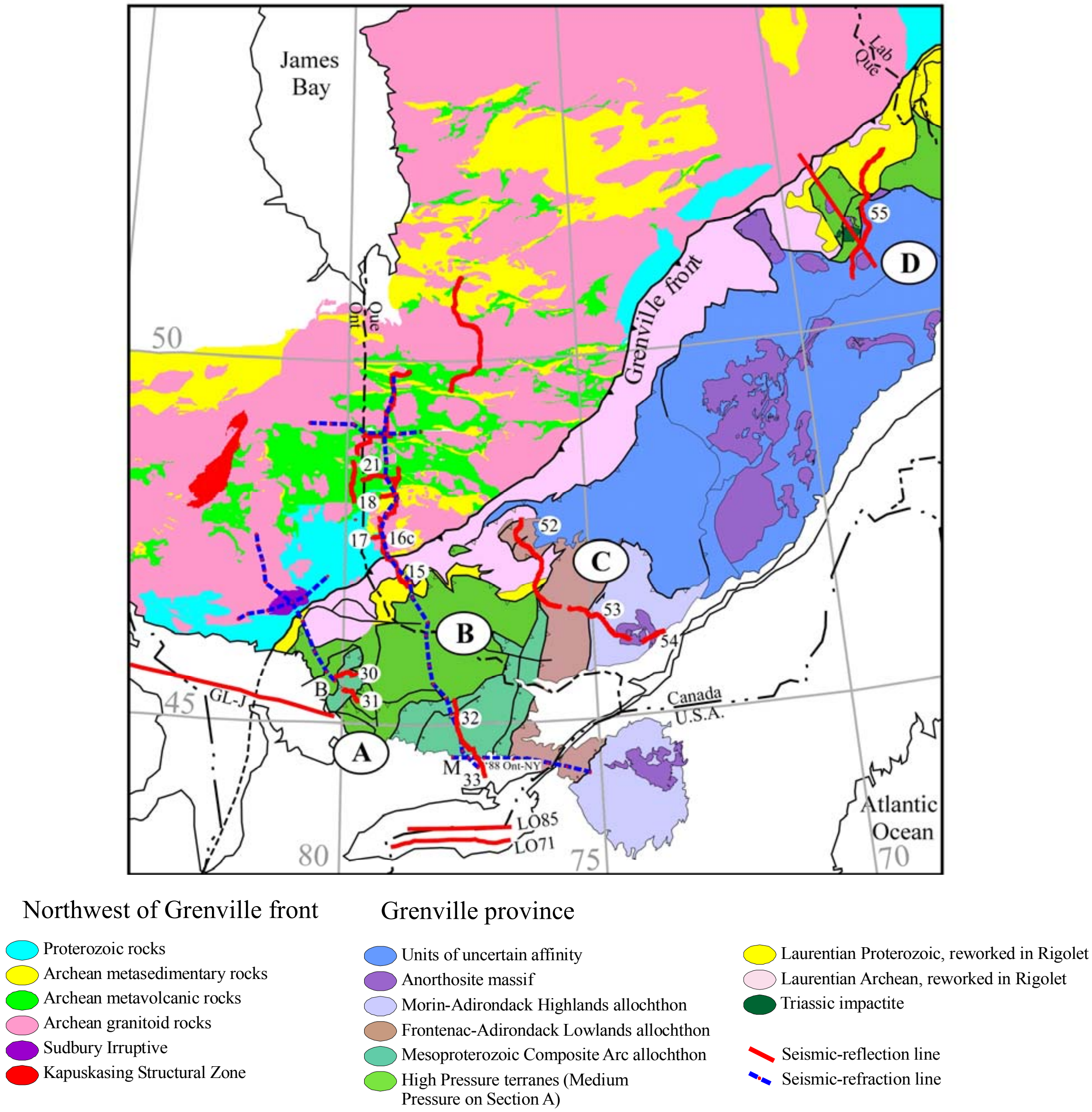

Figure 4. Geological sketch map of part of the Grenville Province and adjacent Superior & Southern provinces from Ludden and Hynes (2000), showing locations of the major seismic reflection and refraction lines and composite cross sections A - D depicted in Fig. 3. Section A is derived from GLIMPCE-J line, Abitibi-Grenville lines 21-33 and Lake Ontario line 71 (White et al. 2000); B is from Abitibi-Grenville lines 15, 32 and 33 (Kellett et al. 1994); C in western Quebec is from Abitibi-Grenville lines 52-54 (Martignole and Calvert 1996 and Martignole et al. 2000); and D in eastern Quebec is from Abitibi-Grenville line 55 (Eaton et al. 1995).

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LITHOPROBE – A Legacy of Benefits to Canada

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The most lasting legacy that any scientific project can have is rooted in both the quality of its scientific results and what those results contribute to the country and humanity. On this basis, LITHOPROBE has been an outstanding success. The invited oral and contributed poster presentations that we will hear and see during the three days of this conference attest to this statement. In this presentation, I will reflect briefly on the history of LITHOPROBE then relate some of our broad-based accomplishments and their significance for Canada.

A Brief History [especially for the younger scientists]

LITHOPROBE was initiated through the efforts of ‘grassroots’ solid earth scientists from the universities and the Geological Survey of Canada (GSC) who recognized the need for a dedicated project of high scientific significance to provide a flagship for, enhance the quality of, and bring cohesion to, their discipline. The concept of LITHOPROBE as a project evolved from a 1981 meeting of university geoscientists to discuss “Earth Sciences in the Eighties”, sponsored by NSERC, and similar ideas being discussed at the GSC (CANDEL, 1981). Subsequently, a LITHOPROBE Steering Committee, comprising highly respected representatives from academia, the GSC and the petroleum and mining industries, was formed. Further broadbased discussions followed. In 1983, the GSC committed funds for a preliminary geophysical program to be run in 1984, and LITHOPROBE academics applied to NSERC for funds for the geophysical program and one of “supporting geoscience studies”. The project was funded in 1984-85 for a 1-year Phase I preliminary program with primary scientific activity on Vancouver Island, part of the Southern Cordillera Transect, and some preliminary activity in the Kapuskasing Structural Zone Transect (Clowes, 1984; Clowes et al., 1984). During the same year, a marine seismic reflection survey, to become part of the Lithoprobe East Transect, was conducted off the northeast coast of Newfoundland as part of the GSC’s Frontier Geoscience Program.

During Phase I activities and extending throughout 1984 to 1986, development of a Phase II proposal, that received strong support through a 1985 national LITHOPROBE workshop, continued. Simultaneously, analysis of results from Phase I proceeded and support from the operations budget of the GSC enabled continuing acquisition of multichannel seismic reflection data, thereby maintaining important momentum. The GSC Frontier Geoscience initiative also continued its activities on the continental margins.

Outstanding results from Phase I and indications of more quality results from the interim reflection surveys, coupled with a very strong Phase II proposal to NSERC and the GSC, led to full establishment of the project in 1987 with a 5-year scientific program, subject to review and reapplication during the third year. This was followed thereafter with Phase III, IV and V proposals in 1989, 1992 and 1997, respectively, thereby bringing us to the present meeting.

Scientific Contributions

During the LITHOPROBE Celebratory Conference, you will hear about the many scientific achievements of LITHOPROBE and the contributions that we as scientists have made to determining the parameters, understanding the processes and revealing the evolution of the Canadian landmass and its offshore margins. It would be folly for me to try to discuss these further in this presentation. Our continuing activities focus on synthesis of LITHOPROBE results from across the country. Some of this work is included in the conference program. The LITHOPROBE data archive [Roberts and Shareef, 2004 (this meeting)] represents a legacy for future studies.

One of our synthesis activities is the compilation of a digital tectonic domain map of Canada and a Trans-Canada lithospheric cross section [van der Velden et al., 2004 (this meeting)]. The digital map has been compiled from the various transect maps highlighted in LITHOPROBE proposals and additional sources. The version shown in Figure 1 uses a limited number of colors to indicate in a general way the age of last major tectonic deformation. However, individual tectonic domains are included as separate polygons that can be colored or patterned independently, as required by a particular user of the map. Hence, we plan to release electronic versions of the tectonic domain map.

The Trans-Canada seismic transect provides a view of the continent at a scale that emphasizes relationships between orogens rather than detailed patterns within individual orogens. The geometry of suture zones interpreted in the Archean Superior craton bear a remarkable similarity to features observed in the modern Cascadia subduction zone, furthering the proposition that modern-style plate tectonics was active as long ago as the Neoarchean era. The Mesozoic Cordillera developed on a base of North American cratonic rocks that form the middle-to-lower crust below at least the eastern two thirds of the orogen, demonstrating that the accreted terranes are relatively thin flakes and have lost any lower lithospheric component that they may have had. In a similar fashion, Archean rocks of SE Laurentia extend for 100s of kilometers below the surface expression of the Mesoproterozoic Grenville orogen. Grenvillian rocks in turn form the basement and backstop to the Paleozoic Appalachian orogen of the Atlantic provinces. In contrast to these tectonic developments, the Paleoproterozoic rocks of the Trans-Hudson orogen comprise the entire lithospheric column. On both east and west margins of the orogen, the younger rocks are thrust below the older Archean rocks of the Superior and Hearne-Rae cratons. The Moho is generally flat across the continent, although average crustal thickness does vary. Two prominent crustal roots, one below the ~1.8 Ga western Trans-Hudson orogen and one below the ~1.9 Torngat orogen in northern Labrador, are identified. Below the 1.1 Ga mid-continent rift zone in Lake Superior, crustal thickness exceeds 60 km, presumably due to magmatic underplating within the lower crust.

Benefits to Canada

For the Canadian earth science community, and for Canada as a country, LITHOPROBE has been more than a successful scientific project; it has brought wide-ranging benefits to Canada, as noted below.

- *Regional information for industry*. The new and improved understanding of Earth history in regions that are amenable to resource exploration provides petroleum and mining companies with an enhanced knowledge base from which their own more detailed exploration and development plans can be prepared. In the Western Canada Sedimentary Basin, the first continuous seismic reflection profile across the entire basin has been compiled. In a variety of mining locations associated with base metals, diamonds and uranium throughout Canada, LITHOPROBE's studies provide a valuable framework of knowledge and understanding that otherwise would not exist.

- *Technological innovation and transfer of science and technology to the private sector*. In the mid-1980s, LITHOPROBE seismologists designed a new portable seismic refraction seismograph, the technology for which was transferred to Scintrex Ltd., a Canadian geophysical company. GSC scientists active in LITHOPROBE designed and built new magnetotelluric (MT) instrumentation for which the resultant technology was transferred to Phoenix Geophysics Ltd., a Canadian geophysical company that specializes in MT work,

  LITHOPROBE and related studies have demonstrated the applicability of the high resolution seismic reflection technique to mineral exploration problems, particularly in mining regions where expensive infrastructure is already in place. High resolution seismic reflection studies, applied first by LITHOPROBE and now being refined in the private sector, are identifying new sub-basins and faults associated with uranium deposits in northern Saskatchewan. In a unique spin-off experiment, the applicability of mapping a very thin, dipping, diamondiferous kimberlite dyke from subcrop to 1500 m depth has been demonstrated.
- *New resources and mitigation of hazards.* During the 1990s, LITHOPROBE data and interpretations in the LITHOPROBE East Transect contributed to a petroleum discovery on the west coast of Newfoundland. LITHOPROBE studies on the west coast of Canada, as part of the Southern Cordillera Transect, provided data and a framework for better understanding the mega-thrust earthquake hazard in the region. GSC scientists are continuing and extending such research in the region, thus contributing to a much more fundamental understanding of the hazard and how it may affect the region.
- *Training the next generation of earth scientists.* LITHOPROBE has actively involved more than 450 graduate and undergraduate students, postdoctoral fellows, and research associates who have learned their specific skills in an environment of multidisciplinary collaboration. Many of these scientists have gone on to employment in academia, government, and industry worldwide.
- *Education and public awareness of science and technology*. LITHOPROBE has provided educational material that has been used from high schools to university graduate courses. It has enhanced the visibility and relevance of the earth sciences as a discipline through a coordinated effort of public education and media communication. Recently a children's book (ages 9-14), based on results from LITHOPROBE, has been published (Wilson, 2003).
- *A new approach to collaborative science in Canada.* The LITHOPROBE research network has redefined the nature of much earth science research in Canada. It has successfully fostered an unprecedented degree of cooperation among earth scientists in universities, federal and provincial/territorial geological surveys, and the mining and petroleum industries. It has spawned a new and healthy atmosphere of scientific cooperation among geologists, geophysicists, and geochemists who are working and learning together, thereby enhancing results beyond those that could be achieved through any one subdiscipline.
- *Enhancing the international renown of Canadian earth science.* Quality scientific results resulting from LITHOPROBE's unique combination of collaborative research and multidisciplinary studies have been foremost in establishing the project as the best of its kind in the world. LITHOPROBE has served as a model for other network projects in Canada and around the world. Indeed, EUROPROBE, a multidisciplinary, collaborative Earth science program in Europe, selected both its name and procedures based on the LITHOPROBE example.

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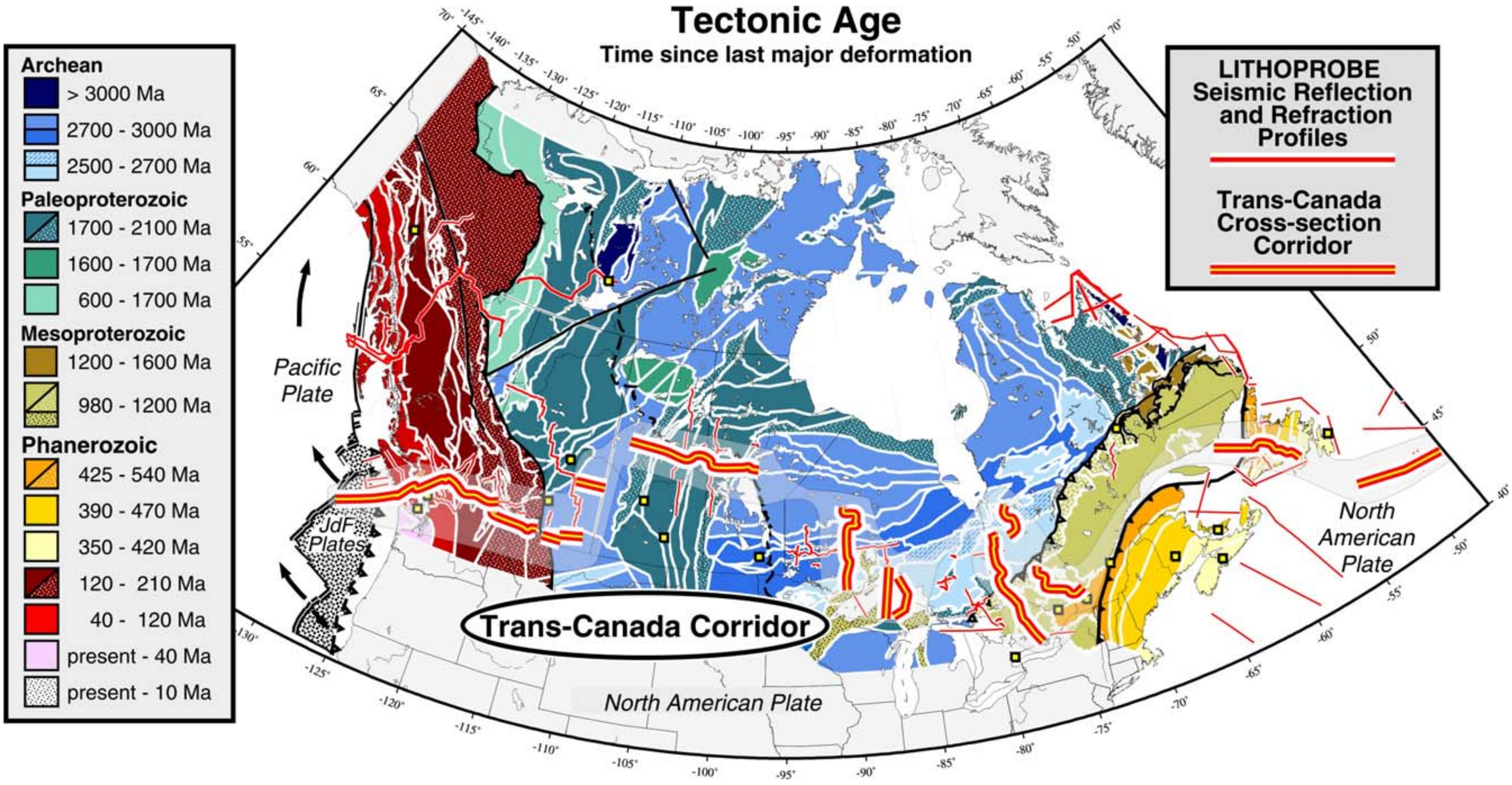

Figure 1. Map of Canada showing general tectonic age; i.e., the time since the last major deformation. Bold red-yellow lines show the location of the Trans-Canada Seismic Transect. The corridor follows selected coincident reflection and refraction lines, providing a near-continuous transect across the principal tectonic features of the continent. Other seismic lines acquired by LITHOPROBE and other groups are shown as thin red lines.

Probing the Lithosphere of the Wopmay Orogen

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The Lithoprobe SNORCLE (Slave Northern Cordillera Lithospheric Evolution) transect across the Mesoproterozoic (ca. 1.92-1.84 Ga) Wopmay orogen in northwestern Canada has produced some of the most detailed images of the lithosphere that are available anywhere in the world. Because the orogen was built on the western margin of the Archean Slave province, it forms the crust and lithosphere beneath much of northwestern Canada. Accordingly, the transect provides both a spatial and a temporal link between the Archean Slave Province and the Phanerozoic Cordillera and therefore addresses how northwestern North America has evolved since the early history of the Earth. Lithoprobe work was designed to establish the processes of Mesoproterozoic accretion as well as how the associated structures influenced later development of the Cordillera and the Western Canada sedimentary basin.

Orogenic activity took place during at least two major stages of collision and accretion of arc terranes: the Hottah terrane (age: 1.9-2.3 Ga; accretion: 1.90-1.88 Ga) and the Nahanni-Fort Simpson terrane (age: ~1.845 Ga; accretion: ~1.84 Ga). As a result, the orogen consists of five distinctive tectonic domains from east to west: Coronation margin, Hottah terrane, Great Bear magmatic arc, Fort Simpson- Nahanni terrane and Fort Simpson basin. The Coronation margin consists of westward thickening supracrustal rocks that were deposited on the margin of the Slave craton and that were collapsed and thrust eastward during 1.90-1.88 Ga accretion of the meta-supracrustal and magmatic rocks of the Hottah terrane (Calderian orogeny). The Great Bear magmatic arc, an extensive continental arc that formed on the previously amalgamated Hottah-Slave continent, was active between 1.88-1.84 Ga and was probably formed by eastward subduction of a basin that separated the Hottah from the outboard Nahanni-Fort Simpson terrane. The Nahanni-Fort Simpson terrane accreted to the western Hottah some time after 1.84 Ga because Great Bear magmatism ceased at that time. Post-orogenic extension and subsidence produced the Fort Simpson basin on the west and initiated the post-ca. 1.8 Ga western margin of proto-North America that truncated regional trends of the Canadian Shield (e.g., structural, potential field, etc).

The Coronation margin, Hottah terrane, Great Bear magmatic arc and Nahanni-Fort Simpson terrane all strike north-south and project from outcrop southward beneath the Western Canada Sedimentary basin where Lithoprobe recorded seismic reflection, seismic refraction and electromagnetic profiles. The geophysical data have clear images of Mesoproterozoic subduction surfaces to ~100 km depth, lithospheric wedging that formed during terrane accretion, and the base of the subduction-related Great Bear magmatic arc. Intracrustal deformation appears to have taken place by low-angle contraction that was listric into, or slightly above, the Moho, which in turn underlies nearly the entire orogen at ~35 km. The Fort Simpson basin is up to 25 km deep, but is largely buried beneath the thin Western Canada sedimentary basin. Some of the shallow Proterozoic strata within the Fort Simpson basin outcrop in thrust uplifts near the Cordilleran deformation front in northeastern British Columbia.

These results provide strong evidence that Mesoproterozoic accretion and orogenesis took place by subduction of lithosphere, the remnants of which are still visible today as seismic reflection and refraction surfaces that dip from the crust to ~100 km depth. Detailed images of structures within the upper mantle attest to its complex developmental history as well as its highly variable lithological properties in this region.

The Evolving Cordilleran Lithosphere

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The Canadian portion of the North American Cordillera, one of the great mountain belts of the world, has been a target of major Lithoprobe studies for 20 years. Although the primary objective of the effort has been to develop an understanding of the geometry and mechanisms of accretionary orogenic processes, the data also provide a regional framework for understanding Cordilleran structures and tectonic evolution.

In many respects, the Canadian Cordillera is a "typical" orogen in that it has a major thrust contact on its inboard (craton) side, is characterized by plate convergence on its outboard (Pacific) side, and developed in a time frame from initial rifting in the Neoproterozoic to post-accretionary Tertiary extension that is comparable to other orogens. While these are common features of collisional orogens such as the Alps (Tertiary), the Appalachians (Paleozoic), and even the Wopmay (Mesoproterozoic), the Cordillera is unusual in that no large continental plate has collided on its outboard side. Indeed the origin of the present configuration and developmental history of the Cordillera can now be traced back to long before the initial rifting, soon after the termination of orogenic activity of the Mesoproterozoic Wopmay orogen at about 1.8 Ga.

Initiation of the post-1.8 Ga western margin of North America, beyond which the Shield trends are no longer visible, is now observed in the subsurface as a crustal scale monocline that predated the Cordilleran Neoproterozoic rift sequence by more than 1.0 billion years. The associated basinal deposits of the 1.8-1.4 Ga Wernecke-Ft. Simpson supracrustal rocks in the north and Belt-Purcell strata in the south truncated the Wopmay and older Shield trends at high angle and established a margin with sinuous recess-and-promontory geometry similar to the Iapetus and Atlantic margins. These strata are distributed in localized basins whose outer margin is unclear, but whose distribution is oblique to the Cordilleran trend. The open/trailing plate margin that began at this time has been in existence for more than 1.5 billion years, a situation that may be unique, and the search for matching plate margins in Australia, China and Siberia is ongoing. In any case, these rocks record the establishment of the new craton edge and, as a result, the strike variations observed today along the Cordillera may largely result from tectonic inheritance of this geometry combined with oblique convergence during orogenesis.

Although multiple episodes of deformation are recorded from 1.8 Ga until the present, most of the observed surface complexity results from the youngest (Phanerozoic) orogenic activity. Plate convergence and episodic accretion have been ongoing since at least the Jurassic, and perhaps even the Devonian. Over that time more than 10,000 km (linear) of oceanic lithosphere have been subducted beneath western Canada while the continent has grown westward by only a small fraction of that amount. As Lithoprobe work has shown, however, the distribution of accreted terranes at the surface provides a substantial overestimate of the amount of lithospheric material that has been added to the continent during orogenesis.

Pre-Cordilleran North American crust and upper mantle persist across most of the orogen. Accordingly, accreted rocks are largely confined to the crust, and in many cases to the uppermost crust, in the part of the orogen where North American lithosphere can be projected in the subsurface (east of the Fraser River Fault in the south and east of the Coast Mountains in the north). This implies that the bulk of the orogen lithosphere is of North American affinity and thus that most of the accreted terrane lower lithosphere has been excluded from the orogen (i.e., the accreted terranes at the surface are detached thin flakes). The remainder of the orogen (Coast Mountains and Insular region) may consist of subcreted lithosphere (e.g., Wrangellia, Alexander, etc. terranes). How far inboard the subcreted lithosphere projects is uncertain; it is likely, however, that the relict Kula plate is present beneath the eastern Coast Mountains in the northern Cordillera and similar structures may be present beneath the eastern Coast Mountains in the south. Some strike slip faults (e.g., Tintina fault, Fraser River fault) appear to penetrate through the entire crust and upper mantle, while others appear to be detached within the crust. This may be due to decapitation of earlier formed steep structures by later detachments. In any case, these strike-slip structures allow for orogen-parallel redistribution of lithosphere, but do not appear to be major plate boundaries.

The thickness of the crust (~35 km) is uniform throughout most of the Cordillera, even though regional Tertiary extension is recorded in the south but not in the north. Indeed, new stratigraphic data have even challenged the magnitude of crustal extension in the southern Cordillera. In addition, the relationship between crustal thickness and age of orogenesis is unclear, as the thickness of the Cordilleran crust is virtually the same as that of the Archean Slave province, the Mesoproterozoic Wopmay orogen and even the hinterland of the Paleozoic Appalachians. The only major step in Moho depth in the vicinity of the eastern Cordillera occurs at the Rocky mountain trench (~ 10 km) in the south and at the Fort Simpson (Proterozoic) ramp (~8 km) east of the deformation front in the north. Indeed, the configuration of the Moho and adjacent structures (e.g., listric lower crustal structures and relict subduction zones) are not consistent with processes such as late magmatic underplating to form the bulk of lower crust and/or large-scale lithospheric delamination to remove the bottom half of an overthickened crust.

The Lithoprobe results lead to a major conclusion that the amount of “new” lithosphere added to the plate has been minimal since at least the end of Wopmay orogenesis (ca. 1.8 Ga). Indeed, palinspastic restoration of accreted and allochthonous components implies that the pre-Cordilleran plate edge projected much farther west than the present edge and thus that the western margin of the plate has actually retreated toward the craton during Phanerozoic Cordilleran orogenesis.

An 1800-km cross section of the lithosphere through the northwestern North American plate: Lessons from 4.0 billion years of Earth's history

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The Lithoprobe SNORCLE (Slave Northern Cordillera Lithospheric Evolution) study across northwestern North America, in combination with related crustal studies, has been synthesized into an 1800-km long cross-section of the lithosphere that is constrained by high resolution geophysical data (seismic reflection, refraction, electromagnetic, potential fields) and detailed bedrock geology. The cross section offers one of the longest "continuous" profiles of the continental lithosphere anywhere in the world that is constrained by combined geophysical measurements of seismic reflection, refraction and electromagnetic properties as well as exposed bedrock geological relationships. The primary conclusion of the study is that, during all major orogenic episodes recorded from Archean to present in that part of Earth's lithosphere, the crust, and perhaps much of the mantle, was reorganized and redistributed rather than being differentiated from the mantle at the time of orogenesis. The observed subsurface geometries of relict subduction zones, accretion boundaries and magmatic arcs all lead to the inference that the crust includes a dominant proportion of reworked material. A similar conclusion appears applicable for the origin of subcrustal lithosphere in the region – i.e., that much of the lithosphere, whether Archean in the Slave Province or Proterozoic in the Cordillera, is old and thus that the amount of "new" lithosphere added to the plate during orogenesis is surprisingly small. A corollary is that many accreted rocks at surface that record orogenic complexity are detached from their originally underlying lithosphere and were emplaced upon unrelated crust and mantle during deformation.

Evolutionary Tectonic Development of the Trans-Hudson orogen - a tale of three cratons, a large ocean, accretionary and collisional tectonics

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The Trans-Hudson orogeny (THO) represents one of the most significant craton-building events in the evolution of North America. Significantly, continental plates that had formed over the time-span of the Archean had finally attained the order of spatial dimensions and physical properties akin to modern continental plates, thus providing similar boundary conditions for depositional and tectonic processes. This presentation focuses on the closure of the Manikewan Ocean and ensuing Churchill-Superior collision, based on constraints from the western THO and Baffin/Cape Smith segments.

During the opening and closure of the Manikewan Ocean, the following sequence of events occurred: 1) Deposition of passive margin sequences, beginning at ca. 2.16 Ga; 2) Ocean closure beginning at ca. 1.92 Ga in the western THO, leading to the formation of the La Ronge/Lynn Lake and Flin Flon/Glennie arcs; 3) Beginning at about 1.88 Ga, accretion of the La Ronge/Lynn Lake arcs to the Hearne margin and related deposition of an extensive molase/foredeep sequence. This event was contemporaneous with intraoceanic accretion leading to the formation of the Flin Flon/Glennie accretionary complex; 4) Continental arc magmatism along the SE margin of the Churchill plate between 1.86 Ga and 1.85 Ga; 5) Cessation of continental arc magmatism at about 1.850 Ga, perhaps related to collision of the Flin Flon/Glennie complex (western THO) and Narsajuaq arc (Baffin segment), with the Churchill plate. 6) Opening of the Kissinew back-arc basin during the interval 1.85-1.84 Ga, with the Flin Flon complex now forming part of the active arc and Granville Lake Structural Zone forming part of the remnant arc. 7) Collision between the Sask Craton and Churchill Plate, beginning at ca. 1.84 Ga, leading to the inversion of the Kisseynew basin and deposition of molasse deposits. 8) Terminal collision involving the Superior Province, beginning at ca 1.83 Ga and ongoing until approximately 1.77 Ga.

One notable feature of this model, common to both the western THO and Baffin segments, is the early history of terrane accretion along the northwestern, Churchill side of the orogen, followed by progressive oceanward crustal growth. Although there is evidence in the western THO of deformation as early as 1.88 Ga along the Superior Craton margin, collision between this craton and the orogen internides likely did not occur before ca. 1.83 Ga. This might be reflected in the timing and extent of basement reactivation, which is demonstrably much older and greater on the Churchill side than on the Superior side of the orogen. Once collision ceased along the THO, convergence migrated to the southeastern margin of the Superior Province, where accretionary tectonics dominated until the formation of Rodinia.

The Middle Earth I: Ancient Oceanic Crust in the Middle of the Prairies and Formation of the Canadian Shield 2000 to 1800 Million Years Ago

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The Canadian Shield forms an intrinsic part of our country, woven in our history from the early fur trade industry to the exploration of the continental interior, to the more recent events of base and precious mineral discovery. Thoughts of the Canadian Shield invoke quintessential visions of clear northern lakes, the boreal forest and Tom Thompson's paintings of rocky shorelines. From a geological perspective, the Shield is an equally important benchmark of the Canadian natural landscape, forming the stable continental "backbone" onto which the North American continent was eventually built. Although it is now essentially free of earthquakes and volcanic activity and, for the most part, thoroughly peneplained, its geological history was not always so quiet. Prior to about 2 billion years (b.y.) ago, the North American continent as we know it did not exist. Instead, smaller continents and microcontinents were dispersed around a large, probably Pacific-size ocean named the "Manikewan Ocean", sitting approximately where Saskatchewan and Manitoba lie today. About 1.92 b.y. ago, the microcontinents started to move towards each other and the intervening Manikewan Ocean began to slowly shrink with time. A snapshot at about 1.9 b.y. would have found the Prairies looking somewhat similar to today's southeastern Asia, with plate tectonic activity forming features including deep ocean trenches, sedimentary basins and long, arcuate belts of volcanoes. World-class mineral deposits such as Flin Flon, Thompson, Raglan and Shefferville formed in specific settings within this plate tectonic configuration. The oceanic plates were eventually all consumed through this convergent process, leading to the final collision between continents, that essentially stitched together northwestern and southeastern Canada. During this event, which lasted between about 1.83 b.y. to 1.77 b.y. ago, a mountain belt formed, called the "Tran-Hudson Orogen", that spread across the North American continent from Colorado through Hudson Bay and Baffin Island, and beyond to Greenland and Scandinavia. By approximately 1.65 b.y., the Trans-Hudson Orogen was pretty much eroded to its present level and the central part of the Canadian Shield had essentially stabilized. Important features of this plate tectonic assembly were recognized for the first time during the Lithoprobe Trans-Hudson Orogen Transect.

Enhancing Base Metal Exploration Through Seismic Reflection Studies Adapted for the Crystalline Rock Environment

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Lithoprobe high-resolution seismic profiles at several Canadian mining camps have served as a catalyst for focused research efforts aimed at developing useful and cost-effective seismic technology for deep base metal exploration and mine planning, including 3-D seismic surveys (Figure 1). Although significant challenges remain, seismic exploration of the mining environment promises exciting new opportunities for discovery. Modern digital recording equipment – including "off-the-shelf" seismic sources and geophones – do not appear to require special adaptation for most mineral-exploration environments. Typical data characteristics, including low SNR, discontinuous reflections, and complex scattering effects, can be overcome by careful data acquisition, processing, forward modelling and interpretation. Some considerations that have emerged from Lithoprobe and other studies are:

1) Ore deposits are generally characterized by anomalous elastic properties, especially density. Nevertheless, comprehensive knowledge of physical properties, including density, P- and S-wave velocity, is essential for robust interpretation of seismic data for mineral exploration. In previously unexplored areas, laboratory physical rock property studies and borehole logging are an essential prerequisite to seismic exploration.

2) Forward modeling studies provide an important basis for survey design and interpretation of field data. In general, economic ore deposits have length scales similar to seismic wavelengths. Unlike point diffractors or spherical bodies, dipping lenticular or ellipsoidal inclusions at this scale appear to focus scattered P waves in the specular direction, down-dip from the orebody. Accurate forward modeling using a fully elastic algorithm and a physical properties database is necessary to understand seismic scattering response of an ore deposit.

3) In geological terranes where steep dips prevail, downhole seismic imaging (DSI) methods provide a way to image features around an existing borehole. Nearly complete coverage of the volume around a borehole can be achieved using a set of 5 or more sources arranged in a concentric ring around the borehole collar. New techniques, such as the image-point transform offer innovative approaches to enhance downhole seismic images.

4) In the case of surface profiles or 3-D surveys, high-fold, broadband datasets are essential. Traditional rules-of-thumb for minimum fold, as applied to data acquisition in more familiar

settings, must be revised and amended. As a result of the relatively high seismic velocities that prevail in hardrock environments, higher-than-normal source frequencies (> 100 Hz) are needed to ensure adquate resolution of the targets.

5) Data processing tends to be more costly and time consuming than anticipated. Key data processing steps include statics (refraction and residual), prestack noise attenuation, surface-consistent deconvolution and dip moveout.

6) In cases where isolated scattering bodies such as ore deposits are of paramount interest, it is advisable to make extensive use of unmigrated data (in addition to migrated sections) to pinpoint diagnostic diffraction responses.

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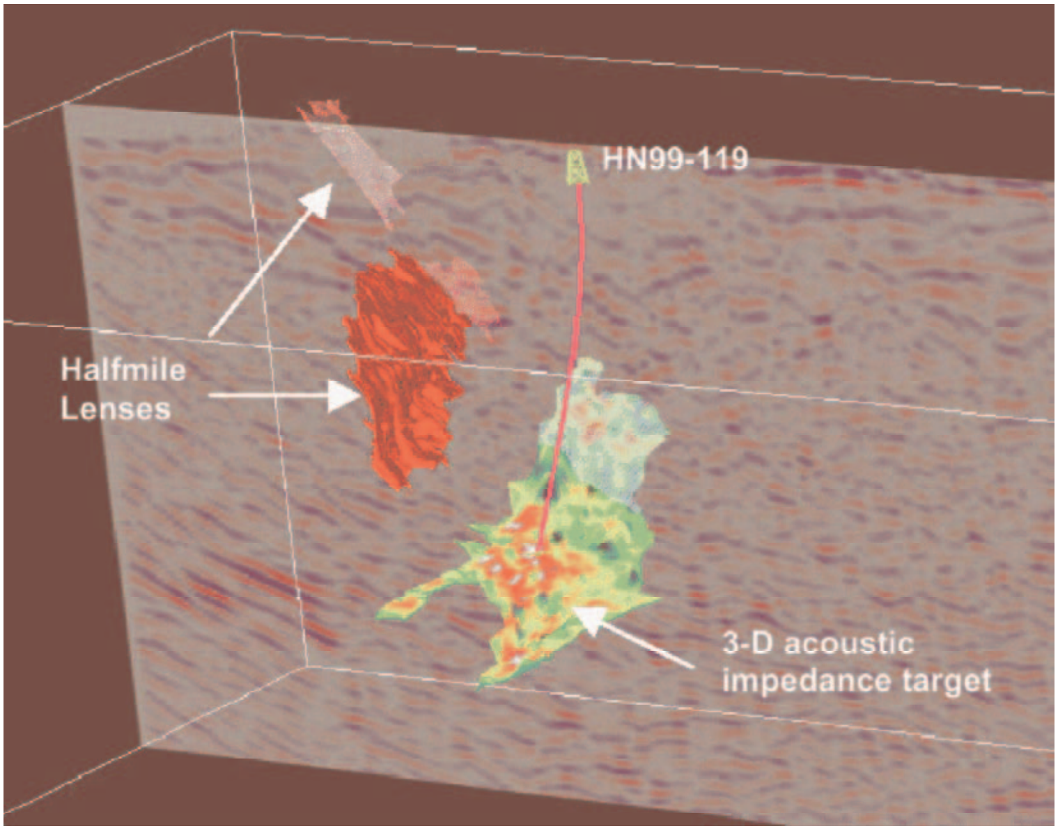

Figure 1. Cross-section through 3-D seismic reflection cube at Halfmile Lake, Bathurst camp, New Brunswick, showing massive sulfide deposit discovered at a depth of 1300 m by seismic reflection, as well as shallower, more steeply dipping lenses known from previous mapping and drilling. Modified from Gingerich et al. (2002). No vertical exaggeration.

Probing the Cordilleran Lithosphere with Mafic Lavas and Mantle Xenoliths

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The occurrence of Recent alkaline volcanism (0-15 Ma) across the disparate terranes of the northern Canadian Cordillera provides a unique window into the lithospheric mantle underlying the edge of the North American Craton. Not only do the basaltic lavas of these alkaline volcanic centres exhibit regional chemical and isotopic changes that correlate with major Cordilleran terrane boundaries, implying the existence of important lateral discontinuities in the lithosphere, but many of the more alkaline lavas carry xenolith fragments of the actual underlying lithospheric mantle.

The recent alkaline lavas of the northern Canadian Cordillera can be modeled as mixtures of two end-members, olivine nephelinite (Ol-Neph) and hypersthene-normative olivine basalt (Hy-norm). The highly enriched Ol-Neph lavas are volumetrically minor and appear to be derived from amphibole-bearing veins within the lithospheric mantle. The dominant Hy-norm basalts are characterized by the lowest incompatible trace element contents, but are still relatively enriched in the most incompatible elements compared to primitive mantle. The isotopic signature of the Hy-norm basalts varies with tectonic terrane, which may reflect the preservation of distinct lithospheric mantle roots beneath these terranes. The most dramatic change occurs between the Intermontane Belt (IMB) and the Omenica Belt (OMB). Although Hy-norm basalts dominate the Recent alkaline lavas of the IMB, compositions range through alkaline olivine basalt (AOB) to olivine-nephelinite (Ol-Neph) at many smaller centers, and suites of spinel lherzolite mantle xenoliths are relatively common. In contrast, slightly more alkaline AOB basalts dominate the Recent volcanic centres of the OMB, but neither Ol-Neph lavas nor mantle xenoliths have ever been found. Furthermore, there is a discontinuous eastward increase in Rb content, and Sr and Pb isotopic ratios, but decrease in Nd isotopic ratios in Hy-norm/AOB basalts along the Stikine Volcanic Belt between the Teslin and Cassiar Faults, approximately 20 km to the East of the surface boundary of the IMB and OMB. The isotopic differences in the basalts suggest that either their mantle source under the OMB is older and/or has been affected by a different enrichment event than that under the IMB, and may represent the leading edge of ancestral North America. The low Ca/Na ratios of all the Recent alkaline magmas of the Cordillera, and pericratonic alkaline lavas around the world in general, compared to their oceanic equivalents, appears to reflect lower degrees of partial melting in the garnet stability field associated with the greater lithospheric thickness beneath the continents.

Most of the mantle xenolith suites along the Canadian Cordillera exhibit unimodal populations with a prominent mode corresponding to relatively fertile spinel lherzolite, with ~ 3.3 wt.% Al_2O_3 and an $Mg^\#$ of ~ 0.893 (Table 1). This lherzolitic composition is significantly more fertile than the harzburgitic lithospheric mantle (Al_2O_3 < 1.0 wt.%) beneath the central North American Craton, and is interpreted to reflect the prevalent lithospheric mantle beneath the Canadian Cordillera. Os isotope model ages indicate that the Cordilleran lithospheric mantle stabilized in the mid-Proterozoic (~1.5 Ga), significantly more recently than the 2.7^+ Ga model ages of the lithospheric mantle beneath the central Northm American Craton, but consistent with a compilation of Os isotopic results from pericratonic mantle xenolith suites around the world that demonstrate the Proterozoic age of lithospheric mantle peripheral to many of the Earth's continental cratons. The most fertile lherzolite xenoliths have Sr, Nd, and Pb isotopic compositions that are equivalent to those of their host alkaline lavas, and approach those of MORB. These lherzolites also have Os isotopic compositions that are similar to those of the majority of modern MORB samples with significant Os contents (^{187}Os/^{188}Os ~ 0.13). These isotopic characteristics, in combination with their light rare earth depleted character and the co-linearity of the MORB picrites and Proterozoic mantle xenolith arrays, suggest that the fertile lherzolite that dominates the Cordilleran lithospheric mantle may represent the stagnant remnants of the convecting upper mantle source for MORB, trapped and preserved along the margins of continental cratons. The consistent Proterozoic model ages obtained for such fertile lherzolite xenoliths would imply that the present Pyrolitic convecting upper mantle that produces MORB is a Proterozoic feature of the Earth.

Three Cordilleran xenolith sites clustered near the Yukon - British Columbia border are characterized by bimodal populations, with one mode corresponding to the fertile spinel lherzolite observed in the other Cordilleran xenolith suites, while the other mode corresponds to relatively refractory spinel harzburgite with lower Al contents (~ 0.8 wt.%) and higher Mg nos. (~ 0.912). Although these harzburgites are major element depleted (although not as depleted as most cratonic harzburgites), they are trace element enriched compared to the dominant lherzolite of the Cordilleran lithospheric mantle. The Cordilleran harzburgites also exhibit more radiogenic Sr and Pb isotopic compositions than the lherzolite lithosphere, and the alkaline lavas that hosts them, but which are similar to the isotopic compositions of the Late Cretaceous Carmacks or later Eocene Sloko-Skukum volcanics. The anomalous abundance of harzburgites in the three xenolith suites near the Yukon - northern British Columbia border overlies a tele-seismic S-wave slowness anomaly underlying asthenospheric mantle, and has been proposed to reflect melting due the ingress of volatiles and heat into the overlying lithospheric mantle associated with Late Cretaceous or Eocene volcanism.

The absence of both mantle xenoliths and Ol-Neph in the recent alkaline lavas of the OMB could indicate that lithospheric thinning is more advanced there than under the IMB to the West, consistent with heat flow results indicating temperatures at the base of the OMB crust 150°C hotter than under the IMB, and magneto-telluric results indicating that the mantle under the OMB is more conductive at lithospheric depths than that under the IMB. . The high heat flow values reported in the northern Canadian Cordillera extrapolate to temperatures that are above the wet-peridotite solidus at lithospheric mantle depths, consistent with a model in which the alkaline lavas reflect recent melting and thinning of the lithosphere beneath the northern Canadian Cordillera.

The Ascendency of a Late Paleoproterozoic and Mesoproterozoic Tectonic Dynasty: an Eastern Laurentian Perspective

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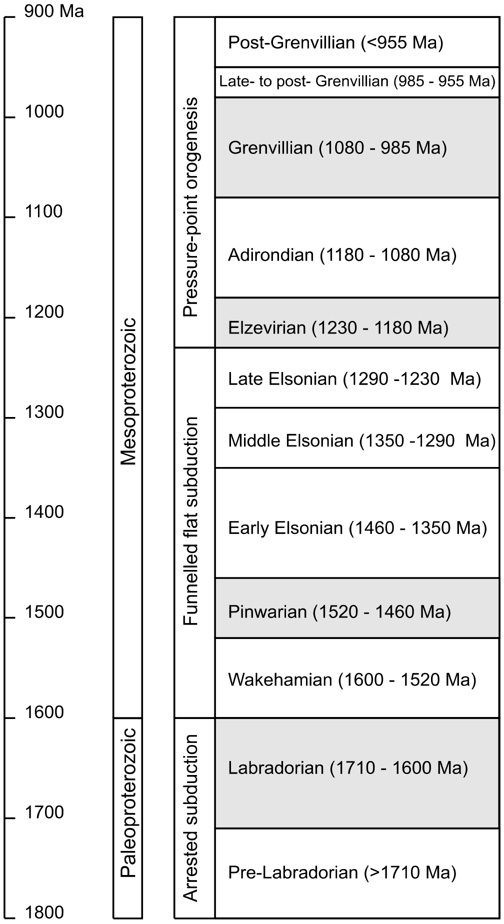
A dynasty is defined as a succession of kings of the same family; by analogy, a tectonic dynasty is a succession of orogens of similar ancestry. Both usually ended in violent upheavals that established new world orders. In the former, the end product was a re-alignment of power in kingdoms and countries; in the latter, it resulted in a fundamental rearrangement of continental landmasses.

To be addressed in this presentation is a tectonic dynasty that existed between two fundamental, violently achieved, continental arrangements, namely that which produced the supercontinent Columbia between 1900 and 1800 Ma, and that which established Rodinia between 1085 and 980 Ma.



A tectonic dynasty is a time of relative stability and continental growth, compared to the destructive forces that herald its birth and cause its downfall - but it is not uneventful. Dynasties evolve as one emperor or king succeeds the previous one, each reign being individual in its nature and characterized by the social, political and economic forces of the times. Similarly, tectonic dynasties evolve as one orogenic condition gives way to the next, governed by plate tectonic forces and the disposition of continental landmasses. Recognition of meaningful stages within a tectonic dynasty is more difficult than recording the coronation and death of a king, but is equally necessary, if events are to be understood in the context of the times.

Figure 1 presents a subdivision of the post-Columbian - pre-Rodinian tectonic dynasty, as it is envisaged to apply to easternmost Laurentia (Gower and Krogh, 2002). Some periods were more violent than others, especially during accretionary times when new crustal entities were being acquired. These times are termed orogenic (grey blocks in Figure 1), but the distinction between orogenic episodes and those of calm and stability (anorogenic) is far from clear cut, and, as in the political world, upheavals of varying intensity were generally occurring somewhere at any given time.

The energy of the various global continental crustal combatants having been depleted during the Trans-Hudsonian, Makkovikian, Ketilidian and related tectonic events, the tectonic dynasty opened with a period of relative calm that resulted in the widespread deposition of clastic sedimentary rocks. The exact time that these were deposited remains uncertain, but it was probably early, perhaps prior to 1780 Ma. Not all was peaceful however, as warm spots of activity remained and produced granitoid rocks as late as 1740 Ma.

Expansionist forces were at work, however, which culminated in the acquisition of a large region of new territory. Gower and Krogh (2003) have recently reviewed this conflict, the Labradorian orogeny, as well as events leading up to it and its aftermath. The struggle itself was very short lived, lasting from 1665 to 1655 Ma, but it was intense, involving metamorphism and deformation, including the upthrusting of crust once buried 30-40 km below the surface. The scars of the conflict are still recognizable in the seismic record, identified and interpreted through ECSOOT Lithoprobe investigations (Gower et al., 1997). Events leading up to the climactic clash remain somewhat murky, but preliminary crustal skirmishes occurred as early as 1710 Ma. In contrast, events that followed the orogenic confrontation are well known. It was at the interface between the two crustal factions that the consequences of the accretionary encounters were first expressed, in the form of the 1654-1646 Ma Trans-Labrador batholith. This was the offspring of the crustal union, brought about by crustal thickening and melting. Emplaced at the interface between pre-Labradorian Laurentia and the accreting fragment, it served to bond the two crustal entities for evermore. Now thoroughly united, subsequent deep fusion of the crust gave birth to triplets, termed trimodal magmatism (mafic-anorthositic-monzogranitic) by Gower and Krogh (2003); these arrived between 1645 and 1620 Ma. After this time, crustal cultures were thoroughly integrated, so this phase of the tectonic dynasty progressed into crustal equilibrium as Labradorian magmatism, deformation and metamorphism gradually dwindled into its sunset years between 1620 and 1600 Ma.

What must be among the longest and most widespread periods of stability and quiescence in the history of any tectonic dynasty then ensued. Although tectonic strife was rampant elsewhere in the world during this time, there is very little direct evidence of an active geological history in Laurentia between 1600 and 1520 Ma. The same is also demonstrated indirectly, by the dearth of detrital zircons in Phanerozoic sediments for the period between 1600 and 1530 Ma. The Labradorian, Mazatzalian and Gothian orogenic kings left a truly remarkable heritage.

Peace never lasts forever, but when change comes it often ushers in a new era. Such was the case with this tectonic dynasty. As is commonly the case in its political counterparts, the first murmurings of tectonic discontent began in the fringe regions, later to spread throughout the land. In easternmost Laurentia, these subversive (correction, subductive) forces, termed Pinwarian and active between 1520 and 1460 Ma, undermined the southern dominions of eastern Laurentia. The calm and stability of the preceding 80 million years became but a memory as deep-seated magmatic fermentation gave rise to granitoid rock emplacement and periodic felsic volcanic surface outbursts. At first, these were tentative and intermittent, but gained in vigour and volume to a crescendo between 1490 and 1470 Ma.

Shallow in its nature, the subduction then attempted to spread its influence into the interior of the post-Pinwarian Laurentian realm. Although there was little threat of it destroying the crustal accomplishments of the preceding 300 million years, the shallow subduction left its mark as it migrated inwards, but only between the dynastically conservative Archean Superior and Nain cratons. Although an outgrowth from Pinwarian elements, these incursions were of sufficiently different character to deserve a separate title, namely Elsonian. This stage in the tectonic dynasty lasted from 1460 to 1230 Ma. Michael-Shabogamo gabbroic magmatism was active between 1450 and 1420 Ma, invading, what thus revealed itself to be, a zone of long-lasting dynastic weakness at the site of union between pre-Labradorian Laurentia and its accreted partner. Progressing north, the deep undercurrent of instability successively produced anorthositic and related magmatism in the Harp Lake, Michikamau and Mistastin complexes, and, yet later and even farther north, the 1350-1290 Ma Nain Plutonic Suite. Both the crust and the subductive movement finally failed completely with the emplacement of various dyke swarms and a final venting of basaltic magma to create the Seal Lake Group between 1250 and 1225 Ma.

As in political regimes, the overthrow of a tectonic dynasty may be preceded by a long period of unrest. In the case of the global upheaval that brought about Rodinia, this instability can be traced back to at least 1230 Ma. These events will not be addressed in this presentation but are mentioned for completeness. The earliest tectonic rumblings were in far-off Elzevirian regions and beyond, and left easternmost Laurentia initially unscathed, but between 1180 and 1120 Ma, the southernmost part of eastern Laurentia was again in crustal turmoil, as demonstrated by anorthositic and related magmatism. The tectonic climax occurred during Grenvillian (sensu stricto) orogenesis (1080 - 985 Ma), obliterating all but vestiges of the old tectonic dynasty, bringing it to a close, and creating a new global order with the establishment of the Rodinian supercontinent.

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The Trans-Hudson and East Alberta Orogens of Western Canada-Geophysical Characteristics of Complex Collisional Processes and Delineation of the Sask Craton

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In the early stages and just prior to the initiation of the LITHOPROBE program, analysis of aeromagnetic anomaly trends led to the subdivision of the Churchill Province of the Canadian Shield, west of the Superior craton and the establishment of the complex orogenic belts of the Trans-Hudson and Alberta orogens. Numerous geophysical programs were launched to investigate the crustal signatures of these new tectonic models of the region, through the national geosciences project.

The ~ 500 km wide internides (Reindeer Zone) and the distinct eastern and western margins of the Trans-Hudson Orogen (THO) were imaged by over 1000 km of deep sounding reflection, comparable magnetotellluric, gravity and ~ 2000 km of refraction/wide-angle reflection surveys. At the eastern limits the Superior Boundary Zone (SBZ) forms the northwestern margin of the Archean Superior craton and constitutes a tectonic foreland of the ca. 1.8 Ga THO. The coincident regional and magnetotelluric data reveal spatially variant crustal characteristics of the boundary zone. In the south, the profiles indicate: 1) The Reindeer Zone accretionary collage comprises an east dipping , eastward-steepening, crustal-scale tectonic stack of moderate conductive rocks near the SBZ. 2) The SBZ is characterized at shallow depths (4< 5-6 km) by steep to moderate east-dipping reflectivity that is associated with the limbs of third generation folds (F3, D3) and east-side-up shear zones. At great depths, the SBZ crust is highly resistive and is contiguous to the east with resistive crust beneath the superior craton. 3) The Superior Boundary Fault (SBF) is recognized in the subsurface as an abrupt resistivity contrast between the Reindeer Zone and the SBZ, extending subvertically to 15 km depth. 4) Moderately conductive rocks of the Reindeer Zone extend eastward for 30 km beneath the SBZ at depths of 15-45 km. Seismic data located ~ 100 km NE, along the strike, indicate a similar crustal structure with some notable exceptions: 1) The SBF is recognized in the subsurface as a truncation of interpreted collisional fabric, extending subvertically to ~ 30 km depth. 2) There is no compelling evidence for the eastward continuation of Reindeer Zone lower crust beneath the SBZ. It is proposed that the present day regional SBZ crustal structure evolved over its ca. 200 ma convergent margin history from a lower plate collisional thrust belt setting at 1.88-1.81 Ga, through lithospheric delamination at 1.82-1.80 Ga to steep transpressive plate boundary at 1.80-1.72 Ga.

The interior of the convergence zone is examined by the orogen wide > 500 km EW and six attached, but spatially distributed NS trending variable length reflection profiles. This novel survey configuration established significant level of 3D perspectives of the subsurface seismic images. The EW section is characterized by well-defined east and west dipping reflections suggesting that the Paleoproterozoic accreted rocks of the surface project to lower crustal depths beneath the bounding Archean cratons. These imbricate low angle thrusts, with variable depths (< 1 to 10 km), form the surface carapace of the collisional belt. The sole of these allochtonous bodies is the Pelican thrust. Correlation of its characteristic seismic signatures from Archean windows, through a number of seismic sections, defined it as an orogen-wide basal decollment zone. The comparable tracing of the exposed Archean rocks below the basal detachment allowed the discovery of the Sask craton, a previously unknown micro-continental block. The regional extent of this enigmatic body is recognizable over at least 100,000 km^2 within the THO. It can be traced from surface to at least 25 km depth. It is associated with a well recognized crust root with a length of ~ 200 km and a N-NE structural trend. Refraction/wide angle data indicate anomalous upper mantle velocity signatures below this Archean block (8.0-8.5 km/s), with characteristic lithospheric discontinuities, suggesting that a segment of the original mantle of the micro-continent was preserved after the orogenic convergence although with some alterations. The depth of the Moho is highly variable but generally significantly deeper than 40 km (> 13 s TWT). In several localities, the depth changes, over 20 km distance, within the range of 40 to 54 km outlining major structural relief. Sporadic presence of sub-Moho reflections is indicative of the involvement of the lithospheric mantle in the collisional process.

The geologic elements of the western margin are crossed by two major profiles revealing comparable crustal signatures along the convergent zone over 500 km apart. The Wathaman batholith, a prominent Andean type magmatic arc has no significant seismic signature on either of the profiles. The Needle Fall Shear Zone (NFSZ), separating the juvenile terranes from the cratonic margin and tens of km of dominantly dextral displacement, is recognized in the south, as a steeply west-dipping seismically transparent zone, with associated diffractions, but has no comparable signature along the northern section. The crustal structural images, of the two seismic sections, outline a bimodal orogenic wedge of complex convergence of the Sask craton with the margin of the Hear craton, comparable to the structural signatures of the central Alps. The imbricate set of thrust sheets between the western limit of the Sask craton and the NFSZ are characteristics of “pro-wedge” development, westernly dipping and converging towards the inernides. West of the NFSZ the east dipping west-verging backthrusts and associated folds define the “retro-wedge” portion of the orogenic belt. In comparison to the earlier tectonic model of the THO, the current data indicates that the Sask craton is a significantly larger body than recognized previously and consequently it played a significant role in the convergent process. The coincidence of the highly similar magnetic signatures along distance of > 500 km between the two margin crossing profiles suggests that they are interconnected and the potential data indicate the active margin convergence was analogous starting from 52^0 latitude to the NE as defined by the magnetic signatures. The position of the Sask craton and the Dakota Block, between the Superior and the Hearne cratons and the preservation of a prodigious amount of juvenile terranes, between them, implies that the Trans-Hudson orogen is an incomplete arrested orogenic belt. An intriguing set of bright reflections (Wollaston Lake Reflector) are revealed, on the northern section, extending at least 160 km across the margin of the craton, with travel times ranging from 2.0 to 4.5 s (6.0- 13.5 km). Presently this enigmatic sheet-like zone of reflectivity is interpreted as a subsurface expression of the ca. 1265 Ga (POST-Hudsonian) Mackenzie diabase suite.

The magnetotelluric investigations, within the THO, established the three-dimensional signature of the North American Central Plains conductivity anomaly (NACP) and its connection to the orogen from North Dakota to northern Saskatchewan. The anomaly is remarkable in its continuity along strike, a testimony to the along strike similarity of orogenic processes. Where bedrock is exposed, the anomaly is attributed to sulphides that were metamorphosed during subduction and compression and emplaced deep within the internides of the orogen to the cratonic boundary. More recent compilation indicates an anomaly within the upper mantle beginning at depths of approximately 80-100 km. This lithospheric mantle conductor has properties similar to those of the Central Slave Conductor which lies directly beneath the diamondiferous kimberlite field. Whilst the Saskatchewan mantle conductor lies not directly under the Fort a la Corne kimberlite, the spatial correspondence is close.

Modeling of total field magnetic and Bouger gravity data along a 800 km long all orogen inclusive crustal section, in consideration with seismic, resistivity and velocity based density models generated a number of key results: 1) Definition of two new sub-Phanerozoic domains (Kindersly and Assiniboia). 2) Evidence for west-vergent crustal stacking and exhumation in the eastern Trans-Hudson orogen in the form of preserved Moho topography and presence of higher-grade (high velocity) rocks in the hanging wall of an east dipping crustal stack. 3) Definition of the eastward extent of the Archean Sask craton in the subsurface based on distinct lower crustal properties. 4) 400 m of present-day surface topography and 6-8 km of relief on the Moho are isostatically compensated for primarily within the upper mantle by a westward increase in upper mantle temperatures by 40^0 to155^0 C and/or a decrease in lithospheric thickness ranging from 16-107 km.

The Alberta Transect consists of two major distinct phases of reflection investigations, both in regions of significant Phanerozoic cover. The refraction/wide angle reflection program (Southern Alberta Refraction Experiment-SAREX) is limited to a long NS profile along the eastern margin of the orogen, in conjunction with the several thousand km long Deep Probe investigation which extends through the Alberta corridor and a major portion of southern United States.

The 520 km Central Alberta Transect (CAT) is intended to investigate the crustal geometry of the Hearne craton and the syncollisional rocks that form a set of tectonic elements immediately west of the craton, and the Southern Alberta Transect (SALT) traversing an 832 km long broad region of the buried Archean crust of the Hearne and Wyoming Provinces. The crystalline basement rocks of the region are subdivided based on their magnetic signatures, into the most southernly Medicin Hat Block (MHB), a part of the Wyoming craton, to the north is the east-west trending ~ 350 km long and 40-70 km wideVulcan structure (VS) and further to the north the ancient Loverna Block (LB). The crust is characterized by moderate to strong reflectivity along the CAT lines. The Moho displays remarkable lateral continuity, consistency and persistence with significant topographic variations, including a sudden structural offset of 7-10 km. Overall the crustal thickness varies from ~ 38 to 47 km. The mantle is relatively transparent with the exception of the area beneath the Rimbey domain where strong reflections within the mantle (18 s TWT) dip 45^0 SE with a strike of N34^0E, in agreement with the crustal structural trends inferring evidences of southeastward subduction. In general the seismic data define three different crustal domains: 1) a strong northwest verging thrust domain, that contains the Hearne province, 2) a domain of intersecting reflections with opposite dips that define a crustal wedge beneath the Rimbey granites and 3) a region of subhorizontal and northwest dipping reflections that characterize the Wabamun and Thorsby domains respectively.

The mainly NS trending profiles of the SALT map sedimentary fill of the Western Canada Sedimentray Basin (WCSB) to a depth of ~ 2 s (TWT), followed by a multiple infested zone between 2-4 s, a variable reflective and/or diffractive units in the upper to middle crust to 10 s TWT, including a crustal culmination broadly coincidental with the VS , a reflective lower crust and an unreflective upper mantle below 14-15.8 s TWT. The reflectivity of the southern portion of the VS dips to the south, under the MHB The LB is characterized by complex diffraction and discontinuous reflections in the upper and horizontal reflectivity in the lower crust. Along this structure, the Moho depths appears variable (11.6- 16 s TWT) under the different NS traversing profiles. The upper crust of the MHB is seismically transparent; the lower crust is imaged by zones of strong and weak reflectivities. The integrated synthesis of potential and seismic data suggests that the VS structure is a narrow continental collisional belt. Current aeromagnetic images show that the VS structure curves toward the southeast and merges with the THO. The seismic images imply crustal delamination and south directed subduction of the lower crust of the LB. Cross-cutting relationships inferred from aeromagnetic data indicate that the timing of collision postdated formation of Archean fabrics in the MHB but predated terminal collision in the adjacent THO. The geographic extent, inferred net shortening and tectonic setting of the VS appear to resemble the modern Pyrenees belt, although the deep structure appears`to be more akin to the Scandinavian Caledonites. Either scenario is consistent with an interpretation of the VS as the Proterozoic collisional suture between the Wyoming and Hearne Provinces of the Laurentian craton. The Deep Probe/SAREX experiments indicate that the Wyoming province is characterized by thicker crust (~ 50 km) than the Hearne Province (~ 40 km). In addition, the western side of the Wyoming Province is underlain by a thick high-velocity (. 7.0 km/s) layer. The transition from the Wyoming-type to Hearne-type crust is not well defined but it is constrained to lie well north of the Great Falls Tectonic Shear Zone. Synthesis of seismic reflection geometries between the CAT and the THO, mainly north of the 52^0 north latitude, establishes basic links between the two orogens. The model outlines a structural fan that forms in the crust trapped between opposing zones of convergence, i.e. two-sided orogen, a tectonic vise.

Evolution of the Southeastern Churchill Province and Development of the Torngat Orogen in Northeastern Labrador – Results from Extensive Geological and Geophysical Studies

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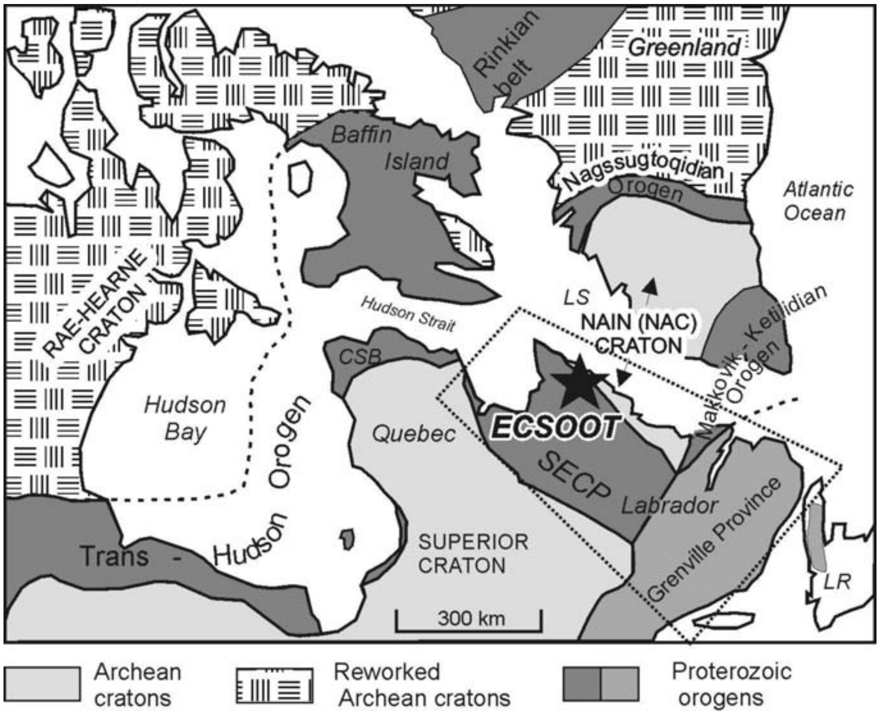
The Eastern Canadian Shield Onshore/Offshore Transect (ECSOOT) focused on the processes by which the northeastern Canadian Shield evolved firstly by coalescence of Archean cratons around 1.9-1.8 Ga and then by addition of juvenile crust from the south during 1.9-0.9 Ga. In this review, the Paleoproterozoic history is evaluated in a plate tectonic context. The Torngat orogen, with its preserved crustal root, plays a central role. Tectonostratigraphic correlations and plate configurations are established to link the history of the Torngat orogen with those of the Trans-Hudson orogen to the west and north, the Rinkian belt and Nagssugtoqidian orogen in NW Greenland, the Makkovik orogen of eastern Labrador and the Ketilidian orogen of SW Greenland. Complex relationships of geometry and timing are resolved by appeal to the evolution of triple-point plate junctions, involving divergent, convergent and transform boundaries.



Map of the northeastern Canadian Shield and Greenland, restored for continental drift, showing the location of the ECSOOT study region (dotted boundary). Asterisk shows focal region of the Torngat Orogen. SECP, Southeastern Churchill Province; CSB, Cape Smith Belt; LS, future Labrador Sea; NAC, North Atlantic Craton.

Precambrian Mafic Magmatism: An Overview

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Mafic magmatism is a fundamental component of all Precambrian terranes and has played a pivot role in moderating the relatively hot thermal state of early Earth. There are three broad characteristics of Precambrian mafic magmatism preserved in continental regions that are distinct from modern tectonic settings: 1) Archean mafic magmatism is dominated by the formation of long linear greenstone belts, 2) komatiite is significantly more abundant in early Earth, and 3) the Proterozoic heralds a shift towards proliferation of continental flood basalt provinces and associated giant mafic dyke swarms. This dramatic change from a greenstone belt style of mafic magmatism in the Archean to a more modern-like style of large igneous province development at about 2.5 Ga was accompanied by numerous global changes that are reflected in core evolution, increase in mantle plume activity, crustal growth, ocean chemistry, and climate. Lithoprobe-sponsored research has been instrumental in demonstrating that two of the most prolific periods of Precambrian mafic magmatic activity worldwide (2.8-2.7 Ga and 2.5-2.4 Ga) are linked to significant growth of the subcontinental lithosphere (substantial underplating of mafic material to continental crust), high-temperature low-pressure granulite grade metamorphism in the lower crust, and continental rifting.

THE SUPERIOR CRATON –WHAT HAVE WE LEARNED FROM GEOLOGICAL, GEOCHEMICAL AND GEOCHRONOLOGICAL STUDIES? LESSONS ON THE DEVELOPMENT OF THE ARCHEAN EARTH AND PROCESSES INVOLVED

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By the time the Western Superior LITHOPROBE Transect got underway in the mid-1990's, an extensive geoscience data base had been assembled for much of the Archean Superior Province by federal and provincial geological surveys as well as university and company researchers. The first-order feature of the province, its internal pattern of lithotectonic belts, known as subprovinces, had been well established, and attempts had been made to interpret the subprovince arrangement in western Superior Province in terms of "terrane" accretion, analogous with plate tectonic interpretations of Phanerozoic orogens, in particular the Western Cordillera of North America. After the Abitibi-Grenville LITHOPROBE Transect obtained seismic images of a possible Archean mantle suture under the Abitibi-Opatica subprovinces boundary, the objectives of the Western Superior Transect were to further test the Archean accretion hypothesis 1) by investigating geological relationships between and within subprovinces at depth in order to understand further the processes involved in the formation, assembly and stabilization of Archean crust, and 2) by determining, comparing and contrasting deep crustal and upper mantle structure beneath the different types of subprovinces. Western Superior Transect geophysical data acquisition and supporting geoscience projects, augmented by the massive Western Superior NATMAP program conducted by the Geological Surveys of Ontario, Manitoba and Canada, produced a wealth of new data that allow considerable refinement of the internal makeup of the tectonic building blocks and the nature of their boundaries within Western Superior Province. Combining results of these recent integrated geological, geochemical and geochronological studies with those of the earlier work, a robust data base is established that not only permits distinction of terranes with independent tectonostratigraphic histories, but that enables tracking the accretion of terranes into superterranes prior to final amalgamation of the composite superterrane that we now recognize as Superior craton. It also permits a reinterpretation of the previously recognized subprovince structure within the newly evolving accretionary framework. One of the major results of the recent work is a better understanding of ages and extent of Mesoarchean (>2.8 Ga) continental crust in Superior province. In spite of the pervasive Neoarchean structural, metamorphic and magmatic overprint, increasing numbers of basement domains have been recognized, and these are now interpreted as belonging to at least five independent crustal blocks or microcontinental fragments that are separated by belts of younger supracrustal rocks. The oldest continental crust (ca. 3.8-2.81 Ga) occurs in the only recently recognized Northern Superior superterrane (NSS) which extends along the northern fringe of Superior Province through northern Manitoba, Ontario and Quebec. To the south, and separated from the NSS by the supracrustal Oxford-Stull Lake terrane, is the 3.0-2.87 Ga North Caribou-La Grande-Goudalie superterrane (NCLGG), the largest continental block of Superior Province that formed the continental nucleus for Neoarchean Superior Province assembly. In western

Superior Province, the granite-greenstone terrains of the Uchi subprovince evolved along the southern margin of the North Caribou terrane. Further south is the ca. 3.4-2.81 Ga Winnipeg River terrane (WR) which includes the Winnipeg River subprovince, but is now known to extend eastward into the northern parts of central and eastern Wabigoon subprovince. The ca. 3.0 Ga Marmion terrane (MM), occupies the south-central part of the Wabigoon subprovince. Although it evolved separately, it may have been accreted to the WR by ca. 2.9 Ga. At the southern margin of western Superior Province, south of the Wawa-Abitibi subprovince, is the Minnesota River Valley terrane (MRVT), which includes rocks as old as 3.6 Ga. No new data have been obtained for this terrane, but LITHOPROBE seismic reflection images and chronological constraints suggest that it may have been thrust beneath the southward accreting western Superior collage at ca. 2.68 Ga.

Younger supracrustal rocks developed on and separating the Mesoarchean basement domains include locally preserved rift sequences, extensive oceanic domains dominated by tholeiitic and komatiitic rocks, mostly of oceanic plateau affinity, but also including widespread remnants of rocks resembling mid-ocean ridge basalts (N-MORB), and various calc-alkaline assemblages both of island and continental arc affinity. Examples of oceanic domains are the Oxford-Stull Lake terrane, in the north, and the western Wabigoon subprovince and Wawa-Abitibi subprovince, in the south. Inferred major suture zones are marked by regionally extensive belts of metaturbidites, best developed in the English River and Quetico subprovinces. Their depositional ages constrain the docking events between superterranes, first between the NSS and the NCLGG (at ca. 2.72 Ga), and then successive southward accretion to the composite Superior superterrane (CSS) of the Winnipeg River-Wabigoon superterrane (at ca. 2.71-2.70 Ga), the Wawa-Abitibi superterrane (at ca. 2.69 Ga), and the Minnesota River Valley terrane (at ca. 2.68 Ga). Post-collisional events, such as transpressive faulting, sanukitoid magmatism, rare alkaline magmatism and molasse deposition (Timiskaming-type conglomerates and sandstones) show a corresponding age distribution. Post-tectonic granitic magmatism and deep-crustal high-grade metamorphism continued throughout the Superior Province from ca. 2.68-2.64 Ga and ca. 2.66-2.62 Ga, respectively. Ar-Ar ages for hornblende, muscovite and biotite suggest that post-orogenic uplift along major faults lasted at least until ca. 2.4 Ga.

Surface observations are supplemented in the third dimension by wide-angle seismic reflection-refraction and near-vertical-incidence seismic reflection data acquired mainly in the southern part of western Superior Province, utilizing the road network and rail access. Teleseismic and magnetotelluric studies were conducted with portable instruments to extend data acquisition further to the north. Seismic reflection and refraction data reveal a geometry consistent with crustal imbrication and suturing. In particular, an extensive zone of anomalously thick, high-velocity lower crust in the southern part of the area, detected in refraction, reflection and teleseismic experiments, has been interpreted as a ca. 10 km thick panel of oceanic crust, underplated by northward, shallow-angle subduction, and now preserved as garnet amphibolite. Teleseismic studies have distinguished a northern domain of isotropic mantle lithosphere, under the North Caribou terrane, and a southern domain characterized by east-west anisotropy. These domains are separated by a steeply north-dipping high-velocity zone extending to a depth of about 300 km. Domains in electrical conductivity structure resemble the teleseismically defined domains, with minimal anisotropy under the North Caribou terrane and pronounced east-west anisotropy in the south. The steep high-velocity zone separating the two domains corresponds to a tabular zone of high resistivity.

The accumulated evidence leaves little doubt that rock assemblages, structural evolution and architecture of the Archean continental crust preserved in the Superior Province are analogous to those of modern accretionary orogenic belts. Crustal domains are reflected by domains of different mantle lithosphere structure. As discussed further in two companion papers on the Superior craton in this session, earlier hypotheses advocating an origin of the Superior Province by terrane accretion, though modified in detail, are essentially confirmed.

Giant Earthquakes Beneath Canada's West Coast

A new earthquake hazard along the coast of Vancouver Island, Washington and Oregon

Roy D. Hyndman
On behalf of the many scientists that have contributed to defining the great earthquake hazard on the west coast

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Introduction

Few people question the severity of the earthquake hazard in California or in Japan. However, until recently southern British Columbia had been thought to have a significant but lesser earthquake hazard. This view has changed with the recognition of the potential for giant subduction thrust earthquakes beneath the coast of Vancouver Island. No such great earthquakes characteristic of convergent margins have occurrent in the ~200 year historical period. However, recent evidence from Lithoprobe and Geological Survey of Canada studies leaves little doubt that great earthquakes have occurred in the past and that they will occur in the future.

The hazard from very large earthquakes in this region has been difficult to determine. The locations and the frequency of occurrence of large but infrequent earthquakes usually can be estimated from the pattern and frequency of the more frequent small events. The average occurrence of large damaging earthquakes can thus be estimated even if there have been no such events in the historical record. Probability assessment of earthquake hazard is usually based on this relation. Buildings and other structures can be designed accordingly.

The failure of the magnitude-frequency of occurrence approach is especially serious in the coastal Cascadia region of western North America where the Juan de Fuca oceanic plate is underthrusting the North American continent. Although the regional earthquake activity is quite high (magnitude ~7 events occurred in 1872, 1918, 1946, 1949, and 2001), no earthquakes of any size have been detected on the subduction thrust fault itself. In a global perspective, the lack of large thrust earthquakes, is surprising. Most of the world's great earthquakes (M8 and greater) have occurred on subduction zone thrust faults, and most subduction zones have experienced historical great earthquakes. The Cascadia subduction zone appears to be an anomaly. However, the written historical record is short, it is only a little more than 200 years since the first visits by Captains Juan Perez and James Cook.

There are three possible explanations for the lack of historical great earthquakes: (1) The Juan de Fuca plate is no longer converging and underthrusting North America. (2) Underthrusting is accommodated by smooth stable sliding. (3) The thrust fault is completely locked. The third explanation implies that there is a potential for very large and damaging earthquakes that was not included in earlier hazard estimates.

That convergence is continuing is now well established, and there is increasing evidence from geodetic measurements of elastic strain building up near the coast, that the thrust fault is completely locked. Also there is now good evidence for large events from coastal paleoseismicity (the traces of past great earthquakes preserved in the geological record). We are left with the third alternative. Great earthquakes do occur, but the last one occurred prior to the historical written record.

Past great earthquakes in the geological record

A remarkable record of past great earthquakes at intervals of ~500 yrs is found in sheltered inlets and bays along the coast. At depth intervals of 1/2 to 2 metres there are buried peat layers consisting of vegetation identical to that of the present intertidal marsh surface. The peat layers are interpreted to be former intertidal marsh vegetation that was submerged by abrupt coastal subsidence at the time of past great earthquakes. Following each great event, coastal mud accumulated on the drowned marsh, building the surface back to mid-tide level allowing vegetation to became re-established. Further convincing evidence comes from sand layers that cover the buried marsh surfaces. The sand is interpreted to have been carried in by the great tsunami that rushed into the subsided coastal region. Both theoretical modelling and the effects preserved in the coastal geological record indicate that the waves may have had heights of 5 to 10 m on the open coast and much higher still in some confined inlets. Radiocarbon dating shows the last great event to have occurred about 300 years ago with successive great earthquakes 500-600 years apart.

Other evidence for past great earthquakes comes from sediment deposits well offshore on the floor of the Cascadia deep sea basin. Core samples show turbidite fine-grained mud layers alternating with sandier layers; the coarser layers are interpreted to be formed by submarine landslides triggered by great earthquakes. The intervening mud layers formed by the slow continuous rain of finer sediment settling from the ocean. The turbidite chronology is similar to that obtained from the coastal marsh deposits.

An additional clue comes from ancient records of tsunami damage on the coast of Japan. In contrast to the short record on the Cascadia coast, Japan has a long and well documented historical record of damaging tsunamis. The most recent Cascadia great earthquake appears to have generated a tsunami that travelled across the Pacific ocean and did considerable damage on the coast of Japan. The wave heights of 2 to 3 metres in Japan and numerical tsunami models predict tsunami wave heights on the Canadian coast of about 10 metres. Correcting for the tsunami travel time to Japan and the time zone difference, the source great earthquake must have occurred along the North American coast on January 26, 1700 at about 9 p.m.

Another support for the occurrence of a great earthquake on a winter night is provided by the strong oral tradition of the coastal native people. In the period not long before European contact, a giant earthquake is described that occurred on a winter night. It was followed by a tsunami that destroyed the village at the head of Pachena Bay on the west coast of Vancouver Island. In another account, the canoes came down in the trees.

The great earthquake deformation cycle

The basic process of great earthquakes may be represented by the elastic rebound model first developed for the San Andreas Fault. Ongoing convergence of the oceanic plate results in bending and buckling of the continental crust, and the accumulation of elastic stress in the vicinity of the locked fault. After some time, the stress exceeds the sliding strength of the fault and there is abrupt slip. The stored elastic energy radiates as earthquake waves. The fault then relocks and the cycle resumes. For the Cascadia subduction zone, the ~40 mm yr^{-1} rate of convergence represents a shortening between events of ~20 metres if the event interval is 500 years. Such a slip represents a very great earthquake indeed.

Modern distance measurements using GPS and other geodetic techniques have allowed us to map the deformation associated with the locked thrust fault. Ongoing convergence drags down the seaward nose of the continent and causes an upward flexural bulge farther landward. There is also a region of crustal shortening. At the time of the earthquake, the edge of the continent springs back seaward and the bulge collapses. The abrupt uplift of the outer continental shelf is responsible for the great tsunamis. The collapse of the flexural bulge further landward causes the sudden coastal subsidence recorded in intertidal marshes.

Geodetic measurements and the fault locked zone

Only a portion of the thrust fault ruptures in great earthquakes. The extent of the seismic source zone is limited both updip and downdip. The landward downdip limit is important for seismic hazard since it determines the closest approach to the major population centres located 100 km inland of the outer coast. The seaward updip limit is important for tsunami generation. The total seismogenic width perpendicular to the margin has an important influence on the maximum size of great earthquakes.

The extent of the locked zone on the thrust fault may be determined from the pattern of elastic interseismic crustal deformation. If the locked zone is narrow, extending only a short distance downdip from the trench, the zone of elastic deformation is narrow. If the locked zone is wide, the deformation zone will extend a long distance inland. GPS and other geodetic surveys now achieve remarkable accuracy; about 1mm/yr deformation can be resolved. For the Cascadia margin there is present uplift at rates that vary along the coast from 1 to 4 mm yr^{-1}, and the coast is being squeezed landward at rates of up to 12 mm/yr. The pattern of deformation determined from geodetic surveys shows that the subduction thrust fault is locked along the whole coast from southern British Columbia to northern California. The locked zone and predicted rupture area lies beneath the continental shelf approximately to the coast; it is widest off the Olympic Peninsula of northern Washington and narrowest off central Oregon. The large fault rupture area indicates giant earthquakes of magnitude 9.

Important support for the conclusions of the geophysical modelling is provided by a comparison of measured uplift rates and thus predicted coastal earthquake subsidence, with the seismic subsidence inferred from the buried marshes. The present coastal uplift rate of 1 to 4 mm per year, accumulated over an interseismic period of 500 years, gives an expected earthquake subsidence of 1/2 to 2 metres. The marsh burial depths, after allowing for eustatic sealevel rise, postglacial rebound and the interseismic earthquake cycle uplift, give similar earthquake subsidence. However, there are differences in detail that remind us that we have simplified the complex earthquake process.

What limits the width of the downdip seismic zone?

The pattern of current deformation allows us to estimate which part of the thrust fault is locked. But what controls the limits of the locked seismogenic zone? Many factors have been suggested but temperature appears to play a dominant role. The megathrust seismic zone is bounded seaward by a region extending to the deep sea trench that does not generate earthquakes. Free slip in the latter zone may be a consequence of the stable sliding clay minerals that are common in the region of subduction zone faults. With increasing temperature these clays become dehydrated and transform to stronger minerals. The fault becomes seismogenic where the temperature reaches 100-150°C which is estimated to occur beneath the lowermost continental slope.

The downdip landward limit of the seismogenic zone also may be thermally controlled. At some depth, a temperature is reached on the thrust fault where the rocks behave plastically. The "brittle-ductile" transition has often been taken as the reason that crustal earthquakes are confined to depths less than 20-30 km. More precisely, the critical depth is where the fault zone no longer exhibits frictional instability. Laboratory measurements on continental crustal rocks indicate that the critical temperature marking the transition to stable-sliding is about 350°C, which corresponds well with that estimated for the maximum depth of earthquakes in many continental areas. The maximum depth is greatest in low heat flow cool areas where the temperature increases slowly with depth. The temperatures on the Cascadia thrust plane are unusually high because the young incoming oceanic plate is hot and because there is a thick insulating sediment cover. As a result, the 350°C temperature is reached at an unusually short distance landward downdip on the fault.

How well do the thermally predicted downdip limits correspond to the actual limits obtained from the current deformation data? Thermal modelling constrained by measurements of the heat flux from the earth, provide a model constraint. The position of the 350^{o}C temperature is in good agreement with the downdip limits of the locked zone inferred from the deformation data.

One more obvious question remains; how do we know that the estimated locked portion of the subduction thrust fault actually corresponds to the area of great earthquake rupture? We noted above one supporting correspondence. The predicted earthquake subsidence generally agrees with that deduced from studies of buried coastal marshes. Another approach has been to apply the Cascadia type of analysis to subduction zones marked by well documented, historical great earthquakes. For the Nankai margin of southwest Japan, the downdip rupture areas of the 1944 and 1946, M=8, great earthquakes correspond closely to the locked seismogenic zone, inferred from analysis of current deformation data and from thermal modelling.

The hazard

A detailed discussion of the hazard associated with great subduction zone earthquakes is beyond the scope of this presentation. We present here only a few general comments. The distribution of ground shaking expected from a great Cascadia earthquake can be estimated in two ways. The first is to make comparisons with the experience from great earthquakes elsewhere. The other approach involves theoretical models based on the estimated seismic rupture area and displacement. The conclusions are similar; the ground shaking in coastal areas will be strong for the expected events with magnitudes well over 8. The larger cities of Vancouver, Seattle, and Portland, that lie 100-200 km inland from the outer coast, are fortunate that the earthquake generating portion of the fault is restricted to beneath the continental shelf. It extends little if at all below the coast. However, the shaking for such large earthquakes decreases rather slowly with distance, so the hazard at these cities is still large.

The maximum magnitude for Cascadia thrust earthquakes depends mainly upon the along-coast length of rupture. Simultaneous rupture of the whole locked zone from Vancouver Island to northernmost California would be an unusual occurrence in the global experience. Such long narrow rupture areas are rare, but there is increasing evidence that this has occurred, at least for the most recent Cascadia event. The long inter-event period allows for truly giant earthquakes of magnitude 9 if the whole Cascadia locked area of nearly 100,000 km^2 ruptures at once. There have been only two events of this size in the ~100 years of global earthquake recording, the 1960 earthquake along the coast of southern Chile and the 1964 earthquake off the coast of Alaska. For such giant earthquakes, strong ground shaking lasts for a long time, at least several minutes, a feature that presents an increased hazard for some structures.

The earthquake threat from widespread smaller earthquakes for coastal of British Columbia and Washington is large even without great earthquakes. The new evidence for giant subduction zone events results in hazard estimates that are similar to those for regions well known for very large earthquakes such as California and Japan.

The Middle Earth II: A Himalayan-scale Mountain Range through Southern Ontario and Quebec – Colliding Continents Enlarge Proto-North America from 1100 – 1000 Ma

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A prominent result of plate tectonics is the creation of ocean basins by the rifting apart of continents, and the destruction of ocean basins by continental collision. On today's Earth, the results of continental collision are evident in the Himalayan mountains and the Tibetan plateau, which resulted from the collision of India with Asia. Although this collision occurred 50 Myr ago, convergence between the two continents continues to this day, and both the Himalayas and the Tibetan plateau are still growing. Much can be learned about continental collision from the Himalayas and Tibet, but a different perspective is available from examination of the eroded roots of former continental collision zones. Going back in time, the previous major collisions were those that joined Africa and Eurasia to North America to produce the supercontinent Pangea, 250 Myr ago, but the present Atlantic ocean opened along this collision zone, so that it is not easily accessible to study. An earlier supercontinent, Rodinia, was assembled about 1000 Myr ago, and the Grenvillian orogenic belt, which begins in Fennoscandia and extends across eastern North America and Antarctica into India, marks the major collision zone associated with its formation. The surface geology of the Grenvillian orogenic belt shows that the rocks now exposed at the surface were deeply buried at the time of the continental collision. The belt has therefore been deeply eroded since and must have contained very thick continental crust at the time of the collision. It corresponds in its setting and its character to the modern Tibetan plateau but unlike the Tibetan plateau it is no longer active, the lower section of its crust is now exposed at the surface, and it is readily accessible to study.

The largest exposed segment of the Grenvillian orogen lies in eastern Canada. LITHOPROBE ran seismic lines across the Grenvillian orogen in eastern Ontario, western and eastern Quebec and off the coast of Labrador. Seismic studies across the orogen reveal a crustal structure very like that seen on a smaller scale in the upper crust of orogenic belts. The crust is made up of a stack of thrust slices, all inclined in the same direction. This kind of structure results from progressive widening of the orogenic belt. Early-formed thrust slices are carried 'piggyback' on later, lower, thrusts as the deformation migrates outwards at the edges of the orogen. An unexpected feature of the orogen is that much of the volume of the crust in the Quebec part of the orogenic belt is comprised of much older rocks that originally belonged to the Archean Superior province to the northwest of the orogen. These rocks were entrained in the orogen at a late stage as the orogenic front migrated to the northwest. Progressive development of the thrust stack took place over a period of more than 150 Myr.

There is clear evidence for late-stage extension of the thickened crust in the orogen, but there is little evidence that this extension was sufficient to restore the crust to normal thickness. There is a marked contrast between the characteristics of the crust/mantle boundary in the west of the orogen, where it is flat and the lower crust appears to have flowed substantially, and farther to the east, where there is marked relief on the boundary. It appears that despite large amounts of crustal thickening the lower crust in this region never became warm enough to flow. The relative weakening of the lower crust in the west may have been due to the rise of a hot mantle plume in the Lake Superior region.

The characteristics of the lower crust in the Grenvillian orogen differ from those of the equivalent region of the Tibetan plateau, which appears to be warm and invaded by silicate melts. Thus the LITHOPROBE study demonstrates that there are important variations between and even along continental-collision zones. The challenge now is to explain them.

Metamorphic-Tectonic Interactions in Large Hot Orogens: Lower Crustal Flow in the Central Gneiss Belt, Western Grenville Province

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Among the many ways in which metamorphic and tectonic processes interact during orogenesis, partial melting and associated rheological weakening are particularly important. Thermal-mechanical models for large hot orogens that incorporate a viscosity reduction over the temperature range associated with incipient partial melting show a diachronous 3-phase evolution. Phase 1 is associated with crustal thickening and phase 2 with thermal relaxation; a minimum 20-25 My "incubation time" separates these phases. Phase 3 is associated with lateral flow of weak middle to lower crust, which may driven by a topographically-induced pressure gradient or by collision with a strong lower crustal indentor. In laterally homogeneous crust, outward flow takes the form of a low-viscosity channel bounded by thrust-sense and normal-sense shear zones (Beaumont et al., 2001, 2004). Where lower crust is laterally heterogeneous, crustal thickening can lead to the formation and stacking of thrust nappes that may be expelled over a colliding strong lower crustal block. An intermediate flow regime may arise where lower crustal nappes become disrupted by and/or partly incorporated into heterogeneous channel flow at mid-crustal levels (Beaumont *et al.*, this volume).

The Mesoproterozoic Grenville Province represents a Himalayan-scale convergent orogen formed on the southeastern margin of Laurentia at ca. 1200-1000 Ma. In the Central Gneiss Belt (CGB) of Ontario, Laurentian rocks were reworked at synorogenic depths of 25-35 km, mainly during the Ottawan phase of the Grenvillian orogeny (ca. 1090-1040 Ma). Deformation propagated from dominantly juvenile continental arc rocks in the southeast towards older polycyclic rocks in the northwest. Widespread migmatite and granulite record peak metamorphic conditions of 750-900°C at 10-12 kb, probably beneath an orogenic plateau (Culshaw *et al.*, 1997). These features suggest that conditions within this part of the Grenville orogen may have been favourable for channel flow and/or the formation of hot lower crustal nappes.

Based on a combination of Lithoprobe seismic profiles (White *et al.*, 2000) and a wide range of geological, structural, petrological, and geochronological data, we propose that the Georgian Bay-Muskoka region, at the western end of the CGB, may represent the exhumed remnants of a hot nappe-channel system active at the peak of the Ottawan orogeny. Evidence for a low-viscosity channel comes mainly from the Muskoka domain, which comprises mainly shallow-dipping, highly migmatitic orthogneisses that form thin, laterally extensive, lobate sheets. Voluminous syn-tectonic leucosome formed at 1065 Ma (Timmermann *et al.*, 1997; Slagstad *et al.*, in press); the high-strain zone at the base of the Muskoka domain is cut by ca. 1047 Ma granite (Slagstad *et al.*, in press). Underlying rocks of the Rosseau and Algonquin domains, in contrast, are much less migmatitic and contain significant volumes of mafic to intermediate granulite. On the crustal scale, however, the structural style of the CGB and the adjacent Central Metasedimentary Belt Boundary Zone (CMBBZ) comprises moderately dipping reflective zones more in keeping with a "hot nappe" style of deformation. Allochthonous granulites of the Parry

Sound Domain preserve steep, pre-Ottawan structures that could be the remnants of an early Grenvillian (Elzevirian) lower crustal nappe. Fragmental anorthosite and retrogressed eclogite bodies are widespread within the CGB, particularly along domain boundaries (e.g., Ketchum & Davidson, 2000); their petrology indicates that they must have originated at a much deeper crustal level than is currently exposed. These features suggest that "hot nappes" played a role in the tectonic evolution of the CGB and adjacent regions, and that pre- or early Ottawan lower crustal nappes may have been disrupted by and locally incorporated into a low-viscosity channel that operated during the Ottawan orogeny. This study shows how geological and seismic data (parameters) can be used in combination with numerical modelling (processes) to provide more insight into orogenic evolution than is offered by any one technique on its own.

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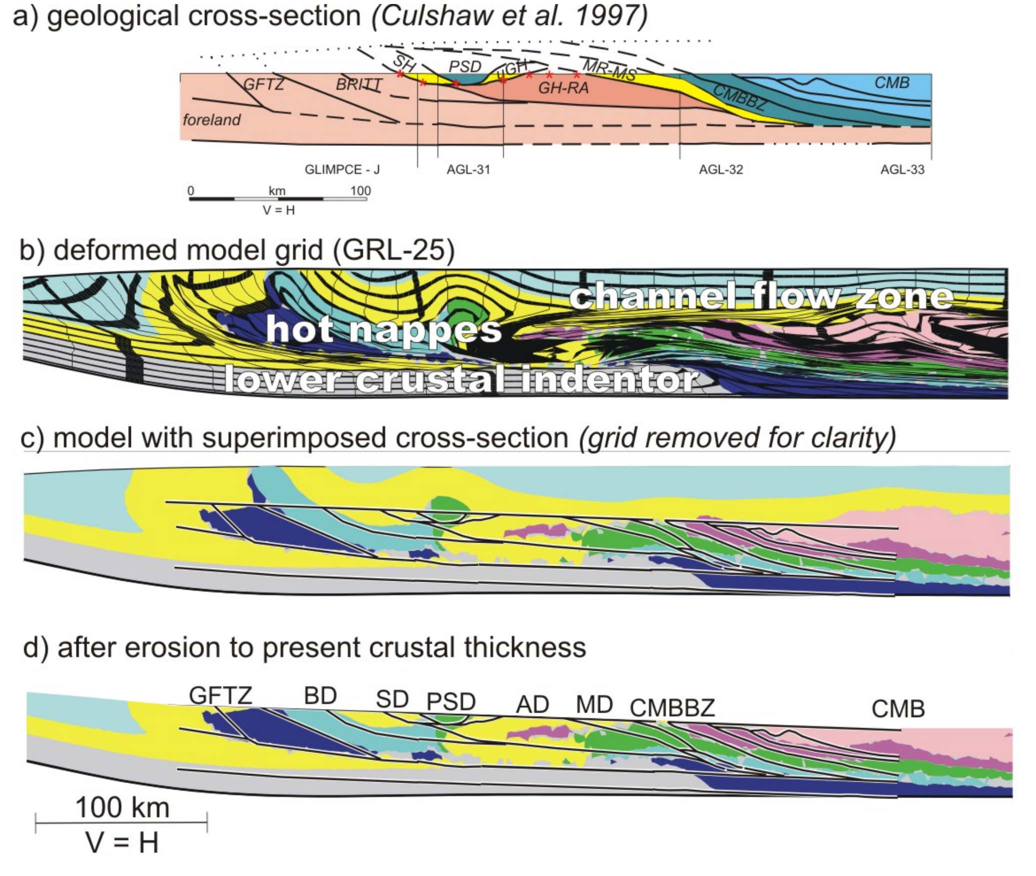

Fig.1. "Hot nappe" model (GRL-25) with Georgian Bay cross-section (Culshaw *et al.*, 1997) superimposed, showing how crustal architecture of western Grenville orogen may represent a combination of lower crustal flow modes (hot nappes + channel). GFTZ = Grenville Front Tectonic Zone; BD = Britt Domain; SD = Shawanaga Domain; PSD = Parry Sound Domain; AD = Algonquin Domain; MD = Muskoka Domain; CMBBZ = Central Metasedimentary Belt Boundary Zone; CMB = Central Metasedimentary Belt

The Slave Craton From Underneath: The Mantle View

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The major outstanding question in the Earth Sciences today is the secular variation of tectonic processes, and in particular the validity of extrapolating the modern-day, highly successful, plate tectonic paradigm *sensu stricto*, or even *sensu lato*, to Paleoproterozoic time, and perhaps back to Neoarchean, Mesoarchean and Paleoarchean times. The surficial rock record of early Earth tectonic processes is cryptic at best, leading to fundamental disagreement between those who advocate secular change in tectonic processes compared to those who believe in the applicability of uniformitarianism to the end of Hadean time. Resolution of this debate can only come through considered analysis and integration of all available geological, geochemical, petrological, geochronological and geophysical data. Models reliant on only one or two such data are, intrinsically, of limited appeal until it can be shown that those models are admissible by all data.

Notwithstanding its small size and that it is but a fragment of an inferred far larger Archean craton, the Slave craton in northern Canada has offered a unique laboratory for geoscientific investigation over the last decade for testing theories of Archean tectonic processes. From a fortuitous confluence of academic curiosity and commercial interest, extensive geoscientific studies have taken place on the Slave craton that rank it arguably as now the best-known of all cratons in the world. This position, formerly held by the Kaapvaal Craton of South Africa, comes as a consequence of intense geochemical sampling of mantle xenoliths, primarily for Canada's diamond industry but also by LITHOPROBE scientists, geological mapping and petrological and geochronological studies by scientists and students from LITHOPROBE, the GSC and the CS Lord Geoscience Centre, and geophysical studies funded through LITHOPROBE and its successor POLARIS. Compiling and integrating this rich dataset from these different geoscientific disciplines facilitates development of a holistic tectonic scenario of the Slave's mantle lithosphere development consistent with them all.

Crustally, for over the last decade the Slave craton was interpreted to have been amalgamated during the 2690 Ma collision between a proto-Slave western basement complex (Central Slave Basement Complex) and an eastern putative island arc terrane (Hackett River) along a N-S suture. Primary evidence for this lies in the N-S Pb and Nd isotope boundaries, and the apparent lack of old basement in the eastern Slave craton. An alternative new interpretation is of extended (eastern) cf. less extended (western) basement. Whichever model is correct, they both have a strong east-west asymmetry with a N-S axis. However, this east-west asymmetry is not reflected in the geometries of geochemical or geophysical signatures from the mantle, nor is this asymmetry reflected in tectonic events for 100 Myr subsequent to either the collision or the eastern extension.

An F1 fold belt located only in the SE part of the craton, with a NE-SW orientation of fold axes and dated at 2640 - 2630 Ma, records intense compressional deformation with a source vergent from the SE. A 2630 – 2590 Ma intrusive event initiated in the SE, the Defeat Suite which subparallels the trend of the fold belt, and subsequently spread to the rest of the Slave craton, culminating in province wide 2590-2580 Ma granite magmatism.

Geochemical analyses of xenocrysts recovered from kimberlite pipes demonstrate the existence of an Archean-aged cpx-absent ultra-depleted harzburgitic upper mantle layer overlying a normal Archean-aged cpx-bearing lherzolitic lower lithospheric layer in the centre of the craton. The ultra-depleted harzburgite layer lies within a NE-SE trending zone defined on the basis of occurrence of G10 garnets.

Seismological studies of mantle anisotropy also provide evidence for a three-zone mantle geometry, with the zones aligned approx. NE-SW and spatially consistent with the three zones defined on the basis of garnet geochemistry. Crustal thickness estimates are also indicative of a NE-SW oriented geometry with shallowest crust in the central part of the craton. Similarly, magnetotelluric studies provide evidence for the existence of a highly anomalously conducting upper mantle lithosphere body spatially consistent with the geochemically mapped ultra-depleted harzburgite layer, and determined to have a NW dip.

Taken together, these data all provide evidence for mantle structures at a high angle to the dominant N-S strike of the crustal suturing event (?), or alternatively the western limit of the eastern stretching event (?), and suggest efficient decoupling of the Slave's crust from its mantle. Further, the geometries of the early folds, the early granites, and the geochemical and geophysical signatures, taken together with the 2590 – 2580 Ma pan-Slave plutonism which provides an argument for lithospheric delamination, can be interpreted with a model of subcretion by exotic, diamond-bearing, Archean-aged lithosphere(s) from the SE.

Thus, we conjecture that a tectonic process occurred during the Neoarchean (2640 – 2580 Ma) closely similar to the subcretion of Indian lithosphere beneath Asian crust, i.e., Tibet, today, and thus that indeed plate tectonics was functioning by Neoarchean time.

Progressive Proterozoic Growth of Southern Laurentia by Magmatic Stabilization of Lithosphere, and Preservation of Proterozoic Suture Scars in the Modern-day Lithosphere

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From 1.8 to ~ 1.0 Ga, Laurentia grew by successive additions of predominantly juvenile oceanic terranes and magmatic arcs to a long-lived compressive/transpressive plate margin. The crust and lithospheric mantle for these accreted juvenile oceanic elements was likely to have been thin, and lithosphere was stabilized by a combination of syn- accretion tectonic thickening and syn- and post- accretion lithospheric differentiation that progressively developed depleted mantle, mafic lower crust, and middle crustal granitoids. A new compilation of the southern Laurentian portion of the Rodinia supercontinent for the IGCP 440 project allows a sequential look at the growth of Laurentia. The Archean cratons of Canada and the northwestern U.S. had stabilized as continental lithosphere prior to 2.5 Ga, were rifted about 2.1 Ga, then were assembled into a large continental mass (Nuna) via craton-craton collisions and reworking of Archean cratonic basement during Trans-Hudson orogenesis from 2.0-1.8 Ga. Juvenile crustal additions ca. 2.4-2.0 Ga documented in western Canada drill cores remain poorly understood. The onset of juvenile terrane accretion to southern Laurentia overlapped with Trans-Hudson collisions and initiated with the Penokean Orogeny at ~1.88-1.83 Ga in which Archean basement and Paleoproterozoic supracrustal rocks were deformed and metamorphosed during the accretion of island arc and back-arc basins. This was followed by the successive collision of broad, NE-trending juvenile terranes to the expanding southern margin of Laurentia. Significant juvenile additions in the southwestern U.S. include the 1.78-1.68 Ga Mojave province (which includes reworked Archean and Paleoproterozoic basement), the 1.8-1.7 Ga Yavapai province and the 1.67-1.65 Mazatzal province. Granitoid magmatism followed each accretion pulse and progressively helped stitch and stabilize the assembled orogens. An underappreciated element was the addition of 1.5-1.3 Ga juvenile crust that underlies much of the mid-continental U.S., extending from Texas through eastern Canada. This was linked to ~1.45-1.35 Ga A-type magmatism and mafic underplating that intruded and helped stabilize all of the older Proterozoic provinces. Accretion of juvenile crust to southern Laurentia culminated with the 1.3-1.0 Ga Grenville orogeny and included voluminous magmatism along the eastern and southern (Llano) continental margins. Grenville orogenic events likely represent the final assembly of Rodinia prior its breakup at ~0.8-0.7 Ga in the “west” and 0.65 to 0.55 Ga in the “east”. Combined seismic reflection and mantle tomography of the southwestern U.S. shows preserved suture zones at the Cheyenne belt, Colorado mineral belt, and Jemez lineament, with crustal geometries showing interwedging of crustal terranes, and mantle geometries suggesting long-lived subduction scars in a thick chemical lithosphere. The subduction-related assembly of Proterozoic juvenile terranes in southern Laurentia resulted in an anomalously hydrous and fertile mantle lithosphere (compared to Archean lithosphere) that has been reactivated by numerous intracratonic events, including neotectonics of the Southwest.

The Northern Canadian Cordillera – A Synthesis of New Geological and Geophysical Results for the Yukon and Surrounding Areas

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Geological, geophysical, geochemical and geochronological investigations of the northern Canadian Cordillera over the past two decades have dramatically improved our understanding of the nature and to some extent the origin of this complex region. Results of the Lithoprobe SNORCLE (Slave Northern Cordillera Lithospheric Evolution) study in particular provide critical information on crustal structure that necessitates major revisions to many existing models for the evolution of the northern Cordillera. Seismic reflection surveys clearly demonstrate that Meso- and Neoproterozoic strata of Ancestral North America (ANM) form a westerly tapering wedge that extends far to the southwest and underlies much of the northern Cordillera. Where crossed by the SNORCLE 2 and 3 transects this wedge comprises Neoproterozoic rocks of the Windermere Supergroup and poorly dated Mesoproterozoic rocks of the Muskwa Assemblage. Along strike to the northwest of the transect strata of the Wernecke Supergroup that were previously correlated with the Muskwa Assemblage and possibly the Belt and Purcell supergroups farther to the south are now known to be much older (at least 1.72 Ga), and are presumed to have been deposited on top and to the west of the ~1.85 Ga Fort Simpson magmatic arc. Lithological and metallogenic similarities between these older strata and rocks in eastern Australia suggest that these two regions may have been attached prior to Neoproterozoic breakup of the Rodinian supercontinent.

Results of the seismic reflection surveys substantiates earlier models that suggested that at least the more inboard of the accreted terranes (Yukon-Tanana and Slide Mountain) in the northern Cordillera are structural flaps emplaced northeastwards over the ANM during mid-Mesozoic contractional deformation. The data indicate that the accreted terranes at least as far west as the Whitehorse Trough comprise a thin collage of stacked structural slices or flakes that have ridden to the northeast above a major crustal scale decollement. Despite the limited vertical extent of the accreted terranes, no structural windows into the underlying Precambrian sedimentary wedge have not been discovered thus far.

Pericratonic assemblages of the Yukon-Tanana composite terrane (YTCT) and related terranes that occupy an inboard position within the northern Cordillera have been studied in detail as part of the Ancient Pacific Margins NATMAP program. Recently completed work indicates that the YTCT mainly comprises middle and late Paleozoic arc assemblages built on (possibly thinned) continental crust. Oceanic rocks of the Slide Mountain terrane that now mainly occur between the YTCT and ACM appear to represent fragments of a relatively small ocean basin that was initiated as a consequence of Mississippian age slab rollback and possibly transform faulting above a northeast-dipping subduction zone. This ocean basin was largely consumed by southwest-dipping subduction during middle to late Permian and was ultimately destroyed by Late Triassic time. The original latitudinal position of the YTCT with respect to the ANM remains uncertain. Mississippian and more widespread Permian crystallization ages from eclogite bodies within the northern Cordilleran are thought to reflect the main mid- and late Paleozoic subduction episodes responsible for much of the YTCT arc assemblages; however the present structural position of the Mississippian age eclogites on the eastern side of the YTCT presents some difficulties for reconstructing the original geometry of the mid-Paleozoic arc. Structural, geochemical and geochronological studies in the Finlayson Lake portion of the YTCT in southeastern Yukon provide plausible solutions to this apparent dilemma.

Mesozoic and Early Tertiary magmatism occurred throughout much of the northern Cordillera. Early and mid-Cretaceous felsic plutons and minor associated volcanic rocks are particularly widespread. This magmatism occurred in a series of short (3-10 m.y.) pulses each of which produced spatially, lithologically, and geochemically distinct plutonic suites that young progressively from the southwest (~112 Ma) to the northeast (~90 Ma). Geochemical and isotopic studies demonstrate that all of these magmas contain a very large component of assimilated continental crust and that most are probably entirely crustal in origin. It is likely that these crustally derived magmas formed by partial melting of mainly sedimentary assemblages below the main crustal decollement that separates the accreted terranes (and thrust panels of the foreland fold-and-thrust belt within the ANM) from the underlying wedge of Precambrian sediments. Magmatism occurred during the mid-Mesozoic to early Tertiary northeastward displacement of these structurally higher panels; thus the plutons have been displaced to the northeast from their original source region. Much of the compositional variation within the Early and mid-Cretaceous magmas likely reflects the composition(s) of the underlying Precambrian sediments (and possibly crystalline basement to these sediments) and the whole rock and isotopic geochemistry and patterns of inherited zircon ages in the magmas therefore provide a valuable if imperfect sampling of the deeper portions of the crust.

Late Cretaceous and Early Tertiary magmatism mainly occurs in the more westerly portions of the northern Cordillera. Late Cretaceous igneous units display a strong magmatic arc geochemical signature throughout much of the region although in parts of west-central Yukon units of this age appear to reflect the influence of a mantle plume. Early Tertiary igneous units also mainly show a magmatic arc signature, thought to result from northeast-dipping subduction of the Kula plate; however strongly bimodal magmatism of Early Tertiary age with a within-plate signature also occurs farther east in close proximity to the Tintina Fault Zone. This bimodal igneous suite is interpreted to represent portions of an originally continuous igneous province that was emplaced during initial stages of displacement along the Tintina Fault and originally straddled the trace of the fault; the province was subsequently dextrally offset by several hundred kilometers in Paleocene and Eocene time. This offset igneous province is the youngest of a number of piercing points for evaluating the age and magnitude of displacement along the Tintina Fault. All of these piercing points suggest a total dextral displacement of ~425 km along the Tintina Fault, and indicate that this offset is definitely younger than 67 Ma and most if not all of the offset occurred after ~58 Ma. The Tintina Fault is the only presently recognized major fault structure within the central and eastern portions of the northern Cordillera that appears capable of accommodating significant northwards displacement; this poses a serious challenge for interpreting paleomagnetic data sets from central and western Yukon, some of which appear to require northward displacements in excess of 2000 km since the Late Cretaceous.

Anomalously high heat flow has been demonstrated across much of the northern Cordillera, and thermal modeling suggests that strong, relatively cold crust only exists at shallow crustal levels in this region. These data, together with results of present-day crustal deformation estimates based on GPS monitoring, indicate that the upper crust in southern and central Yukon and northwestern British Columbia forms a thin, relatively rigid plate which is floating on a thermally weakened substrate. Regional stresses related to accretion of the Yakutat Block on the southwest are transferred across this rigid plate to the southern Mackenzie Mountains, where they are now responsible for recent seismic activity in the Nahanni area.

Orogenic framework for the Superior Province: Dissection of the "Kenoran Orogeny"

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New bedrock mapping and associated geochronology in Manitoba, Ontario and Quebec have improved resolution on the timing and style of tectonic assembly of the Superior Province. Microcontinental fragments and juvenile oceanic terranes were amalgamated into a composite Superior superterrane (CSS) in a series of orogenic events between 2.72 and 2.68 Ga, formerly collectively known as the Kenoran orogeny. Defined on the basis of ca. 2.5 Ga K-Ar ages from the Superior, Slave, Churchill and Nain Provinces (Stockwell, 1964), this age peak now appears to represent coincidental cooling within individual cratons carrying separate and distinct accretion histories (cf. Bleeker, 2003), and not amalgamated until the Paleoproterozoic.

In the western Superior Province, precisely dated thermotectonic events show a systematic progression from north to south over a 40 m.y. time span, and can be tied to assembly of tectonic entities (cf. Stott, 1997; Percival et al., 2004). The Northern Superior superterrane (3.8-2.8 Ga), an arcuate belt extending from Assean Lake in Manitoba to Porpoise Cove in northern Quebec, docked with the North Caribou terrane (NCT; 3.0-2.8 Ga) at 2.72 Ga during the northern Superior orogeny. In the west the boundary is overprinted by the broad, greenschist-facies, dextral transcurrent North Kenyon shear zone. Amalgamation of the Wabigoon (2.77-2.72 Ga) and Winnipeg River (3.5-2.8 Ga) subprovinces in the western Superior Province occurred ca. 2.715 Ga, in the central Superior orogeny. During the Uchian orogeny (ca. 2.70 Ga) the Wabigoon-Winnipeg River superterrane collided with and was subducted beneath (White et al., 2003) the active southern margin of the CSS, resulting in deposition and burial of the English River turbidite wedge. Collision between the largely juvenile Abitibi-Wawa subprovince and its subduction beneath the CSS resulted in the 2.69 Ga Shebandowanian orogeny, including deposition and burial of the Quetico turbiditic prism. The final, ca. 2.68 Ga Minnesotan orogeny is responsible for collision and underthrusting of the Minnesota River Valley terrane (3.6-2.7 Ga) beneath the CSS.

Correlation of terranes and orogenies through the large oroclinal bend in north-central Quebec has been facilitated through recent mapping, geochemical and geochronological work. There, correlative basement terranes are recognized through inheritance in widespread Neoarchean granitic plutons. In comparison with the southern Superior Province, juvenile Neoarchean terranes are sparse and continuous metasedimentary belts are absent. In some parts, the structural history appears to be dominated by pluton emplacement processes. The orogenic framework for the western Superior Province appears to continue northeastward into the Minto block, based on common ages of magmatism, sedimentation, deformation and metamorphism. In particular, the Uchian orogeny is expressed in 2.70 Ga ages of high-grade metamorphism in the western Minto block, making the scale of Archean orogens comparable to that of Alpine-style mountain belts.

Common elements of the five discrete orogenies recognized in the western and southern Superior Province include: 1) widespread calc-alkaline arc magmatism on the upper plate preceding collision; 2) deposition, rapid burial and deformation of syn-orogenic sediments (conglomerate, greywacke) in suture zones over strike lengths of >1000 km; 3) high-temperature, low-pressure regional metamorphism over broad regions; 4) steep foliation and orogen-parallel strike-slip faults attributed to transpressive deformation; 5) emplacement of mantle-derived, post-orogenic plutons of the sanukitoid suite; 6) widespread emplacement of late granitic plutons of crustal derivation; and 7) rapid post-orogenic uplift and cooling. The scale, nature and timing of tectonic features of the Superior Province are best explained within the context of 2.72-2.68 Ga accretion of small continental plates and trapped oceanic terranes in a tectonic regime resembling that of the rapidly changing southwestern Pacific Ocean (cf. Hall, 2002).

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Some Recurring Themes in Cordilleran Orogenic Evolution: Tectonic Heredity, Tectonic Wedging, and Retrograde Mantle Flow

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The Cordillera of western Canada and the conterminous United States is a continental margin orogen; however, the story of its evolution began long before the rifting that culminated with the separation of Laurentia from the Siberian craton and the establishment of passive-margin sedimentation in the Cordilleran miogeocline. Conspicuous transverse offsets along the western margin of Laurentia in southern Canada and the adjacent conterminous United States, which controlled the location and configuration of the Cordilleran miogeocline, can be linked by tectonic heredity to the crustal structure of the antecedent Paleoproterozoic (~2000-1700 Ma) supercontinent that encompassed both Laurentia and the Siberian craton. The latest Neoproterozoic to early Cambrian (~600-530 Ma) rifting that culminated with the break-up of this supercontinent included reactivation of segments of some of the Paleoproterozoic crustal structures that were embedded within it. These structures had formed >1000 Ma earlier, as the supercontinent was being assembled through amalgamation of various smaller Archean cratons that were linked, and encircled by Paleoproterozoic juvenile magmatic arcs, and as it was being disrupted by major Paleoproterozoic crustal shear zones that had formed during the amalgamation.

The Vulcan structure, which extends into the Cordillera from the crystalline basement beneath southwestern Alberta, is a prime example of a Paleoproterozoic structure that was reactivated during the evolution of the Cordilleran orogen. The Vulcan structure is a northeast-trending collisional suture that separates the Paleoproterozoic Hearn domain of the Laurentia craton, on the northwest, from the Archean Medicine Hat block, on the southeast. Its distinctive aeromagnetic and gravity signatures extend across the Canadian Rockies under the Cordilleran foreland thrust and fold belt, and link it to the overlying Crowsnest Pass cross-strike discontinuity (CPCD). Palinspastic reconstruction of the thrust and fold belt shows that the CPCD initially was aligned with the northeast-trending Vulcan structure.

The CPCD is defined by abrupt along-strike changes in Paleozoic and Proterozoic stratigraphy and in the style and orientation of regional fault and fold structures within the foreland thrust and fold belt. The changes are associated with two large, anomalous, northeast-trending transverse faults in the Purcell Mountains and western Rocky Mountains. These faults are northwest-dipping Mesozoic dextral reverse faults; but stratigraphic relationships across them show that both dextral reverse faults formed by reactivation and inversion of older antecedent crustal-scale structures that were aligned with the Vulcan structure and were downthrown to the northwest. These antecedent northeast-trending extensional structures affected patterns of sedimentation and erosion associated with the development of the Belt-Purcell (1500-1400 Ma) and Windermere (750-600 Ma) intra-continental rift basins; and one of them, now partly represented by the northeast-trending Moyie-Dibble Creek dextral reverse fault, defined a 225-km dextral offset of the boundary between rocks of the Cordilleran miogeocline and the coeval platformal cover rocks of the Laurentian craton. The offset extends from the western Front Ranges of the Rocky Mountains (Bourgeau thrust) in southeastern British Columbia to the Selkirk Mountains of northeastern Washington. This northwest-dipping extensional structure, which was aligned with the Paleoproterozoic Vulcan structure, can be accounted for by reactivation of part of the Vulcan structure during the late Neoproterozoic-early Cambrian rifting and separation of western Laurentia and the northern Siberian craton. Subsequent intermittent reactivation of this conspicuous "progeny" of the Vulcan structure accounts for the profound along-strike changes in the character and thickness of Early Cambrian to Triassic supracrustal rocks between the Cordilleran miogeocline, which lay northwest of the offset, and "Montania", a western extension of the Laurentian craton encompassing most of that part of the Belt-Purcell basin that lay southeast of the offset. Montania, in contrast with the Cordilleran miogeocline, is distinguished by a very thin and incomplete succession of shallow-water Paleozoic and early Mesozoic cover rocks

Tectonic heredity also helps to elucidate broad regional characteristics of the configuration and the orientation of the foreland thrust-and fold belt structures that developed in the Purcell and Rocky Mountains during the Late Jurassic to Late Paleocene oblique convergence between Laurentia and the tectonic collage of accreted mainly oceanic terranes that comprise the western Canadian Cordillera. The steep margins of the Belt-Purcell and Windermere rift basins, and of the Cordilleran miogeocline were defined by extensional structures. Most of these were new Mesoproterozoic, Neoproterozoic or early Paleozoic structures that truncated and offset older Paleoproterozoic crustal structures; however, some, such as those discussed above, were the progeny of reactivated Paleoproterozoic basement structures. During oblique convergence, when basin-fill strata were scraped off the under-riding margin of Laurentia and accreted to the northeastward over-riding Intermontane terrane, basin-bounding extensional structures were reactivated as oblique thrust ramps. As basin-fill strata were detached from their basement and juxtaposed over the flat regional basal detachment of the thrust and fold belt, the displaced sedimentary basins were tectonically inverted. Large deep basins became large structurally high culminations within the thrust and fold belt. The main Belt-Purcell basin became the Purcell anticlinorium; a shallower embayment on its northeast flank was transformed into the broad culmination with the Lewis thrust sheet that straddles the International Boundary and includes most of Glacier and Waterton Lakes Parks. The eastern part of the Cordilleran miogeocline which formed a younger basin east and northeast of the Belt Purcell basin, became the Main Ranges and Western Ranges of the Canadian Rocky Mountains. The part of the Windermere basin that underlay the Cordilleran miogeocline north of about 50^0 30' N latitude, contributed to the structural relief between the Front Ranges and the Main Ranges; but southward, the eastern margin of the Windermere basin is deflected westward, and truncated and offset southwestward along the CPCD from the west flank of the Purcell anticlinorium in British Columbia into northeastern Washington.

Tectonic wedging is a common manifestation of tectonic convergence in the Canadian Cordilleran; it occurs on various scales ranging from a hand specimen to the entire crust. The "triangle zone" that marks the eastern tip of the Cordilleran thrust and fold belt in the subsurface of western Alberta and northeastern British Columbia is a well-documented mid-scale example of tectonic wedging. It is a wedge-shaped thrust-duplex structure comprising stratified sedimentary rocks that have been horizontally compressed and vertically thickened by brittle thrust faults and thrust-related folds. The thrusts are bounded above by a retrograde shear zone (the roof thrust) and below by a prograde shear zone (the floor thrust). Propagation of the wedge along a stratigraphically controlled detachment zone has tectonically delaminated the foreland basin strata, and has tilted the overlying strata eastward to form the west limb of the Alberta syncline. The Alberta syncline is a rolling-hinge fold; its hinge line migrated northeastward along with the propagating tip of the wedge. The western flank of the Porcupine Creek fan structure in the western Main Ranges of the Rocky Mountains is an example of larger tectonic wedge structure that developed within the foreland thrust and fold belt. Ductile retrograde folding and thrusting of miogeoclinal argillaceous limestones and marls occurred during sub-greenschist facies metamorphism within the roof zone of the eastward tapering Dogtooth thrust-duplex wedge. The Dogtooth duplex consists of more competent Neoproterozoic and Lower Cambrian siliciclastic rocks and is underlain by the prograde basal detachment of the foreland thrust and fold belt. The western flank of the Selkirk fan structure in the Omineca crystalline belt is an example of an even larger tectonic wedge structure. It involves Middle Jurassic retrograde folds and thrusts that developed under greenschist to amphibolite metamorphic conditions above the eastern edge of Kootenay terrane as it was wedged between the distal, deeper water facies of the miogeocline and the underlying thin extended Paleoproterozoic continental basement that formed the basement of the miogeocline. Other crustal-scale examples of tectonic wedging occur in many Lithoprobe seismic reflection sections from the Cordillera and elsewhere, notably, in the section of the Paleoproterozoic continental lithosphere along the SNORCLE transect.

Retrograde mantle flow above the main Cordilleran subduction zone may provide a link between the crustal scale tectonic wedging along the outboard margin of the Cordilleran miogeocline and the preceding obduction of Slide Mountain terrane. Asymmetric mantle flow that rises under the eastern Cordillera and descends under the western Cordillera where it is entrained with the subducting Juan de Fuca plate has been proposed to account for the anomalously high heat flow and upper mantle electrical conductivity and the anomalously shallow mantle asthenosphere beneath the south-central Canadian Cordillera. The shallow asthenosphere and high heat flow are anomalous because of the time (> 40 Ma) that has elapsed since the east-west crustal stretching that occurred in this region; the high elevations and relief in the southern Canadian Rockies and adjacent Columbia Mountains is anomalous because of the time (~ 60 Ma) that has elapsed since the northeast verging thrusting and folding that produced the crustal thickening in this area. The retrograde mantle flow model may account for uplift of the southern Canadian Rockies and the adjacent Columbia Mountains as well as the high heat flow and shallow asthenosphere in the south-central Canadian Cordillera. Moreover, the same conceptual model may also elucidate the enigmatic disappearance of lower crustal and mantle lithosphere rocks during the Jurassic obduction of Slide Mountain terrane, which occurred during the initial stages of the transformation of the Canadian Cordillera from western Pacific type convergent plate margin with offshore volcanic arcs and back-arc or marginal basins to an Andean type convergent margin. The collapse of the Slide Mountain basin and obduction of Slide Mountain terrane involved convergence between Laurentia (the Cordilleran miogeocline) and the northeast dipping subduction zone along which the Cache Creek ocean was being ‘consumed’ beneath the Nicola magmatic arc. Slide Mountain terrane is basically a tectonic flake comprising an accretionary complex of oceanic supracrustal rocks. The underlying oceanic crust and mantle lithosphere that formed the basin in which Slide Mountain terrane resided disappeared as the outer part of the Cordilleran miogeocline was thrust under Slide Mountain terrane. This may have been accomplished by southwestward and downward retrograde flow that was entrained above the subducting oceanic lithosphere of the Cache Creek ocean as it sank into the mantle under the Nicola magmatic arc. Following the disappearance of the Slide Mountain basin, with continuing convergence between Laurentia and the Late Triassic Nicola magmatic arc, the Cache Creek subduction zone flattened, Kootenay terrane was wedged under the distal part of the Cordilleran miogeocline, and the Early Jurassic magmatic arc migrated northeastward into the evolving retrograde thrust and fold belt of the western flank of the Selkirk fan structure.

Coupled Mantle-Crust Dynamics and Its Relevance for Tectonic Processes Effect of Mantle Dynamics and Properties on Lithospheric Structure

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Fluid convection in the mantle is thought to be a “thermal engine” that drives plate motion (both horizontal and vertical), but many aspects regarding the thermal-mechanical interaction between the crust and mantle are still poorly understood. As an example, during continental plate collision the evolution of the shallow crust may often be deduced through direct observation of surface geology and indirect methods of geophysical imaging. More difficult to investigate is the sub-crustal lithosphere (mantle lithosphere) and as a result even the first-order behaviour of this near-surface region of the mantle and its interactions with the crust are uncertain. In this regard, a significant contribution of the Lithoprobe project has been a unique multidisciplinary exploration of the nature of the deep crust and uppermost mantle lithosphere. These endeavors have revealed some of the first primary evidence about the structure and properties of the mantle lithosphere at ancient plate boundaries (e.g., Calvert et al., 1995; Bostock, 1997).

Further insight into the evolution of the sub-crustal lithosphere may be gained by forward modeling of the coupled crust-mantle system. Using numerical models, we attempt to identify the preferred style of deformation of the mantle lithosphere under what may be Earth-like conditions of continental collision (Pysklywec et al., 2000). The results suggest that there are a number of deformational modes of the model mantle lithosphere: (1) a dripping or Rayleigh-Taylor-type instability; (2) an asymmetric underthrusting or subduction; (3) symmetric, ablative plate consumption (4) slab breakoff, the failure and detachment of the strong lithosphere; and (5) mixed modes with combinations of these processes. The development of the modes is controlled by the rate of convergence associated with the background tectonic regime, the density field, and the rheology of the mantle lithosphere.

To help interpret these generic modeling results, we consider similar models in the context of the active continental plate collision at South Island, New Zealand. This region represents a useful analogue for studying the evolution of the mantle lithosphere during continental orogenesis since it is a young (relatively uncomplicated) and well constrained location of active convergence. The numerical experiments suggest that during the initial stages of plate collision, the mantle lithosphere is characterised by plate-like behaviour and underthrusting/subduction of the upper region in conjunction with distributed thickening and Rayleigh-Taylor type viscous instability of the lower portion (Pysklywec et al., 2002). Depending on the material rheology, temperature regime, and imposed convergence velocity, the mantle lithosphere demonstrates various combinations of these ‘end-member’ behavioural modes. As the orogen matures, there may be a transition from one style of mantle lithosphere deformation to another.

The experiments also demonstrate that the evolution of the crust is intimately related to the time-dependent mantle lithosphere dynamics. Plate collision gives rise crustal thickening and surface uplift, although the character of each is dependent on the degree of coupling that (dynamically) evolves between the crust and mantle lithosphere. The formation of fault-type features of localized strain which may be expected in the crust have been recognized to be dependent on the style of mantle lithosphere deformation and the existence of active surface erosional processes (Beaumont et al., 1996). However, our most recent experiments suggest that the influence of surface processes may extend below the crust to potentially alter the plate boundary evolution of the deep lithosphere. During plate collision the modification of crustal mass flux by surface denudation can profoundly change the stress regime within the crust and at the crust-mantle interface. Surface erosion sets up localized regions of high strain/stress within the crust which tends to promote subduction-like behaviour of the underlying mantle lithosphere. On the other hand, in the absence of surface erosion crustal deformation and stress is distributed. This tends to promote a de-coupling between the crust and mantle lithosphere, and even in certain cases can cause the mantle lithosphere to delaminate and/or roll-back from the collision zone.

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Architecture and Tectonic Evolution of the Grenville Province: Part of a Hot Wide Orogen that Developed over 200 M.y. on the Southeastern Margin of Laurentia

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The late Mesoproterozoic collisional Grenville orogen, developed in part on the site of a long-lived Mesoproterozoic continental-margin arc on southeastern Laurentia, was a result of collision between Laurentia and one or more continental blocks (possibly including South America) that subsequently rifted away in the Neoproterozoic, leaving the Grenville Province as an orogenic scar characterized by mid- to lower-crustal, high-grade, poly-deformed metamorphic rocks. This scar, which is exposed for over 2000 km on the southern margin of the Canadian Shield in Labrador, Québec and Ontario and continues in the subsurface a further 3000 km to Texas and Mexico, is truncated by younger structures at both ends. It is at least 600 km wide, implying that the Grenville orogen was an immense mountain belt of Himalayan proportions. Available data indicate that it developed over a period of about 200 M.y. from ca. 1190 to 990 Ma.

Much of the Grenville Province consists of reworked older continental crust of Laurentian affinity. The northwestern margin of the province, the Grenville Front, truncates several Archean and Paleoproterozoic orogens along its length, and units in the Grenville Province typically exhibit higher metamorphic grades than their counterparts in the orogenic foreland. Accreted late Mesoproterozoic juvenile terranes constitute only a minor component of the exposed Grenville Province, being limited to two widely separated belts of probable peri-Laurentian affinity in Ontario/Québec and Texas. However, subsurface continuity between these two remnants appears possible, and if proven would considerably increase the amount of juvenile crust in the orogen. The suture(s) with the other continental block(s) to the southeast (present coordinates) that collided with Laurentia have not been recognized, indicating that only the Laurentian side of the orogen (including peri-Laurentian terranes) is preserved in North America.

The structural grain of the interior Grenville Province is complex, but in the northwest it is generally SE-dipping and parallel to the ENE-trending Grenville Front. LITHOPROBE deep seismic reflection surveys show that the predominant ductile shear zones in the orogen, including the Grenville Front, are SE-dipping structures, many of which penetrate the full thickness of the crust, although there are important along-strike variations in crustal structure and an overall doubly-vergent architecture has been imaged in some transects.

Three episodes of collisional orogeny have been distinguished on the basis of their time/space distributions within the ca. 200 M.y. period of construction of the Grenville orogen, but many details of these and of the tectonic subdivision of the Grenville Province remain to be determined. The current tectonic subdivision includes the Parautochthonous Belt (PB), the lowest unit in the orogenic stack, which is characterized by some of the youngest metamorphic ages in the province (ca. 1000 ± 10 Ma – Rigolet orogeny). The PB is tectonically overlain to the southeast by the discontinuous High Pressure Belt (HPB), characterized by (relict) eclogite-facies assemblages that developed between ca. 1090 and 1050 Ma (Ottawan orogeny).

Terranes overlying the HPB lack evidence for HP metamorphism. In the eastern Grenville Province, the HPB is overlain by a collection of disparate terranes that have been loosely assembled into a Low to Medium Pressure Belt (L-MPB). Subdivision of the L-MPB is ongoing, but it contains at least two distinctive components: (i) metamorphic terranes that underwent high temperature-medium pressure metamorphism during the Ottawan orogeny approximately coeval with HP metamorphism in the HPB; and (ii) pre-Grenvillian metamorphic terranes that did not undergo penetrative Grenvillian metamorphism and are inferred to have been at high structural levels throughout all Grenvillian orogenic events (i.e., they comprised a metamorphic lid).

In the southwestern Grenville Province, the place of the L-MPB is taken by two belts of accreted terranes composed of rocks younger than ca. 1300 Ma of probable peri-Laurentian affinity. The more northerly, the Composite Arc Belt (CAB), consists of several arc and/or backarc terranes that formed on oceanic or transitional oceanic crust and were assembled in the ca. 1250-1190 Ma accretionary Elzevirian orogeny under greenschist- to amphibolite-facies conditions. Evidence for oceanic terranes and an accretionary event of similar age to the Elzevirian orogeny is also present in the Llano uplift in Texas, indicating that this episode of pre-Grenvillian accretionary orogenesis was widespread along the Laurentian margin as a whole. In the southwestern Grenville Province, the CAB is tectonically overlain by the predominantly metasedimentary Frontenac-Adirondack Belt (FAB), which is inferred to have formed on continental crust and underwent LP granulite-facies metamorphism ca. 1190-1140 Ma during the Shawinigan orogeny. The FAB overlies the Adirondack Highland terrane, which is characterised by granulite-facies metamorphism at ca. 1050 Ma (Ottawan orogeny), along a prominent NW-dipping shear zone. Metamorphic ages in some of the Grenvillian inliers in the southern Appalachians are also mainly Ottawan, but some are as young as ca. 980 Ma (Rigolet orogeny).

The regional distribution of metamorphic ages in much of the Grenville Province is consistent with a northwestward migration of the orogen into its foreland with time, implying an overall in-sequence orogenic evolution, with the older metamorphic terranes being carried passively in the orogenic superstructure as a metamorphic lid during younger events. However, there are significant along-strike variations, especially with respect to the distribution of the accreted terranes and the doubly-vergent nature of some of the transects, and in addition the ca. 980 Ma metamorphic ages in the southern Appalachians imply an episode of out-of-sequence reworking that has only recently been recognized and is not well understood.

Ductile structural effects attributed to the prevailing high temperature of metamorphism in the lower to mid crust are widespread. For instance, lower to mid-crustal thrust imbrication during the Ottawan orogeny is associated locally with nappe-like tectonics in gneissic units, which has been interpreted in terms of subhorizontal channel flow driven by thrust loading in the orogenic hinterland. Furthermore, in addition to thrust-sense shear zones, major ductile shear zones with normal-sense displacement are also important. For instance, ductile normal-sense displacements in the hangingwall of the HPB in the central Grenville Province were approximately coeval with ca. 1050 Ma reverse-sense shear zones in the footwall, leading to uplift of the HP units by tectonic extrusion during the Ottawan orogeny. Other examples come from the western part of the province, where ca. 1020 Ma structural modification of the thrust stack by ductile normal-sense shear zones has been interpreted in terms of orogenic collapse of overthickened Ottawan crust, and a LITHOPROBE seismic experiment has documented a major post-Rigolet, crust-penetrating normal-sense shear zone in the PB. The combined result of the multiple episodes of crustal-scale thrust and normal displacements is that a wide range of crustal levels and metamorphic ages is exposed at the present erosion surface.

An ongoing enigma in the Grenville Province concerns the origin of the voluminous anorthosite-mangerite-charnockite-granite (AMCG) suites. Some are pre-Grenvillian bodies that were reworked during the Grenvillian orogeny, but others were emplaced during Grenvillian orogenesis. For instance, large AMCG suites were emplaced in the intervals ca.1160-1130 Ma and 1080-1040 Ma, approximately coeval with or immediately following the Shawinigan and Ottawan orogenies respectively, and emplacement of small AMCG bodies at ca. 980 followed the Rigolet orogeny. Most of these suites, and other smaller bodies of mantle-derived magmas, appear to have crystallized in the mid crust and many were subsequently tectonically transported in large thrust slices and nappes. The temporal and spatial association between mantle magmatism, including mantle components of AMCG suites, and Grenvillian tectonics implies an important link between the chemical state of the underlying mantle lithosphere and crustal processes, but its root cause and the reason for its particular importance in the Grenville orogen remain poorly understood.

In summary, the Grenville Province is a fragment of a wide hot collisional orogen that propagated deep into the Laurentian margin on account of the high ambient temperature and concomitant ductile state of the orogen during repeated episodes of collision. The orogenic model that is emerging incorporates pre-Grenvillian continental-margin arc magmatism and accretionary tectonics followed by repeated episodes of continental collision in the long-lived Grenville orogen. Collisional tectonics resulted in crustal thickening, and locally overthickening due to the ductile nature of the crust, followed by orogenic collapse and emplacement of mantle- and lower-crustal-derived magmas, including AMCG complexes. Individual episodes of collisional tectonics were separated by some 50-80 M.y., each episode resulting in propagation of the orogen deeper into its foreland as the former footwall was incorporated into the high-grade base of the expanding orogenic wedge and the previously developed high-grade terranes were reworked and/or passively transported in the non-metamorphic superstructure. Temporal and spatial relationships between orogenesis and mantle magmatism, including mantle-derived components of AMCG suites, implies an important, but little understood linkage between mantle lithosphere and crustal tectonics.

Secular Changes in Tectonic Evolution and the Growth of Continental Lithosphere

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Many of the major changes in Earth's secular evolution occurred in the early Precambrian and these include the emergence of plate tectonics, growth of continental lithosphere, and development of stable continental margins. Some of these changes are related to cooling of the Earth and reflect the strong influence of temperature on mantle rheology, density, process rates and phase equilibria. The Earth has cooled from an initial partly molten state with heat supplied from accretion, core separation and decay of short-lived isotopes, to its present state where heat loss is largely accommodated by convection of the mantle and cooling of lithospheric plates. Observational constraints on models of the Earth's thermal history come in part from the fragmentary chemical and structural record of the continental lithosphere. Ancient mantle-derived volcanic rocks and xenoliths help constrain changes in the composition and thermal structure of the Earth's interior. To a first order, cooling of the Earth is reflected in the decreasing Mg content of high temperature, ultramafic magmas with time: komatiites (>18% MgO) were common in the Archean, komatiitic basalts (13-18% MgO) in the Proterozoic, and picrites (10-13% MgO) in the Phanerozoic. There is continuing debate however, on the temperature, source and depth of formation of komatiites that has major implications on constraining models of the thermal evolution of the Earth. If komatiites are the products of dry melting of peridotite, extreme liquidus temperatures that range from 1800 to 1675°C are required to explain the observed range in MgO contents. Komatiites are commonly thought to have originated from deep-seated mantle plumes (Campbell et al. 1989). Analogue and numerical modeling suggest plumes originate as temperature instabilities at thermal boundary layers (Campbell and Griffiths 1989), and in the case of komatiites these may include the core-mantle boundary and transition zone. Thus the high temperatures indicated by dry melting of peridotite to form komatiitic magma do not reflect conditions in a well-stirred upper mantle, but at boundary layers in the lower mantle. Allegre (1982) proposed that komatiitic magmas were derived by partial melting of wet peridotite, and this model has seen renewed attention and debate (Grove and Parman 2004; Arndt et al. 1998). Wet melting of peridotite can generate ultramafic melts at mantle temperatures only 100° warmer that at present (Grove and Parman 2004). Some Archean komatiites are associated with calc-alkaline volcanic rocks and boninites, and like their latter modern counterparts, may be derived by the wet, shallow melting of hot, depleted peridotite in the mantle wedge above a subduction zone (Grove and Parman 2004). Further downward revision of the mantle temperature of komatiite formation is warranted by consideration of their oxygen fugacity as reflected in the geochemistry of vanadium (Canil 1997). Komatiites have calculated oxygen fugacities similar, or slightly higher (Ni-NiO ~ +1 to –2) than is measured for modern oceanic basalts and inferred for their mantle source. The calculated olivine liquidus temperatures are ~50°C lower relative to temperatures calculated making the common assumption of a more reduced Archean mantle. It is possible that Archean komatiites, like modern basalts, formed in a number of different tectonic settings (Grove and Parman 2004), and include plume related, hot, dry magmas originating in the lower mantle, and cooler, wet komatiitic magmas derived from a hydrated mantle wedge.

The onset of plate tectonics on Earth is highly debated and has been addressed from a number of perspectives including predictions from thermal modeling, observations from the geological record, and more recently, lithospheric scale geophysical surveys. The temperature of the upper mantle is a critical parameter in numerical models in constraining the onset of subduction. Modern oceanic lithosphere cools, thickens and becomes dense with time, eventually sinking at subduction zones where deformation in the lithosphere is brittle and yields by faulting. At some point in the past, the Earth's mantle was sufficiently hot so that the increased thickness of buoyant crust and residual mantle formed at ridges, and increased heating at the base of the lithosphere due to vigorous convection, sustained a neutrally buoyant lithosphere. Davies (1992) suggested that this critical condition occurred when the mantle was only 50° C hotter than today, and as recently as 0.9-1.4 Ga. More recently, Thienen et al. (2004) calculate that subduction could only occur if the temperature of the upper mantle was below 1500°C (~200°C hotter than today). Prior to this time lithosphere would have had to delaminate buoyant crust to allow the rigid lower lithospheric mantle to subduct, or alternatively, if weak, the lower boundary layer would "drip" into the mantle (Davies 1992). However, there is now widespread geological and geophysical observations to support modern-style plate tectonics operating as far back as the Paleoproterozoic and this include key features such as rift sequences, passive margins, ophiolites, arc terranes, foreland fold thrust belts and large scale strike-slip faulting. Notably accretionary mélange terranes are absent in the Paleoproterozoic, and the oldest known blueschist on Earth is 850 Ma. Mantle reflectors interpreted as Paleoproterozoic fossil subduction zones have been imaged in the Baltic (BABEL Working Group, 1993) and northwestern Canada (Cook et al. 1999). The possibility that plate tectonics started in the late Archean is hotly debated (Hamilton, 1998; De Wit 1998). Recent Lithoprobe and NATMAP studies in the western Superior Province provide field, geochemical and deep probing geophysical evidence that builds a compelling case for plate tectonic-like processes in the Neoarchean (<2.8 Ga) (Percival et al. 2003). Tectonostratigraphic, geochronological and isotopic tracer and geochemical data are used to identify discrete microcontinental and oceanic blocks. The acrretion of these disparate terranes follows arc magmatism and later collision resulting in regional deformation and synorogenic sedimentary belts that bury paleosutures. The timing of deformation, synorogenic sedimentation and plutonism decreases southward across the western Superior Province recording accretionary growth. Lithoprobe seismic reflection profiles have imaged crustal-scale moderate- to shallow-dipping reflectors reflecting collision, mantle dipping reflectors interpreted as fossil subduction zones beneath crustal terrane boundaries (Calvert et al. 1995), and along with refraction data, a 10 km thick lower crustal, high velocity layer interpreted to be accreted oceanic crust (White et al. 2003). Deep probing magnetotelluric data across the western Superior Province record electromagnetic anisotropy in the lithospheric mantle that is concordant with regional strain fabrics (e.g. foliations and faults) in the crust, and is interpreted as evidence for plate scale deformation (Craven et al. in prep.). In lithospheric sections, prominent tabular electromagnetic anomalies coincide with seismic mantle reflections, and continue to penetrate as nonconductive slabs to 200 km depth. The thick Archean lithospheric mantle (Kendall et al. 2002) underlying 2.7-3.5 Ga crustal terranes in the western Superior, preserves subduction- and accretion-related structures indicating growth during collisional orogeny at 2.7 Ga.

There are however, important differences between the Archean and Paleoproterozoic records of plate interaction. With one possible exception, Archean supracrustal belts lack the thick passive margin sequences that characterize the geological record since the Paleoproterozoic and are preserved in foreland fold thrust belts. In the western Superior Province, Archean continental margin sequences comprise thin clastic sedimentary units overlain by thick sediment-starved sequences of submarine tholeiitic basalt, with lesser komatiite and felsic volcanic rocks (Skulski and Sanborn-Barrie in prep). Hynes and Skulski (in prep.) investigated the formation of Archean continental margin sequences and found that uniform extension of thin continental lithosphere overlying asthenosphere that was 200 °C warmer than at present, resulting in initial subsidence that was largely filled by tholeiitic basalt derived by adiabatic melting. Extension of thin lithosphere resulted in little uplift to drive erosion, accommodation space flooded with basalt, and little thermal subsidence. The 2.9 Ga Pongola Supergroup and related lower Witwatersrand sequences in South Africa are interpreted as a 2.97-2.94 Ga, 3.5-5 km thick continental platform to passive margin sequence (locally tide-modified) that overlies a 3.07-2.94 Ga, 0.5-6 km thick, continental rift sequence of coarse clastic rocks and continental tholeiitic basalt (DeWit et al. 1992). The Kaapvaal craton is believed to have stabilized a thick continental lithospheric root by 3.2-3.3 Ga. The appearance of thick Precambrian continental passive margin sequences may have required a pre-existing continental lithospheric root. In the Superior Province, a thick lithospheric root was stabilized during 2.7 Ga accretionary orogeny, and prior to the onset of Huronian rifting at 2.45 Ga that resulted in a thick passive margin sequence. The appearance of passive margin sequences stabilized widespread stromatolitic carbonate platforms on Earth that could accelerate the oxygenation of the atmosphere through photosynthesis in the Paleoproterozoic.

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Diamonds and kimberlite intrusions – contributions from LITHOPROBE and related geophysical, geochemical and petrological studies

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Diamond exploration is largely an enterprise of probability. During the exploration process, individual ore deposits become sequentially labelled as “anomalies”, kimberlites, diamondiferous, and finally, as economic. The number decreases by an order of magnitude in each of these steps, and in remote parts of Canada’s North each step represents a large expenditure of cash and logistical effort. Any guidance or weighting of factors from additional information or observations is critical to success. Most LITHOPROBE transects preceded the current “diamond rush” in Canada’s North, but the framework information that LITHOPROBE produced is very valuable to key exploration decisions.

Although LITHOPROBE transects focussed on crustal structure, they also led to recent developments in seismic, magneto-telluric, and geochemical analytical techniques. These significantly increased our capacity to explore the mantle lithosphere to depths of several hundred kilometres, to map its structures, and through geological interpretations, to assess its potential as a diamond reservoir. The independent techniques combine to provide a synergistic, multidisciplinary approach that is now the world-wide ‘trademark’ of LITHOPROBE and where one technique compensates for inadequacies in another.

In both the Slave and the Superior craton, teleseismic and magnetotelluric surveys are either coincident or extensions to LITHOPROBE transects such as SNORCLE, Abitibi-Grenville and Western Superior and reveal dipping mantle structures that correlate with similar crustal structures attributed to convergence tectonics. Similarly, ages of the crustal structures determined by LITHOPROBE transect studies are now complemented by U/Pb or Re/Os dating of mantle xenoliths. Mantle petrology is estimated from the sparse xenoliths, from the geochemistry of more populous garnet xenocrysts, and from geophysical properties such as observed P- and S-wave speeds. A crude mantle pseudo-stratigraphy emerges and it becomes possible to favour one region over others for diamond potential using more profound geological logic than that it has Archean crust and high mantle velocities. More specific studies of anisotropy and individual ore bodies indicate tectonic control on the kimberlite eruption process and help delineate the shape and volume of individual kimberlite pipes or sills.

Major contributions to this research in Canada have come from: Michael G. Bostock & Maya Kopylova (University of British Columbia), Dante Canil (U. Victoria), W. J. Davis (GSC Ottawa), Bill Griffin (GEMOC, Australia), Alan G. Jones (Dublin Inst. Adv. Studies & GSC Ottawa), G.D. Lockhart (BHP-Billiton Diamonds Inc.), Stephane Rondenay (MIT, USA).

The Northern Appalachian Orogen – From Rifting and Ocean Opening to Accretion of Oceanic Terranes and Collisional Events

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The final break-up of the Neoproterozoic supercontinent Rodinia at c. 570 Ma led to a very rapid northward movement of Laurentia from a high southerly latitude to a near equatorial position towards the end of the Neoproterozoic (c. 550 Ma), in the process opening the Iapetus Ocean. While Laurentia was moving north, Gondwana, was being assembled at high southerly latitudes as a result of late Neoproterozoic to Early Cambrian collisions. The southern arm of Iapetus separated the south-facing margin of Laurentia from the west Gondwanan cratons of Amazonia and Rio de la Plata, whereas the northern arm separated Laurentia's east-facing margin from Baltica, which was an isolated continental plate.

By the end of the Cambrian (c. 490 Ma), the southern arm of Iapetus had achieved a significant width, locally in the order of 4000 to 5000 km. During the Early Cambrian another rifting phase led to departure of a ribbon-shaped microcontinent, referred to as Dashwoods, from Laurentia's Appalachian margin. Such rifting presumably happens as a result an inboard ridge jump, which if correct, demands that a spreading ridge system must have been present near the Laurentian margin during the Neoproterozoic-Cambrian boundary. Laurentia was situated at a low southerly latitude (c.19^{o}S) at this time, with Iapetus having already developed into a substantial ocean due to spreading from presumably intraoceanic centers. In Newfoundland, faunal, palaeomagnetic and isotopic evidence suggests that the oceanic basin separating Dashwoods from Laurentia (the Humber Seaway) was not a wide ocean. However, it was wide enough to induce arc magmatism following its subduction beneath Dashwoods, and thus likely had a width on the order of 500-1000 km. The presence of the Humber Seaway explains the apparent contradiction between uninterrupted passive margin sedimentation until the late Arenig on the Humber margin and the evidence for Tremadoc arc magmatism and Late Cambrian orogenesis of Laurentian rocks on the adjacent Dashwoods microcontinent.

Subduction on the Laurentian side of Iapetus initiated immediately outboard of Dashwoods at c. 510 Ma, producing the suprasubduction zone Lushs Bight Oceanic Tract (LBOT). An oceanic assemblage of basalt, sheeted dykes, trondhjemite and gabbro, mainly with island arc tholeiitic or boninitic compositions, represents the LBOT. Zircon inheritance in stitching Notre Dame arc plutons and post-tectonic, crosscutting dykes contaminated by continental lithosphere indicate that the LBOT was deformed and emplaced onto Dashwoods before 490 Ma. After accretion of the LBOT to Dashwoods, subduction stepped into the Humber Seaway at c. 490 Ma generating the Baie Verte Oceanic Tract (BVOT), which is compositionally similar to the LBOT, but significantly younger (489-478 Ma). The simplest interpretation is that the BVOT was generated during subduction initiation of the Humber Seaway and occupied in part a forearc setting with respect to the Ordovician phases of the Notre Dame Arc (first phase: 490 to 478 Ma; second phase: 469 to 458 Ma) built on Dashwoods. The slightly younger, c. 485 Ma Bay of Island Ophiolite Complex (BOI) represents a small, peri-cratonic oceanic basin formed by rifting of the Cambrian infant arc lithosphere of the Coastal Complex (CC, 508-502 Ma), which was already magmatically extinct and locally deformed. A combination of dextral movements and rollback of the trench into oceanic lithosphere trapped in re-entrants in the Humber margin may be responsible for its formation. The age of the CC, suggests a link to the infant arc crust of the LBOT. Stratigraphic evidence shows that loading of the Humber passive margin must have started by at least 474 Ma and continued until the Late Ordovician. Loading was probably due to a combination of BOI/CC obduction and Taconic collision with the trailing Dashwoods microcontinent. Loading coincides with a magmatic gap (478 to 469 Ma) that separates the first and second phases of the Notre Dame Arc. The c. 462 Ma tonalitic flare-up of the second phase of the Notre Dame Arc is mainly related to break-off of the oceanic slab attached to the subducting Humber margin and a large influx of fresh asthenosphere beneath Dashwoods. Arenig to Llanvirn suprasubduction zone ophiolites and island arc volcanic rocks were generated east of the Dashwoods in the Annieopsquotch Accretionary Tract (AAT), while the Dashwoods and Humber margin were colliding (Taconic Orogeny) further to the west. Structural relationships, the presence of boninite and isotopic data, indicate that the AAT comprises a c. 480 Ma infant arc generated by west-directed subduction initiation to the east of Dashwoods and several thrust slices of younger arc volcanic rocks (473 to 460 Ma) separated by incomplete ophiolite suites that become progressively younger towards the east. Accretion of the AAT to the Dashwoods started at c. 470 Ma, with all of the AAT accreted to Laurentia by at least 450 Ma when the peri-Gondwanan Popelogan – Victoria Arc started to collide with Laurentia. After this arc-arc collision, west-directed subduction stepped back into the Tetagouche – Exploits back-arc basin, generating the third, Early Silurian phase of the Notre Dame Arc and caused the Early Silurian accretion of Ganderia to Laurentia (Salinic Orogeny). Accretion of Avalonia to Laurentia at c. 421 Ma and the subsequent arrival of Meguma between 400 and 390 Ma, were probably responsible for the Acadian Orogeny, and continuing Devonian orogenesis.

The Late Earth 1: the Story of the Appalachians – Opening and Closure of Ocean Basins and the Arrival of South American and African Pieces in Atlantic Canada

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The physiography of the eastern seaboard of North America is dominated by the Appalachian Mountains, which are the remnants of a once impressive mountain range that prior to the Mesozoic opening of the Atlantic Ocean rivalled the present-day Alpine belt in length. The Appalachian mountain belt formed between c. 500 and 250 Ma, first in response to punctuated accretion of numerous small oceanic and continental terranes related to closure of the Iapetus and Rheic oceans, and finally during a large collision that welded North America into the Pangean supercontinent. Of these two oceans, Iapetus is the oldest having existed since c. 570 Ma. Iapetus separated ancient North America from a large continental mass called Gondwana that was positioned near the South Pole and which included Africa and most of present-day South America. In addition, palaeomagnetic evidence shows that during this period in earth’s history, the eastern seaboard of North America was generally positioned at low latitudes, near the equator; at c. 500 Ma Iapetus locally may have achieved a width of up to 5000 kilometres and was truly a large ocean, not unlike the Pacific Ocean today. The closure of the Iapetus Ocean led to the calving-off of three ribbon-shaped microcontinents between 490 and 460 Ma from Gondwana: namely Avalonia, Ganderia and Carolina. Their departure from Gondwana and subsequent drift northward towards North America progressively opened the Rheic Ocean behind them. Another microcontinent: Meguma rifted-off later, probably at c. 440 Ma and was one of the many terranes present in the Rheic Ocean. Ganderia arrived at the North American margin between 450 and 430 Ma, whereas Avalonia docked at c. 421 Ma. Meguma probably arrived later between 400 and 390 Ma and underlies a large part of southern Nova Scotia, Scotian shelf and parts of the Gulf of Maine.These three microcontinents form the bulk of the bedrock present in Atlantic Canada (Carolina occurs only in the Southern Appalachians of the USA). Thus North America grew in size due to their accretion. Detailed investigations, using many different disciplines suggests that Ganderia was derived from South America and Avalonia mainly from North Africa, whereas Meguma was originally probably positioned off the Saharan shield of North Africa.

The Superior Craton – What have we learned from reflection, refraction, teleseismic, magnetotelluric and heat flow studies? Lessons on development of the Archean Earth and processes involved

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The Archean Superior province in Canada is the type area for proposed Archean plate tectonics. The belt-like pattern of alternating granite-greenstone, metasedimentary, and plutonic terranes within the western Superior Province led to proposed accretionary models in analogy with Phanerozoic orogens (e.g., Langford and Morin, 1976). Similarly, accretionary models had been proposed for the construction of the mantle lithosphere beneath Archean cratons (e.g., Helmstaedt and Schulze, 1989). LITHOPROBE geophysical studies in the Superior Province were designed to test these conceptual models, and with few exceptions have imaged present-day lithospheric architecture that is consistent with the operation of accretionary processes in the Archean involving oceanic lithosphere.

The most convincing geophysical evidence for the accretion of terranes in the Superior Province comes from the crustal suture zones that have been clearly imaged in at least 3 different locations (Calvert et al., 1995; White et al., 2003). The most graphic of these images is from the eastern Superior Province where a paleo-subduction zone is imaged extending from the base of the crust at 35 km depth, dipping moderately to almost 70 km depth within the upper mantle. Images of similar suture zones in the western Superior Province are more subtle, but are recognized in several of the geophysical images. The first suture zone is imaged where the reflective lower crust dips northward beneath the Berens River metaplutonic complex, an interpreted Andean-type magmatic arc, along the southern margin of the 3.0-2.87 Ga North Caribou superterrane and marks the ca. 2.713-2.710 Ga collision with the Winnipeg River terrane that terminated northward subduction. A younger suture zone is observed further south where a panel of reflective lower crust, which extends for ~ 200 km beneath the central Wabigoon subprovince, dips northward into the uppermost mantle. The composition of this lower crustal slab, based on 8% azimuthal seismic anisotropy with very high seismic velocities (7.4-7.5 km/s) in the N-S direction and relative densities of –7%, is consistent with a garnet amphibolite having a subhorizontal N-S lineation. It has been interpreted as remnant accreted oceanic crust preserved at the base of the crust (White et al., 2003; Musacchio et al., 2004).

The southern suture is coincident with a major transition in properties within the lithospheric mantle as indicated in all of the geophysical images. Shear-wave splitting measurements (Kay et al., 1999) show a change in mantle fabric across this zone with uniform anisotropy azimuths of 62 ± 7^{O} and 87 ± 3^{O} to the south and north, respectively. A zone of high electrical resistivity is observed dipping steeply northward from the lower crustal suture to >150 km depth, and a north-dipping tabular high-velocity anomaly is imaged in seismic tomograms to depths exceeding 300 km (Sol et al., 2002). These high velocities and resistivities can be explained by the presence of remnant accreted oceanic lithosphere within the mantle suture.

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Recombining the Fragmented Structure and Memory of Cratons

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Large-scale experiments across cratons such as Lithoprobe and the Kaapvaal Seismic Project have finally dispelled the concepts that Archean cratons are simple granite-greenstone terrains underlain by homogenous depleted upper-mantle keels. Rather, these remnants of Earth's earliest continents comprise mosaics of fragments that were tectonically assembled and reshaped over extended periods of time; some were subsequently destroyed and recycled, whilst others were enlarged during later events. Thus, the anatomies of some cratons are now reasonably well understood as geochemical and geophysical heterogeneities inherited from early Earth processes, but since then episodically reshaped, altered and with their "memories" in part erased. For example, the geological history of the Kaapvaal mantle turns out to be at least as long and complex as that of its overlying crust; and their combined geological and geochemical "fingerprint" is unique to the Kaapvaal Craton. This realisation rules out a number of simple models for craton formation, and marks an important step forward for craton studies globally. Only when the "fingerprints" of all cratons can be compared and contrasted, will a more complete model for early Earth processes emerge. Greater and more robust merging between time-integrated geochemistry (including that of mineral deposits) and geophysics (in particular paleomagnetism) is now needed to help us achieve the task that lies ahead: Archean Earth system analyses and the rebuilding of more precise models of Earth's secular changes.

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LITHOPROBE Trans-Canada Transect
Arie J. van der Velden, Kris Vasudevan, Frederick A. Cook, Ron M. Clowes, Philip T.C. Hammer and Alastair F. McClymont

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John W.F. Waldron

Lithoprobe Transect:- The Kapuskasing Structural Zone. A Summary and Personal Interpretation of Results
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J.C. White, D.C. Copeland, M.R. St-Onge, N. Wodicka and D.J. Scott

Elastic thickness and mechanical anisotropy of the lithosphere: Implications for the depth scale of lithospheric deformations.

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We have determined the two dimensional coherence between Bouguer gravity and topography in the Canadian Shield to determine the elastic thickness T_e of the lithosphere and to detect anisotropy in the flexural response. We have averaged the coherence for all wavelengths <350 km within an azimuthal wedge. We interpret the direction of maximum average coherence as the direction where the lithosphere is weakest. Throughout the Canadian Shield with the exception of Hudson Bay, the flexural response of the lithosphere is strongly anisotropic. In general, this anisotropy is correlated with the geology and the weak axis is perpendicular to the main tectonic discontinuities: the Grenville Front and the Appalachian orogen in southeastern Canada, the east-west tectonic fabric of the south Superior Province, the New-Quebec and the Torngat Orogens in northern Quebec and Labrador, the Trans-Hudson Orogen in central Canada. There is also a strong correlation between the mechanical anisotropy and the seismic and electrical conductivity anisotropies where they have been observed. The weak (flexural) axis is oriented perpendicular to the seismic fast axis and the high electrical conductivity direction. In the areas of the Shield where the seismic and electrical measurements have not been determined, the weak axis for the flexural response is generally observed perpendicular to the boundaries between the main tectonic provinces.

Shear-wave splitting results and the impedance tensor in magneto-telluric soundings mostly depend on the fossil strain recorded by the upper mantle while the flexural response is more sensitive to the mechanical properties of the crust and very shallow mantle. In all the regions where mechanical, electrical, and seismic anisotropies have been determined, they are correlated. These observations suggest that the same strain field was recorded in the entire lithosphere, crust and upper mantle, during the last tectonic event. They are also consistent with the absence of major subsequent tectonic reworking. On the other hand, (seismic or flexural) anisotropy is absent beneath the Hudson Bay basin, possibly because it was obliterated by the thermal perturbation preceeding the Basin subsidence.

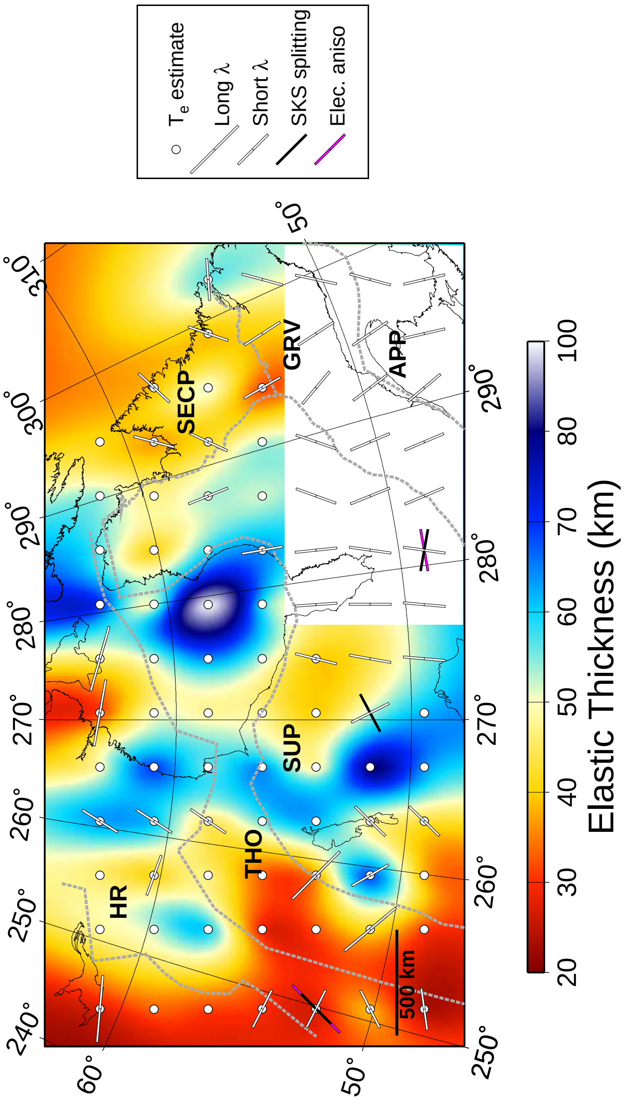

Figure 1: Map of the elastic thickness of the Canadian Shield showing the variations in isotropic elastic thickness and the direction of maximum coherence in the different wavelength regimes. White circles indicate the center of regions where T_e could be estimated. The region where T_e could not be estimated is left white. Black and purple bars indicate the fast seismic axis and the high electrical conductivity direction. The dashed lines are boundaries between the main geological provinces: Archean Provinces: Superior (SUP), Hearne Rae (HR); Paleo-Proterozoic Provinces: Trans Hudson Orogen (THO), Southeastern Churchill Province (SECP); Mid-Proterozoic: Grenville Province (GRV), and Paleozoic Appalachians: (APP).

Terranes in the Appalachian Orogen of Maritime Canada: The Devil is in the Details

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Supporting geoscience projects in Cape Breton Island that were linked to the Lithoprobe East Transect led to much enhanced understanding of geological details. Although all of Cape Breton Island had been included in the Avalon Zone in older models, mapping and geochronological studies prior to Lithoprobe East had indicated already that a more complex situation existed. Four separate subzones or terranes had been defined, from north to south the Blair River inlier, Aspy terrane, Bras d'Or terrane, and Mira terrane (Fig. 1). Only the Mira terrane matched in detail the classical Avalon Zone east of the Dover - Hermitage Bay Fault in Newfoundland. Magnetic and gravity data supported the latter correlation, and further suggested linkages between the Bras d'Or and Aspy terranes and components of the Central Mobile Belt in Newfoundland. The Blair River inler was linked both in rock types (granulite-facies gneiss and AMCG suites) and geochronology (ca. 1.0 to 1.5 Ga ages) with the Grenville Province of the Canadian Shield, like the basement rocks of the Humber Zone in Newfoundland. Lithoprobe supporting geoscience projects facilitated these comparisons, and included additional U-Pb geochronology and the acquisition of Sm-Nd isotopic data from granitic and felsic volcanic rocks. The latter data display the same pattern as determined in Newfoundland, including dominantly positive values in the Mira (Avalon) terrane, low to moderately negative values in the central terranes, and strongly negative values from Grenvillian terranes, consistent with different source rocks for the felsic magmas and hence different crustal components.

Parallel studies in southern New Brunswick resulted in the recognition of terranes equivalent to Mira, Bras d'Or, and Aspy in an area that also had been traditionally assigned to the Avalon Zone (Fig. 1). An additional inboard Neoproterozoic terrane (New River) may correlate with rocks of similar ages in western Cape Breton Island. In southern New Brunswick, rare remnants of high-pressure metamorphic belts such as the Hammondvale metamorphic suite (up to 9.5-12 kbar and 580-420^{o}C) and Pocologan metamorphic suite (up to 9.7 kbar and 560^{o}C) provide evidence for accretionary complexes and hence terrane boundaries between Caledonia (=Mira), Brookville (=Bras d'Or), and New River (=western Aspy) terranes. This interpretation is further supported by the recognition of a belt of Silurian arc rocks between the Brookville and New River terranes. Magnetic and gravity models, constrained by magnetic susceptibility and density measurements from surface samples, require geophysically distinct bodies at depth (ca. 6 km or more) under these terranes that are interpreted to correspond to the Avalon, Brookville-Bras d'Or, and Ganderia basements.

Dextral offset between terranes in New Brunswick and Cape Breton Island is postulated to be accommodated by the Canso Fault, evidence for which is preserved in a major mylonite zone trending north-south and of probable Devonian age in the Strait of Canso area (Fig. 1). However, the details of terrane boundaries in the southwestern Gulf of St. Lawrence are uncertain as they are obscured by Carboniferous and younger rocks, salt tectonics, and faults.

In spite of this large body of accumulated field, petrochemical, and geochronological data, many details of these interpretations remain unresolved. Interpretations vary depending on whether one emphasizes the similarities, or the differences, in composition, age, and Late Proterozoic - Early Paleozoic evolution. Particularly enigmatic is the distribution of characteristic Avalonian Cambrian - Ordovician cover sequences in fault-bounded slivers associated with inboard non-Avalonian terranes. The role of detachment and/or thrust faults in the present distribution of units is unresolved. Terrane correlations between Cape Breton Island and Newfoundland seem well resolved, in large part as a result of Lithoprobe East-related and subsequent new data from Newfoundland. However, extension of terranes from New Brunswick into eastern New England remains controversial because of complications related to the presence of abundant Silurian and Devonian igneous units, and to apparently sinistral offsets in the southwestern part of the Bay of Fundy.

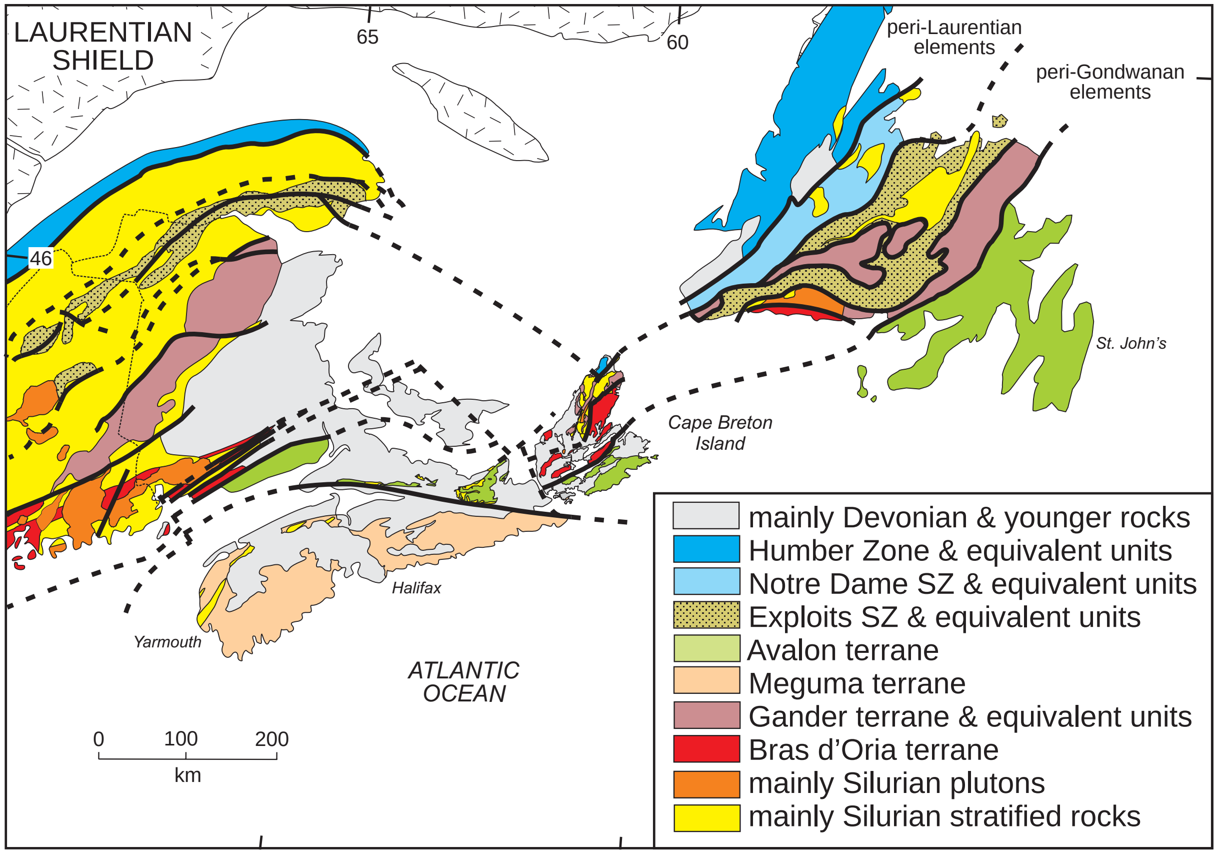

Figure 1. Northern Appalachian terrane map after van Staal et al. (1998), Barr and Raeside (1989), and current work by the authors.

Subduction-Driven Continental Assembly in the Late Archean: The LITHOPROBE Abitibi Transect Across the Southeast Superior Province

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Between 1988 and 1993, seismic reflection and refraction surveys were acquired across the medium- to high-grade Opatica plutonic gneiss belt, the low-grade Abitibi greenstone belt, and the Pontiac metasedimentary belt, all of which form part of the late Archean Superior Province. Shallowly north dipping reflections define a structural style consistent with the northward underthrusting and accretion over about 30 Ma of various exotic terranes against a backstop provided by the Opatica belt. This rapid southward growth of the Archean protocraton was driven by at least one north dipping subduction zone as revealed by reflections that dip to the north at 30-45 degrees and extend to 65-km depth in the upper mantle below the Opatica belt. In contrast to the mainly orthogneissic Opatica and Pontiac belts, the midcrust of the Abitibi belt comprises metasedimentary and igneous rocks, plus imbricated units of unknown affinity. Relict midcrustal accretionary complexes of substantial size, which are indicative of primary suture zones, are interpreted near the northern and southern limits of the Abitibi belt. An interpreted basal decollement and significantly older ages in the north suggest that the upper crustal greenstone rocks are allochthonous. Evidence of large-scale extension appears to be confined to the Southern Volcanic Zone of the Abitibi, which developed into a half graben as the original suture zone was reactivated in extension. Unusually high seismic P wave velocities, 7.5-8.2 km/s, are present in the lower 8 km of the Abitibi crust, and they correlate well with a downward reduction in seismic reflectivity attributable to late modification of the deepest part of the crust. Crustal xenolith studies suggest that this process may be linked to early Proterozoic magmatism, although the introduction of melts in the lower crust following slab break-off has also been proposed.

Reflections of the Cordilleran Lithosphere in Canada: An Integrated View

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For 20 years Lithoprobe has acquired a variety of geological and geophysical data to map the properties of the lithosphere in western Canada. The latest results from the Lithoprobe SNORCLE (Slave-NORthern Cordillera Lithospheric Evolution) transect offer a view of the Cordilleran lithosphere that can be compared and contrasted with previous results from the southern Canadian Cordillera. The Mesozoic-early Tertiary accretion history was similar in both regions with island arcs and associated terranes forming much of the Intermontane belt and Coast Mountains. In contrast to the south, however, the northern Cordillera is characterized by minimal cratonward translation of thrust sheets, little or no Tertiary extension, no metamorphic "core complexes", and substantially more orogen-parallel dextral strike-slip faulting. A primary objective of ongoing synthesis efforts is to address the relationships between these structural and stratigraphic differences and lithospheric structure. To this end, various data have been compiled along two regional lithospheric cross sections from the Canadian Shield across the Cordillera, one in the north along ~60^0 N. Lat., and the other in the south along ~50^0 N. Lat. This provides an opportunity for comparative analyses at a scale that was not previously possible.

Construction of the Cross Sections

The cross sections incorporate geological and geophysical data on the thickness, age, and internal structure of the lithosphere. Lithospheric thickness is obtained from teleseismic information, xenolith studies, and magnetotelluric data. The age of the subcrustal lithosphere is estimated primarily from xenolith studies, and the internal structure of the lithosphere is obtained primarily from controlled-source seismic data (reflection and refraction), with additional information provided from teleseismic and magnetotelluric studies.

The northern section was constructed by: (1) removing portions of the seismic data lines that are oriented parallel to strike, (2) projecting along strike from SNORCLE Line 1 to Line 2b using potential field anomalies, (3) removing 350 to 400 km of dextral offset along the Tintina fault zone, and (4) removing ~500 km of dextral offset along the Denali fault in the western Yukon and Alaska. The first two geometrical operations provide a single section that is oriented at high angle to dips. The third has the result of providing an image of the lithosphere following the Mesozoic accretionary episodes of Cordilleran orogenesis but prior to the Mesozoic-Tertiary dispersal effect of the Tintina/Northern Rocky Mountain Trench fault system. The reconstruction of the estimated offset along the Denali fault places the southern portion of the Trans Alaska Crustal Transect (TACT) profile (Fuis et al., *J. Geophys. Res.*, 1991) adjacent to the western end of SNORCLE Line 3. This provides information on the geometry of the Kula Plate prior to major orogen-parallel displacement on the Denali fault.

In the south the section was constructed by (1) combining Lithoprobe controlled-source seismic data from southern Alberta and the Cordillera into a semi-continuous seismic cross section of the crust and upper mantle, and (2) projecting along strike where portions of the section overlap within the Cordillera. Lithospheric thickness along the eastern portion of this section is less constrained than it is in the north, although some information from Tertiary extrusive rocks and teleseismic information is available.

Results

Along both cross sections, the lithosphere thins from the Canadian Shield to the Cordillera. In the north, the base of the lithosphere rises between the Slave craton (~250 km) and the Wopmay orogen (~150-200 km), and again between the Wopmay orogen to the interior of the Cordillera (~50-70 km). The detailed geometry of the transitions is not known; however, teleseismic data near Yellowknife have an image of an east-dipping boundary that has been interpreted as the Lehmann discontinuity (Bostock, *Nature,* 1999) implying that this transition dips eastward. The base of the lithosphere beneath the Wopmay orogen is likely near ~150 km, and it continues to rise to less than 100 km beneath the Cordillera (probably 50-70 km beneath the Omineca and Intermontane belts; Fredriksen et al., *Tectonophysics*, 1998).

In the south the geometry of the lithospheric thinning is less well constrained, but it likely thins from >200 km beneath the Hearne craton of eastern and central Alberta (Schragge et al., *Can. J. Earth Sci.,* 2002) to ~50-60 km beneath the interior of the Cordillera (Wickens, *Can. J. Earth Sci.,* 1977). Whether this change occurs as a single step, or whether it is accommodated in two (or more) separate steps is not known.

The age of the mantle lithosphere is Precambrian along most of the cross sections. In the east, it is Archean (Slave craton in the north, Hearne craton/Medicine Hat block in the south) and in the west, it is Proterozoic (ca. 1.1-1.8 Ga beneath the Cordillera). This result appears to require that North American mantle lithosphere (and probably much of the crust) project across the entire Cordillera to the Coast Mountains. Accordingly, there is no evidence that the lithosphere of any terranes that were accreted during the Mesozoic is present beneath the central and eastern part of the Cordillera. It is, however, possible that some accreted terrane upper mantle dips eastward beneath the Coast Mountains and western Intermontane Belt (Kula plate and possibly Stikinia in the north; Kula plate and possibly Quesnellia in the south), but this remains to be tested.

Crustal thickness varies little along the sections. In the north the largest change in Moho depth is about 8-10 km at the Fort Simpson ramp east of the Cordillera. In the south a similar magnitude change occurs near the southern Rocky Mountain Trench. Whether these are both related to Precambrian crustal thinning, or whether the transition in the south is associated with Tertiary extension is not yet clear. Elsewhere the Moho is surprisingly flat. Indeed, the uniform crustal thickness (30-35 km) in both the southern Cordillera, where Tertiary extension occurred, and the northern Cordillera, where no regional extension took place, implies that regional extension is not a requirement for relatively thin crust.

Lateral and Vertical Growth of Cratons: Seismic and Magnetotelluric Evidence from the Western Superior Transect

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Deep seismic reflection and magnetotelluric profiles across the western Superior Province demonstrate lateral growth of a cratonic shield during the NeoArchean. Teleseismic and refraction data also provide evidence of continental growth in the form of seismic velocity and anisotropy variations and layers bounded by discontinuities. Two competing end-member hypotheses are often suggested as primary growth mechanisms during the Archean. The first is embodied by vertical growth of the lithosphere through discrete melt extraction events. The second hypothesis suggests that lateral growth through tectonic accretion of the crust and underlying mantle is fundamental. The presence of sutures along the Moho within the seismic reflection section and the presence of slabs within the deeper magnetotelluric and tomographic images (Figure 1) are primary lines of evidence indicating lateral growth of the Superior craton was a fundamental NeoArchean process. The geochronology of oceanic crust formation and sediment accumulation between the large superterranes comprising the Superior Province are also key evidence for lateral growth. Significant volumes of granitic melts arose from metasomatized subduction wedges and intruded the stacked crustal core.

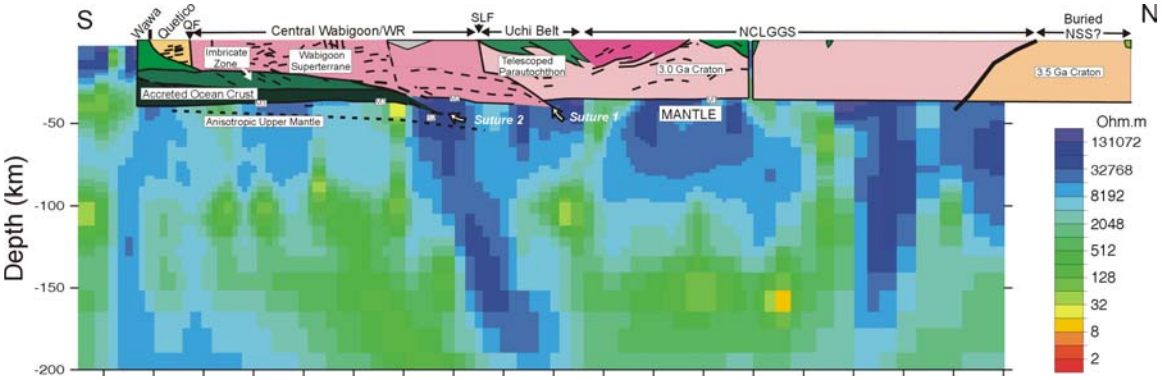

Figure 1. Interpretation of the crustal structure superimposed on the electrical model (VE 2:1). The electrical model details the resistivity in ohm m of the subsurface along a north-south transect across the major superterranes of the western Superior craton. Seismic interpretations of possible suture locations in the subsurface are identified. An anisotropic upper mantle identified from seismic refraction studies is also shown.

Structural Evolution of the Makkovik Province, Labrador, Canada: Tectonic Processes During 200 Ma at a Paleoproterozoic Active Margin

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In the Makkovik Province of Labrador, structures and plutonic rocks of the reworked southern edge of the Archean Nain craton (parautochthon) and an adjacent juvenile domain form a spatially concentrated record of ca. 200 Ma at a Paleoproterozoic active margin. D1 thin- and thick-skinned structures, affecting the Paleoproterozoic rift and drift assemblages (Post Hill and Moran Lake groups) and the Archean foreland, formed during terrane collision before ca. 1896 Ma. Following terrane collision, cratonward-dipping subduction was accompanied by D2 transpressive structures present across the entire parautochthon that had been thermally softened by emplacement of arc plutons of the calc-alkaline Island Harbour Bay Plutonic Suite at ca. 1895 - 1870 Ma. Between ca. 1860 and 1850 Ma, the Aillik Group was deposited in a rifted arc or back-arc setting oceanward (south) of the Island Harbour Bay Plutonic Suite. D3 transpressive inversion of the Aillik Group basin occurred sometime before 1802 Ma. This phase may have been driven by accretion of the Cape Harrison Metamorphic Suite and broadly overlapped with ca. 1815-1780 Ma granitoid plutonism that was mostly contained in the juvenile terranes. D4 strike-slip shearing formed structures at the oceanward margin of the parautochthon and were responses to events in the active arc that was now widely separated from the parautochthon by accreted terranes. The tectonic isolation of the parautochthon ended by the time of D5 (ca. 1740 – 1700 Ma) with the reappearance across the orogen of A-type granite and low-grade shear zones probably accompanying crust-mantle detachment and incursion of mafic magmas. The record of crustal development suggests that spatially and temporally linked structural and plutonic activity, and a trend to increasingly more localized deformation occurred throughout the tectonic history of the Makkovik Province. These features may reflect the increasing isolation in the back-arc over time and may be characteristics of a rapidly growing accretionary margin.

Proterozoic Deformation of the Superior Province from Palaeomagnetic Studies of Dyke Swarms: Contributions to the Origin of the Kapuskasing Zone and Hudson Bay Embayment.

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The Superior Province is divided into two halves along the Kapuskasing Zone [KZ], a fault-bounded belt of Archean crust, uplifted at about 2 Ga, that cuts across the craton, approximately from Lake Superior to James Bay. Several ages of Proterozoic dyke swarms occur in the vicinity of the structure and the oldest of these (the 2446 Ma Matachewan swarm) has been subject to detailed palaeomagnetic studies (Halls & Palmer 1990,Bates & Halls 1990,1991) that, together with follow-up gravity surveys (Halls & Mound 1998; Nitescu & Halls 2002), and studies on feldspar clouding in the dykes (Halls & Palmer 1990; Zhang & Halls 1995) have led to an extension and revision of the overall KZ structure (Halls *et al.* 1994; Nitescu & Halls 2002; Halls & Zhang 2003). In particular, the overall structure of the KZ is found to be a series of sinistrally offset NE- to NNE-trending segments of uplifted crust bound on both sides by inward-dipping reverse faults. About 70 km of dextral motion is known to have occurred along the KZ, and if applied along a system of left-stepping en echelon faults, regions of crustal uplift would occur where the faults overlap and these would alternate along the zone with regions of relative crustal subsidence as is broadly observed for the Kapuskasing structure [Nitescu and Halls 2002].

Regional changes in palaeomagnetic direction across the Matachewan swarm (Bates & Halls 1991; Halls & Stott 2003) show that it has been regionally distorted from an originally linear radiating pattern, and that this deformation increases where the swarm crosses the KZ. Two elements of the deformation are the dextral displacement along the KZ and a relative rotation between the two halves of the Superior Province across the KZ. This rotation has now been supported by subsequent palaeomagnetic and U-Pb radiometric studies on 2170 Ma dykes (Halls & Davis 2004) and ~2070 Ma dykes (Buchan *et al*. 2004), both of which occur on either side of the KZ. Paleomagnetic comparisions of all three dyke sets across the KZ indicate that the western half of the Superior Province has rotated counter-clockwise relative to the eastern half by about 20 degrees. This movement may have accompanied rifting beneath Hudson Bay at ~ 2 Ga, which could explain the origin of a first order feature of the Superior Province – the large embayment beneath Hudson bay that gives the Archean craton its characteristic butterfly shape (Halls & Davis 2004).

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Lithospheric structure in northwestern Canada: A synthesis of LITHOPROBE seismic refraction, wide-angle reflection and related studies

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The SNORCLE refraction/wide-angle reflection (R/WAR) experiment, SNORE97, included four individual lines along the three transect corridors. A combination of SNORE97 results with those from earlier studies yields a 2000-km-long lithospheric P-velocity model that extends from the Archean Slave craton to the present Pacific basin. S-velocity and Poisson's ratio models are also constructed along the SNORE corridors. The velocity structural models correlate well with the near-vertical incidence (NVI) reflection sections and provide additional structural, compositional, and thermal constraints. Using these models together with coincident NVI reflection data and geological information, an interpreted cross section that describes 4 Ga of lithospheric development is generated (Clowes et al., in review).

Laterally variable crustal velocities are consistently slower beneath the Cordillera than beneath the cratonic crust. This is consistent with the high temperatures (800-900 ºC) required by the slow upper mantle velocities (7.8-7.9 km/s) observed beneath much of the Cordillera. These high temperatures reduce the measured P-velocities by as much as 0.25 km/s (Hammer et al., 2004).

A variety of orogenic styles are imaged across the profile. These range from thin- to thick-skinned accretion in the Cordillera and crustal-scale tectonic wedging associated with both Paleoproterozoic and Mesozoic collisions. The details of these orogenic structures are not imaged by the R/WAR data, but are clear in the NVI profiles. The most significant interpretation from the SNORCLE reflection data in the Cordillera is that much of the crust from east of the deformation front to western British Columbia, a cross-strike distance of ~500 km, consists of Proterozoic metasedimentary rocks, even though the surface geology shows primarily Phanerozoic rocks (Cook et al., 2004). Independent support for this interpretation derives from sections of Poisson's ratio values determined from a joint analysis of P-wave and S-wave R/WAR data (Fernandez Viejo and Clowes, in review). The interpretation that a thick wedge of Proterozoic material underlies the Mesozoic-Cenozoic northern Canadian Cordillera has implications for the manner in which estimates of crustal growth are made.

The Moho remains remarkably flat and smooth (31-37 km depth) across the entire SNORE97 profile, regardless of the age of the crustal rocks or the age at which the last major tectonic deformation occurred. Only to the west of the LITHOPROBE corridors, beneath the most recently accreted terranes, does the crust begin to thin (27 km beneath the Insular superterrane, and 10 km at the base of the oceanic crust). Across the profile, the only significant offsets in Moho depth occur at major tectonic boundaries. These observations from the R/WAR models are consistent with those from the NVI reflection data. Such equivalences are observed throughout the SNORCLE study, indicating that the velocity change that defines the Moho equates closely with the change in reflectivity that defines the crust-mantle boundary for NVI reflection data.

Reflections from the upper mantle are recorded at various locations across the profile. The wide-angle reflections occasionally match well with the NVI reflections, but in many cases they do not correspond at all. This lack of correlation is neither unusual nor unexpected. The wide-angle data have lower frequency content (1-12 Hz) than the NVI reflection data (10-40 Hz) and sample the crust at much greater angles of incidence, resulting in different reflection responses and scattering effects. Indeed, the discrepancies in coincident locations provide an opportunity to further investigate heterogeneity of the lithospheric mantle.

Crustal-scale strike-slip faults are difficult to image, either by NVI or R/WAR seismic data. Nevertheless, the Tintina fault of the northern Cordillera is clearly identified on the NVI data by a narrow zone of little or no reflectivity and cutoffs of prominent reflectivity to either side. Based on the R/WAR data, the Tintina fault is inferred from very low velocities over a limited lateral extent in the uppermost crust and from more subtle velocity variations in the lower crust and changes in crustal thickness.

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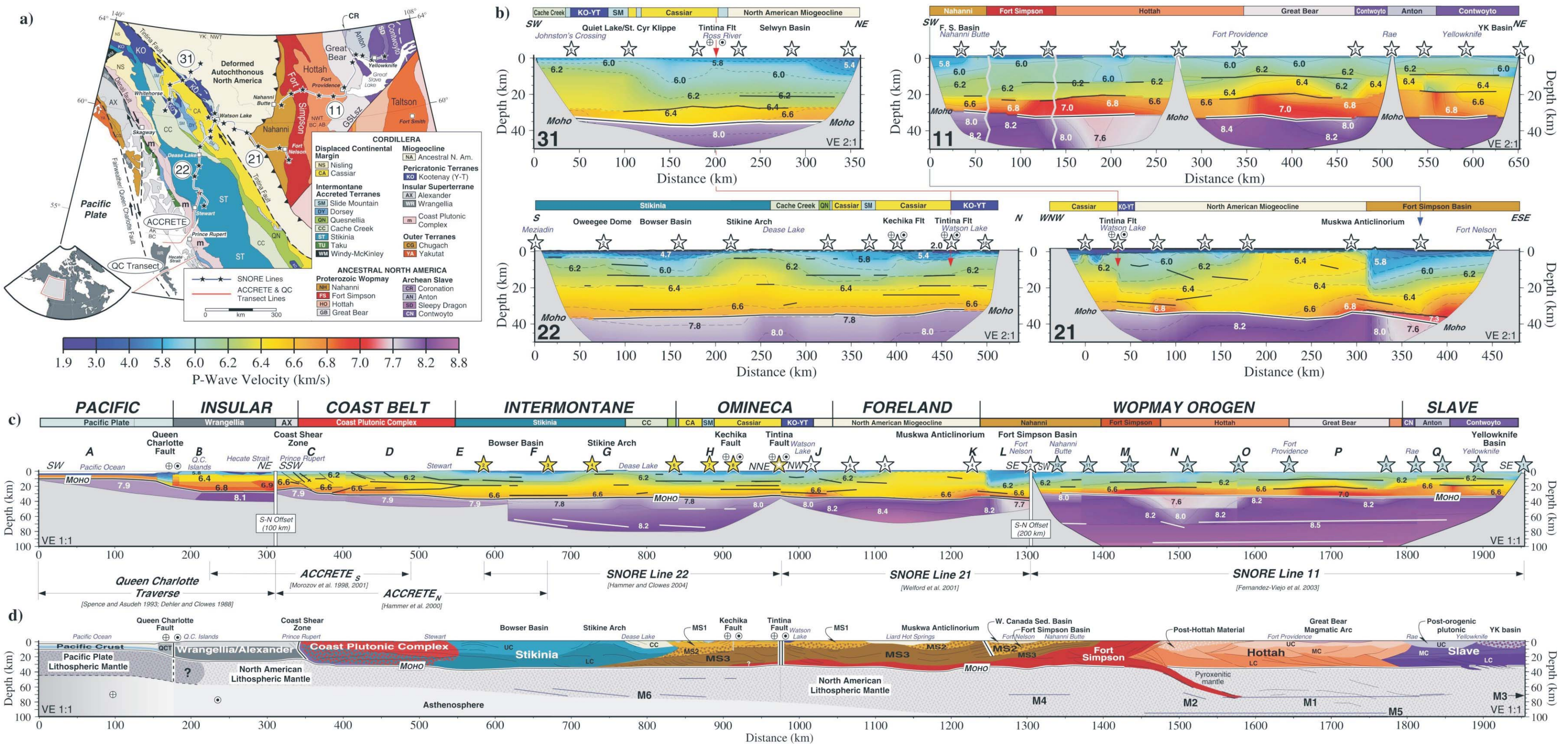

Fig. 1. (a) Tectonic domain map for SNORCLE with the four seismic refraction/wide-angle reflection lines marked; stars show shot locations. Locations of the main ACCRETE profile and the earlier Queen Charlotte (QC) transect also are shown. Dashed white line in the Contwoyto domain of the Slave Province shows the Pb isotopic boundary of Thorpe et al. (1992). **(b)** Velocity structural cross sections for the four lines of SNORE'97. Stars with numbers show shot locations. The primary tectonic domains crossed by the lines (Fig. 1a) are indicated by the bar strip at the top of each model. Velocities from the individual interpretations are presented with a common color scale (below the map of (a)). Solid black lines indicate locations from which wide-angle reflections are observed and interpreted. **(c)** Lithospheric velocity section from the Slave craton to the Pacific basin; sources for the individual components of the compilation are indicated. Thin white solid lines show locations of wide-angle reflectors within the lithospheric mantle. Abbreviations: AX, Alexander terrane; CA, Cassiar terrane; CC, Cache Creek terrane; CN, Contwoyto domain; FS, Fort Simpson; KO-YT, Kootenay-Yukon Tanana terrane, QC, Queen Charlotte; QN, Quesnellia terrane; SM, Slide Mountain terrane; YK, Yellowknife. **(d)** Interpreted lithospheric cross section based on velocity model of (c), reflection data and interpretations of Cook et al. (1999, 2004) and geological information. Thin solid black lines schematically indicate the reflection data. UC, MC and LC identify the upper, middle and lower crust, respectively. Three episodes of sedimentary deposition that established the metasedimentary wedge of Cook et al. (2004) are: MS3, 1.8-1.5 Ga; MS2, 1.2-0.8 Ga; and MS1, 0.8-0.6 Ga. M1 to M6 identify wide-angle reflectors in the lithospheric mantle.

Thermal State of the Mantle Lithosphere beneath the Northern Cordilleran Volcanic Province, British Columbia

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A suite of peridotitic mantle-derived xenoliths was collected from basanite lavas within the Llangorse volcanic field, northwest British Columbia. The xenoliths comprise spinel lherzolite and subordinate spinel harzburgite. Two-pyroxene thermometry based on the Brey & Kohler (1990) calibration was applied to 44 xenolith samples. The geothermometry is used to define the minimum (800-850°C) and maximum (1050-1100°C) temperatures of our xenolith suite, providing estimates of the thermal conditions in the lithospheric mantle. We take the minimum temperatures as indicative of the maximum MOHO temperature; the maximum xenolith temperatures approximate the temperature near the lithosphere / asthenosphere boundary. The geothermometry data are combined with measured heat flow data (Lewis et al, 2003) to produce a set of model geotherms for the northern Cordillera. These geotherms constrain the thickness of the mantle lithosphere in the northern Canadian Cordillera to as thin as 18 km and no thicker than 39 km. A mantle lithosphere of this thickness could correspond to minimum and maximum depths to the convecting asthenosphere of 54 - 75 km (Figure 1). Significantly, our model indicates that hotter MOHO temperatures correspond with higher geotherms and consequently a thinner mantle lithosphere. Our interpretation of this model denotes three possible scenarios where melting of the mantle can occur. The first scenario involves melting of amphibole-bearing lithospheric mantle (e.g., Francis and Ludden, 1995). However, temperatures in this scenario are well below (> 200°C) the calculated liquidus temperature of Llangorse Mountain basanite lavas, and scenario 1 is too shallow to sample the deepest xenoliths observed at Llangorse Mountain. The second scenario involves melting of two potential sources: the base of the mantle lithosphere or the uppermost, spinel-bearing asthenosphere. The third scenario allows for partial melting of the deep asthenosphere in the garnet stability field. Our preferred source region is represented by scenario 2 for the following reasons: i) this source is coincident with temperatures near the calculated liquidus temperature for basanite; ii) this source allows for sampling of the full mantle lithosphere observed in peridotite xenoliths at Llangorse Mountain; 3) this source is consistent with the absence of garnet or amphibole-bearing peridotite xenoliths throughout the northern Cordillera. However, although no garnet-bearing peridotites are observed at Llangorse Mountain, melting scenario 3 cannot be ruled out. In addition to this model, we examine the variation in peridotite properties with depth (Figure 2). A distinct layering is observed, indicating that the mantle lithosphere in the northern Canadian Cordillera is heterogeneous.

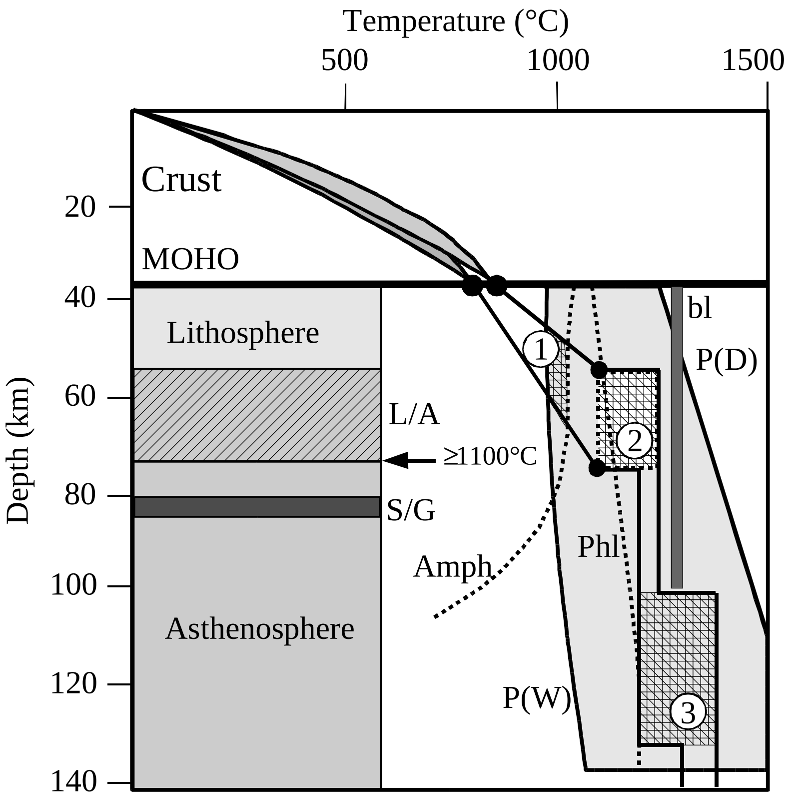

Figure 1: Predicted temperature distributions for the northern Cordilleran lithosphere contains the following elements: i) a MOHO depth of 36 km is assumed (Hammer and Clowes, 2004); ii) a family of crustal geotherms which are consistent with our values of T_{MOHO} (800-850°C); iii) two limiting geotherms for the mantle lithosphere based on these models and extrapolated to the maximum xenolith temperature (1100°C). The temperature along the geotherm is below the dry solidus temperatures of peridotite (P(D)) and the 1 atm basanite liquidus (bl), but above the amphibole (Amph) and phlogopite (Phl) melting curves (see hatched box); iv) three zones of possible melting are illustrated (numbered regions): (1) mantle lithosphere melting in the amphibole stability field; (2) melting at the base of the lithosphere due to high temperatures sustained by the underlying asthenosphere; (3) melting within the convecting, garnet-bearing asthenosphere.

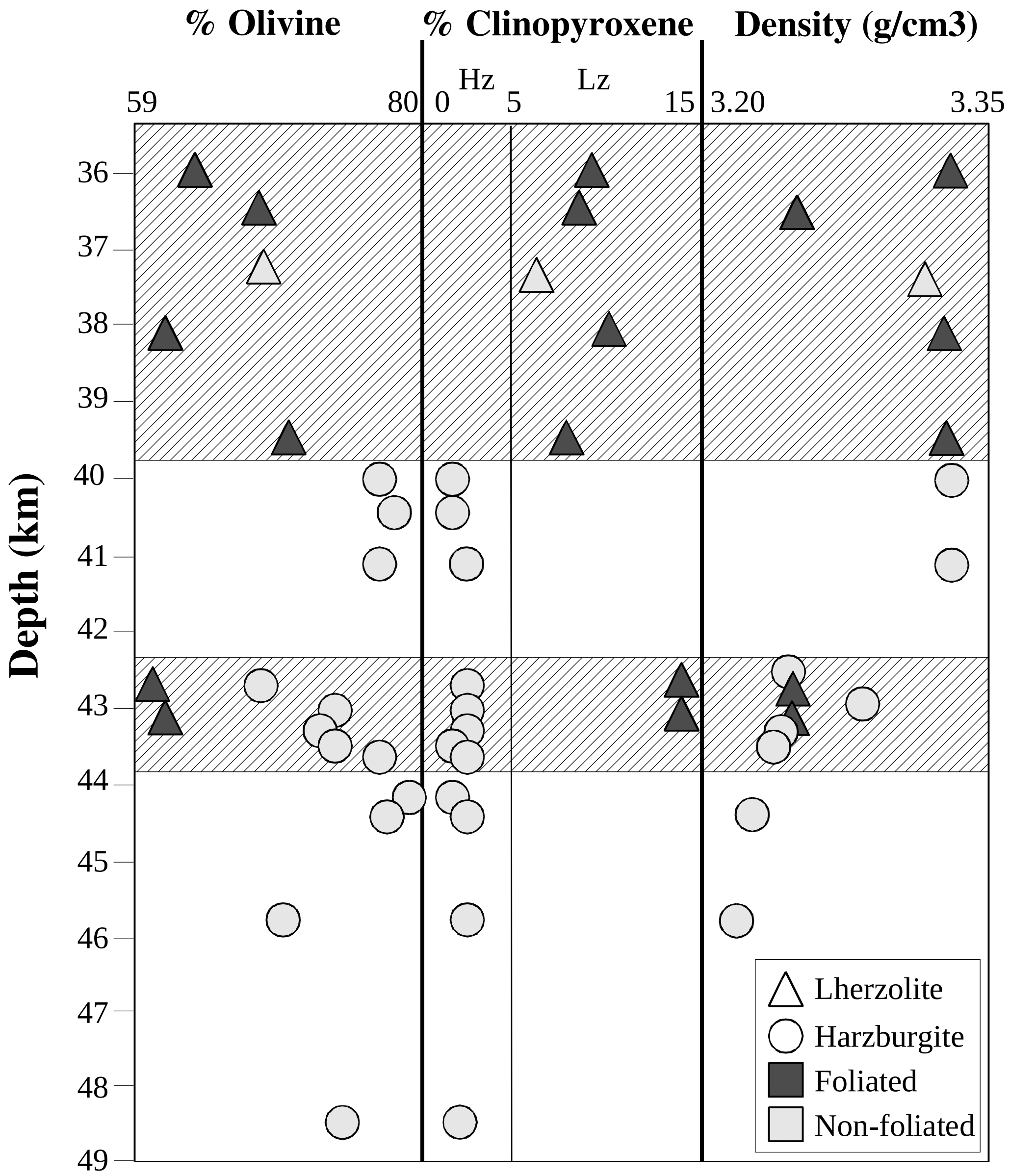

Figure 2: Variation in peridotite mineralogical, chemical, and physical properties with depth. % olivine and % clinopyroxene represent modal mineralogy of peridotites. Depth values for each sample are based on thermometry results and an average model geothermal gradient (10.2°C/km; Figure 1). Dark circles represent foliated lherzolites, light coloured circles represent non-foliated harzburgites and rare lherzolites.

Mantle Temperatures and Archean Passive Margins

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The Archean supracrustal record is dominated by submarine mafic volcanic rocks and associated sedimentary rocks. Although there are instances of thick sequences of terrigenous metasedimentary rocks, well-developed passive-margin sequences are rare.

It is likely that the Archean mantle was warmer than the modern one. Continental plates underlain by such a warmer mantle would have experienced less subsidence than modern ones following extension, because the extension would have led to widespread melting of the underlying mantle and the generation of large volumes of mafic rock. A 200-degree increase in mantle temperature leads to the production of more than 12 km of melt beneath a continental plate extended by a factor of 2, and the resulting thinned plate rides with its upper surface little below sea level. The thick, submarine, mafic-to-ultramafic volcanic successions on continental crust that characterize many Archean regions could therefore have resulted from extension of continental plates above warm mantle.

Long-term subsidence of passive margins is driven by thermal relaxation of the stretched continental plate (cf. McKenzie). With a warmer mantle, the relaxation is considerably reduced, because the equilibrium geotherm is characterized by thinner thermal and mechanical boundary layers. For a continental plate stretched by a factor of 2, underlain by a 200-degree warmer mantle than at present, the thermally-driven subsidence drops from 2.5 km to 1.5 km. The combined initial and thermal subsidence declines by more than 40%, and by even more than this if, as is likely, there is proportionately greater stretching in the mantle than in the crust. The greatly reduced subsidence results in a concomitant decline in accommodation space for passive-margin sediments, and may explain their scarcity in the Archean record.

The formation of diamonds in the Archean requires geotherms similar to modern ones, which in turn probably reflect the presence of cool mantle roots beneath the continents. Stretching of continents underlain by cool mantle roots would yield passive margins similar to modern ones. Thus, development of significant passive margins may have occurred only through rifting of continents underlain by cool mantle roots. Furthermore, the widespread subcontinental melting associated with rifting of continents devoid of roots may have been a significant contributor to development of the roots themselves.

Evolution of the Slave Province and Abitibi Subprovince Based on U-Pb Dating and Hf Isotopic Composition of Zircon

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Introduction: Zircon ($ZrSiO_4$) is a physically- and chemically-robust mineral that occurs in a wide variety of rock types. During mineral growth, zircon crystals typically incorporates trace amounts of uranium but largely excludes lead from its crystal structure. As U radioactively decays to Pb at a known rate, this allows zircon to be exploited as a natural chronometer –particularly in determining the absolute age of plutonic and volcanic rocks. Zircon also incorporates significant amounts of the element hafnium during its crystallization. Hf is useful in that its isotopic composition (a type of geological 'fingerprint') provides insights on the relative contributions of crustal and mantle sources involved in the generation of continental crust.

We have determined the U-Pb age and Hf isotopic composition of zircons separated from rock samples from the western Slave Province and southern Abitibi subprovince of the Canadian Shield. These regions were targeted in separate LITHOPROBE transects that both addressed the origin and evolution of Archean continental crust (i.e., crust formed during the period 4.0-2.5 billion years ago). The western Slave Province has a protracted history of crustal growth between 4.0 Ga and 2.6 Ga whereas the southern Abitibi subprovince formed over a relatively short interval at ca. 2.7 Ga.

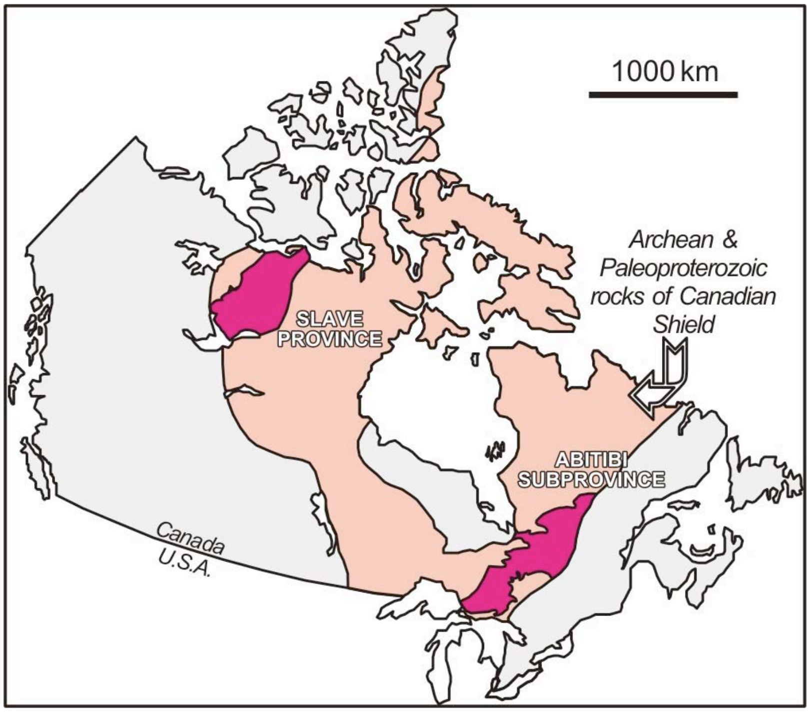

Figure 1. Location of the Slave Province and the Abitibi Subprovince (Superior Province) in the Canadian Shield. The studied samples are from the western, 'old' segment of the Slave Province and the southwestern portion of the Abitibi subprovince in Ontario.

Data collection and interpretation: The U-Pb age of zircon was measured by one or more of three techniques: (i) isotope dilution – thermal ionization mass spectrometry (ID-TIMS); (ii) laser ablation – inductively coupled plasma mass spectrometry (LA-ICPMS); and (iii) sensitive high resolution ion microprobe (SHRIMP). Hf isotopes in zircon were measured by a single technique: laser ablation – multiple collector – inductively coupled plasma mass spectrometry (LA-MC-ICPMS). Both laser ablation and SHRIMP analysis of zircon allows small areas within single zircon grains to be studied, which is important as some grains contain multiple growth zones or zircon cores inherited from older rocks.

The combined U-Pb and Hf isotopic data are depicted in two ways. The first diagram type compares zircon age with the ^{176}Hf/^{177}Hf isotopic ratio, back-calculated to the time of zircon formation. This calculation is required because zircon contains trace amounts of lutetium, and ^{176}Lu radioactively decays to ^{176}Hf over geological time. However this correction is very minor because of the low Lu/Hf of zircon. The second type compares zircon age with epsilon Hf, also calculated at the time of zircon formation. Epsilon Hf represents the deviation (multiplied by 10,000) of the ^{176}Hf/^{177}Hf ratio from this ratio for the bulk Earth, which is modelled on the composition of chondritic meteorites. This model has the acronym CHUR (chondritic uniform reservoir). Epsilon Hf may be either positive or negative depending on the nature of the material(s) that melted to form the magma from which the zircon crystallized. Values that are significantly positive suggest that the source rock(s) mainly reside in the Earth's mantle and experienced earlier periods of melt removal to form the oceanic and continental crust. Hf is concentrated in the melt relative to Lu during this process, yielding a residual mantle with relatively high Lu/Hf, known as the depleted mantle (DM). On the other hand, significantly negative epsilon Hf values indicate that pre-existing continental crust was involved in magma genesis. However this crust must be more than ~100-200 million years old at the time of melting in order to produce isotopically distinct magmas. Hence the Lu-Hf isotopic system, in conjunction with precise age control, provides a window on the mechanisms of continental crust formation over time.

Slave Province data: Eighteen granitoid rock samples from the western Slave Province with ages between 4.0-2.58 Ga have initial ^{176}Hf/^{177}Hf isotopic compositions that plot mainly between the DM and CHUR evolution lines. However, important exceptions exist – most apparent in the epsilon Hf vs age diagram. The oldest zircons, from samples of Acasta gneiss, suggest both the existence of a depleted mantle at 4.0-3.8 Ga and the involvement of older crust in magma genesis, particularly at ca. 3.8 Ga and again at 3.53 Ga. The most positive epsilon Hf values (above DM) must be treated with caution at this stage until we can fully assess whether zircon alteration or partial recrystallization has modified Hf initial ratios. Additional work on these samples is underway. At younger ages, both depleted mantle and crustal signatures are apparent at various times. For example, zircons with ages of 3.32-3.25 Ga show mainly high epsilon Hf values with little evidence for a distinct crustal signature. This situation is reversed at 3.0-2.8 Ga with most analyses lying well below DM and extending to negative epsilon Hf values. Both depleted mantle and crustal signatures are evident at 2.73-2.67 Ga.

Abitibi subprovince data: Our data for seven granitoid samples from the Kenogamissi and Round Lake plutonic complexes indicate generation predominantly from a juvenile source such as the depleted mantle or very young crust formed from depleted mantle. This is consistent with

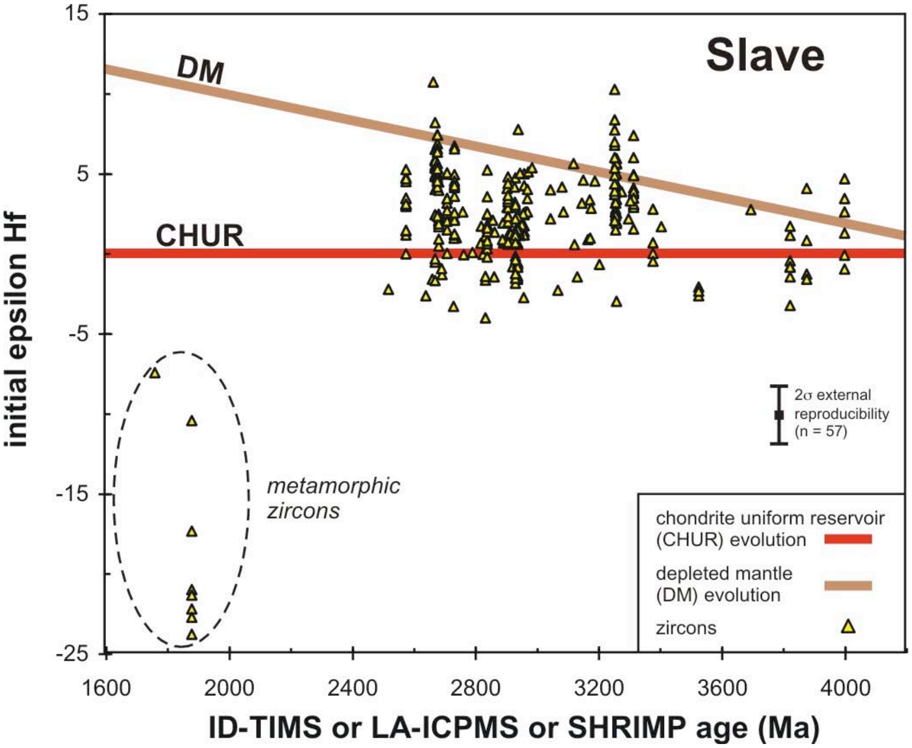

Figure 2. U-Pb age versus initial epsilon Hf for zircons from (mainly tonalitic) rocks of the western Slave Province. Most zircons are plotted at an 'assigned age' based on extensive U-Pb dating. This minimizes errors in epsilon Hf associated with U-Pb discordance. Detrital zircons from one sample are plotted at their ^{207}Pb/^{206}Pb ages (mostly concordant and near-concordant analyses). Ca. 1.88 Ga zircons labelled as metamorphic (not discussed in text) are from an exposure of Slave basement gneiss in the Proterozoic Wopmay orogen.

the results of earlier workers. Epsilon Hf values are negative only for a sample of 2684 Ma quartz diorite from the Kenogamissi complex. This sample is geochemically similar to post-2.7 Ga sanukitoid suites that occur throughout the Superior Province and may have been isotopically influenced by a subducted slab component, in this case probably subducted older sediments. The quartz diorite also has evidence of crustal contamination in the form of two zircons with ages of ca. 2725 Ma. We interpret these grains to have been inherited from ca. 2725 Ma Abitibi crust during formation and/or transport of the quartz diorite magma.

Our U-Pb results suggest the presence of even older crust in this region of the Abitibi subprovince. In an early TIMS analytical session, four single zircon crystals from two Kenogamissi samples provided ^{207}Pb/^{206}Pb ages of 2.84 Ga. Attempts to find more zircons of this age during later TIMS and LA-ICPMS sessions were unsuccessful, and we are therefore uncertain whether the 2.84 Ga zircons are 'real' or represent a rare and unusual case of laboratory contamination. However, the presence of inherited zircons of the same age in two units of the batholith complex is not unexpected, and variations in ^{176}Hf/^{177}Hf for nearly all Kenogamissi samples are much greater than for Round Lake samples, suggesting that variable crustal contamination of may have played an important role in Kenogamissi plutonism.

^{176}Hf/^{177}Hf isotopic variations: As alluded to above, our Hf isotope data from both study areas indicate significant ^{176}Hf/^{177}Hf variations within individual samples. We are confident that the sampled units have igneous protoliths (with the exception of one metasedimentary unit from the Slave Province) and therefore that the zircons are derived predominantly from igneous populations (as demonstrated by U-Pb age; inherited and metamorphic components providing the

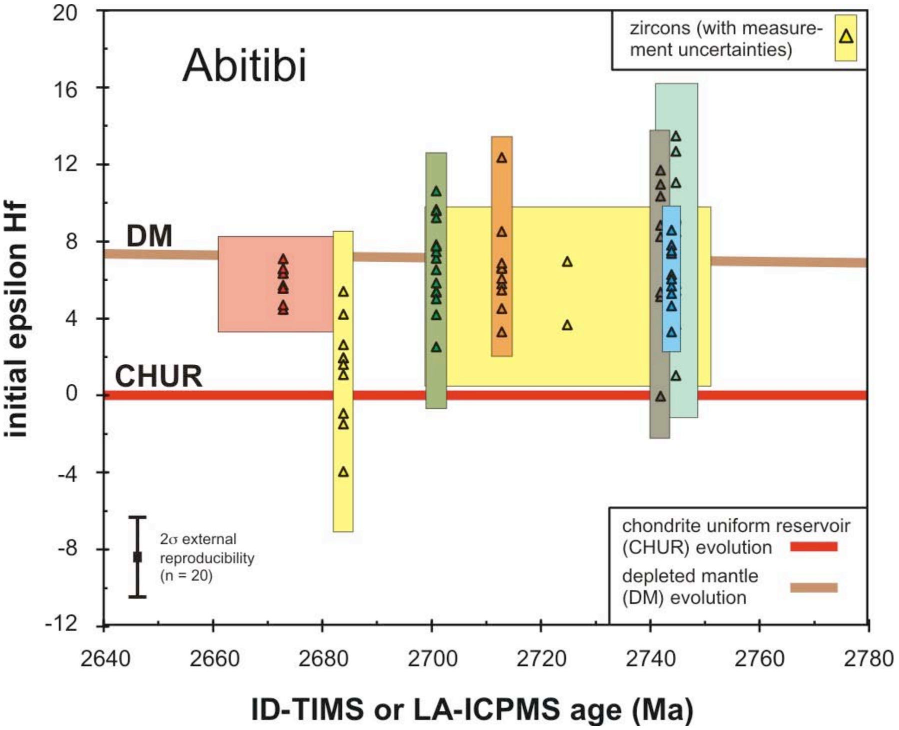

Figure 3. U-Pb age versus initial epsilon Hf for zircons from the Kenogamissi and Round Lake batholiths, Abitibi subprovince. Zircons ages are based mainly on precise ID-TIMS dating confirmed by LA-ICPMS dating, with most analyses concordant or near-concordant. DM and CHUR evolution lines shown here and in Fig. 2 are based on parameters discussed in Griffin et al. (Geochim. Cosmochim. Acta., 64: 133-147, 2000).

exceptions). Variations of ^{176}Hf/^{177}Hf in these populations therefore must reflect analytical uncertainty and/or isotopic heterogeneity. Assessment of the former indicates that the observed Hf isotope variation typically exceeds analytical error, so a geological explanation is required. It has been previously demonstrated that the Lu-Hf system can be disturbed during episodes of zircon alteration or recrystallization. In some cases, open-system behaviour results in the addition of radiogenic Hf, often in conjunction with partial resetting of the U-Pb system so that significant Pb loss correlates with higher ^{176}Hf/^{177}Hf. Addition of Lu represents another possible disturbance, although this would influence ^{176}Hf/^{177}Hf significantly only if the zircons are old (e.g., Archean) and Lu addition occurred not long after zircon crystallization. Although we have tried to select grains or portions of polished grains of good to excellent quality for analysis, some samples simply do not contain high-quality zircon, with the result that U-Pb discordance ± Hf isotopic disturbances may be unavoidable. Although this is of concern for some of our Slave Province samples, on the other hand some of the greatest Hf isotope variability is seen in very high quality Abitibi zircons with concordant U-Pb ages.

Another geological explanation that is probably applicable to this study involves isotopic variations that can occur in a magma chamber. Large epsilon Hf variations in igneous zircon have been reported in recent laser ablation studies and are interpreted to reflect the mixing of isotopically distinct source magmas, such as those that would likely occur if both mantle and crustal sources or even just a variety of crustal sources were involved. In addition to zircons that crystallize in the primary magma chamber before, during, and after this mixing, each source magma may potentially contribute its own zircons of unique (and in some cases end-member) Hf isotope composition. The U-Pb age of all these zircons will be essentially the same, therefore Hf isotope variations within and between grains will provide the evidence of this mixing process. Less pronounced isotopic variations have been observed in studies where single- or multi-grain zircon fractions are dissolved and analysed in solution, but this procedure will naturally disguise to some degree the isotope variability within (and in some cases between) individual zircons. Except in instances where core and rim components of different age were analysed, we have not investigated intragrain Hf isotope variations in detail. However, these variations are evident in some zircon populations due to the time-resolved nature of the laser sampling technique.

Speculations on crustal growth: Variations in the Hf isotopic signature of Slave Province magmatism likely indicates both local and regional changes in the competing processes of crustal growth and crustal recycling. At various times, magmas derived from the depleted mantle were fundamentally involved in crustal growth whereas at other times, new magmas contained a much higher proportion of melted older crust. What is interesting is that our data suggest that during periods of crustal melting, the melted rocks were probably no more than a few hundred million years old, or contributed only minor volumes of magma, thus accounting for epsilon Hf values that extend to no lower than -4. This is somewhat surprising as very old crust was available for melting during late Archean magmatic events. One possible reason for this is that pre-3.5 Ga crust was mainly restricted to the core of the Slave proto-continent and was therefore isolated from melting during later crustal growth around the continental margins. Another reason may be that once a melt is extracted from a crustal volume, it becomes difficult to extract subsequent melts from the same volume. In a tectonically and magmatically active regime, crustal melting is more likely to have occurred relatively soon after crust formation. Yet another consideration is the bias of our sample set toward tonalitic protoliths, which are thought to represent predominantly juvenile additions of crustal material.

In the southern Abitibi region, both this study and earlier work indicate that crustal growth was dominated by mantle-derived magmatism. However, epsilon Hf for some of our zircons extend well above DM, suggesting one or more of: (i) some degree of mantle heterogeneity, including the presence of ultra-depleted mantle, at 2.7 Ga; (ii) granitoid magma generation from different sources (e.g., plume, shallow mantle, juvenile crust), and; (iii) the possible need for another depleted mantle model for this region at 2.7 Ga. Limited involvement of older crust is suggested by our data, and there is already some existing U-Pb evidence for the presence of pre-2.8 Ga crust in the subsurface. The Hf isotope data permit, but are not able to clearly identify the involvement of ~100 m.y. old crust during construction of the two plutonic complexes. It should be remembered that not all Abitibi lithologies such as the well-studied mafic and ultramafic volcanic assemblages need have interacted with remnants of older continental crust, and therefore their juvenile chemistry and isotopic signatures do not rule out the existence of this crust. We observe from our U-Pb and Hf data that the Kenogamissi plutonic complex has reasonable evidence for crustal contamination whereas the Round Lake complex does not. Given the closer proximity of the Kenogamissi complex to the Wawa subprovince, which is underlain by rocks as old as 2.93 Ga, this observation is perhaps not surprising. The presence of remnants of 2.9-2.7 Ga sialic crust in the Abitibi subprovince, perhaps originating from the adjacent Wawa and Opatica subprovinces, has already been postulated by one of us (WB). If additional evidence for the presence of this crust at depth is obtained, this will help to further clarify the plate tectonic setting of the Abitibi subprovince.

Evolution of the southern margin of the Wabigoon Subprovince, Beardmore-Geraldton Belt, SW Ontario

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The Beardmore-Geraldton belt occurs along the southern margin of the Wabigoon granite-greenstone subprovince, Archean Superior Province, SW Ontario. The belt consists of interleaved shear-bounded panels of ca. 2725 Ma, mafic to intermediate, metavolcanic rocks of MORB, island arc, and back-arc geochemical affinity, and ca. 2696 Ma to 2691 Ma turbiditic sandstone and polymictic conglomerate. The metasedimentary rocks, which potentially correlate in age with turbiditic sandstone of the adjacent metasedimentary Quetico subprovince to the south, were likely deposited in a foreland basin that developed south of a southward advancing orogenic front. The basin was subsequently imbricated from 2696 Ma to 2691 Ma during D1 thrusting and accretion of the Wabigoon, Quetico, and Wawa subprovinces.

Post-accretion <2691 Ma D2 deformation produced regional F2 folds that transposed lithological units parallel to the axial plane S2 cleavage of the folds. During regional D3 dextral transpression, the folds were overprinted by a regional S3 cleavage oriented anticlockwise to F2 axial planes, and lithological contacts and S2 were reactivated as planes of shear within dextral regional shear zones that generally conform to the trend of the belt. Similar D1 to D3 structures occur across the Wabigoon, Quetico, and Wawa subprovinces. Gold occurrences in the Beardmore-Geraldton belt and Shebandowan belt, Wawa subprovince, are associated with folds and dextral shear zones that formed during the regional dextral transpression event.

The Northeastern Superior Province in Quebec's Far North: A Regional Synthesis

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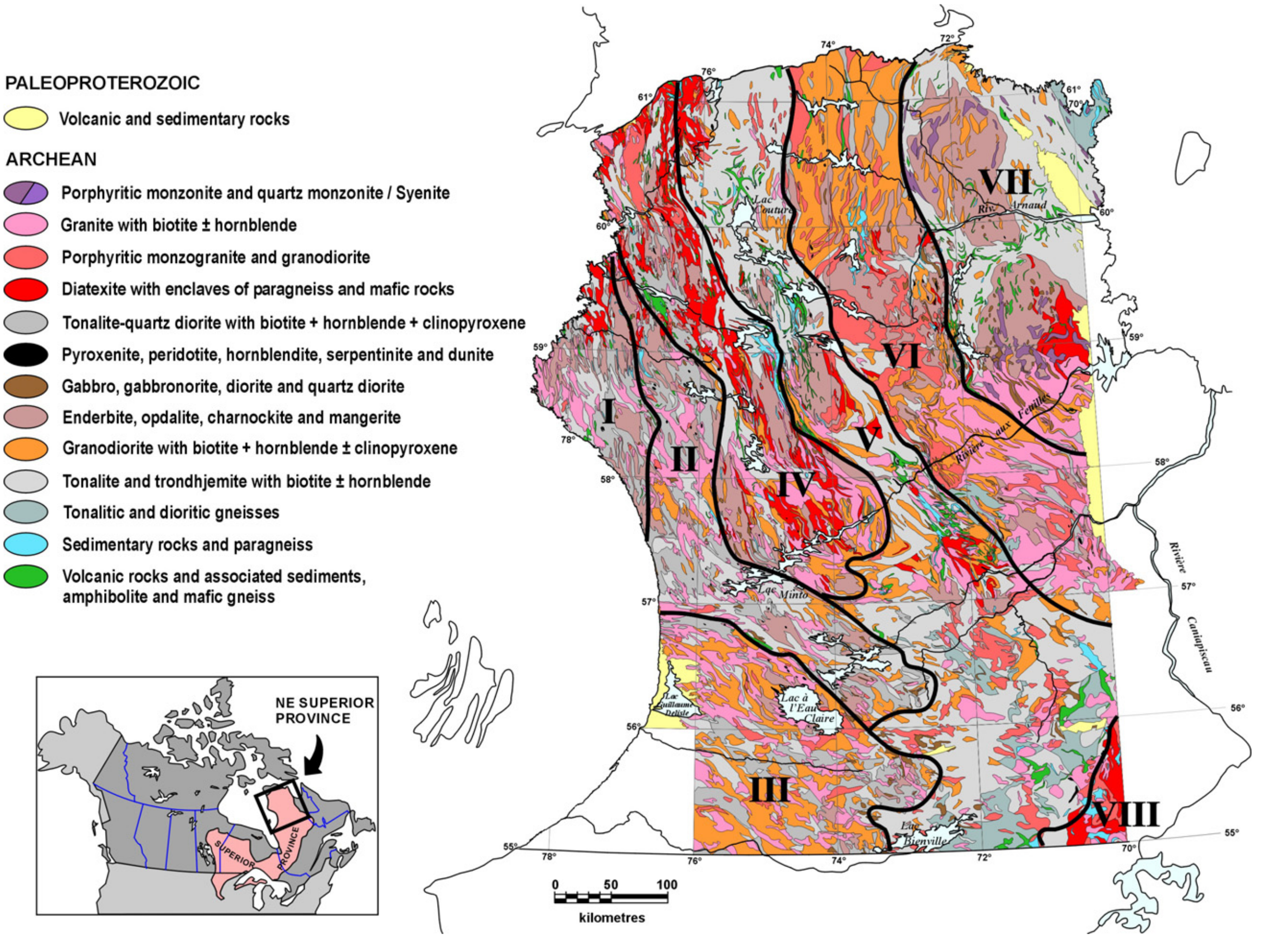
According to the results of recent studies at 1:250,000 scale in northern Quebec, the Northeastern Superior Province (NESP) consists of mainly plutonic rocks enclosing remnants of supracrustal rocks, with a complex geological history spanning over a billion years of the Archean eon. These studies reveal the presence of a variety of foliated, biotite-, hornblende- and pyroxene-bearing plutonic rocks, ranging in composition from felsic to ultramafic. They also reveal numerous, isolated belts (< 20 km wide by <120 km long) of amphibolite- to granulite-facies supracrustal rocks which are characterized by <10% of bedrock exposure. Together, these rocks preserve a remarkable record of deposition, magmatism, deformation and metamorphism which attests to episodic growth and repeated reworking of the Archean crust in the interval between about 3.82 and 2.62 Ga. The overall stratigraphy and geochronology of the NESP can be defined as follows:

- A unique ca. 3.82 Ga volcano-sedimentary sequence exposed in an open synform with mylonitic borders containing ca. 3.65 Ga tonalite gneisses.
- Pre-2.9 Ga, tonalitic gneisses limited to rare occurrences within younger tonalites, probably representing vestiges of an old sialic crust underlying the region.
- 2880-2870 Ma, tonalite-trondhjemite intrusions and supracrustal sequences of tholeiitic mafic volcanic rocks interbedded with komatiitic rocks and paragneiss. Also present within these sequences are felsic tuff, iron formation, marble and calc-silicate rocks, and sills of peridotite, pyroxenite and gabbro.
- 2850-2760 Ma, basalt-dominated volcanism, with diorite, gabbro-anorthosite and ultramafic intrusions, minor komatiitic rocks, and locally intercalations of mafic to felsic volcaniclastic rocks, rhyolite, iron formation and paragneiss; abundant synvolcanic tonalite-trondhjemite intrusions, and early deformation.
- 2760-2745 Ma, supracrustal sequences of mainly mafic to felsic volcanic and volcaniclastic rocks, with abundant paragneiss and lesser ultramafic rocks; widespread tonalite-trondhjemite-granodiorite plutonism, possibly diachronous across the region from northeast to southwest; local nepheline syenite plutons.
- 2740-2710 Ma, bimodal or intermediate to felsic volcanism of mainly calc-alkaline affinity and associated clastic sedimentary rocks; voluminous felsic to ultramafic plutonism comprising three main types: a) pyroxene-bearing granitoids, b) mafic-ultramafic rocks and c) porphyritic granite-granodiorite; coeval 'craton-scale' deformation resulting in north- to northwest-trending regional fabric, and onset of extensive migmatisation associated with diatexites.
- 2715-2680 Ma, syn- to late-kinematic, biotite granite, granodiorite, quartz monzonite, and pegmatite; associated intracrustal melting/recycling producing diatexite migmatites; sparse

intrusions of leucotonalite and enderbite, and small, isolated plutons of massive mafic-ultramafic rocks.

- 2680-2620 Ma, rare, spatially-restricted, post-kinematic alkaline intrusions of nepheline syenite and carbonatite; late- to post-metamorphic hydrothermal activity producing fluids channelled along permeable zones, including brittle-ductile faults. This is concomitant with a major episode of magmatism and protracted metamorphism occurring in the southeasternmost part of the region.

A revised subdivision of the NESP, based on lithological and aeromagnetic features, suggests the presence of at least eight major N- to NW-trending domains (labelled I to VIII on figure 1). The gross lateral heterogeneity in the distribution of various lithologies across the region appears to mainly reflect the extent of widespread, younger (<2.79 Ga) magmatism that is responsible for extensive occlusion of older rocks. Herein, we briefly describe the first-order characteristics of each domain, in light of new data acquired from extensive geological and structural mapping, U-Pb dating and Nd isotopic studies. The westernmost domain I is characterized by a relatively low aeromagnetic anomaly trending north and an abundance of clinopyroxene-bearing tonalite-diorite, enderbite (2.73-2.70 Ga) and granite (2.71-2.69 Ga) enclosing older tonalitic units (2.84-2.75 Ga). It also contains the oldest volcano-plutonic sequence (ca. 3.8-3.6 Ga) recognized in the NESP, and is distinguished from domains to the east by generally older Nd isotopic signatures (model ages of 3.0-4.0 Ga). Domain II also consists mainly of pyroxene-bearing plutonic rocks and older tonalites, similar in age to those of domain I, but displays a higher magnetic intensity with NW-trending negative anomalies in the south. The tonalitic units contain rare supracrustal rocks and enclaves of tonalitic gneisses (ca. 3.02 Ga). Many lithologies of domain II appear to continue southward into domain III where they have been intruded and largely assimilated by voluminous granite-granodiorite plutonic suites (ca. 2.71-2.69 Ga). Domain III displays curvilinear, northwesterly trending aeromagnetic anomalies, and is bordered to the north by a major deformation zone. Rocks of this domain have inherited xenocrystic zircons and Nd model ages in excess of 3.2 Ga. Domain IV contains a significant amount of supracrustal rocks and coeval tonalites (<2.76 Ga), along with pyroxene-bearing plutonic rocks, migmatitic paragneiss and related diatexite and granite intrusions (2.73-2.70 Ga). It displays a distinct striated aeromagnetic pattern of alternating, narrow positive and negative anomalies. Domain V forms a NW-trending aeromagnetic low, with patchy highs, that extends along the central part of the NESP and appears to merge with the volcano-plutonic La Grande Subprovince to the south. This domain is characterized by large belts (20 x 120 km) of volcano-sedimentary rocks ranging in age between about 2.88 and 2.71 Ga. These rocks are engulfed by widespread, coeval tonalite-trondhjemite-granodiorite plutonic suites, and intruded by enderbite, diatexite and granite plutons (2.73-2.68 Ga). Rare tonalitic units with ages up to 3.0 Ga are also present. To the east, domain VI forms a prominent, broad, N- to NW-striking aeromagnetic high that is associated predominantly with plutonic rocks. It is dominated by enderbite, granodiorite and granite intrusions (2.74-2.69 Ga), with sporadically preserved tonalites and supracrustal rocks. The inherited zircon and Nd isotopic records also indicate involvement of crust as old as ca. 3.0 Ga. In the northeasternmost domain VII, two large, ovoid charnockitic massifs (2.74-2.73 Ga) with mottled aeromagnetic patterns are emplaced in an aeromagnetic low which corresponds to a vast tonalitic complex (2.88-2.75 Ga) containing several small volcano-sedimentary belts. All these rocks are intruded by some granodiorite, granite and monzonite plutons (ca. 2.73-2.69 Ga) and are overprinted to the northeast by Proterozoic ductile deformation. Again, the zircon inheritance and Nd isotopic data reflect the presence of older recycled crust (2.9-3.1 Ga). Further to the southeast, domain VIII corresponds to the northern part of the Ashuanipi Complex which is characterized by irregular aeromagnetic anomalies associated with high-grade metamorphic and plutonic rocks. It consists of metasedimentary rocks, an early tonalite-diorite suite (ca. 2.72 Ga) and rare metavolcanic rocks (ca. 2.71 Ga), all of which were deformed and metamorphosed to the granulite facies. These rocks are intruded by widespread orthopyroxene-bearing diatexites (ca. 2.68-2.66 Ga), by granite, granodiorite, tonalite and syenite plutons (2.65-2.62 Ga) and by A-type granite plutons (2.57 Ga).



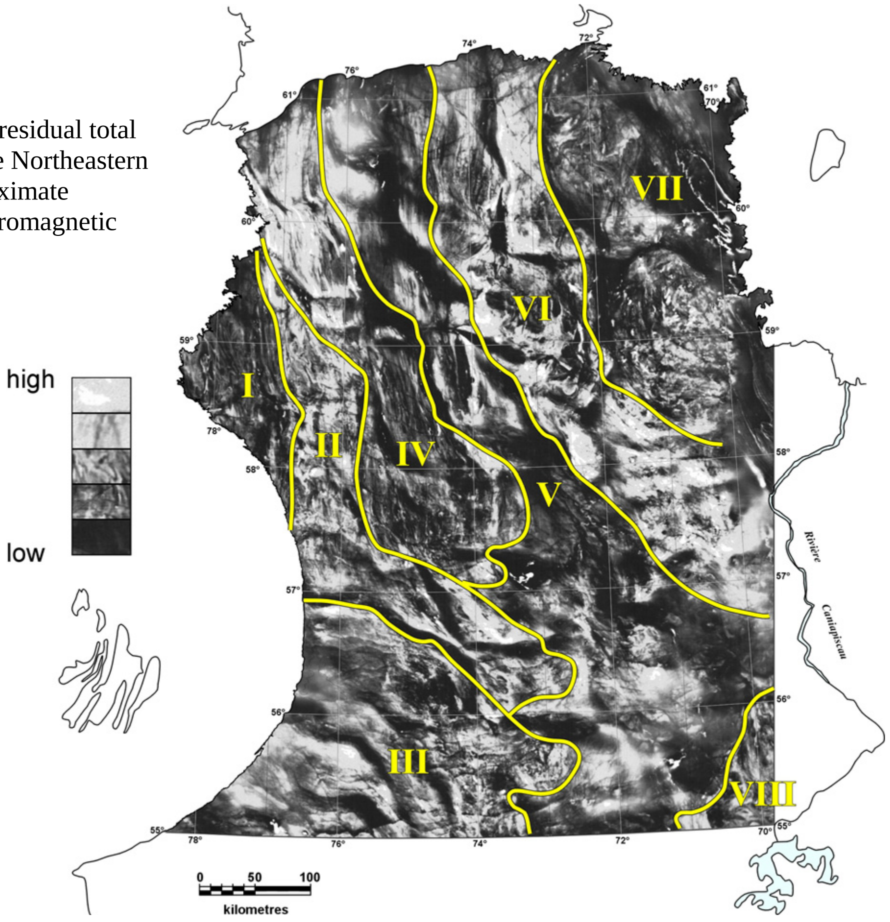


Figure 1. Simplified geology and residual total field aeromagnetic signature of the Northeastern Superior Province, showing approximate boundaries of major geological-aeromagnetic domains.

Synchronous Vertical and Horizontal Tectonism in the Archean: Kinematic Evidence from a Synclinal Keel in the Northwestern Superior Province, Manitoba

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The northeast-trending Carrot River greenstone belt in the northwestern Superior Province in Manitoba (Fig. 1) is >50 km long and mostly <2 km wide, and is bounded on both sides by granitoid plutons. Observed younging direction reversal indicates that the greenstone belt represents a narrow synclinal structure, i.e. a synclinal "keel" between two granitoid "domes".

Deformation in the belt varies from very intense to very weak and is localized in a northeast-trending zone ~300 to 1000 m wide (the high-strain zone) that runs along the belt (Fig. 2). In the high-strain zone, both foliation and lineation are very well developed. The foliation is subparallel to the high-strain zone boundary and is subvertical. The lineation has variable orientations. An important observation is that the high-strain zone can be divided into two parallel and well-defined subzones with distinct kinematics (Fig. 2). In the northwestern subzone, the lineation plunges moderately to steeply to the west, and the folds are southeast-vergent. Well-developed shear sense indicators indicate northwest-over-southeast dip-slip movement with dextral strike-slip component. In contrast, in the southeastern subzone, the lineation plunges moderately to steeply to the east, and the folds are northwest-vergent. Shear sense indicators indicate southeast-over-northwest dip-slip movement, also with dextral strike-slip component. The dip-slip movement components show that greenstone in the synclinal keel moved down relative to the plutonic domes on both sides (Fig. 3). Such a kinematics is consistent with a diapiric origin ("vertical tectonics") for the "dome-and-keel" structure, but not consistent with a buckling mechanism ("horizontal tectonics") for the formation of the structure (Fig. 4). On the other hand, the dextral strike-slip movement can only be explained by horizontal tectonics, especially considering that it is consistent on a regional scale. The data thus shows that vertical and horizontal tectonics were synchronous in this part of the Superior Province.

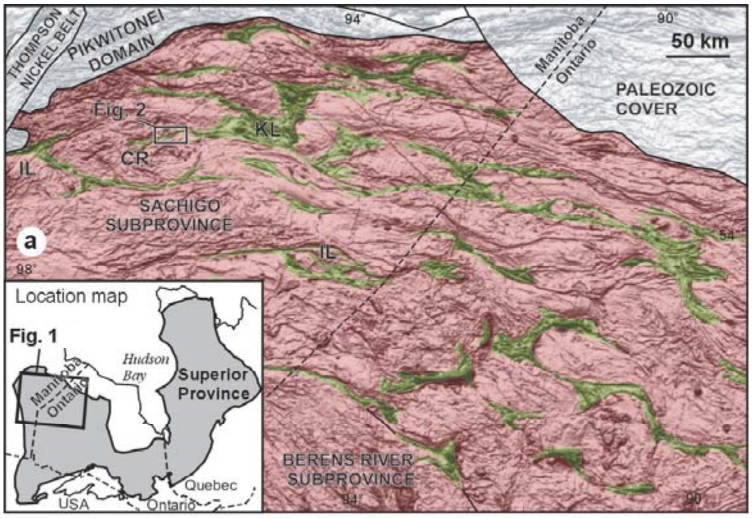

Figure 1: Simplified geological map superimposed on shaded image of total magnetic field of northwestern Superior Province, showing distribution of greenstone belts and granitoids (shown in green and red, respectively) and general geometry of the area. CR: Carrot River; CL: Cross Lake; IL: Island Lake; KL: Knee Lake. Magnetic map from Geological Survey of Canada.

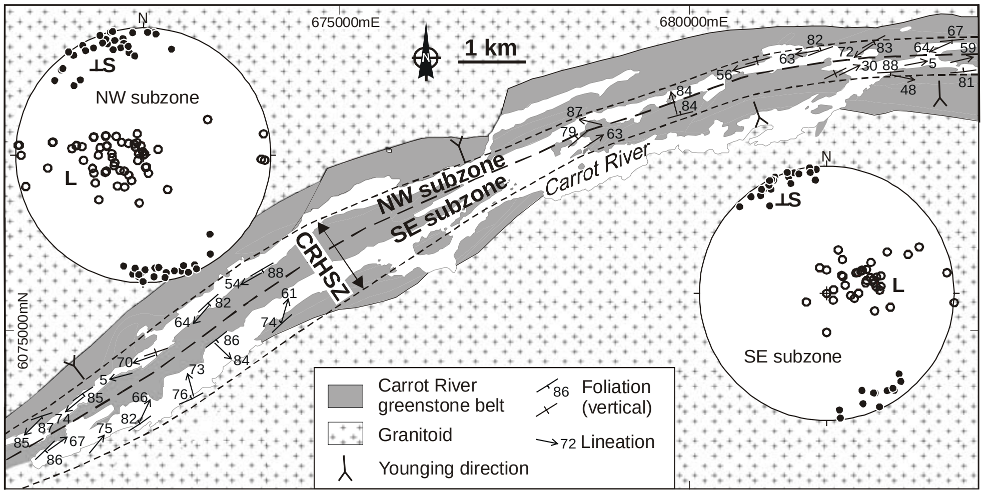

Figure 2: Simplified structural geology map of part of Carrot River greenstone belt showing main structural features of Carrot River high-strain zone (CRHSZ), approximate boundary of which is indicated. Also shown are equal-area lower-hemisphere projections of poles to foliation (S) and stretching lineations or ductile striations (L) from the high strain zone.

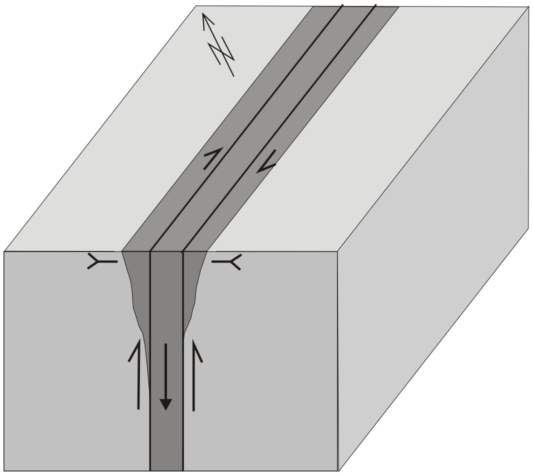

Figure 3: Schematic diagram summarizing geometry and kinematics of Carrot River high-strain zone.

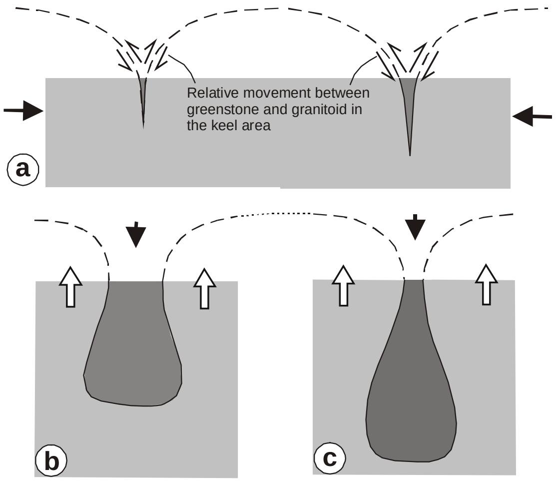

Figure 4: Schematic diagrams showing contrasting kinematics predicted for (a) buckle folding driven by horizontal stress and (b & c) vertical tectonics driven by gravity inversion.

Deep Thermal Structure of the Lithosphere from Inversion of Seismic Surface Wave with Constraints from Heat Flow Data.

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We present the results of a joint inversion of seismic surface wave dispersion and heat flow data for the seismic and thermal structure of the lithosphere beneath central and southeastern Canada. The inverse problem is formulated as a Monte-Carlo inversion of surface-wave dispersion in which surface heat flow measurements are introduced as an a-priori constraints [*Shapiro and Ritzwoller*, 2004]. The assimilation of the heat-flow data reduces the uncertainties in both the estimated seismic and temperature models by rejecting models with non-physical temperature profiles.
The Monte Carlo inversion gives an ensemble of models that fit the data, providing estimates of uncertainties in model parameters. The seismic velocity is converted to temperature following the approach outlined by *Goes et al.* [2000] and *Rohm et al.* [2000]. Each seismic velocity profile yields three thermal parameters: the temperature at Moho depth, the mantle heat flow (or the mantle temperature gradient), and the potential temperature of the sub-lithospheric convecting mantle. Prior physical information on these model parameters is based on surface heat flow and heat production measurements as well as some thermodynamic constraints. Seismic profiles that are not consistent with the thermal data or with the thermodynamic constraints are rejected. From the resulting upper mantle shear wave velocity and temperature profiles, we have also estimated lithospheric thickness. The mantle temperature gradient derived from the inversion is superadiabatic in the uppermost mantle but becomes adiabatic in the convecting mantle. We use the depth where the temperature gradient changes to determine lithospheric thickness. We have also estimated the effect of uncertainties in the interconversion between temperature and seismic velocity. Within the Shield, variations in lithospheric temperature and shear velocity are not well correlated with geological province or surface tectonic history. Mantle heat flow and lithospheric thickness are anticorrelated as expected. The mantle heat flow is ≈ 11 mW m^{-2} over most of the Shield but increases to about 24 mW m^{-2} in the southeast. Lithospheric thickness could be as high as 400km to the northwest but decreases to $\approx$ 180km to the southeast. The relation between lithospheric thickness and mantle heat

flow is consistent with a power law relation similar to that proposed by *Jaupart et al.* [1998] who argued that the lithosphere and asthenosphere beneath the Canadian Shield are in thermal equilibrium and heat flux into the deep lithosphere is governed by small scale sublithospheric convection.

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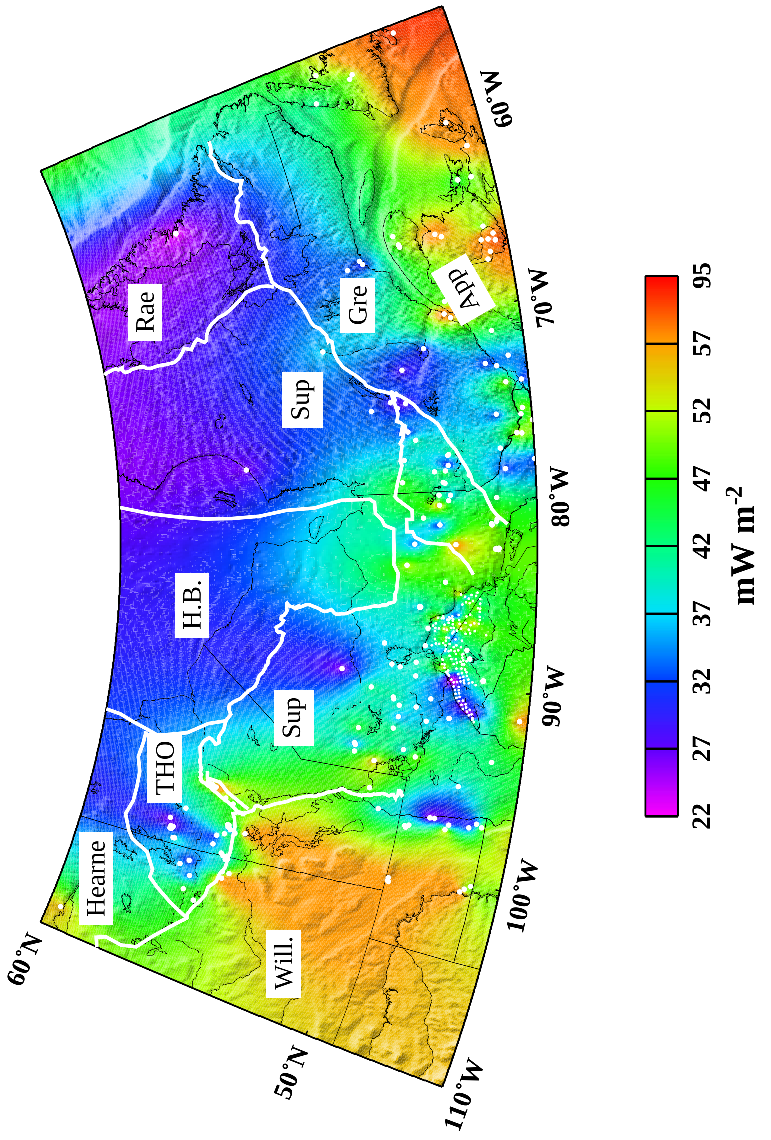

Figure 1: Heat flow map of the Canadian Shield Canada with the location of the heat-flow data used in this study (white dots). The main Provinces of the Canadian Shield and adjoining regions are shown. (Abbreviations: SUP: Superior Province; THO: Trans Hudson Orogen; Gre: Grenville Province; App: Appalachians; H.B.: Hudson Bay Basin; Will: Williston Basin.)

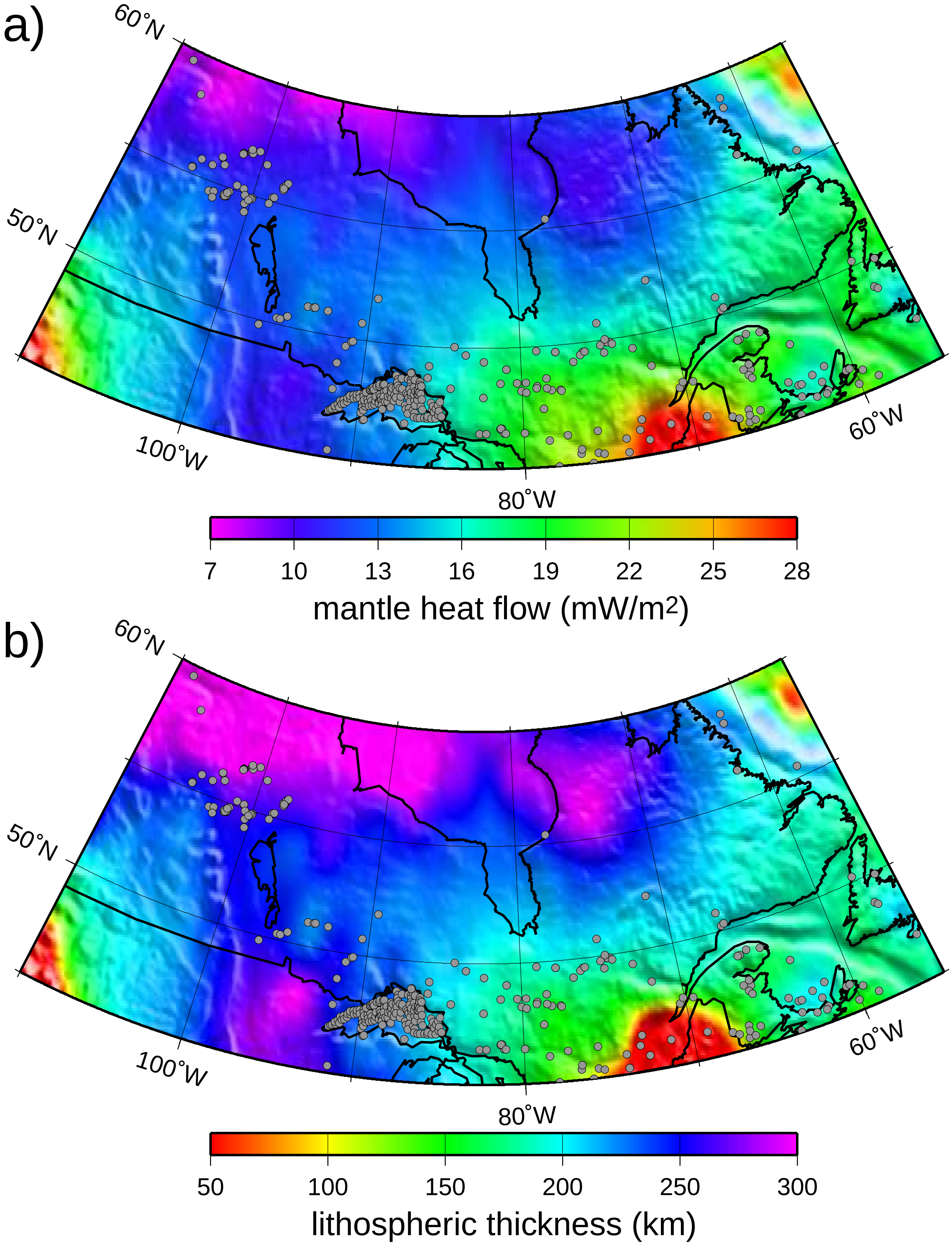

Figure 2: (a) The mantle component of heat flow estimated from the seismic inversion; (b) The lithospheric thickness defined as the depth where the mantle temperature gradient from the seismic inversion becomes adiabatic.

Multiple Episodes of Volcanism in the Island Lake Greenstone Belt: Evidence for a Volcanic "Megasequence" and Implications for the Extent of the North Caribou Craton in the Northwestern Superior Province

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The northwestern Superior province is a relatively inaccessible area compared to the southern Superior province. Studies in the south connected with the Western Superior and the Abitibi-Grenville Lithoprobe transects have revealed evidence for accretion of diverse terranes. The relationship of events in the southern half of the Superior province to those in the northwest, and the style of terrane accretion in the northwest, is poorly understood. The Island Lake greenstone belt occupies an important position between the Mesoarchean North Caribou terrane and the Paleoarchean Northern Superior superterrane (Fig.1). It therefore may contain key evidence concerning the assembly of these terranes and its influence on accretionary processes in the south.

A combined U-Pb and field mapping study of the Island Lake greenstone belt has led to the recognition of three distinct, fault bounded supracrustal assemblages. The assemblages record volcanic episodes at 2897 Ma, 2852 Ma and 2744 Ma. Plutonic activity occurred in many distinct episodes and is often chronologically associated with volcanic activity and range in age from 2984 Ma to 2730 Ma, with a concentration of activity at 2744 Ma. Age correlations between the Island Lake belt, the Munro Lake terrane to the north, and the Favourable Lake, McInnes Lake, Hornby Lake, and Red Lake belts to the south argue for the existence of a volcanic "megasequence". In combination with Nd isotope data, these suggest that the Munro Lake, Island Lake, and North Caribou terranes be considered part of a larger reworked Mesoarchean crustal block, the North Caribou Craton (Fig. 1). These data confirm that the Island Lake greenstone belt experienced a long and complex geological history that spanned at least 200 m.y., which is typical of greenstone belts in the northwestern Superior province. It appears that the Superior province was assembled by accretion of large independent crustal blocks, whose individual histories involved extended periods of autochthonous greenstone development.

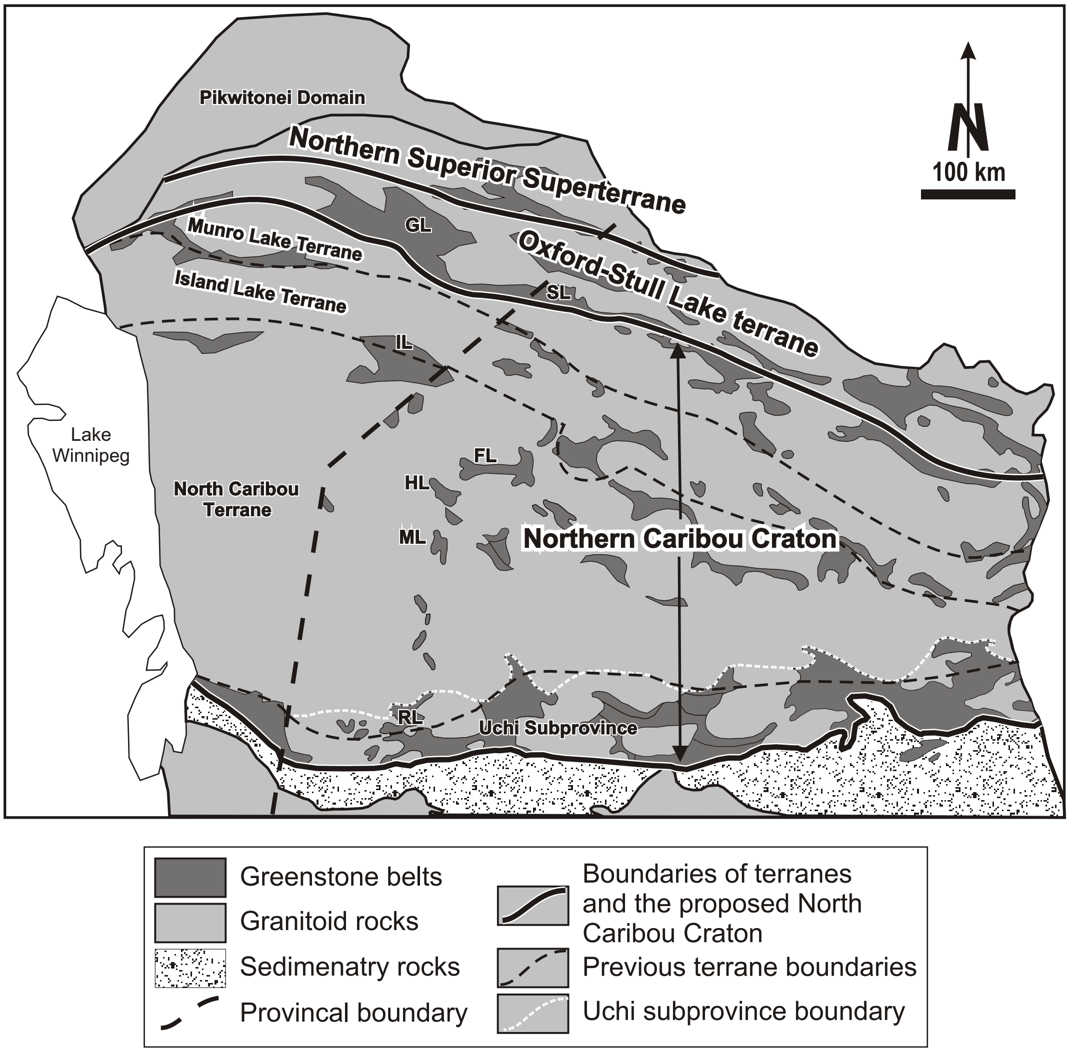

Fig. 1. Regional terrane map of the northwestern Superior Province. The proposed extent of the North Caribou craton is shown. Locations of the greenstone belts cited in text and relevant terrane boundaries are shown. Abbreviations for greenstone belts: IL- Island Lake, RL- Red Lake, GL-Gods Lake, SL-Stull-Edmound Lake, HL-Hornby Lake, ML- McInnes Lake, FL- Favourable Lake.

Evolution of Thought on the Evolution of a Craton: New Perspectives on the Origin and Reworking of the Western Churchill Province

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The western Churchill Province is one of the largest yet most poorly known cratons of the Canadian Shield. Situated in Canada's northern frontier, and bounded by two Paleoproterozoic orogens, it has been called 'that part of the Canadian Shield left over after the adjacent, better defined, younger and older structural provinces have been delineated' (Davidson, 1972).

First regionally explored as part of the Geological Survey's helicopter reconnaissance programs of the 1950's and 1960's, it was defined by Stockwell (1962), as a province of Archean and Paleoproterozoic domains that had been severely deformed and metamorphosed during the Hudsonian (Trans-Hudsonian) orogeny. Targeted regional mapping continued through the 1970's and 1980's and culminated with preliminary subdivisions (Heywood and Schau, 1978; Eade, 1985; Lewry et al., 1985), which recognized a NE-SW trending limit of 'Hudsonian' reworking stretching from Chesterfield Inlet to Lake Athabasca. Hoffman's 1990 subdivision of the Churchill established the Archean Rae and Hearne Provinces, separated by the Snowbird tectonic zone (STZ). This major geophysical feature has been interpreted both as a Paleoproterozoic suture (Gibb and Walcott, 1982; Hoffman, 1990; Ross et al., 1991) and an intracontinental accommodation fault (Hanmer et al., 1995).

More recent studies, founded on the western Churchill Natmap and Targeted Geoscience Initiatives, have established a more complex, rich evolution for the western Churchill. New subdivisions of the existing provinces and multiple phases of Paleoproterozic reworking are recognized, the latter resulting from its location in an upper plate setting between 2.5 and 1.7 Ga.

The Archean Rae domain is characterized by major crust formation events in the 2.75-2.58 Ga range, but with widespread U-Pb and Sm-Nd isotopic evidence for incorporation, assimilation or erosion of 3.4-2.85 Ga crust. Zircon inheritance and Tdm patterns on 2.6 Ga and older rocks suggest a crustal age zonation perpendicular to the regional structure grain. Evidence for the continuation of the Archean Prince Albert Group, with its komattite-quartzite association, into the southern Rae is presently lacking. Both these features raise the possibility of a distinct southwestern Rae domain.

The Archean Hearne domain has been subdivided into the northwestern and central Hearne subdomains on the basis of crust formation ages, crustal contamination and tectonothermal reworking. Isotopic data from supracrustal and plutonic rocks again suggest a crustal age zonation, with evidence for older crust involvement in the genesis of the northwestern and southern Hearne, but little or no evidence for older crust in the central Hearne. Whether the Rae, northwestern Hearne, and central Hearne have been intact since the Archean (as a telescoped continent-transitional margin--oceanic domain) or the central Hearne was accreted in the Paleoproterozoic (possibly as a microcontinent of Superior Province vintage), remains to be tested.

The long history of subsequent reworking began with a cryptic ca. 2.68-2.61 Ga tectonic event. This was followed at ca. 2.55-2.5 Ga by mafic-felsic magmatism and high-P metamorphism along the STZ, moderate-P metamorphism and crustal thickening in the northwestern Hearne and a cryptic high grade metamorphism in the Queen Maud block. Shortly thereafter the central Hearne domain experienced 2.45 Ga mafic magmatism and extension. These events may be linked to a coeval worldwide phase of convergent margin magmatism and metamorphism that led to formation of a new supercontinent.

A second crustal thickening event at ca. 2.35 Ga has been recognized in the western and central Rae domain, and is ascribed to collisional orogenesis following continental arc magmatism on the western Rae margin. Syn-collisional felsic magmatism and an epi-continental sedimentation are localized in the southwestern Rae. Limited U-Pb ages suggest a similar thermomagmatic event in the southernmost Hearne, whereas the central Hearne experienced thermal subsidence and deposition in a shallow epicontinental sea.

Widespread extension of both the Rae and Hearne domains characterize a third Paleoproterozoic tectonic phase at ca. 2.2-2.1 Ga. Major mafic dyke swarms at 2.19 to 2.11 Ga indicate a protracted period of extension–related magmatism. Development of intracratonic basins and eruption of continental flood basalts across more than 1000 km of the Rae highlight the broad extent of the extensional regime that may be part of the 2.17 Ga global superplume breakout event..

Between 1.96 and 1.87 Ga, an overlap sequence of continental clastic and marine carbonate rocks was deposited across both the Rae and Hearne domains. This sequence accumulated during, or just prior to, a period of regional-scale folding and thrusting in the northwestern Hearne and high-pressure metamorphism and mafic magmatism in the lower crust of the Rae and STZ. Recent field, thermobarometric and petrologic studies have recognized that the high-pressure domain along the Rae-northwestern Hearne boundary is much more extensive than originally thought, and that its southeastern boundary does not follow the Snowbird tectonic zone as previously defined. Accretion of microcontinental blocks (possibly including the central Hearne domain) early in the Trans-Hudson orogenic cycle may have been the driving force for this phase of orogenesis, and provides a mechanism to achieve the ca. 1.9 Ga eclogite-facies conditions locally recorded within the deep crust.

Regional folding and/or thrusting and low- to moderate-pressure metamorphism characterize the main ca. 1.85-1.80 Ga, Trans-Hudonsian overprint, which extends as far north as the Arctic ocean on Committee Bay. The amount of shortening, it’s the degree of penetrative deformation, and peak temperature and pressure conditions vary across the province, but has a consistent neutral to NW vergence. This shortening was broadly coeval with deposition of epicontinental clastic and ultrapotassic mafic volcanic rocks along a corridor just NW of the possible 1.9 Ga suture involving the central Hearne.

A marked contrast is apparent in the character of upper plate reworking associated with the two major bounding Paleoproterozoic orogens. The tectonothermal overprint related to the 1.99-1.93 Taltson-Thelon orogen on the western margin of the Rae domain is comparatively narrow, with focused magmatism and limited supracrustal basin formation. Trans-Hudsonian (s.l.) reworking in all its manifestations extends 1000’s across strike and was associated with abundant magmatism and sediment accumulation in a variety of foredeep to foreland-related settings. This broader overprint appears to reflect stronger plate coupling induced by shallower subduction during the Trans-Hudson orogeny.

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LITHOPROBE SEISMIC & MT DATA ARCHIVE: A RICH LEGACY OF CRUSTAL GEOPHYSICAL DATA COLLECTED ACROSS CANADA

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The Canadian LITHOPROBE Project has completed seismic and magnetotelluric (MT) transects that span the country. The LITHOPROBE Seismic Processing Facility (LSPF) at the University of Calgary has been the primary custodian of the seismic data while the MT data has mostly been archived at the Geological Survey of Canada (GSC). Now these data have been collected into one repository from which some products are freely downloadable and larger volumes can be provided on tape media for a small handling fee. The archive currently contains over 170 deep crustal seismic reflection lines, 280 refraction/wide-angle reflection shot points, and 1800 long period MT sites. Metadata describing the data have been derived to enable line/shot point/site selection with a web-enabled GIS tool and are currently accessible though the Canadian Geoscience Knowledge Network's data catalog at http://www.cgkn.net. Plans are currently underway at the GSC to integrate the LITHOPROBE seismic and MT data into a single Geophysical Data Repository (GDR), which also contains aeromagnetic, gravity, and radiometric data (http://gdcinfo.agg.nrcan.gc.ca/gdr/index_e.html).

For further details, to order data, or to browse data holdings please visit the following web site:

http://www.cg.nrcan.gc.ca/lith_arch

Seismic evidence for the lateral and vertical growth of cratons

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Deep seismic reflection profiles collected across Proterozoic-Archean margins are now sufficiently numerous to formulate a consistent hypothesis of how continental nuclei grow laterally to form cratonic shields. Similarly, teleseismic (earthquake) studies across the cores of cratons now provide evidence of growth structures in the form of seismic velocity and anisotropy variations and layers bounded by discontinuities. Within the upper 150 km of several Canadian cratons seismic anomalies and discontinuities indicate that the earliest continental blocks grew by underthrusting and stacking of relatively thin (80-100 km) lithosphere. At the craton margins, the older (Archean) block appears to form a wedge of uppermost mantle rock embedded into the more juvenile (Proterozoic) block by as much as 100-200 km at uppermost mantle depths and Archean lithosphere is therefore more laterally extensive at depth than at the surface. Particularly bright reflections along the Moho are cited as evidence of shear strain within a weak, low-viscosity lower crustal channel that lies along the irregular top of the indenting wedge. The bottom of the wedge is an underthrust/subduction zone, and associated late reversal in subduction polarity beneath the craton margin emerges as a common characteristic of these margins although related arc magmatism may be minor. The Proterozoic subduction zones can be traced beneath the cratons at 150-300 km depths. Geochronology of granitic intrusions and xenoliths suggests that the stacked cratonic core was intruded, metasomatized and generally modified by melts rising from these subduction zones. An increasingly better documented history of sporadic kimberlite eruptions indicates that mantle melts unrelated to subduction also contributed to craton growth at depth by partly destroying lithopshere..

On the Geodynamic Evolution of the Northern Border of the Congo Craton in Cameroon: Evidences from New Petrological, Isotope Geochemical and Geochronological Data from the Bafoussam-Makenene Region.

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The territory of Cameroon includes the northern part of the Congo Craton and its boundaries with the very large area of the Trans-Saharan belt, affected in the Neoproterozoic by the Pan-African orogeny. The position of the main suture zones and the character of the different tectonic units are still matters of debate. In this work we present new petrological, geochronological and isotope geochemical data from rocks of the Bafoussam-Makenene region of West Cameroon, that are critical for a better understanding of the regional crustal evolution. In this area, a large elongated zone trending NE-SW occurs, where numerous small bodies (2-4 km) of mafic rocks are described, mainly pyroxenites and pyroxene-amphibolites. It separates two very distinct geotectonic domains, the northwestern one made up of K-rich granitoid rocks, and the southeastern one made up by calc-alkaline granulites.

In the northwestern domain, between Bafoussam and Tonga, orthogneisses predominate. The rocks exhibit a poorly constrained and imprecise Rb-Sr isochron of Neoproterozoic age. Their Sm-Nd T_{DM} model ages are between 1500 and 2000 Ma, indicating that their protoliths were formed by crustal reworking, possibly with some mixing with juvenile Pan-African material. This domain may represent the possible continuation of the Adamawa block. In the central part of the area, the intrusion of the Bangangte Syenite is localized, with an age of about 580 Ma indicated by precise and concordant Ar-Ar measurements in biotite and amphibole.

In the southeastern domain, the high grade gneisses and granulites occurring near Makenene yielded an early Proterozoic Rb-Sr isochron of about 2050 Ma, and Archean Sm-Nd T_{DM} model ages close to 3000 Ma. These rocks can be correlated with the granulites of the Ntem Group that characterize the northern part of the Congo Craton.

In our view, the more important conclusion of this work is that the mafic rocks tectonic zone can be considered an important suture separating the reworked border of the Congo Craton from the main area of the Pan-African Trans-Saharan belt. In addition, 18 Ar-Ar measurements were carried out on biotite and amphibole from rocks belonging to both tectonic domains. With one exception, they were all comprised in the 550-610 Ma interval, indicating that, although rock formation may be quite old, the entire region was heated to more than 500 ^{o}C in the latest Neoproterozoic, during a high temperature event of the Pan-African orogeny.

A Review of Greenstone Belts in the Superior Province and the Evolution of Archean Tectonic Processes.

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Introduction

The origin and development of Archean greenstone belts continues to be strongly debated, particularly with regard to the roles of subduction, plume magmatism, rifting, diapirism and autochthonous vs allochthonous development (e.g. de Wit, 1998; Hamilton, 2003). It is apparent from studies in the Superior and Slave Provinces of Canada that strongly contrasting tectonic styles may have been in operation at the same time. For example at ca. 2.7 Ga, large diapiric batholiths and synclinal greenstone keels may suggest that diapirism was an important tectonic process in the Slave Province (Bleeker, 2002), whereas in the Superior Province the linear distribution of belts suggests that accretionary tectonics (i.e. plate tectonics) may have dominated (e.g. Stott, 1997). Neither theory precludes the other, and in developing models for Archean tectonic evolution, no one model will be equally applicable to all areas.

Greenstone belt types

In the Superior Province, greenstone belts are typically collages that contains more than one sequence of rocks. These sequences may have different ages and distinct histories. There are several common types of sequence (or stratigraphic associations) that are found in volcanic-dominated greenstone belts, and their features indicate certain environments of formation. These features can also be used to suggest tectono-magmatic settings but are usually open to interpretation.

1) **Flood volcanism on submerged (shallow water) continental platforms** – these sequences contain thick, laterally extensive tholeiitic mafic flows, pillow basalts, hyaloclastite ± komatiites and minor amounts of felsic tuff, BIF, cherty and clastic sedimentary units. Rarely unconformities are preserved at the base of these sequence, where thin conglomerate-quartzite-arkose-carbonate units overly tonalitic basement. More commonly the base of the sequence is not preserved but detrital zircon ages in sedimentary rocks correspond to the age of nearby granitoid rocks which are inferred to represent basement. The volcanic rocks may also contain xenocrystic zircons, Nd isotopic evidence of older crustal involvement, and geochemical signatures suggesting felsic crustal assimilation. These sequences typically occur early in the development of Archean cratons and are common at 3.0-2.9 Ga in the Superior Province (North Caribou and Marmion terranes). In the North Caribou terrane evidence of graben development exists in the basement suggesting extension prior to volcanism, and plume-driven rifting has been suggested as the environment of formation. This environment does not have a true modern analogue as the continental flood basalts on the modern Earth are subaerial.

2) **Submarine volcanic plains** – comprise massive and pillowed tholeiitic mafic flows ± komatiite, BIF, mudstones and rare greywackes. The lavas have juvenile Nd isotopic

signatures, lack significantly older zircon inheritance and have primitive mantle normalised REE profiles that are flat to slightly depleted in light REE (but less depleted than modern MORB) or slightly enriched in light REE. The sequences often have tectonic contacts and may be fragments of thicker sequences. They appear to have formed in oceanic environments, and suggested tectonic settings are oceanic plateau, back-arc basin, primitive island arc, oceanic island or possibly mid-ocean ridge. These sequences often flank older continental blocks and may have been accreted to continental margins. Examples are the older (ca. 2.88 Ga?) parts of the Oxford-Stull Lake terrane flanking the northern margin of the North Caribou terrane; the older (ca. 2.78 Ga) parts of the Western Wabigoon terrane flanking the Winnipeg River and Marmion terranes; and parts of the ca. 2.75-2.70 Ga Abitibi subprovince.

3) **Diverse volcanic sequences –** comprise a variety of submarine to lesser subaerial units, dominated by basalt, with lesser andesite, dacite and rhyolite flows, and dacite-rhyolite pyroclastic units. In some belts komatiites are also present. Both tholeiitic and calc-alkaline signatures are often observed, with basalts ranging from slightly light REE depleted (but less depleted than modern MORB) to moderately light REE enriched with negative Nb anomalies (similar to modern arc related basalts). These sequences are commonly associated with syn-volcanic granitoids. Nd isotopic data suggest that some sequences are juvenile while others have experienced minor interaction with older enriched sources (metasomatised mantle or crustal contamination?). They are suggested to represent arc magmatism (both island arc and continental arc on a thin margin), arc-plume interaction, arc rifting or back-arc magmatism. Examples are 2.83 Ga sequences in the Oxford-Stull Lake terrane flanking the northern margin of the North Caribou terrane; various ca. 2.9-2.74 Ga sequences in the Uchi subprovince at the southern margin of the North Caribou terrane; 2.75-2.71 Ga sequences in the Western Wabigoon terrane; and parts of the ca. 2.75-2.70 Ga Abitibi subprovince

4) **Continental felsic volcanic centres –** comprise thick sequences of massive calc-alkaline dacite-rhyolite flows and pyroclastics with lesser calc-alkaline basalts and andesites and syn-volcanic plutons. They may unconformably overly older tholeiitic to calc-alkaline sequences but basal contacts are usually tectonised or intruded by younger granitoids. Indirect evidence for eruption on older basement occurs in the form of older Nd model ages, zircon inheritance, evolved geochemical signatures and the maturity of the sequences. They are suggested to represent continental arc magmatism and examples are widespread at 2.73-2.71 Ga in the western Superior Province, occurring along both the northern and southern flanks of the North Caribou terrane (in several greenstone belts along a 2000 km long continental margin), and in the eastern part of the Wabigoon subprovince.

5) **Late alkaline-shoshonitic sequences –** occur locally in the Superior Province associated with late transpressional faults (at ca. 2.71-2.68 Ga, younging from north to south), following the major N-S shortening event. They comprise alkaline volcanic rocks with evolved Nd isotopic signatures and geochemistry, and continent-derived alluvial-fluvial sedimentary rocks with a large diversity of detrital zircon ages. The sequences are thought to have formed in late pull-apart basins and well-developed examples include

2.71-2.70 Ga sequences along the north and south margins of the North Caribou terrane (in the Oxford-Stull Lake terrane and the Uchi subprovince); and 2.69-2.68 Ga sequences in the Abitibi subprovince where the type locality of this “Timiskaming” sequence occurs.

Plate tectonics in the Archean

It is clear from the Superior Province that 3.0-2.7 Ga greenstone belts formed in both oceanic and continental environments. Archean “oceanic” sequences may not represent true oceanic crust generated at mid-ocean ridges but an abundance of other oceanic environments appears to be represented by the diverse rock record (e.g. primitive island arc, back-arc and oceanic island sequences). Continental sequences also appear to represent both divergent and convergent plate settings, related to rifting or hot-spot magmatism and subduction-zone magmatism. The diversity of greenstone belt sequences requires a diversity of tectono-magmatic processes to generate them, and is most consistent with the operation of plate tectonics (or something resembling it) in the Archean.

It has been suggested from the secular evolution of Archean granitoid rocks (e.g. Smithies et al., 2003; Martin and Moyen, 2002), that plate tectonics may have evolved through the Archean to become more similar to present day plate tectonics. They suggest that prior to 3.1 Ga the angle of the down-going oceanic plate in subduction zones may have been shallow or even flat and hence excluded development of a mantle wedge. Tonalites were generated by melting of the subducted oceanic plate, but the magmas did not interact with the mantle wedge prior to their emplacement in the crust. After 3.1 Ga a systematic increase of Cr and Ni in tonalite suggests increasing interaction of slab melts with a mantle wedge, indicating a gradually thicker mantle wedge and hence steeper angles of subduction. Mantle wedge processes in subduction zones therefore became increasingly important after 3.1 Ga which is consistent with the increasing presence of mantle wedge-derived rocks (such as calc-alkaline basalts, sanukitoids and Nb-enriched basalts) in the mid to late Archean record.

The role of vertical tectonic processes in generating Archean crust is controversial but is suggested to have been widespread (e.g. Bleeker, 2002). Such vertical tectonic readjustments are superimposed upon a pre-existing crust, with gravity forces acting independently of plate tectonics and regardless of the initial origin of the crust. The degree of vertical readjustment of the crust is dependant upon the gravitational stability of the crust and the presence of a trigger (such as an external or internal heat source). In the Pilbara craton where diapirism is best developed, a buoyant sialic crust was overlain by a thick dense greenstone (flood basalt) sequence creating a density inversion. Punctuated partial convective overturn of the crust involved both solid state re-mobilisation of TTG crust and the emplacement of further plutonic suites into evolving domes, accompanied by the sinking of greenstone belts (Van Kranendonk et al., 2004). Vertical tectonic readjustment of this nature may have been more common in the Archean because of greater heat production. It also appears to have been more common in cratons that contain an abundance of old felsic basement overlain by an extensive flood basalt sequence (type 1 sequence above), as this particular configuration of Archean crust is most likely to have been gravitationally unstable. Readjustment of the crust by diapirism may not have been an important tectonic process in the Superior Province because greenstone belt sequences were more diverse, and hence the nature of the crust was more heterogeneous.

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Deep Seismic Reflection Structure of the Newfoundland Appalachians

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The structure of the crust beneath the island of Newfoundland is revealed on two deep seismic reflection profiles. Newfoundland was assembled during the Appalachian orogeny, a mountain-building episode that happened 500-350 million years ago. Prior to the Appalachian orogeny, the eastern margin of Canada was in western Newfoundland (e.g., Corner Brook - Stephenville area). Two microcontinents were then accreted to the margin: Ganderia and Avalonia, as well as some smaller fragments. These two microcontinents originated at the edge of Gondwana before they drifted across the ancient Iapetus ocean and became attached to North America during the Ordovician to Devonian.

The seismic reflection patterns on the two profiles show structures related to the Appalachian orogeny to depths of ~50 km. The crust beneath Ganderia is characterized by prominent reflections that taper to the northwest and merge with reflections that project into the upper mantle. These reflection patterns are interpreted to represent a relict subduction zone that accommodated convergence between Ganderia and North America.

The prominent crustal reflectivity that characterizes Ganderia is likely caused by transposed compositional layering within Neoproterozoic-Cambrian (>515 million year old) arc basement. The reflection Moho (base of the crust) occurs at ~35 km and may have been established by partial melting of the lower crust during the Devonian. Reflection truncations outline a near-vertical strike-slip fault zone, the Baie Verte line - Cabot fault, that cuts the entire crust.

LITHOPROBE Trans-Canada Transect

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We present a lithospheric cross section that traverses the North American continent at ~50°N (Fig. 1). The section is based on seismic reflection and refraction data combined with geological information. From east to west, the transect crosses the Atlantic passive margin and Grand Banks continental shelf, the ~0.4 Ga Newfoundland Appalachians, the ~1.0 Ga Grenville orogen, the ~2.7 Ga Superior Province, the ~1.8 Ga Trans-Hudson and Alberta orogens, the ~0.1 Ga southern Cordillera, and the Recent Cascadia subduction zone and Juan de Fuca Plate. We also present a partial traverse of the continent at ~60°N, which begins in the ~2.7 Ga Slave Province near Yellowknife and proceeds westward across the ~1.9 Ga Wopmay orogen and the ~0.1 Ga northern Cordillera. A third partial transect at ~60°N crosses the ~2.5 Ga Nain Province and the ~1.9 Ga Makkovik orogen offshore Labrador (Fig. 1).

The Trans-Canada seismic transects provide a view of the continent at a scale that emphasizes relationships between orogens rather than detailed patterns within individual orogens. Orogens are stacked upon one another such that one forms basement to the next. For example, the volcanic arcs and microcontinents that were assembled at ~2.7 Ga to form the Superior Province are basement to the ~1.0 Ga Grenville orogen, which in turn is basement to the ~0.4 Ga Appalachian orogen. The Appalachian orogen is basement to the modern Atlantic passive margin (Fig. 1). Thus, "basement" is a relative term that varies with geologic age and describes rocks beneath the zone of interest.

The transect compilation includes LITHOPROBE data collected between 1984 and 2000. These are supplemented by data collected by: the Frontier Geoscience Program of the Geological Survey of Canada (1985, 1986, 1989), the ACCRETE transect (1994), and the Scotian Margin Transect (2001). This range of vintages highlights improvements in data acquisition technology and processing techniques during this time interval. Modern near-vertical incidence (NVI) reflection data have better signal-to-noise ratios, and display clearer geometric relationships between the surface, crustal reflection patterns, the reflection Moho, and mantle reflections. The refraction and wide-angle reflection (R/WAR) data complement the NVI data by providing velocity models from which structural, compositional, and thermal constraints can be inferred.

With a few notable exceptions, the Moho is generally flat across the continent, irrespective of the age of the crustal rocks or the time when the last major deformation occurred. Most significant changes in Moho depth occur at rifted margins (active and preserved) and at relict subduction zones. Two well-preserved crustal roots are imaged within Canada - beneath the ~1.8 Ga western Trans-Hudson orogen and the ~1.9 Ga Torngat orogen in Labrador. Perhaps crustal roots are only preserved within unextended continent-continent collision zones. This interpretation is consistent with observations elsewhere (e.g., crustal roots beneath Pyrenees, Alps, and Urals).

In addition to crustal features, the NVI and R/WAR data also reveal heterogeneity within the lithospheric mantle. Some mantle reflections are interpreted as relict subduction zones. These mostly dip beneath older cratons and away from the accreting terranes. Two possible reasons for this are (1) mantle reflections are preferentially preserved beneath older domains; or (2) during final phases of accretion, subduction zones preferentially dip beneath the craton.

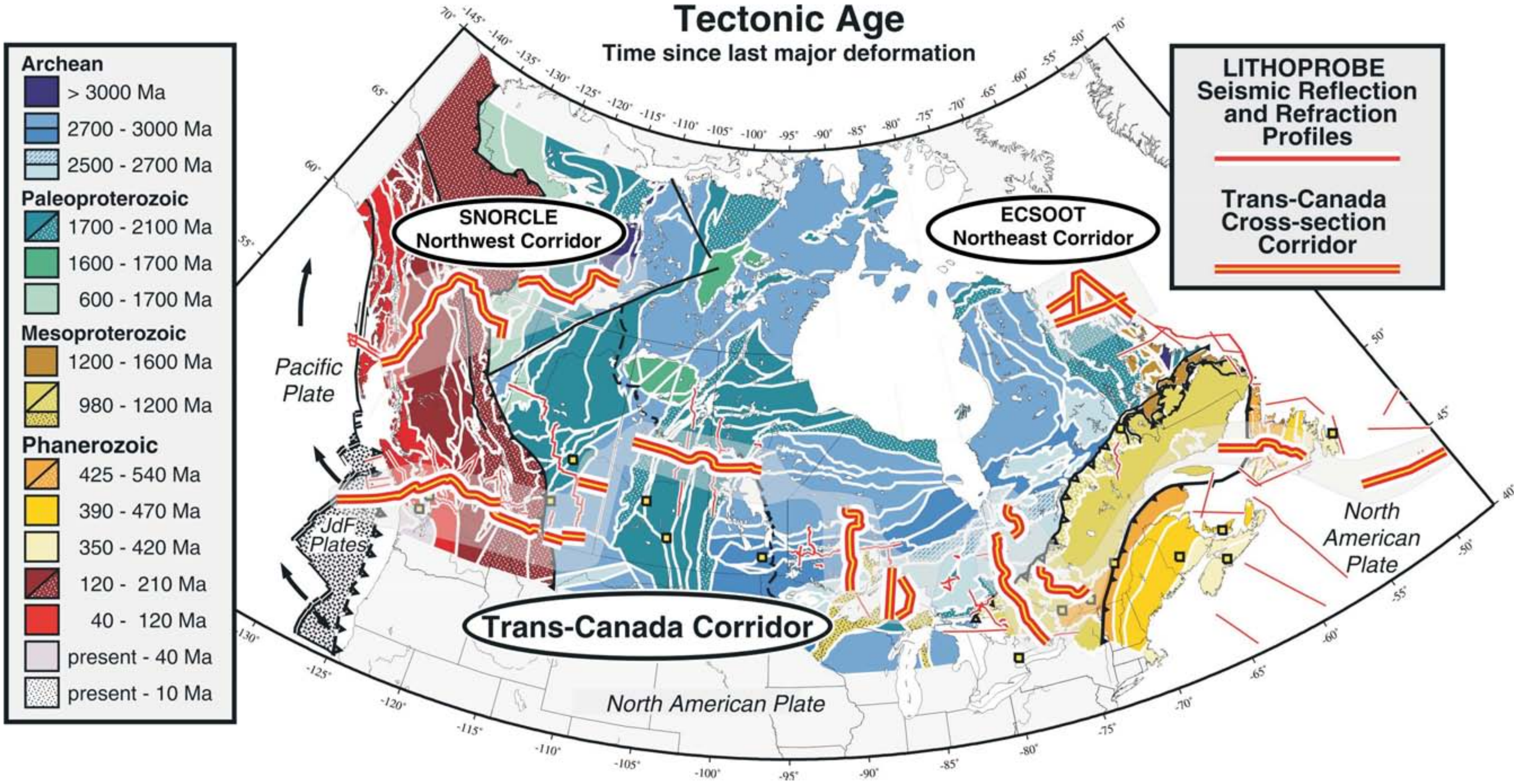

Fig. 1. The map of Canada indicates general tectonic age; the time since the last major deformation. The location of the Trans-Canada Seismic Transect is shown by the bold red-yellow lines. The corridor follows selected coincident reflection and refraction lines, providing a near continuous transect across the continent. Two additional corridors are also highlighted: the SNORCLE northwest transect and the ECSOOT northeast transect. Other seismic lines acquired by LITHOPROBE and other groups are shown as thin red lines.

Sedimentary Basins Related to Late-Orogenic Strike Slip: LITHOPROBE East and the Maritimes Basin in the Appalachians

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Many of the orogenic belts imaged by Lithoprobe contain deep sedimentary basins, formed late in the history of the orogen, and associated with major strike-slip faults. For example, Paleogene basins formed in the southern Cordillera, and late Archean basins are found in the Slave and Superior cratons. Such "successor basins" are particularly prominent in the Lithoprobe East area, where sedimentary basins of Carboniferous (Mississippian-Pennsylvanian) age are superimposed on the mosaic of Appalachian terranes assembled in the Devonian Acadian orogeny. The largest of these basins, the Maritimes Basin (Fig. 1), contains numerous sub-basins, many of which record evidence for strike-slip motion, mainly dextral, during their development.

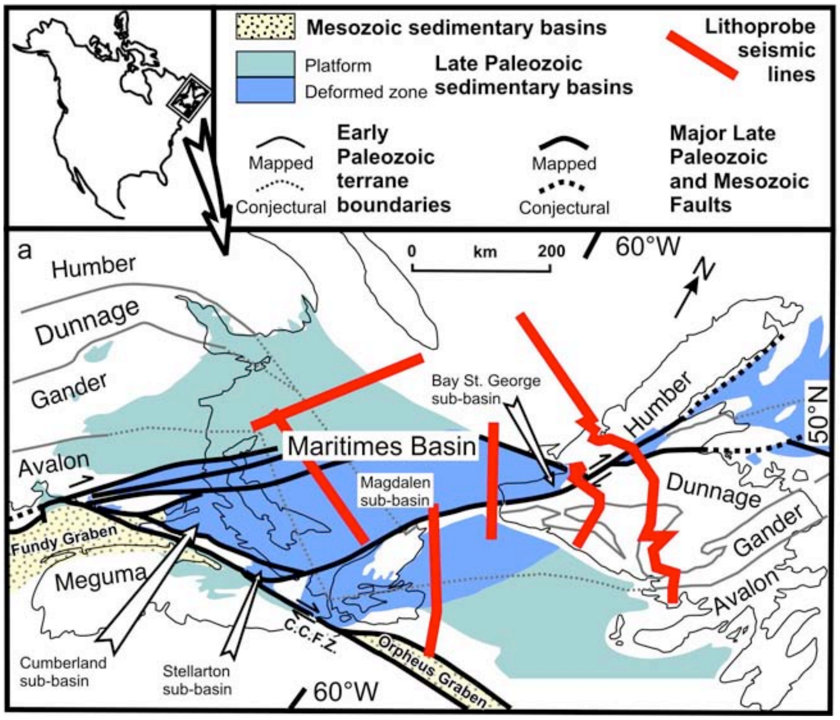

Figure. 1. Map showing extent of the late Paleozoic Maritimes Basin in the Canadian Appalachians

The Maritimes Basin is located at a right handed stepover on a dominantly dextral, NE-SW fault system that extends from New Brunswick to Newfoundland. Within the basin, graben and half-graben fills (locally inverted) of Early Mississippian age (Horton Group) are overlain by extensive evaporite-bearing marine successions (Windsor Group). Exceptionally thick Windsor successions were probably located in the Bay St. George sub-basin in Newfoundland and in the Cumberland sub-basin of Nova Scotia, although in some of these areas Windsor evaporites have been largely removed during later halokinesis. Industry seismic data show that major normal faults are present at both the north and south extremities of the basin, and were probably active during Mississippian time, creating accommodation space and controlling sedimentation in the Windsor Group and probably the overlying, non-marine clastic Mabou Group. In contrast, the lateral bounding faults of the basin show relatively little offset of major stratigraphic units. At the south margin of the basin, extension was interrupted by dextral strike-slip motion along the east-west Cobequid-Chedabucto Fault Zone at the end of the Mississippian, producing a profound but very localized unconformity between the Mabou Group and overlying Pennsylvanian rocks. Subsequent Pennsylvanian successions, exceptionally well imaged in Lithoprobe seismic profiles, accumulated in accommodation space created by a combination evaporite withdrawal and thermal subsidence.

These relationships can be explained by a model in which strain, localized on linear fault strands to the NE and SW, becomes distributed over a wide area at a releasing stepover, producing a basin in which deformation is dominated by normal faults, with contemporary rotation of fault blocks. This model, though developed from observations of a small pull-apart basin (Stellarton sub-basin) can explain many features of the broader Maritimes Basin, including the presence of major depocentres, bounded by predominantly dip-slip faults at the NE and SW extremities of the basin, and the relatively minor offsets at the NW and SE bounding faults. It is likely that a similar style of deformation has affected many sedimentary basins developed late in the history of other orogens, where strike-slip motion between bounding continental blocks continued after the peak of convergence. To understand the geometry of orogens as a whole, it is necessary to determine the kinematics of such basins, and to take out-of-plane movements into account in the development of cross-sections and models.

Lithoprobe Transect:- The Kapuskasing Structural Zone
A Summary and Personal Interpretation of Results

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The Kapuskasing Structural Zone (also known as the KSZ, the Kapuskasing Uplift or KU) was selected in 1983 by Project LITHOPROBE as the locus of its first multi-disciplinary transect study. It is an elongate, 400 km long, anomalous tectonic feature which runs NE - SW between James Bay and eastern Lake Superior and it bisects the archetypical Archean craton, the Superior Province, into eastern and western blocks. In it, rocks metamorphosed to the granulite facies in the mid to lower crust have been tectonically uplifted ~20 km or more to the surface.

Before Lithoprobe's research program, geological mapping of the KSZ was already extensive (by J. A. Percival of the GSC and other earlier geologists). However, the origin and projection to depth of the structure was not very certain. Nevertheless, it was clear, despite the relative paucity of outcrop in the area, that the KSZ could provide important opportunities to study lower crustal geological processes.

Lithoprobe's scientific program began in 1984, with J. A. Percival and G. F. West as co-transect leaders, and it continued vigorously for about 5 years. Several tens of scientific participants contributed results to the program, some partially funded by Project Lithoprobe and others not. The largest Lithoprobe-financed components were a crustal scale seismic refraction survey carried out by university and GSC seismologists in 1984 and a set of crustal scale seismic reflection profiles carried out by an industry contractor in 1987-8.

A summary volume of scientific findings was published in the Canadian Journal of Earth Science in 1994 (v31, n7), edited by J. A. Percival. This poster summary draws heavily on that volume. It consists of about a dozen poster-sized (90 x 80 cm) pages describing the transect program and the significance of its results. The material is also available on CDROM, but is not in any standard GIS format as the basic data were acquired before GIS technology was available. This poster presentation also includes some later results and gives the author's personal conclusions of what was learned about crustal tectonics. Some transect participants may hold contrary or alternative views about some aspects. The investigation results are too extensive and diverse to be described in this abstract, so it concentrates mainly on the interpretation of results.

At the inception of the transect program, a widely accepted view was that the KSZ was a post-Archean, pre-Keweenawan thrust front of some kind, the result of many tens of kilometers of lateral convergence of the crust along a major, regional, crust-penetrating, listric, thrust fault dipping shallowly to the north-west. Earlier views were that it was a late Archean uplift of some kind, possibly a horst.

Because deducing a more complete picture of the KSZ's evolution has required many kinds of evidence, the KSZ Transect program is an excellent example of the value of the multidisciplinary approach espoused by Project Lithoprobe. Some of the key investigations and results are the following. The metamorphic depth of rocks outcropping in the south-central parts of the KSZ was mapped out in considerable detail. Isotopic studies and other evidence confirmed that the main period of uplift was at about 1.9 Ga. The seismic refraction survey showed that the present thickness of the crust is is indeed anomalously large under the KSZ. The reflection survey lines revealed numerous shallowly dipping reflectors in the crust which dip (broadly) to the northwest like the supposed thrust surface. However, several lines of evidence indicate this reflectivity arises from the ubiquitous shallow dipping, irregular compositional layering formed during the Archean metamorphism of the mid and lower crust and now much closer to the surface. There is also evidence of a very late Archean episode of tectonic uplift in the KSZ Chapleau block, which may be related to a Temiscaming type event involving N over S thrusing, but does not seem causatively connected to the whole KSZ.

Analysis of the numerous post Archean dyke swarms that cross the KSZ region and which are (in some cases) horizontally deformed by it showed that the cumulative horizontal strain (including fault displacement) in the KSZ deformation is dextral transpressive and attenuates southwest of Chapleau. Relative lateral displacement at the main fault lines likely never exceeded 30 km. Thus, the regional fault structure that encloses the uplifted zones of the KSZ is not principally a shallow dipping thrust with a very large lateral convergence.

Although in most parts of the KSZ, deformation likely began with west-over-east duplication of relatively brittle upper crust by faulting, and this was responsible for the overall NW –SE asymmetry of the present KSZ structure, the initial fault dominated phase of deformation soon evolved into a steady ductile accumulation of metamorphosed lower crust in “popups” along the KSZ. Because the hot lower crust was so very much weaker than the cool upper crust, deformation focused mainly in the ductile material as crustal shortening continued. As fault–elevated upper crust was removed from the surface by erosion, ductile lower crust beneath it rose isostatically to replace it. Isostatically coupled with the gradually loss of low density upper crustal material from the popup areas was a progressive depression of the M discontinuity and local thickening of the whole crust there.

In summary, as a consequence of an extended period of regional crustal shortening that in the KSZ that may have totaled ~ 30 km and facilitated by a very high ductility of the lower crust and focussed by a relatively rapid erosion of any local surface uplifts, local patches of deep-seated Archean-metamorphosed rocks near the KSZ boundary faults were gradually and locally uplifted by amounts as large as ~ 20 km with respect to neighboring geology.

The foregoing picture also accords with how the KSZ fault and uplift structure gradually extended itself towards the southwest. Also, the whole scenario integrates gracefully into the larger picture of how a Proterozoic North-American tectonic plate was finally gathered together and welded into nearly its present form at about 1.9 Ga. This event likely included a twisting of the western Superior Province a few degrees clockwise with respect to the eastern block about a hinge point near the east end of lake Superior and significant crustal shortening in the crust under James and Hudson Bay.

The picture of KSZ evolution generated by the Lithoprobe KSZ program also fits well with the findings of the Abitibi and Western Superior Lithoprobe transects. In these areas, it is seen that a stable, peneplaned, cratonic crystalline crust was quickly produced within about 50 Ma (at about 2.55 Ga) at the end of a ~100 Ma period of intense mafic volcanism followed by about 50 Ma of copious felsic plutonism. Although the rocks exposed in these (and most other) Archean cratons) may record very complex and locally different early tectonic histories, they now exhibit an almost layer-cake geophysical structure:- a very uniform crustal thickness, a nearly homogeneous lateral density structure beyond 5-10 km depth, and a ubiquitous, sub-horizontal, intense seismic reflectivity (at least in their middle and deeper parts) that likely images coarse, metamorphically generated, compositional layering there.

It also appears that everywhere in these cratons the lower crust remained (at least throughout lower Proterozoic time) very pliant in comparison to the much cooler upper crust. This great dichotomy in strength and viscosity appears to be a key factor in the sudden and widespread cessation of tectonic activity in the visible parts of Archean cratons. As the upper crust cooled, essentially it was floating like a rigid ice sheet on a layer of mobile deep crust which itself was lying on a thick root of slightly buoyant and (probably) stronger cratonic mantle. As long as a craton's mantle root protected it from large scale regional deformation, its upper crustal sheet was almost completely immune to any kind of local lateral deformation.

That older Precambrian cratonic cores of the continental crust are largely underlain by old (and seemingly long attached) buoyant mantle roots is not a Lithoprobe result. Much of the evidence comes from other continents. The presence of some kind of thick low S velocity lithospheric root under the Canadian Shield was noted early by earthquake seismology. Evidence that much of it probably is very old is (for Canada) a by product of intensive diamond exploration in the last two decades. Nevertheless, it is crucial to incorporate this evidence into the analysis of Lithoprobe results and try to learn more about their nature.

With the above in mind, it is interesting to note that cessation of widespread, penetrative tectonic deformation that is the defining element of cratonization in the Superior Province (and other old cratonic continental crust) was not generally accompanied by a complete cessation of mafic magma injection from deeper (presumably) convecting mantle. Swarms of post cratonic Precambrian mafic dykes abound in many of the cratons. One wonders whether the parent magma of the dykes was transported into the crust through its underlying mantle root or whether it mainly made its way into the crust at points where the cratonic root was perturbed, for example where the craton was rifting or about to rift.

Orogenic Channels in the Paleoproterozoic: Kinematics of Cratonic Collision and Exhumation, SW Baffin Island, Canada

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Elucidation of continental architecture, its evolution through time and determination of the associated geodynamic processes has been central to the LITHPROBE mandate throughout its existence. Numerous field geological, geophysical and numerical modelling studies have directed toward attaining this goal. Mapping from Baffin Island is at once peripheral to specific geophysical transects (THOT, ESCOOT), yet central to overall aims of the program. Specifically, the Meta Incognita peninsula and associated islands provide evidence for focussed flow in the lower crust supportive of current models for continent-continent collision.

The Quebec-Baffin Is segment of the Paleoproterozoic Trans-Hudson orogen comprises a craton-to-craton record extending from the foreland fold-thrust belt in the south to exhumed lower crustal lithologies formed during continental collision of the Superior and Rae cratons (lithosphereic slabs) and the intervening Ramsay River microcontinent. The Archean craton – Proterozoic contact comprises a first-order protolith boundary that is variously expressed, with increasing structural level, as an unconformity, a discrete zone of detachment, a zone of localized ductile shear, through to a zone of intense lower crustal deformation involving both craton and cover units. Within SW Baffin Is, the protolith boundary is well exposed as intensely deformed Archean and Proterozoic metasedimentary and metaplutonic units (Mina shear zone) exhumed from the lower crust conditions.

The principal spatial (Fig. 1) and temporal elements of this collision zone are: (1) juxtaposition of cratonic and allochthonous units of distinct paleogeographic provenance; (2) development of an initially similar kinematic record in both cratonic and allochthonous units indicative of NE-SW convergence with SW verging folds consistent with both burial and exhumation of the Proterozoic rocks; (3) peak metamorphism (granulite grade) concomitant with the coincident amalgamation of the Archean and Proterozoic terranes, formation of a distinct zone of intense shear (Mina shear zone)and introduction of syntectonic partial melts; (4) the apparent reversal of displacement associated with development of the Mina shear zone as recorded by NE-verging structures; (5) a return to SW-vergent fold structures that deform craton, allochthon and the intervening Mina shear zone as a single tectonic unit.

The latter observations can be reconciled by differentiating between material and kinematic reference frames. Initially, collisional interaction produces crustal thickening and inversion of Proterozoic units during underthrusting of the Superior (lower) plate and records SW vergence within both cratonic and accretionary units. The apparent reversal in kinematics coincides with classical peak metamorphic temperature conditions and syntectonic melts that collectively reflect formation of an orogenic channel within which the most significant exhumation occurs. Notably, there is related extensive out-of-plane deformation perpendicular to the tectonic transport direction. Evidence for rapid exhumation is largely contained within the Minas shear zone and in proximity to the protolith boundary (ie. this is the zone of most rapid exhumation or return flow). During exhumation, there is a decrease in the calculated pressures, but an increase in temperature; that is, the first order inverted metamorphic gradient is a true inversion of P/T relationships that cannot represent an exhumed normal crustal geotherm. Whereas SW vergence continues to be recorded in both hanging wall Proterozoic units, and footwall Archean basement, the Minas shear zone records NE (reverse sense) verging structures that develop from relative velocity contrast during the movement of material from depth within the channel. The concentration of the Minas shear zone within a Proterozoic tonalite unit that extends down-structure over several hundred kilometres at near constant thickness and exhibits a monotonous compositional flow foliation suggests that it is the locus for such an exhumation zone. As deep crustal material reaches and equilibrates to shallower P/T conditions, rheological hardening of material defined by the exhumation zone will occur. This is seen in the transition from localized to more "thick thinned" deformation wherein the exhumation zone is itself folded during continued SW vergence. Hence, within this Paleoproterozoic collision, there is a record of thermal-mechanical evolution comprising thickening of the continental root, development and evolution of an orogenic channel, associated exhumation and decay of channel kinematics as changes in rheology occur.

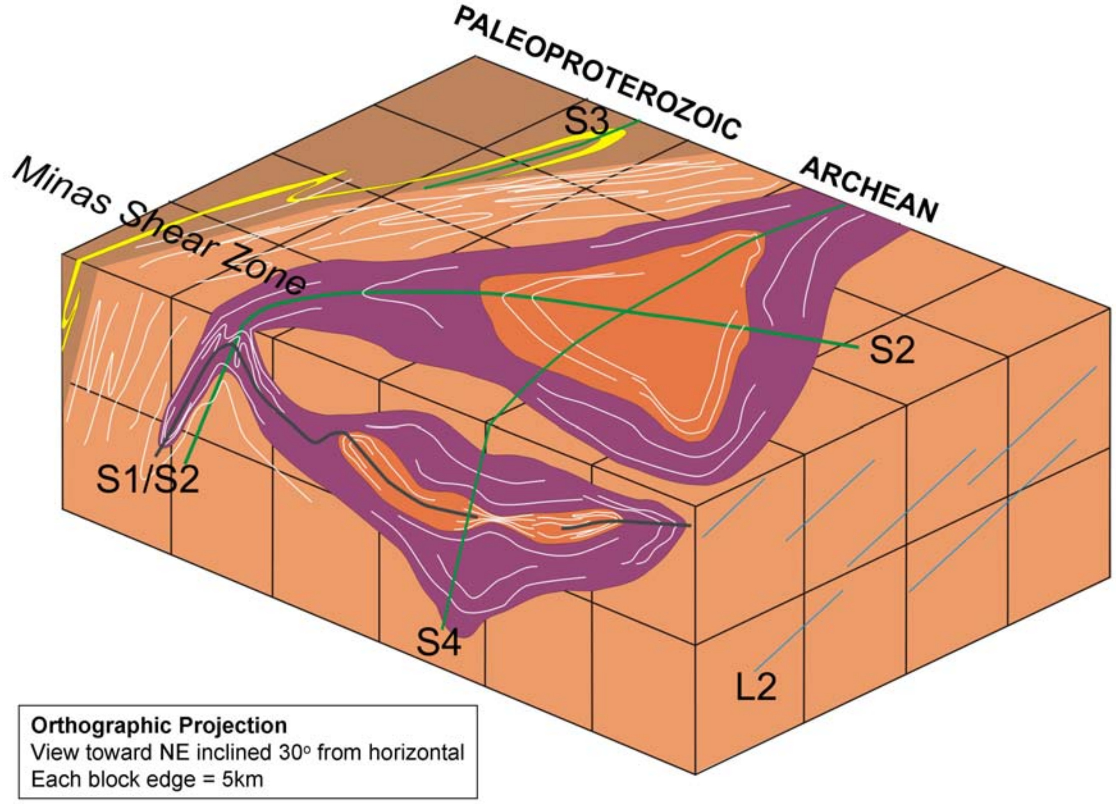

Figure 1 Block diagram of central Big Is across fundamental Archean-Paleoproterozoic protolith boundary that has kinematic and metamorphic similarities with the Main Central Thrust of the Himalaya consistent with orogenic channel flow. The Minas shear zone demarcates a zone of intense deformation associated with both peak pressure (decompression) and peak temperature (thermal equilibrium) records and a transient reversal from thrust-sense to normal-sense flow. Although concentrated within the Minas shear zone, Paleoproterozoic flow involves at least 10 km of Archean crust.