How Will LITHOPROBE's Final Chapter Be Written?

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SUMMARY

Fifteen years after pioneering a program of integrated research in the earth sciences, LITHOPROBE faces the challenge of assembling and integrating results acquired in ten transects across the Canadian landmass that have sampled four billion years of Earth history. Beyond the data legacy that LITHOPROBE will leave, a global synthesis is planned that will serve as a comprehensive conceptual framework for the structure and evolution of the continental crust. A Pan-LITHOPROBE subcommittee, formed to provide guidance through the synthesis process, is proposing that LITHOPROBE insights be used to address current thematic issues of global relevance and interest. To obtain broad input to the synthesis, LITHOPROBE will sponsor a series of thematic workshops on topics including: Variations and Styles of Tectonic Processes through Space and Time; Crustal Growth, Preservation and Recycling; Magmatic, Metamorphic and Tectonic Processes; and Lower Crust, Moho and Mantle Lithosphere. Each workshop will yield a LITHOPROBE report and initiate work on formal publication volumes. We solicit suggestions for additional unifying themes.

RÉSUMÉ

Quinze ans après l'instauration d'un programme de recherches intégrées en sciences de la Terre, LITHOPROBE doit maintenant relever le défi de la collecte et de l'intégration des résultats provenant de dix coupes transversales réalisées à travers le sol canadien et pour lesquelles des échantillons représentant quatre milliards d'année d'histoire de la Terre ont été prélevés. Dans le cadre de LITHOPROBE, en plus de sa récolte de données, on a planifié la production d'une synthèse à l'échelle du globe et qui servira de cadre conceptuel sur la structure et l'évolution de la croûte continentale. Un comité parapluie multidisciplinaire de LITHOPROBE, formé pour guider les travaux de cette synthèse, propose que les nouvelles connaissances provenant des travaux de LITHOPROBE seront intégrées dans la solution de problèmes thématiques courants et d'intérêt global. Afin de favoriser un maximum de contribution à cet essai synoptique, LITHOPROBE commanditera une série d'ateliers thématiques dont : les styles et les variations des processus tectoniques dans le temps et l'espace, l'accrétion, la préservation et le recyclage de la croûte, les processus magmatiques, métamorphiques et tectoniques et, la croûte inférieure, les couches de Moho et du manteau de la lithosphère. Chaque atelier publiera un rapport LITHOPROBE et initiera des travaux menant à un volume de publications formelles. Toutes suggestions sur d'autres thèmes unificateurs sont bienvenues.

INTRODUCTION

In 1996 a Pan-LITHOPROBE subcommittee was formed by LITHOPROBE's Scientific Committee, with the broad mandate to "provide advice, direction and comments on LITHOPROBE scientific activities as they pertain to the global synthesis planned for the project to ensure that results and syntheses from individual transects are considered as a coherent whole and with a view to what has been learned about the overall structure and evolution of the North American continent and the processes involved in that evolution." The members of the subcommittee are Chris Beaumont, Fred Cook, Dave Eaton, Larry Heaman, Roy Hyndman, Alan Jones, Steve Lucas, John Percival, Toby Rivers, Gerry Ross and Tom Skulski. It is chaired currently by John Percival.

An initial meeting took place in December 1996 to discuss the theme "LITHOPROBE results and geodynamical modelling: contributions and needs." About 40 participants from LITHOPROBE and the Geodynamic Modelling Group of the Canadian Institute for Advanced Research (CIAR) Earth Systems Evolution Program, which includes scientists from Canada, the United States and Australia, discussed this theme during the one-day meeting. In addition, other themes relating to fundamental tectonic processes were identified and are discussed below.

Since its inception in 1985, LITHOPROBE has held as its *modus operandi* the integration of information from a broad spectrum of geoscience disciplines. Applied to individual LITHOPROBE transects, this approach has resulted in crustal and lithospheric-scale syntheses of geological and geophysical data (*e.g.*, Clowes *et al.*, 1996; Percival, 1994; Ludden, 1994; Cook, 1995a). As LITHOPROBE enters the last of its five phases and the components of a composite lithospheric profile near completion, the community faces perhaps its greatest challenge, which is a pan-LITHOPROBE synthesis. A portion of the Supporting Geoscience budget has been dedicated to Pan-LITHOPROBE research, an integral part of completing the project. Below, we outline a suggested strategy for achieving some aspects of this goal that will involve a broad cross section of LITHOPROBE workers, as well as other Canadian and international scientists.

The wide scope of LITHOPROBE results (Fig. 1) requires that the ultimate synthesis be approached as a series of manageable pieces, and we advocate subdivision based on themes of current global interest. It is planned that each theme will be addressed through a Pan-LITHOPROBE-sponsored workshop that would assemble representatives from each transect and interested members of the earth science community to draw out common threads among transects, focus on processes underlying observations, and form working groups to advance interpretations that have global impact. Examples of themes are developed below, highlighting LITHOPROBE contributions. One or two workshops per year, comprising groups of 60-100 people, will lead to components of the synthesis volumes to be prepared by LITHOPROBE. Workshop proceedings will be published as LITHOPROBE reports and more formal publications will follow.

VARIATIONS AND STYLES OF TECTONIC PROCESSES THROUGH TIME AND SPACE

Geodynamic Modelling

One of the quantitative approaches being developed by groups around the world to investigate tectonic processes is geodynamical modelling using analog laboratory experiments and/or numerical techniques (*e.g.,* Beaumont *et al.,* 1994; Braun and Beaumont, 1995; Gutscher *et al.,* 1996; Beaumont *et al.,* 1996; Lowman and Jarvis, 1996; Royden, 1996). Geodynamic modelling provides a technique through which relationships between the thermo-mechanical properties of the Earth and deformation processes are being studied. Two components are involved. One is the continuing development of computer simulation capabilities to enable modelling of more realistic and complex processes that have been active in the evolution of the continent. Successful implementation of these capabilities advances our understanding of the processes, from the descriptive or conceptual, to an understanding based on physical principles. The varied and comprehensive geoscience data base and interpreted results from LITHOPROBE transect studies provide a test for the models. However, the model results are also needed as template and glue for binding the multidisciplinary interpretation of transect observations, and in the composite synthesis of the evolution of a continent. Thus, the second component is application of geodynamic modelling to the fundamental tectonic processes inferred within each transect and through Pan-LITHOPROBE studies for the purpose of testing whether such processes generate results similar to the observations.

Within LITHOPROBE, much of the geodynamic research has focussed on plate boundary processes and the role of the crust and mantle components of the lithosphere. Although these models are necessarily limited mathematical simplifications of multi-scale Earth processes, they demonstrate how components of the system act independently and in concert. By inference, it is possi-

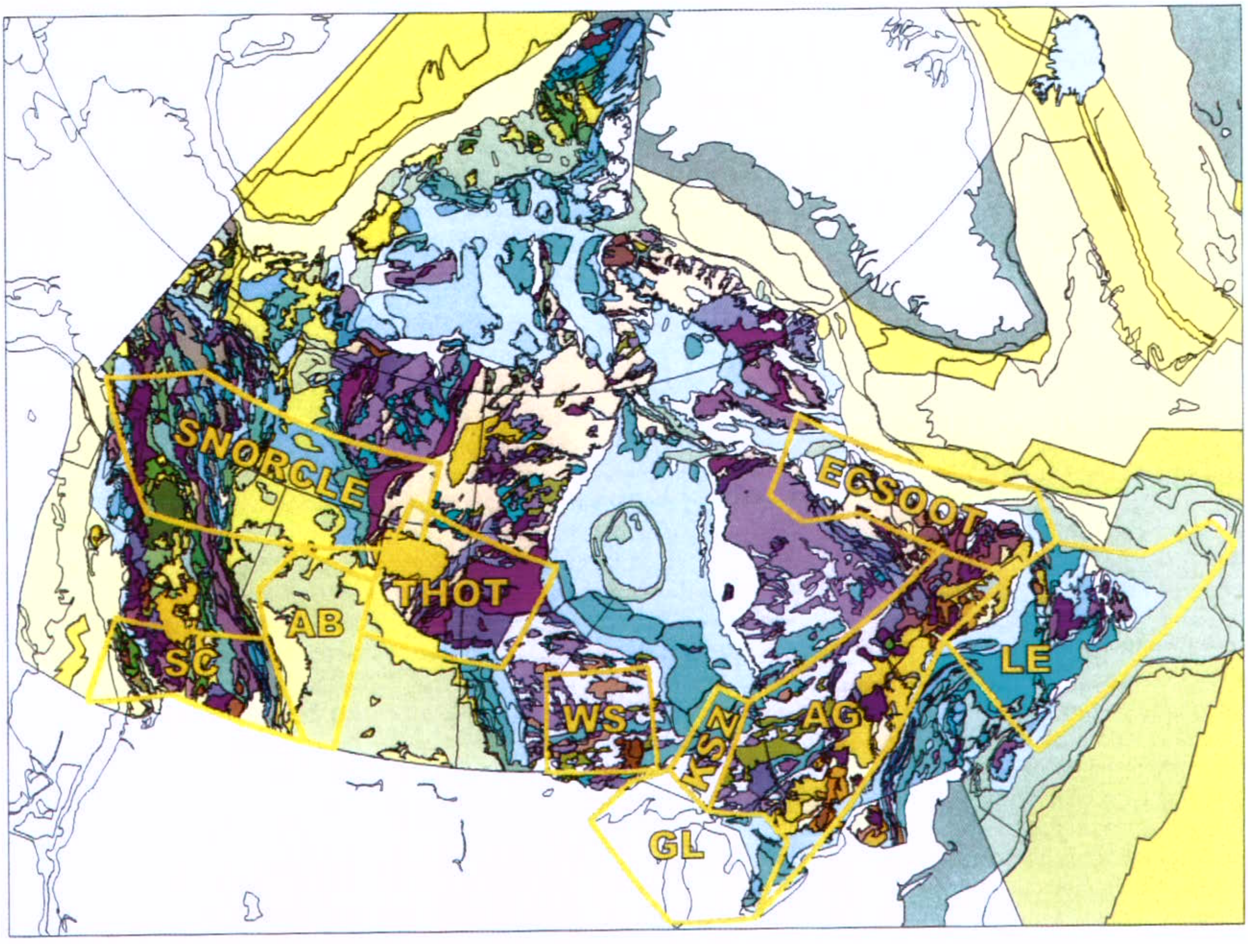


Figure 1 LITHOPROBE transects (after Clowes, 1996) superimposed on a simplified geological map of Canada (after Wheeler *et al.,* 1996). Transects are: SC, Southern Cordillera; SNORCLE, Slave-Northern Cordillera Lithospheric Evolution; AB, Alberta Basement; THOT, Trans-Hudson Orogen; WS, Western Superior; GL, Great Lakes International Multidisciplinary Program on Crustal Evolution (GLIMPCE); KSZ, Kapuskasing Structural Zone; AG, Abitibi-Grenville; LE, Lithoprobe East; and ECSOOT, Eastern Canadian Shield Onshore-Offshore Transect.

ble to propose, and sometimes draw conclusions about, those processes that are primary and those that are secondary during lithospheric interactions. To be helpful, the numerical models must predict dynamic evolution of systems for large deformation. They must make predictions that relate to the tectonic, structural, thermochronological, metamorphic and magmatic processes that occur during continental aggregation and disaggregation. The model predictions must also offer guidance in the interpretation of what is commonly equivocal or enigmatic seismic evidence, such as reflectivity fabric and shear wave splitting, and their relationship to deformation. Geodynamic models can provide the necessary framework to assemble and interpret the inevitably fragmentary, disparate and insufficient data that are available.

Origin of Compressional Orogens

Convergent margin and orogenic (mountain-building) processes are central to continental assembly. Two hypotheses underlie much of the recent geodynamic research on compressional orogens. One proposes that deformation responsible for lithospheric shortening, thickening and the uplift of mountain belts and plateaus stems from a competition between gravitational and horizontal forces acting within the lithosphere. Crust and mantle lithosphere deform in much the same manner, by large-scale "pure shear" thickening, and they remain coupled as a single unit during deformation. Mantle lithosphere may become gravitationally unstable and parts of it may detach and sink into the underlying mantle. This convective instability is considered to be a consequence of the thickening of mantle lithosphere.

The second hypothesis proposes that plate collisional processes leading to orogenesis are essentially similar to subduction. That is, subduction and collision are facets of the same general mechanical process, governed by the fraction of the subducting plate that actually subducts. This fraction depends on the negative buoyancy of the subducting limb and on the properties of the lithosphere: for example, the ease with which the "subducting" and "colliding" parts (loosely crust and mantle) can be separated or delaminated. In this hypothesis, forces that act beneath the orogen, on or within the subducting slab, are equally important to the horizontal and gravitational forces. The buoyancy of the slab and the plate motions control processes like subduction zone advance and retreat, and slab breakoff. Although such end-member hypotheses are useful to highlight distinctions between generalized subduction and large-scale lithospheric thickening, it is likely that natural orogens involve a range of behaviour that encompass the end-members, intermediates and other processes that have yet to be clearly understood and defined, or even discovered.

LITHOPROBE Results: Constraints and Challenges

LITHOPROBE transect investigations have examined many examples of convergent margins and collisional orogens spanning the last 4 billion years of Earth history. The LITHOPROBE data, supported by data from world-wide counterparts, provide constraints never before available on such a continent-wide scale. Does the evidence support either of the end-member hypotheses, lead to their rejection, or can it be used to develop a more refined and realistic model that explains why intermediate and other styles exist? A particular question concerns changes in the styles of plate boundary processes during Earth evolution. Are models developed for modern processes universally applicable, or are there fundamental differences between the Archean and modern thermal and tectonic regimes? One important aspect of the Pan-LITHOPROBE synthesis is to propose and test these more general models of orogenesis. The concepts illustrated in Figure 2 are presented as a prototype; they are based on results of geodynamic models and comparisons with observations from a range of orogens.

More specifically, results of plane-strain finite element model experiments, designed to investigate the mechanical behaviour of convergent margins, lead to a proposed classification based on which components of the system (Fig. 3) are active during convergence. The model results (Fig. 4) show some of the styles, or modes, that are seen when model controls are varied. For example, styles that correspond to near-perfect subduction and various combinations of accretionary wedge (pro-wedge), plug uplift and retro-wedge development are possible. The models also consider subduction of material in the subduction channel, and the effect of tectonic underplating in the slowly deforming subduction conduit beneath the hanging wall of the retro-lithosphere. Modes C and D (Fig. 4), for example, are particularly favoured when the subduction zone respectively retreats or advances during convergence. Retreat of the subduction hinge point separates the subducting and overriding plates, thereby providing room to accommodate tectonically underplated material. Advance of the subduction hinge has the opposite effect and may cause tectonic erosion (ablation) of the retro-lithosphere.

These modes are all examples of the tectonic styles anticipated for Type 1 orogens (Fig. 2). Some of the convergent margins/weakly collisional orogens studied by LITHOPROBE may fit within this classification. For example, the Vancouver Island segment of the modern Cascadia convergent margin has a mode C style, whereas individual Archean accretionary "granite-greenstone" belts may have the complete range of model styles.

The continuing development of numerical procedures to more realistically replicate complex tectonic processes, and the application of these to the tectonic processes being studied within individual transects, is an essential element of the Pan-LITHOPROBE synthesis.

MAGMATIC, METAMORPHIC AND TECTONIC PROCESSES

Magmatism represents an important agent of heat and material transfer within the lithosphere and across the asthenosphere-lithosphere boundary (*e.g.*, Kay and Kay, 1991). A major challenge in many LITHOPROBE transects has been to interpret the tectonic setting of magmatic rocks and to understand interrelationships among magmatic, metamorphic and tectonic processes. In the plate tectonic paradigm, plate rifting and associated alkaline magmatism evolve to spreading centres, producing tholeiitic oceanic crust that is consumed during subsequent subduction and contributes to arc magmatism. Details of these processes in ancient orogens have been elaborated through a variety of approaches in several LITHOPROBE transects.

Magmatic Arc Relics as Orogenic Building Blocks

Although fragments of oceanic crust are

sporadically preserved in the form of ophiolites in the Appalachian and Cordilleran orogens, and are known in the Mesoproterozoic Grenville and Paleoproterozoic Ungava orogens, relics of arc magmatism figure more prominently in the geological record. Accreted oceanic terranes such as the Abitibi subprovince of the Superior Province (Ludden *et al.*, 1986; Desrochers *et al.*, 1993), Hottah terrane of Wopmay orogen (Hildebrand *et al.*, 1990), Reindeer zone of the western Trans-Hudson orogen (Lucas *et al.*, 1996), Kuujjuak terrane of the New Quebec orogen (Perreault and Hynes, 1990), parts of the Dunnage zone of the Appalachians (Johnston *et al.*, 1994; Piasecki, 1995), and Quesnell, Dorsey, Stikine and Cache Creek terranes of the Cordillera (Monger, 1993), represent oceanic arc and back-arc assemblages that became fundamental building blocks of the evolving orogens. Collisions between these <20-km-thick juvenile terranes and adjacent continental masses resulted in the early (D1) deformation recognized in many orogens.

Granitoid Batholiths

In most orogens the resulting sutures are cryptic, both structurally and seismically, having been metamorphosed, reworked by later deformation, and intruded by marginal (Andean-type) arc magmas. These magmas, derived from subducting slabs and the mantle wedges above them and variably influenced by fractionation and assimilation

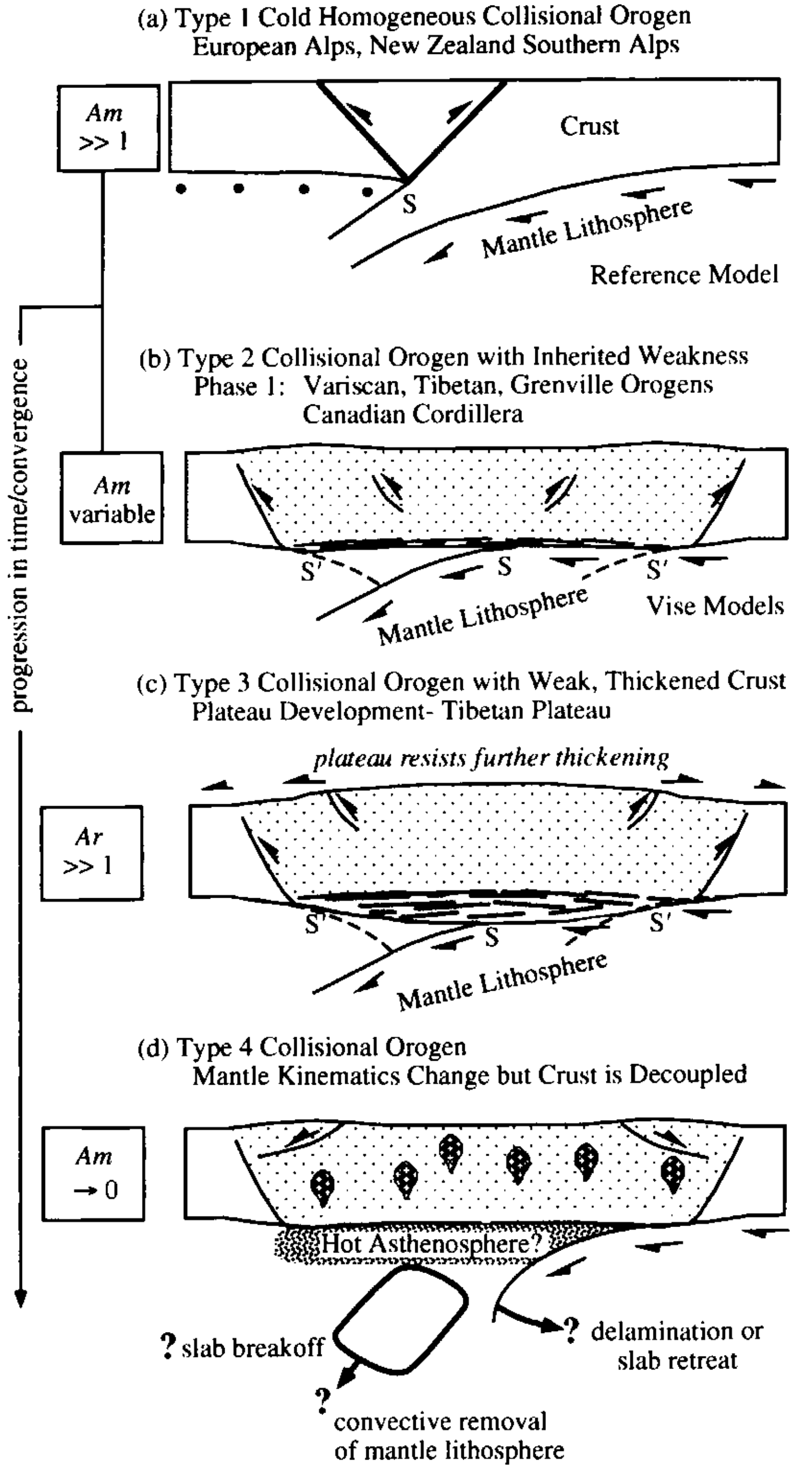


Figure 2 A schematic illustration of types of orogens that span the end member hypotheses. (**a**) Focussed deformation style of simple orogens where deformation of the crust is a consequence of underlying mantle subduction, at point S, and crust is strongly coupled to the mantle, most likely because it is cold. (**b**) Wider orogens develop when the crust is weakly coupled to the subducting mantle. Weak coupling may occur owing to accretion of weak heterogeneous terranes or because the orogenic core becomes hot. These circumstances can be represented by "vise models" in which weaker internal parts of the orogen are squeezed in a vise-like manner by external stronger crust. Unlike (a) the crustal deformation in (b) shows little evidence of underlying mantle processes; that is S, the subduction point, is difficult to detect from the crustal deformation. (**c**) Large orogenic plateaus may evolve from Type 1 or Type 2 orogens when crustal thickening results in heating and additional weakening of the internal part of the orogen. Deformation concentrates at the interface between the plateau and the external stronger crust. Because the crust is then only very weakly coupled to the mantle, it is hard to decipher mantle kinematics from crustal deformation. (**d**) Mantle kinematics no longer correspond to simple subduction. Crust is so weak that it is totally decoupled from the behaviour of the underlying mantle. Widespread extension may occur in the orogenic core. The mantle lithosphere may thicken by pure shear, undergo slab breakoff, be removed convectively or delaminate and undergo slab retreat. Argand (Ar) scaling represents the ratio of gravitational forces to horizontal in-plane forces; Ampferer (Am) scaling the ratio of traction forces at the base of the crust to horizontal in-plane forces. The two end-member hypotheses (Type 1 and Type 4) represent cases where the Ampferer control and Argand controls are dominant, respectively. Types 2 and 3 are intermediate cases. Types 1-4 could occur for any size of orogen. However, given that large orogens are normally the hottest, Types 3 and 4 are usually associated with large orogens. (From Ellis *et al.*, 1998)

(*cf.* Hildreth and Moorbath, 1988), form the impressive granitoid batholiths occupying the hinterlands of orogens (*e.g.*, Berens, Bienville and Utsalik batholiths of the Superior Province (Stern *et al.*, 1994; Skulski *et al.*, 1998; Corfu and Stone, 1998), Great Bear arc of Wopmay orogen (Hildebrand *et al.*, 1987); Taltson (Theriault, 1992), Wathaman-Chipewayan (Meyer *et al.*, 1992), Cumberland (St-Onge *et al.*, 1998) and de Pas (Dunphy and Skulski, 1996) batholiths of the Trans-Hudson orogen; Trans-Labrador batholith of the Labrador orogen (Kerr *et al.*, 1995); granite-rhyolite belt of southeastern Mesoproterozoic Laurentia (Anderson, 1983; Mosher, 1998) and its extensions throughout the southern Grenville province; and Coast plutonic complex of the Cordilleran Coast Ranges (Ghosh, 1995). The ponded residues from these batholiths may constitute significant parts of continental lower crusts. In some arcs, backarc extension produced short-lived oceanic and continental basins that collapsed during subsequent deformation: for example, Kisseynew domain of the Trans-Hudson orogen (Ansdell *et al.*, 1995); Elzevir terrane of the Grenville Province (Rivers, 1997); Bridge River terrane of the western Cordillera (Cordey and Schiarizza, 1993).

Emplacement of large granitoid batholiths, locally up to 1000 km in length (*e.g.*, Wathaman batholith of the Trans-Hudson Orogen, Trans-Labrador batholith of the Labrador Orogen) resulted in advection of large amounts of heat into the mid-crust. In addition to their large volume, many intrusive complexes of Archean and Proterozoic age are charnockitic (containing igneous orthopyroxene), indicating hot, dry magmas generated in settings not well represented in the younger geological record. Although considerable progress has been made in understanding the nature and origin of pre-, syn- and post-tectonic magmatism in individual orogens, it remains unclear why some orogens are dominated by granitoid intrusions, whereas others are virtually devoid. Furthermore, much remains to be learned about the more generic aspects of heat transfer between the upper mantle and crust. Numerical models of cooling following magma emplacement (Jaeger, 1959) and thermal relaxation following tectonic loading (England and Richardson, 1977; England and Thompson, 1984) were developed independently, and have not yet been coupled in a system that might provide a realistic analogue of a natural orogen. In a related problem, the absence of suitable sources of heat in some orogens has prompted investigation of the role of radiogenic heat in the metamorphism of tectonically thickened crust (*e.g.*, Jamieson *et al.*,1998).

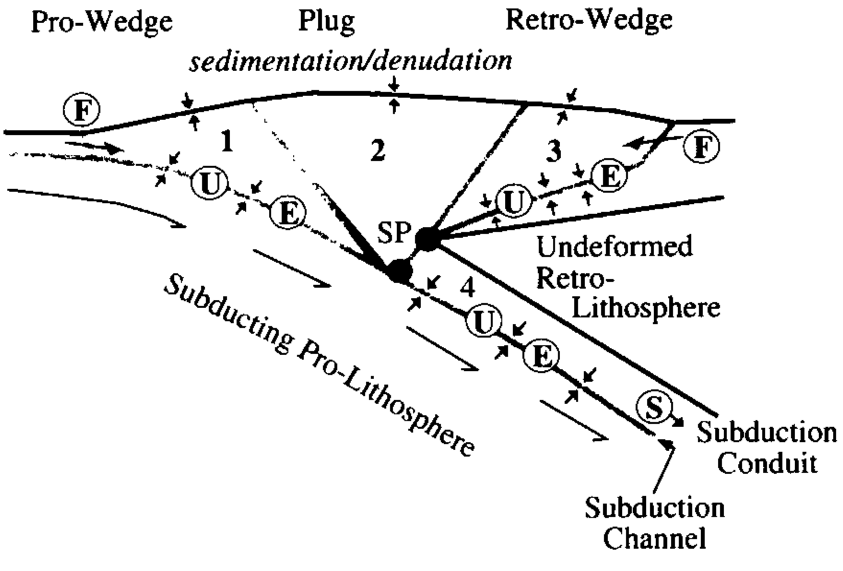


Figure 3 Conceptual illustration of the mechanical components of a convergent margin. During convergence and subduction of the pro-lithosphere, sediments and crust may detach to form an accretionary pro-wedge (1). Material may then be transferred to other components: the plug (2), retro-wedge (3) and subduction conduit (4) (the region above the subduction channel) in which material is permanently tectonically underplated or moves much more slowly than the subducting plate. Material enters the system by: frontal accretion (F) and tectonic underplating (U), and leaves the system by tectonic erosion (E), subduction (S) or surface denudation. A number of modes of this system exist in which various subsets of the components are active. These range from Mode A - pure subduction (1-4 inactive), Mode C (1 and 4 active) to Mode G (1-4 active). Models illustrating some of these modes are shown in Figure 4. SP is the separation point in the flow between material that is obducted and subducted. (From Beaumont *et al.*, 1997)

Proterozoic Anorthosites

Anorthosite massifs and associated granitoid rocks have long been recognized as distinctive features of the Proterozoic. They imply massive transfer of magma and heat from the mantle to the crust in a continental setting, but their origin remains imperfectly understood. The existence of a linear belt of anorogenic anorthosite bodies extending from Laurentia to Baltica was interpreted initially as due to formation over a Mesoproterozoic intracontinental rift or hotspot (*e.g.*, Emslie, 1978; Anderson, 1983; Windley, 1989a,b; Ashwal, 1993). Recent geochronological data suggest, however, that a new paradigm is needed. First, individual anorthosite massifs range in age from *ca.* 1650 to *ca.* 950 Ma (*e.g.*, Emslie and Hunt 1990), and detailed geochronology has revealed that some complexes were emplaced over periods as long as 200 m.y. (*e.g.*, Laramie and Nain complexes; Scoates and Chamberlain, 1997; Emslie *et al.*, 1997). In the Grenville Province, anorthosites may have formed in two distinct tectonic settings: in backarc settings behind Andean-type continental-margin arcs (Rivers, 1997); and in transient extensional regimes during protracted collisional orogeny (Corrigan and Hanmer, 1997).

Deep Crust and Tectonic Adjustments

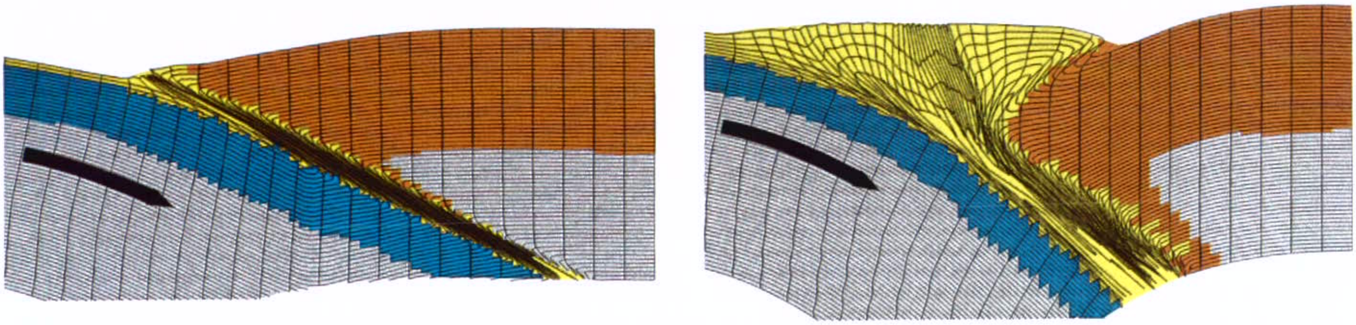
Dating of deep crustal sections (*e.g.*, Moser *et al.*, 1996) and xenolith suites (Davis, 1996) illustrates that the deep crust remained warm and ductile for tens of millions of years in many orogens, and may have facilitated a variety of late tectonic adjustments such as transpression in the Superior, Trans-Hudson, Torngat and Appalachian orogens; and extensional collapse in the southern Cordillera and in the Grenville Province. Because the Cordillera is still active on its western margin, new insights into ongoing magmatic processes have emerged through multidisciplinary approaches: anomalously slow mantle velocities, in concert with compositions of mantle xenoliths from Recent volcanoes (Shi *et al.*, 1998), point to melting of mantle lithosphere through impingement of hot asthenosphere. Distinguishing between structural basement to accreted terranes and subsequently underplated magmatic bodies in xenolith suites is a frontier field requiring full integration of geological, geophysical and geochemical approaches.

In summary, deciphering the processes governing pre-, syn- and post-tectonic magmatism in different orogens, and their roles in the overall orogenic heat budget and subsequent crustal structure, remain significant challenges to improving the 4-D understanding of orogeny. Pan-LITHOPROBE synthesis will provide templates of orogenic evolution at different times and in different settings in Earth's history, a unique database that will provide insight and stimulate discussion on the nature of fundamental orogenic processes.

CRUSTAL GROWTH, PRESERVATION AND RECYCLING

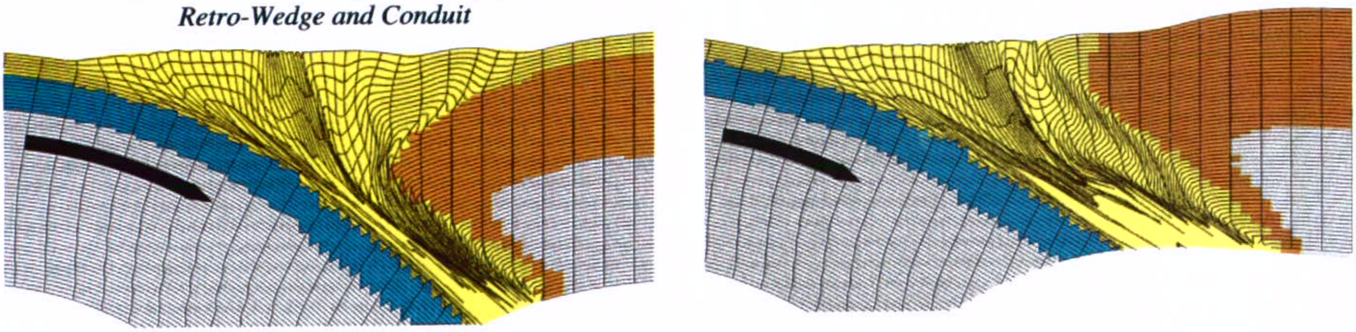
Continental Building Blocks

The North American continent grew through the progressive accretion, dispersal and re-aggregation of continental lithosphere in supercontinent cycles spanning the Archean to the present. The preserved crustal record in Canada spans more than 4.0 Ga and is repre-



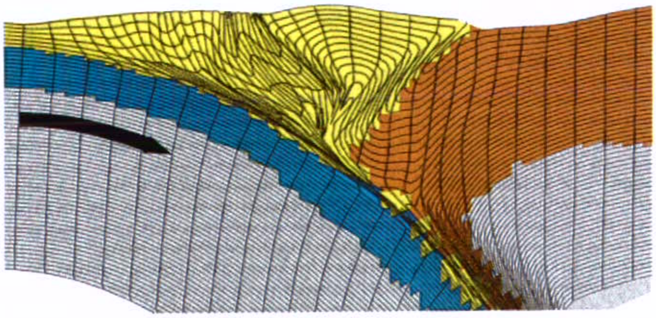
i) Mode A: Near-Perfect Subduction

ii) Mode E: Pro-Wedge, Plug Uplift and Conduit



iii) Mode G: Pro-Wedge, Plug Uplift, Retro-Wedge and Conduit

iv) Mode C: Pro-Wedge and Conduit



v) Mode D: Pro-Wedge and Plug Uplift

Figure 4 Results of plane-strain finite element model experiments designed to investigate the modes of convergent margin systems (shown conceptually in Figure 3). Each panel shows the deformed Lagrangian model grid (undeformed elements shown at base right). Model regions and materials are: weak Coulomb crust or sediments (yellow); strong oceanic (blue) and continental (orange) crust; mantle lithosphere (grey). Depth of models at left and right is 60 km; scale is 1:1. The differences among the models are determined by: the boundary conditions (ratio of convergent and subduction mass fluxes); the subduction load acting to flex the pro-lithosphere downward (*i.e.*, effect of negatively buoyant subducted slab); initial distribution of materials; and advance or retreat of the subduction zone during convergence. It is worth noting that (ii) only differs from (iv) by the inclusion of subduction zone retreat at a rate equal to ten percent of the convergence velocity. By implication, even small amounts of subduction zone retreat or advance are important controls on the tectonic styles of convergent margins and collisional orogens.

sented in a collage of crustal fragments that vary in age and origin. These building blocks of the continent include the 4.012 Ga Acasta gneisses in the northwestern Slave Province (*e.g.*, Stern and Bleeker 1998); significant Middle to Late Archean crust preserved in supracrustal belts and plutonic rocks in the Superior, Nain, Rae, Hearne and Slave cratons; the Paleoproterozoic orogenic belts that permanently welded the Archean cratons together (Trans-Hudson, Wopmay, Thelon-Taltson, Penokean, New Quebec, Torngat, Makkovik); and the Mesoproterozoic Grenville, Paleozoic Applachian, and Mesozoic-Cenozoic Cordilleran orogenies that border the Paleoproterozoic nucleus of the continent. Although an episodicity in continental crust formation is suggested by the geochronology of these crustal fragments and orogenic belts, the fundamental issue is whether the preserved and accessible crustal record provides a reliable means of assessing the history of chemical differentiation of the Earth. Several researchers have proposed that the geologic record reflects an increasing probability of preservation rather than episodic crustal growth (*e.g.*, Bowring and Housh, 1995). The preservation potential of continental crust is linked intimately with its composition (density), erosion potential (topography, climate), and the stabilization of the continents (cratonization, development of lithospheric mantle "roots").

Fundamental Questions of Crustal Growth

The Pan-LITHOPROBE synthesis is targeting crustal growth, preservation and recycling as one of its major themes for research based on the unparalleled resource of the integrated LITHOPROBE transect data sets that span the continent from coast to coast. In this context, three principal questions will be addressed: 1) How much new (*i.e.*, juvenile) crust was extracted from the mantle, accreted to the continents, and preserved through geologic time, and how does the composition of that crust vary with depth and with geologic time? 2) What determines the probability of preservation of continental crust and lithosphere, and does it vary with geologic time? and 3) What processes are responsible for the recycling of crust and lithosphere into the convecting mantle?

The crustal growth debate has long been polarized between two end-member views. One advocates a "no growth" model (Armstrong 1981), in which the present mass of continental crust was extracted from the mantle in the early Archean (*i.e.*, early, (>4 Ga) differentiation into core, depleted mantle and crust), and that subsequent crustal growth has been balanced by recycling. The other end-member favours "progressive growth" (De Paolo, 1980; Reymer and Schubert, 1984; Nelson and De Paolo, 1985), by which the amount of continental crust has increased systematically through geologic time, and where the crust and depleted mantle are complementary reservoirs that form progressively at the expense of the undepleted mantle. The first model predicts substantial recycling of continental crust, in contrast to the second, which is constrained by the preserved crustal record. Crustal growth typically is considered as a lateral accretion process, with additions to continental mass occurring at convergent margins due to the collision and accretion of oceanic island arcs and plateaux. The relative importance of oceanic arc *versus* plateau environments in the development of Archean greenstone belts has seen some debate in recent years (Condie, 1997). Vertical crustal growth at continental arcs associated with basaltic underplating is probably significant in generating "average continental crust" of andesitic composition (57-64% SiO_2), as initial mantle melt extraction today produces basalts (Tarney and Jones, 1994). The fate of the mafic/ultramafic residue remaining in the crust/upper mantle after such intracrustal differentiation (*e.g.*, melting-assimilation-storage-homogenization (MASH) processes; Hildreth and Moorbath 1988) is controlled by processes such as delamination, convective removal of lithosphere, and flaking of terranes during accretion.

LITHOPROBE Constraints on Crustal Growth

The picture of the continental crust and lithosphere revealed through LITHOPROBE 4-D mapping and supporting research provides a number of fundamental new constraints on crustal growth, preservation and recycling models. First, the integration of seismic reflection profiles with tracer isotope data on deep crust and upper mantle samples (xenoliths and plutons) indicates that surface exposures of accreted juvenile terranes are commonly underlain by older crust and lithosphere; for example, Trans-Hudson Orogen (Lucas *et al.*, 1993), Cordillera (Cook, 1995b; Ghosh, 1995). The overlap of accreted juvenile crust on lower plate lithosphere can extend for hundreds of kilometres, suggesting that delamination or flaking of colliding terranes (at the Moho or in the lower crust) is a fundamental accretionary process, at least since the Proterozoic (Lewry *et al.*, 1994). These data require that crustal growth calculations be based on the volume of new crust added to the continent and preserved at any time increment, rather than on surface area alone. Second, geochronological and tracer isotope data indicate the persistence of older crustal signatures throughout significant portions of Neoarchean (*e.g.*, western Superior Province, Rae Province) and younger belts (*e.g.*, Grenville terranes). This suggests that mixing of older crustal material with depleted mantle melts, perhaps dominantly in continental arc settings but also through sediment subduction, is an important chemical recycling process (*e.g.*, Corfu and Stott, 1996). Third, physical recycling processes at subduction zones (*e.g.*, sediment subduction, detachment and subduction of lower crust/mantle from accreting terranes; Cook *et al.*, 1998) and associated with collisional orogeny (*e.g.*, delamination, convective removal of lithosphere) are probably far more important and efficient mechanisms than previously realized in terms of recycling lower crustal material into the mantle. Transfer of lower crustal material into the mantle effectively pushes the bulk crustal composition toward more intermediate or "average" values, while only slightly enriching the mantle in lithophile constituents.

The wealth of 4-D information generated through geophysical, geological and geochronological mapping by LITHOPROBE and geological surveys to date provides an unparalleled opportunity to address the still hotly debated questions of crustal growth, recycling and preservation. The Pan-LITHOPROBE synthesis provides an excellent opportunity to use the LITHOPROBE transect data sets to generate significant advances in our fundamental understanding of these processes.

A workshop on the theme "Tectonic and Magmatic Processes in Crustal Growth: A Pan-LITHOPROBE Perspective" is being organized by John Percival, Toby Rivers, Tom Skulski, and Larry Heaman for the fall of 1999.

LOWER CRUST, MOHO AND MANTLE LITHOSPHERE

An important goal of LITHOPROBE is to elucidate the nature and temporal evolution of sub-continental crust-mantle interaction. The Mohorovicic discontinuity, or Moho, comprises the first-order, globally significant boundary between these two fundamental lithospheric layers. The configuration of the Moho is defined and modified by tectonic processes that transfer mass and heat between the crust and mantle, such as magmatism or lithospheric delamination, as well as by collisional and flexural processes that produce large-scale topographic elements. Knowledge of the present-day structure and stratigraphic setting of the Moho, together with implied crustal thickness, can thus provide important constraints on continental growth, orogenic and post-orogenic processes, and lithospheric rheology.

Significance of the Mohorovicic Discontinuity

Important distinctions exist between various ways in which the Moho is defined. The term Moho, *sensu stricto*, refers to the depth at which average P-wave velocity exceeds 7.6 km·s^{-1}. Alternative, and perhaps more fundamental, definitions are given for: 1) the petrologic Moho, which represents the boundary between predominantly mafic rocks of the lower crust and predominantly ultramafic mantle material (Griffin and O'Reilly, 1987); and 2) the reflection Moho, which represents the base of subhorizontal reflectivity associated with the lower crust (Mooney and Meissner, 1992). Depth discrepancies occur where extensive serpentinization has reduced the velocity of mantle rocks to crustal values, or where mafic lower crustal rocks have been transformed into eclogite facies, thus increasing their velocities into the upper mantle field (Griffin and O'Reilly, 1987). Such discrepancies clearly have a strong bearing on tectonic interpretations of Moho configuration, yet their spatial distribution, significance and means of detection are matters that require additional study.

LITHOPROBE seismic reflection and refraction surveys have systematically sampled a diverse range of tectonic environments in North America. Insights gained from these surveys paint a picture of a structurally and lithologically complex continental Moho that challenges the old paradigm of a simple first-order compositional change. Collective evidence from these surveys serves as the basis for a number of generalizations about the nature of the Moho beneath the Canadian landmass:

1. In areas with a well-defined reflection Moho, its inferred depth typically is consistent with coincident refraction results, to within experimental error (Hammer and Clowes, 1997).
2. Contrary to some earlier suggestions, reflective lower crust is not limited to Phanerozoic crustal regions, but is observed beneath terranes of all ages, from Archean to recent (Clowes, 1993; Clowes *et al.*, 1996).
3. Distinctive patterns of Moho reflectivity can be recognized, but no simple relationship exists between these patterns and geologic age or dominant stress field during the last tectonic episode (Hammer and Clowes, 1997).
4. In some orogenic belts, especially those dominated by accretionary processes (*e.g.*, hinterland of the Canadian Cordillera and SNORCLE) the Moho is smooth and subhorizontal despite dramatic changes in the magnitude of unroofing exhibited at the surface, as inferred from metamorphic isograds.
5. In some regions, especially those dominated by collisional tectonic processes (*e.g.*, eastern Canadian Cordillera; Grenville, Trans-Hudson and Torngat orogens; Alberta Basement; Kapuskasing uplift), short-wavelength Moho topography, up to 10 km in relief and on the order of tens of km in lateral extent, has been preserved over vast intervals of time. This topography may be the result of either structural offset or flexure, but its preservation long after the cessation of plate boundary forces that may have originally supported the load, and in the absence of anti-correlative surface topography, implies both significant temporal changes in the flexural rigidity of the lithosphere and substantial deviations from Airy isostasy at the level of the Moho.

Electrical studies provide complementary insights into the composition and structure of the deep lithosphere, although the crust-mantle boundary generally cannot be imaged owing to the shielding effect of conductive lower crust. Recent magnetotelluric results from the Slave Province indicate an order of magnitude decrease in electrical resistivity at the same depth as the Moho, within uncertainty, an observation permitted by anomalously resistive lower crust beneath the Anton terrane. If this finding can be verified as the general case, it will further constrain the character of the continental crust-mantle interface.

Continental Roots

The composition, extent, age and origin of continental roots remain fundamental problems in earth science. Critical data sets to address the nature of the continental lithospheric mantle were collected in LITHOPROBE Phase IV and are planned for the SNORCLE and Western Superior transects (Fig. 1). Use of extended correlation techniques (equivalent to 36 s listening times) in the initial phase of the SNORCLE Transect has yielded the most continuous upper mantle reflections ever recorded (Cook *et al.*, 1998). Longer offsets acquired in refraction/wide-angle reflection experiments in all of the currently active and recently completed transects are providing better constrained models of upper mantle velocity and anisotropy. These results are complemented by ongoing and planned portable broadband teleseismic studies, and by integrating long-period and wide-band magnetotelluric data. In areas where kimberlites or lamproites have transported mantle and lower crustal xenoliths to the surface, complementary ground-truthing through trace element and isotope geochemistry, geochronology and physical properties studies is available. Through these various studies, Canadian geoscientists are providing one of the most comprehensive multidisciplinary data bases on the variability of the mantle lithosphere. This will lead to improved understanding of large-scale phenomena related to global tectonics and, especially, the interactions between continental plates and the sub-lithospheric mantle to which they are (loosely?) coupled. A workshop on "Where Crust Meets Mantle" is being planned by David Eaton, Alan Jones and Roy Hyndman for the spring of 2000.

CONCLUSIONS

The challenge of framing LITHOPROBE data in a coherent synthesis is being met through two approaches: geody-

namic modelling based on geometric and chronological constraints from LITHOPROBE transects; and a series of thematic workshops focussed on LITHOPROBE contributions to problems of current global interest. The first workshop, to be held in the early fall of 1999, will address the theme "Tectonic and Magmatic Processes in Crustal Growth: A Pan-LITHOPROBE Perspective." The second in the series, "Where Crust Meets Mantle," will take place in the spring of 2000. Other workshops are under consideration for the coming 4 years and we seek suggestions from the community on topics for future workshops. The Canadian earth science community has a unique opportunity to utilize the comprehensive LITHOPROBE data sets in search of new insights on the structure of continents and evolution of the lithosphere through 4 billion years of Earth history. For dates of upcoming workshops and details on attendance, consult the Pan-Lithoprobe web page at:
www.geop.ubc.ca/Lithoprobe/lithopb.html

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