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Lithospheric growth at margins of cratons

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Abstract

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. This picture is made possible both because the length of these regional profiles spans all the tectonic elements of an orogen on a particular cratonic margin and because of their great depth range. Key transects studied include the LITHOPROBE SNORCLE 1 transect and the BABEL survey, crossing the Slave and Baltic craton margins, respectively. In most cases, 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.

Keywords: Craton; Archean; Proterozoic

1. Introduction

Deep seismic reflection profiles worldwide have revealed crustal and mantle structures that provide important clues about the tectonic history of the most ancient parts of the continental crust, the cratons and the surrounding shield margins. The geometry of continental convergence tectonics has now been viewed conceptually from a number of perspectives (Fig. 1), the following among them: (1) as upper crustal flakes (Oxburgh, 1972) formed when the crust delaminates along a near-horizontal detachment surface; (2) as reflection crocodiles occurring throughout the crust and distinctive to convergent regimes because they represent pairs of thrust faults with opposite vergence (Meissner, 1989); (3) as doubly vergent orogens (Willet et al., 1993) formed as a diffuse crustal response to more localized underthrusting within the uppermost mantle; (4) as a composite imbrication and delamination process in which pairs of oppositely verging thrust faults delineate structural wedges at many scales throughout the lithosphere (Beaumont et al., 1994; Cook et al., 1998); and (5) as crust shortened between continental vises (Ellis et al., 1998; Ross et al., 2000). The lithosphere deforms in a depth-coherent manner and it is therefore the depth-averaged vertical stress that drives deformation; this quantity is equivalent to the gravitational potential energy (Tur-

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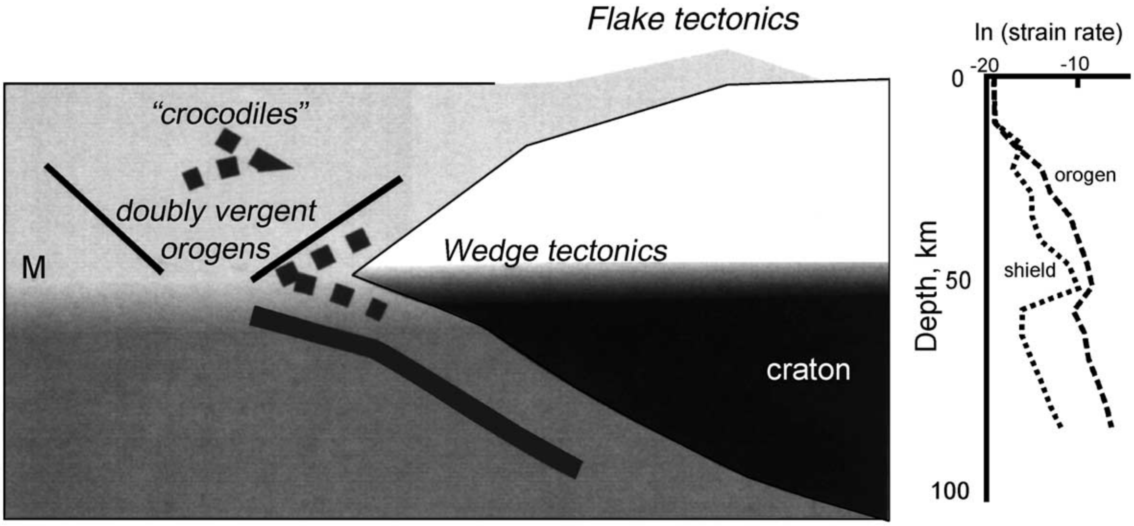


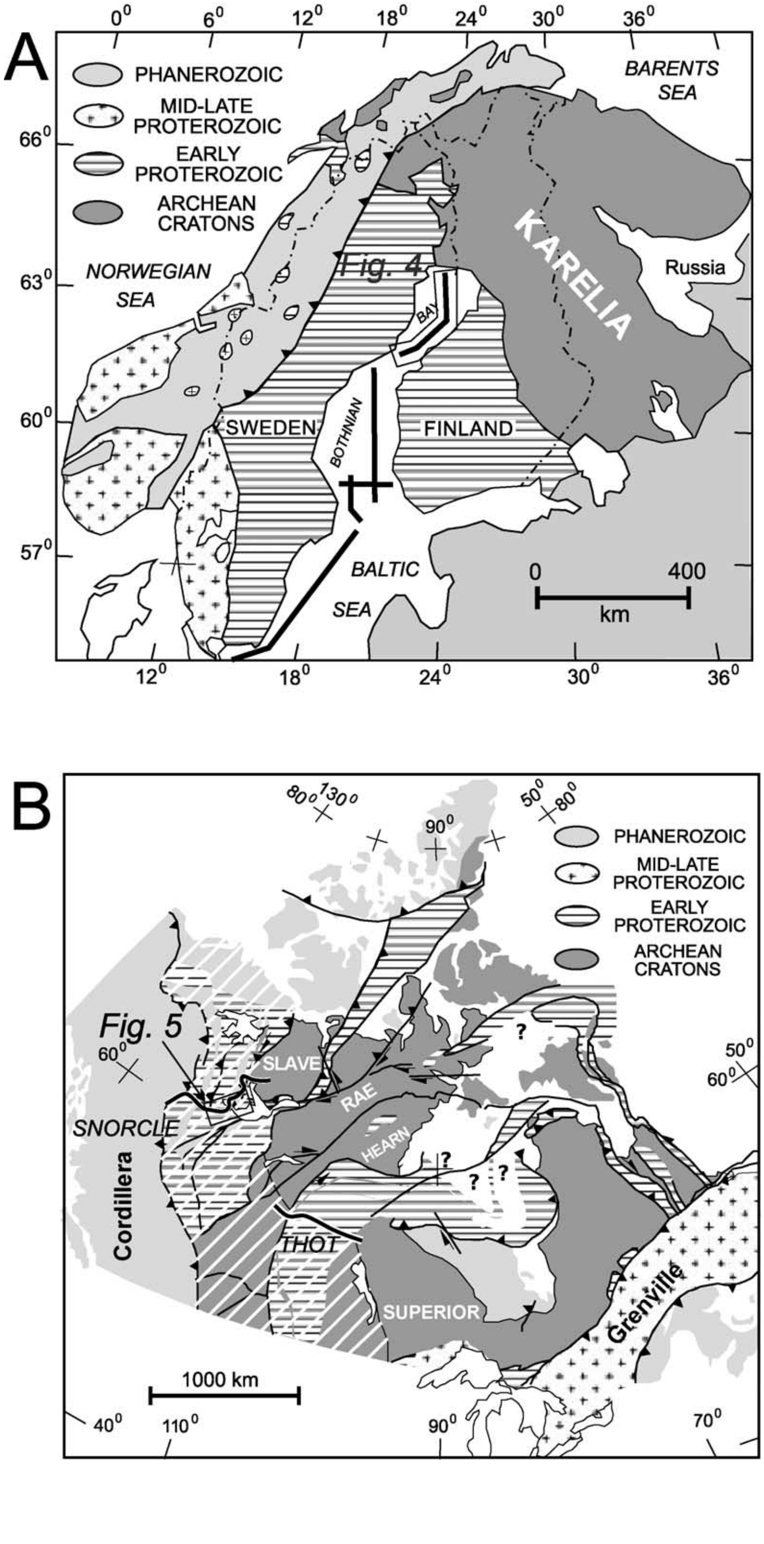
Fig. 1. Cartoon of lithospheric-scale deformation during convergence tectonics that may result in prominent seismic reflections. The upper crustal part of the section illustrates 'flake tectonics' following Oxburgh (1972). 'Crocodiles' (Meissner, 1989) and doubly vergent orogens (Willet et al., 1993) occupy the entire crust. Deformation within the uppermost mantle illustrates wedge tectonics as based on deep seismic reflection sections in Canada (Cook et al., 1999) and Scandinavia (Snyder et al., 1996a). At the right are typical strain rates ($s-1$) versus depth curves based on realistic mineral assemblages and large (orogenic) stresses (Snyder and Hobbs, 1999). The largest strain accumulation occurs in the lowermost crust (40–55 km) and at depths greater than 70 km.

cotte, 1983). Continuum mechanics requires that mantle and crustal structures within one block of lithosphere or at its margin be kinematically linked. The structural geometry revealed by deep seismic reflection profiles thus provides critical information concerning how deformation observed at the surface is expressed at depth, particularly when old, strong continental lithosphere, such as that typical of shield regions, is involved.

Images of the structure or architecture of convergent zones aid our understanding of mountain building processes (e.g. Choukroune and ECORS Team, 1989; Beaumont and Quinlan, 1994; Snyder et al., 1996a). Where one ancient and one juvenile block of lithosphere converge, the structural geometry defined by reflectors indicates the manner in which younger material is added or accreted to the margins of the older continental lithosphere. The older blocks are Archean shield lithosphere, here considered to represent stable continental nuclei designated by the word 'craton'. The deep reflection profiles are used here in conjunction with surface geological and geochemical mapping (e.g. Öhlander et al., 1993) to constrain the shapes of the craton margins. Complementary teleseismic (Bostock, 1998), magnetotelluric (Jones, 1999) and magma/xenolith (e.g. Wooden and Mueller, 1988; Davis, 1997; Kopylova and Russell, 2000) studies provide information on how the cratons thicken (grow downward) with time.

Deep seismic reflection profiles have revealed the geometry of structures in the crystalline crust and adjacent uppermost mantle of several continents (Blundell, 1990; Mooney and Meissner, 1992). Detailed velocity analyses and correlation with outcrop demonstrate that mid-crustal reflections are attributable to shear zones and to intrusions of contrasting (mafic versus felsic) composition into the crust (e.g. Hurich et al., 1985; Percival et al., 1989, 1992; BABEL Working Group, 1993; Rey et al., 1994; Law and Snyder, 1997). Lower strength rocks

Fig. 2. Location map showing the spatial relationships of the deep seismic reflection profiles (thick black lines) discussed here with respect to cratonic margins and mapped Archean–Proterozoic boundary zones in Scandinavia (A) and Canada (B). Rectangles locate seismic sections illustrated in the figure indicated. S is Stockholm; superimposed white diagonal hatching indicates where Phanerozoic sediments cover the indicated basement rocks.


A
PHANEROZOIC
MID-LATE PROTEROZOIC
EARLY PROTEROZOIC
ARCHEAN CRATONS
BARENTS SEA
NORWEGIAN SEA
KARELIA
Russia
Fig. 4
BAY
BOTHNIAN
SWEDEN
FINLAND
BALTIC SEA
0 400 km
B
PHANEROZOIC
MID-LATE PROTEROZOIC
EARLY PROTEROZOIC
ARCHEAN CRATONS
Fig. 5
SLAVE
RAE
HEARN
SNORCLE
Cordillera
THOT
SUPERIOR
Grenville
1000 km

in the lower crust (e.g. Kohlstedt et al., 1995) may undergo more pervasive or penetrative deformation so that some reflectors may result from transposed folds and structures formed in earlier deformations, but it is often possible to assign probable ages to many crustal reflections through correlation with mapped shear zones and intrusives at the surface if the structures are continuous or kinematically linked. Because regional-scale horizontal strains must be accommodated at all levels of the lithosphere, not just the crust, some age correlations further extrapolate to mantle reflectors lying within the same tectonic regime. Here, this logic is used to estimate how and when entire lithospheric segments (not just the uppermost crust) were accreted to continental nuclei.

Cratons represent the oldest parts of the continents, forming cores around which younger belts accreted and became stitched by intrusions (Fig. 2) (Gaál and Gorbatschev, 1987; Hoffman, 1989). Cratons and continents appear to have consolidated over time by the addition of material to their base, in the so-called continental root or keel, probably by the cooling of partial melts in the mantle (Jordan, 1975; Hoffman, 1990). The shape of keels is dimly perceived using long-wavelength seismic velocity variations (Grand, 1994; Van der Lee and Nolet, 1997; Fouch et al., 2000). Keels can have economic significance because, once cooled, the lithosphere can preserve diamonds until transportation to the surface by kimberlite eruptions occurs (e.g. Skinner et al., 1994).

Here, several examples of both ancient and modern convergence zones are compared and contrasted in order to synthesize and hypothesize a generalized model of craton margin evolution. Details of convergent structural geometries from new interpretations of deep seismic reflection sections are emphasized. The goal is to describe a generic cross-sectional architecture of continental blocks cored by Archean cratons. Passive or extensional margins are not considered here because continents do not generally grow along these margins and ancient examples are not as well preserved.

2. Geometry of convergence zone structures

Horizontal extension or shortening implied by upper crustal structures located along continent margins is typically distributed over hundreds of kilometers (England and Jackson, 1989; Shen-Tu et al., 1999). Cumulative horizontal strain observed within the upper crust must also be accommodated at all levels of the lithosphere. The Svecofennian orogen of Scandinavia and the Wopmay orogen of western Canada (Fig. 3) provide excellent examples of inferred convergence architecture within the entire lithosphere.

2.1. Baltic craton: BABEL survey results

Deep seismic reflection profiles in Scandinavia, acquired as part of the BABEL project (Fig. 2), provided detailed information about the geometry of structures along the margin of the 2.6–3.1 Ga Karelian craton and across the Proterozoic Svecofennian terrane (BABEL Working Group, 1993). Although this Archean (2.5–2.1 Ga)–Proterozoic margin exhibits significant variation along its strike (Fig. 2) (Öhlander et al., 1993; Korsman et al., 1999), the observed reflector geometries provide important clues about the Precambrian tectonic history of this craton margin.

Since the time basement formed at 3.1–2.6 Ga, the most important phase of new crustal growth for the Karelian craton is indicated by the Svecofennian metavolcanic, metasedimentary and calc-alkaline granitoids that are 1.95–1.86 Ga in northernmost Sweden, 1.89–1.85 Ga further south, 1.78–1.56 Ga in south-central Sweden and 1.77–1.40 Ga in southernmost Sweden (Skiöld and Öhlander, 1989; Welin, 1992). This part of the Baltic shield lithosphere has experienced only minor thermo-tectonic effects over the last 1.5 Ga (Gaál and Gorbatschev, 1987; Korja et al., 1993). The lack of recent deformation throughout the shield region of interest here creates ideal conditions for acquiring deep seismic data because seismic energy is neither greatly absorbed by near-surface materials nor scattered by complex structures.

Within 200 km of the inferred Archean–Proterozoic crustal boundary zone (Fig. 2) (Öhlander et al., 1993), prominent reflections in the uppermost mantle were interpreted to define a mantle convergence zone where Proterozoic mantle underthrust Archean lithosphere (Figs. 3 and 4) (BABEL Working Group, 1990, 1993). A southward-dipping zone of less reflectivity, along strike from major ore deposits and containing

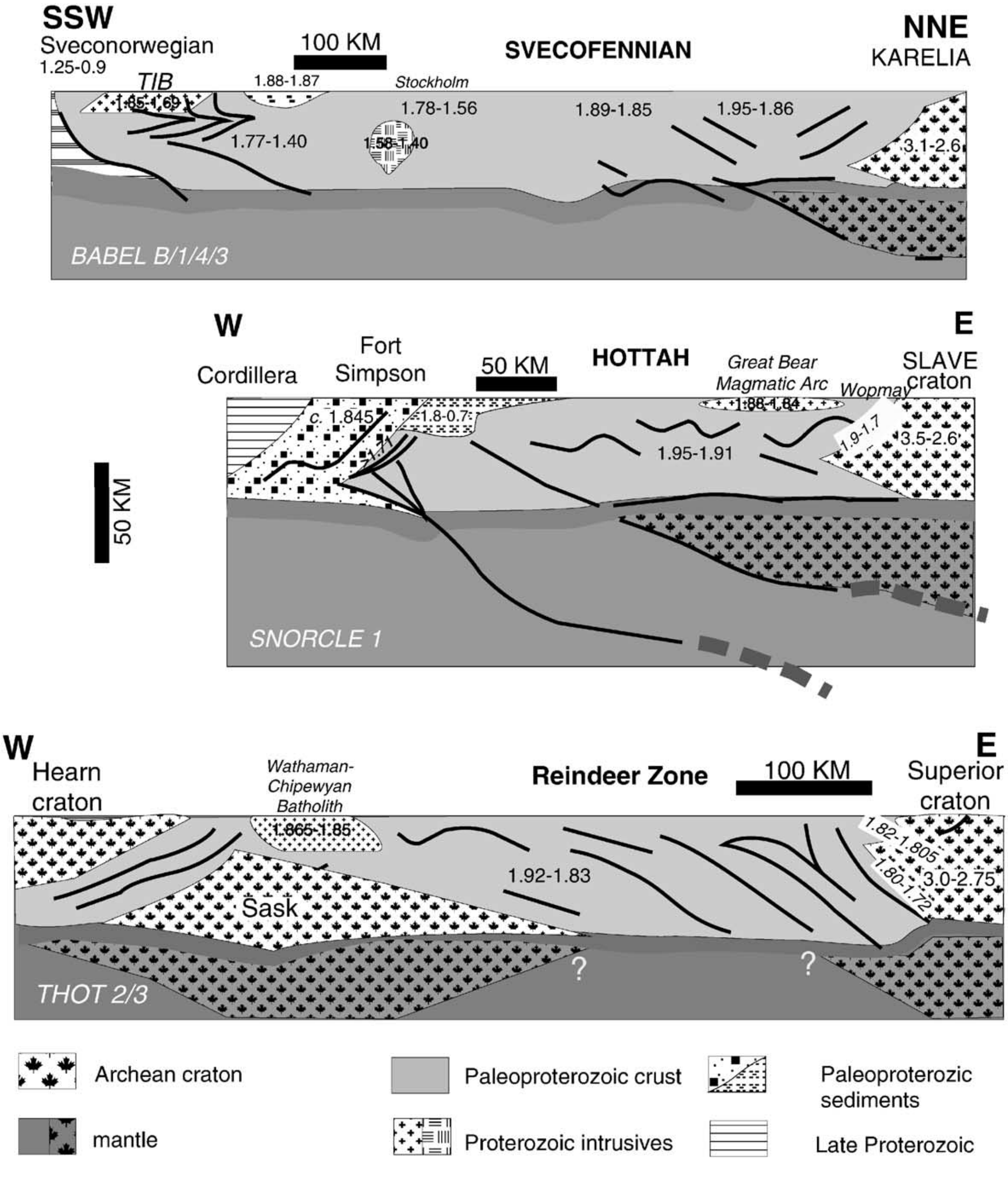


Fig. 3. Cartoons summarizing previously published interpretations of the BABEL 4/3/C/B (BABEL Working Group, 1993; Snyder et al., 1996a), LITHOPROBE SNORCLE 1 (Cook et al., 1999) and Trans-Hudson Orogen transect (THOT) (White et al., 1999 and references therein) seismic sections. Patterns are interpreted and keyed to crystallization ages shown (in Ga); deformation/metamorphism ages are in italics. Solid black lines are observations and represent prominent individual reflections or groups of reflections. Heavy dashed lines on the SNORCLE section are inferred downward projections of mantle reflectors based on prominent P–S conversions observed on teleseismic data (Bostock, 1998). The THOT has no known mantle reflectors.

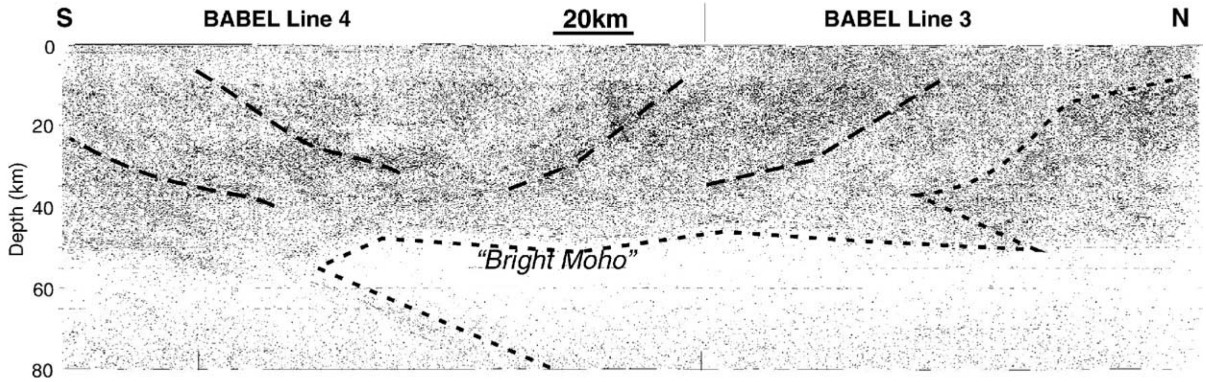


Fig. 4. Part of the BABEL 3 and 4 seismic sections (BABEL Working Group, 1993) that illustrates prominent ('bright') Moho reflections in the region between the inferred dipping crustal boundary between Archean and Paleoproterozoic rocks and the same boundary in the underlying mantle (short-dash line). Representative crustal structures within the Proterozoic crust are denoted by longer-dash lines. The line location is shown by the box in Fig. 2; tics at base of section show where the line direction changes.

significant amounts of reworked Archean basement, was interpreted as the major strain zone accommodating horizontal shortening in the crust (Snyder et al., 1996a). Conceptually, this zone represents a diffuse boundary in a mechanical vise model (Ellis et al., 1998) where the northern limb of a synform defined by crustal reflectors indicates that juvenile Proterozoic Svecofennian crust was thrust up a dipping ramp.

In detail, complications appear. At 40–50-km depths, a 15-km thick wedge inserted between the inferred crust and mantle of the Karelian craton margin (see dotted line 60 km from the north end of Fig. 4) implies that the Archean lower crust was weaker than either its adjoining mantle or mid-crust, consistent with widely accepted strength profiles (Fig. 1) (Kusznir and Park, 1986). Wedging accommodated only part of the convergence, the remainder occurred by thrusting higher in the crust to the south, along more continuous ramp structures. Partitioning of the convergence may indicate that channel flow within the lower crust (McKenzie et al., 2000) alternated with whole crust displacement as the primary mode of deformation.

If correct, this interpretation of deformation along the Karelian craton margin requires that the lower crust acted as a 10-km-thick décollement zone that transferred the localized horizontal shortening that occurred in the mantle up to 150 km to the north. Amphibolite- to granulite-grade rocks exposed regionally onshore indicate that 10–20 km of crust was removed by erosion (Gaál and Gorbatschev, 1987). Implied maximum crustal thicknesses of 55–70 km favor homogeneous thickening within the crust; numerous dipping reflectors probably represent discrete mylonite zones (Law and Snyder, 1997) along which the thickening occurred. Significantly, this segment of the lowermost crust is the only part of the BABEL survey that is consistently characterized by a single strong reflection at the Moho (Fig. 4). This strong reflection may indicate the localization of strain within a horizontal décollement layer represented by a thick series of parallel ultra-mylonites formed by transposed older structures (Talbot and Sokoutis, 1995) or the boundary between translated thickened crust and relatively undeformed mantle. Above this décollement, the doubly vergent reflector geometry resembles that produced in many numerical models of horizontal convergence (e.g. Willet et al., 1993).

2.2. Slave craton: SNORCLE survey results

The Slave Province is an assemblage of Archean supracrustal, granitoid and gneissic rocks, occupying 190,000 km^2 of the northwest Canadian Shield (Fig. 2) and containing some of the oldest known rocks on earth (Bowring et al., 1989; Stern and Bleeker, 1998). Its lack of cover rocks, extensive rock record, numerous diamondiferous kimberlites and the extensive ongoing geophysical and petrological studies (Bostock, 1998; Kopylova et al., 1998; Cook et al., 1999; Griffin et al., 1999) make it an ideal natural laboratory to study the generation, evolution and stabilization of an Archean craton (Bleeker and Davis, 1999). Rocks dated as old as 4.025 Ga are preserved within the Slave craton, and most of the crust was assembled by 2.734 Ga when a large region was covered by a thin and discontinuous cover sequence of quartzites and banded iron formation (Bleeker et al., 1999). This cover sequence was in turn overlain by voluminous tholeiitic pillow basalts, preserved in greenstone belts, erupted 2.722–2.700 Ga and by 2.660 Ga turbidites (Isachsen and Bowring, 1997).

Crust west of the Slave craton accreted to the Archean crust at 1.9–1.7 Ga (Fig. 3); the western limit of Archean crust in the Canadian Shield is the median line of the Wopmay orogen (Hoffman, 1989). To the east are passive-margin sedimentary rocks of the Coronation Supergroup; to the west are the 1.95–1.91 Ga Hottah and onlapping 1.88–1.86 Ga Great Bear magmatic arcs. Dextral shearing, intrusion of 1.86–1.84 Ga syenogranites and 1.84–1.66 Ga conjugate transcurrent faulting of these arc rocks followed, as did subsequent accretion of the 1.845 Ga Fort Simpson terrane, the westernmost element of the Wopmay orogen in this region. West of this assemblage lie scattered middle to late Proterozoic basins, some at least 12–15 km deep (Cook and van der Velden, 1993), and the Phanerozoic Canadian Cordillera (Fig. 3).

Deep seismic reflection profiles in the Northwest Territories of Canada provide structural geometries of the western margin of the Slave craton (Cook et al., 1999). The LITHOPROBE SNORCLE data show several prominent mantle reflectors that are continuous for hundreds of kilometers to depths of 90–110 km. These reflectors provide geometrical constraints on the lithospheric structures interpreted to represent accretion of continental material to the craton at 1.90–1.88 and before 1.71 Ga (Hoffman, 1989). Analogy with modern subduction beneath Vancouver Island suggests that the reflector geometries record the ancient subduction of former oceanic crust (Van der Velden and Cook, 1999). Teleseismic data analysis has extended the structures associated with the deep-

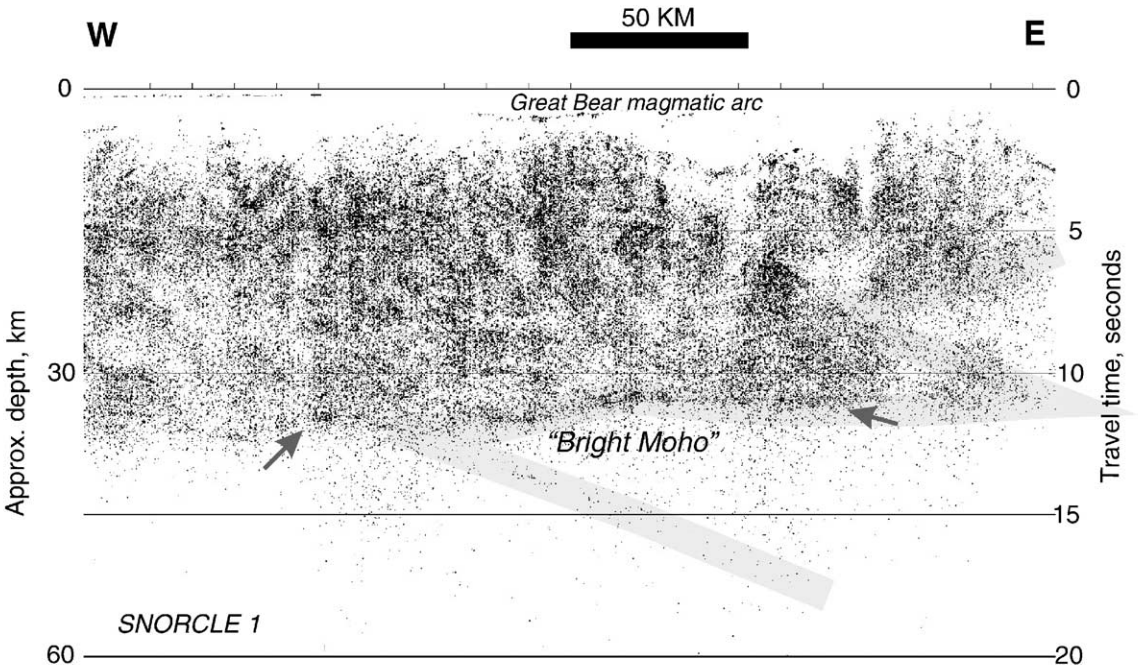


Fig. 5. Part of the SNORCLE 1 seismic section (Cook et al., 1999) that illustrates prominent Moho reflections (between arrows) within the segment of the profile where Proterozoic crust is interpreted to overlie Archean uppermost mantle. Gray band indicates the inferred Proterozoic–Archean boundary. See Fig. 2 for location.

est mantle reflectors eastward to 140 km depth and velocity anisotropy also supports the reflectors originating from a subducted oceanic slab (Bostock, 1998).

Neglecting possible convergence events older than 2.5 Ga within the Slave craton, interpretation of the seismic data implies that several consecutive accretion events added juvenile crustal and mantle material to the Slave craton. In each case, crustal material was mostly thrust upward onto the existing continental crust and mantle rocks were thrust downward (subducted) beneath the existing cratonic margin. The accretion of the inner part of the 1.92–1.90 Ga Hottah terrane occurred along structures very similar to those defined by reflectors beneath the Svecofennian terrane (Fig. 3). This similarity includes: (1) an outward-dipping boundary zone between inferred Archean and Proterozoic crustal rocks, (2) a 15-km thick wedge of Proterozoic rocks within the Archean crust just above the Moho, (3) a single prominent "bright Moho" reflector between the inferred crustal and mantle convergence zones, here nearly 200 km long, and (4) mantle reflectors dipping beneath the cratonic margin (Fig. 5). The primary difference is the absence of one regional synformal structure defined by reflections throughout the whole crustal section. Instead, the Hottah terrane has nearly horizontal reflectors dividing the crust into several undulating structural layers (Cook et al., 1999).

Further additions to the craton occurred when the 1.845 Ga Fort Simpson terrane delaminated along its Moho and thrust onto and beneath the wedge-shaped margin of the Hottah terrane (Fig. 3). Further to the west, even younger accretion occurred within the North America Cordillera, as documented by more recent SNORCLE reflection data not discussed here.

3. Mechanical models of convergence structures

3.1. Conceptual wedge models

The examples of cratonic margins described above provide clear examples of lithospheric structural geometries that can be understood better in the context of conceptual models based on our understanding of rock rheology and deformation mechanisms. From the perspective of the upper crust, 'flakes' of crust thrusted onto older continental margins (Oxburgh, 1972) provides a useful model. Full subduction or more limited underthrust zones (Ampferer, 1940; Dewey and Bird, 1970) help describe the observed mantle structures. From the perspective of the younger lithosphere, doubly vergent orogens (Beaumont et al., 1994) or vise models (Fig. 6) (Ellis et al., 1998; Ross et al., 2000) provide guidance for interpreting many observed structures. Focusing on the older, stronger lithosphere in these tectonic convergence zones led to the widespread recognition of wedge geometries (Cook et al., 1999).

Laboratory measurements on deforming rocks have long led geologists to assume that the lithosphere deforms in a depth-coherent manner but in multiple layers as approximated by a yield strength envelope (Sibson, 1977; Goetze and Evans, 1979; Kohlstedt et al., 1995; Kaikkonen et al., 2000). This envelope is essentially an instantaneous steady-state approximation of the lithospheric mechanical response, oversimplifying effects of variations in composition, water content, temperature, pressure and strain rate. Finite-element models provide more realistic models by incorporating viscoelastic terms (e.g. Albert et al., 2000). Earthquake distribution with depth justifies several layers of relatively greater strength in old, cool lithosphere (Chen and Molnar, 1983), but this justification remains uncertain (Maggi et al., 2000) due to effects of water on long-term viscosity (Kohlstedt et al., 1995). Despite these questions, the viscosity of subcontinental mantle lithosphere is assumed to exceed that of the lower crust (e.g. McKenzie et al., 2000). Recent modeling of flexure confirms that deformation will concentrate in the lowermost crust under reasonable assumptions of temperature, pressure and composition, and thus increase the probability of décollements at this level of the lithosphere (Brown and Phillips, 2000).

Yield strength envelopes (e.g. Kusznir and Park, 1986; Kaikkonen et al., 2000) suggest that both the upper crust and wet uppermost mantle are strong layers within thermally mature lithosphere and therefore, largely control its overall rate of deformation. In contrast and recast in terms of strain accumulation under uniform horizontal stress, lowermost crust and mantle deeper than 70 km will deform first and most (Fig. 1). This discussion neglects the even weaker mantle asthenosphere, and very old lithosphere (cratons) are thought to have thick keels of lithosphere to

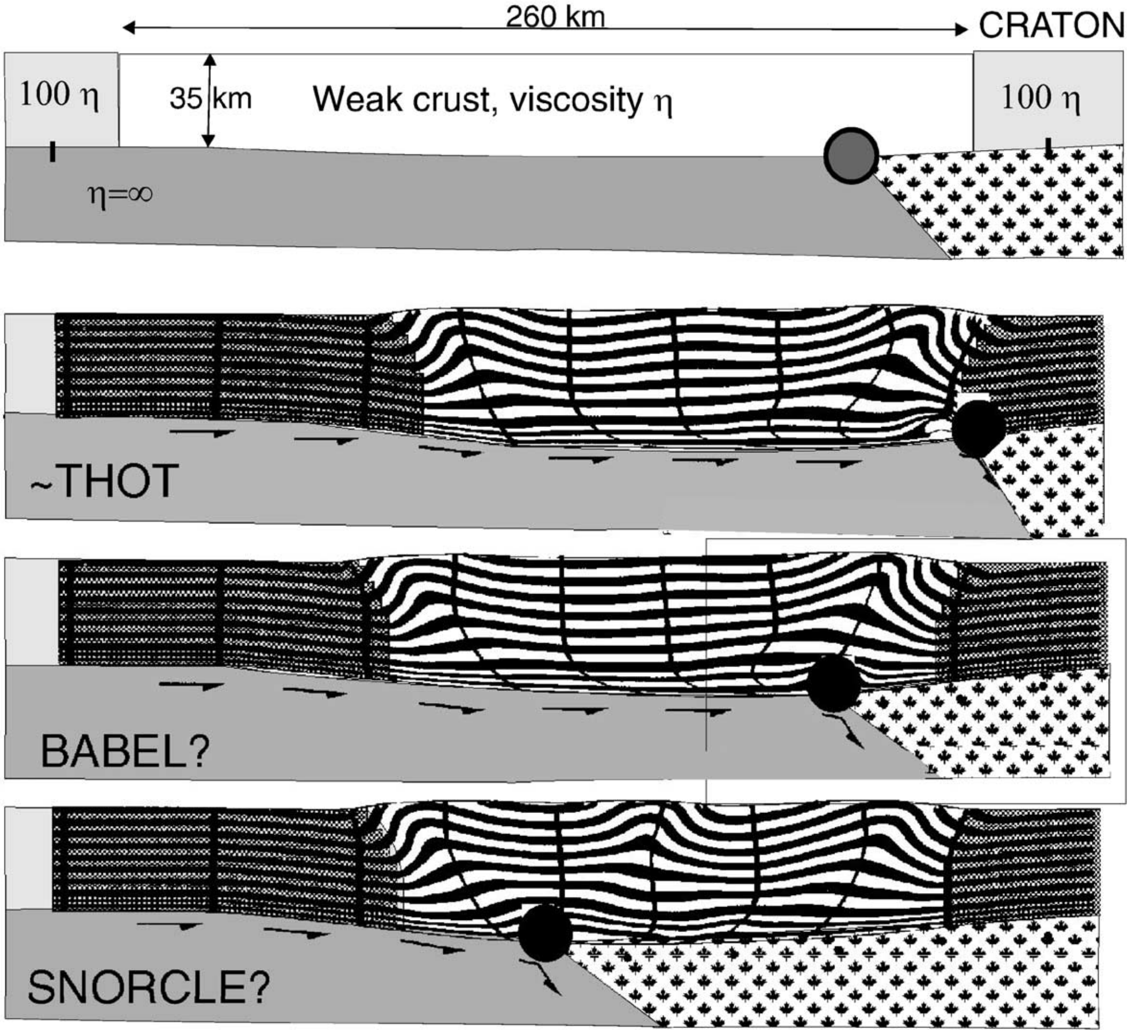


Fig. 6. Diagram summarizing results of numerical modeling of lithosphere convergence mechanics (modified from Fig. 6 of Ellis et al., 1998). Here, several versions of 'vise' models are shown, with the initial condition of the location where mantle underthrusting occurs (large dot) being varied in each simulation. In each case, the block on the left has converged by 105 km from the initial position indicated at the top. The block on the right (craton) remains fixed. Within both rigid blocks, crust and mantle are strongly coupled. These particular models provide some similarities to the THOT, BABEL and SNORCLE examples discussed here, but are oversimplified in several ways as discussed in the text. The BABEL and SNORCLE analogies are queried (?) because no 'closing' block (on left) has been specifically identified to date.

depths of 250 km (Jordan, 1975; Grand, 1994; Van der Lee and Nolet, 1997).

The upper crust fails via brittle deformation and thus complex, sometimes chaotic, fault geometries develop over areas tens or hundreds of kilometres wide during one tectonic period (e.g. Shen-Tu et al., 1999). In contrast, deformation at depths >20 km appears to occur largely within ductile zones that imply more uniform or continuous strain fields (e.g. White and Bretan, 1985; Rey et al., 1994; Talbot and Sokoutis, 1995). The limited observational evidence provided by sparse deep seismic profiles and Wadati–Benioff zones indicates that horizontal strain within the uppermost mantle strength layer is typically accommodated on discrete, dipping shear zones. Some are true subduction zones, others are simply shear zones with normal or reverse sense of shear. The Svecofennian orogen of Scandinavia and the Wopmay orogen of western Canada provide examples of kinematically linked surficial deformation centered over these mantle shear zones, but also offset hundreds of kilometers by décollements located within the lower crust.

3.2. Numerical and analog models

Finite element models can provide a useful framework with which to reconstruct convergent tectonic processes central to the discussions in this paper. The fundamental deformation mechanisms assumed in this modeling are now well tested and justified after a decade of applying this modeling to specific tectonic problems (Willet et al., 1993; Beaumont and Quinlan, 1994; Beaumont et al., 1994). The starting and boundary conditions applied to these models are key to their applicability to a particular problem. While not exactly matching the conditions appropriate to the present discussion, two suites of models nonetheless provide useful insights (Ellis et al., 1998; Pfiffner et al., 2000).

Vise models (Fig. 6) illustrate the general deformation pattern and the diversity caused by varying the distance of mantle subduction with respect to the rigid (cratonic) block. The three examples shown generally bracket the deformation inferred from prominent crustal reflections observed on the BABEL and SNORCLE reflection sections. These models cannot fully reproduce the observed geometry because the modeling assumed that (1) the original rigid craton margin was vertical and (2) crustal viscosity did not vary vertically due to thermal effects or compositional variations (it was simplified to that of pure feldspar). Conditions are better matched by models generated to trace development of the Swiss Alps before arrival of the full-thickness European continental lithosphere (Pfiffner et al., 2000). These models illustrate how the wedge geometry typically starts in the upper crust and evolves to deeper levels, to the lowermost crust.

Analog ‘sandbox’ modeling provides limited choice of physical properties, but does offer a 3-D perspective of structure geometry associated with continental convergence tectonism (Sokoutis et al., 2000). One main conclusion is that orthogonal convergence can produce oblique orogenic belts.

4. Evolution of lithosphere at cratonic margins

4.1. Modern to Paleozoic analogs

Precambrian convergence zones have provided several spectacular examples of craton-wedge geometries as key components in convergence architecture. The metamorphic and crystalline rocks found throughout the crust, and right up to the surface in many cases, provide excellent conditions for acquiring quality seismic data. Geologically, the less positive side is that these orogens often represent a long and complex tectonic history that must be unraveled. Geophysical surveys typically can only provide information about the present structure that primarily results from the last major tectonic event to affect the region. In order to understand better how orogens and convergence margins evolve, it is therefore instructive to examine more youthful examples. Neotectonism also provides earthquake distributions and focal mechanisms and estimates of active deformation via geodetic (GPS) surveys. Seismic data will probably not be as clear in these examples due to large quantities of unconsolidated sediments at the surface, wide brittle fault zones within the upper crust or significant surface topography. All these factors produce strong lateral variations in near-surface seismic velocities that violate basic acquisition-related assumptions and otherwise complicate the processing and modeling of seismic data (e.g. Sheriff and Geldart, 1995).

Here, a few convergence zones that were recently crossed by deep seismic reflection transects provide useful analogs of those already discussed; this does not represent an exhaustive list. The premier neotectonic continent–continent convergence zone involving an Archean craton is the Himalaya, and a series of reflection surveys has explored its lithospheric architecture (e.g. Hauck et al., 1998). Geometries in the deepest lithospheric levels are unclear and coincident magnetotelluric surveys define conductors that suggest that the strongest reflections in the upper crust are magma or fluids, but the overall geometry is of the Indian Shield underthrusting and perhaps delaminating the younger Tibetan block.

Arguably the premier neotectonic arc-continent convergence zone is the Banda Arc of Indonesia, where the northern margin of the Australian craton impinges on SE Asia and subduction polarity is currently in the process of reversing (Hamilton, 1979; Genrich et al., 1996). The Banda Arc was studied via a deep seismic reflection transect that revealed clear reflectivity patterns within the lithosphere of the Australian margin, but only scattered reflections beneath the volcanic arc and accretionary prism (Snyder et al., 1996b). Gravity modeling, geodetic studies and earthquake analysis allow the underthrust lithosphere of the former Australian margin to be traced and the currently active plate margin to be discerned (Genrich et al., 1996). From this and from geological mapping on the island of Timor, the last 40 Ma geological history of this margin can be reconstructed (A–C in Fig. 7) (Snyder and Barber, 1997 and references therein). Upon cursory assessment, the largely oceanic lithosphere of the Banda Sea appears to be wedging apart the sedimentary section from the crust of Australia (C in Fig. 7). However, if deformation is projected logically forward, the denser oceanic lithosphere will eventually underthrust the Archean margin after flaking and thrusting much of the volcanic arc crust onto Australian Archean crystalline basement.

This forward-projected deformation results in structural geometries similar to those observed by a number of deep seismic sections acquired across the former late Paleozoic margin of Laurentia, beneath what is today the Iapetus suture of the British and Irish Isles and the North Sea (Ryan et al., 1995; Snyder and Barber, 1997; Abramovitz and Thybo, 1998). In places within the uppermost mantle, a few continuous reflections correlate with the crustal geological evidence of the Iapetus suture, but none of these reflections are as extensive as the Paleoproterozoic examples cited above. This may indicate a fundamental change in the physical properties (e.g. velocities) of the lithosphere through geological time or that less exotic material has been placed in the mantle by convergence tectonics since the Paleoproterozoic. It may also be a function of our ability to image such structures less well in younger geological settings. In some instances, later extensional processes may have destroyed mantle reflectors. Geological studies along the Iapetus suture suggest that its tectonic history included subduction polarity flips, subduction of an oceanic lithosphere several hundreds of kilometers wide and late transpression (e.g. Dewey and Ryan, 1990; Dewey and Mange, 1999). In the Iapetus examples and in most other margins imaged by deep seismic profiles, the last subduction, as recorded by seismic reflectors, was toward and beneath the older continental mass, usually a craton.

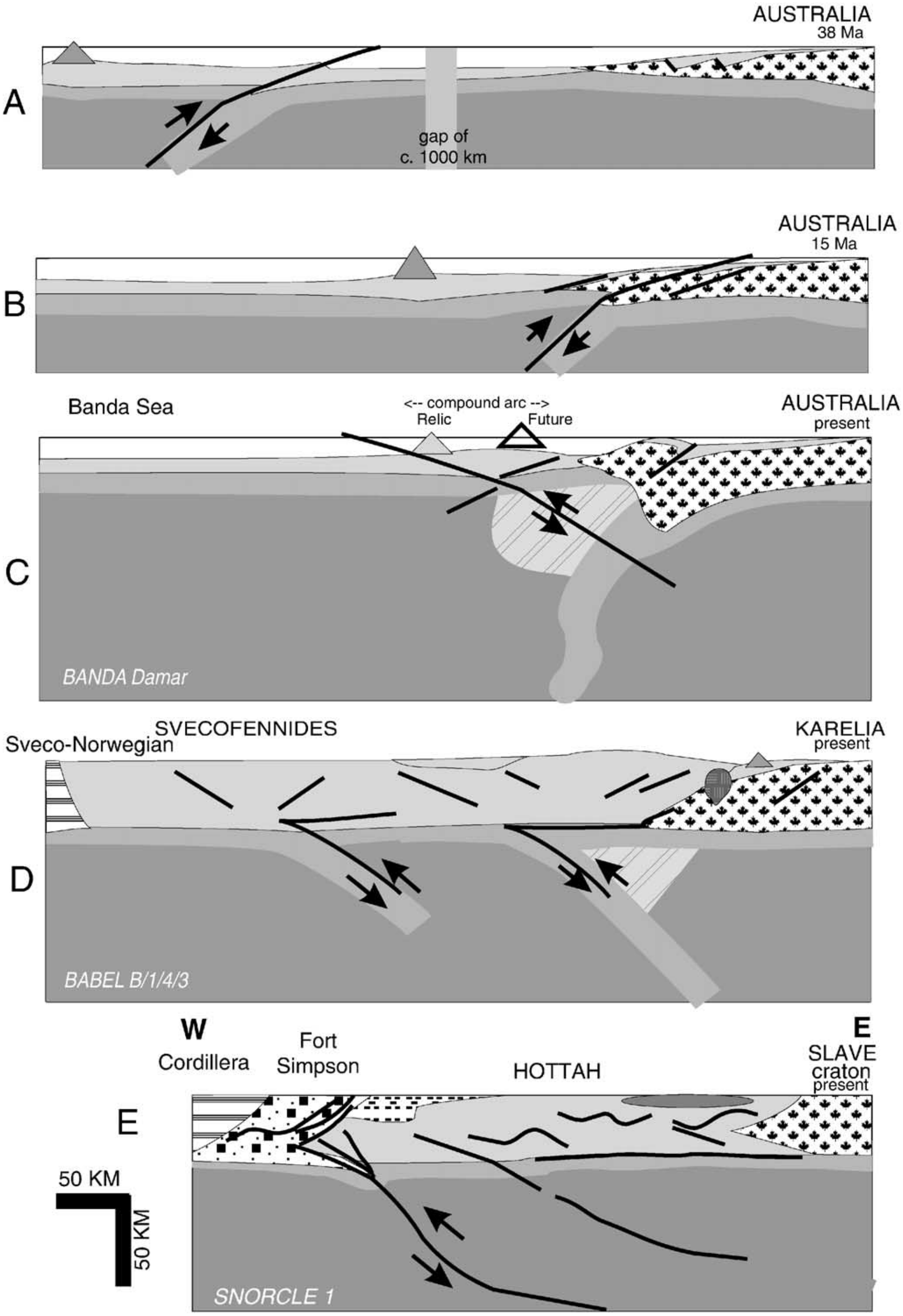
4.2. A generalized cross section

The Phanerozoic examples discussed above show large-scale structures that were observed on deep seismic profiles and that have reconstructed tectonic histories with time resolution of several million years (e.g. Dewey and Mange, 1999). The Precambrian record is more fragmental, both in its spatial completeness and in its temporal resolution. The greater clarity of structural geometries provided by deep seismic reflection profiles in Precambrian shield areas is offset by less clarity in the age and nature of the structures. It is therefore potentially productive to use the more recent examples as templates, assume uniformitarianism over earth history (at least during the last 2.0 Ga), draw on insights from numerical mechanical modeling, and thus extract from the fragments a more complete picture of Precambrian continent evolution.

Drawing almost exclusively on representative cross sections that are directly constrained by deep reflection profiles, one can piece together a typical evolution along the margin of an Archean craton (Fig. 7). These examples indicate that outward dipping subduction outboard from a passive cratonic margin eventually flips polarity within a period of a few million years to create a compound volcanic arc along the craton margin (C in Fig. 7). This is currently occurring in the modern Banda Arc. As accreted arc material accumulates and thickens along the margin, subduction continues beneath the craton margin, but steps outward and away from the margin. This "stepping back" may occur several times over several hundred million years, as possibly occurred in the Svecofennian orogen (B in Fig. 7). In most cases, the last subduction geometry, and the one best preserved as reflectors, dips beneath the craton margin.

4.3. Discussion

Many workers currently argue that while Archean stratigraphy and structural styles are not dissimilar to those forming today and throughout geological his-


AUSTRALIA
38 Ma
A
gap of
c. 1000 km
AUSTRALIA
15 Ma
B
Banda Sea
<-- compound arc -->
Relic
Future
AUSTRALIA
present
C
BANDA Damar
Sveco-Norwegian
SVECOFENNIDES
KARELIA
present
D
BABEL B/1/4/3
W
Cordillera
Fort
Simpson
HOTTAH
E
SLAVE
craton
present
E
50 KM
50 KM
SNORCLE 1

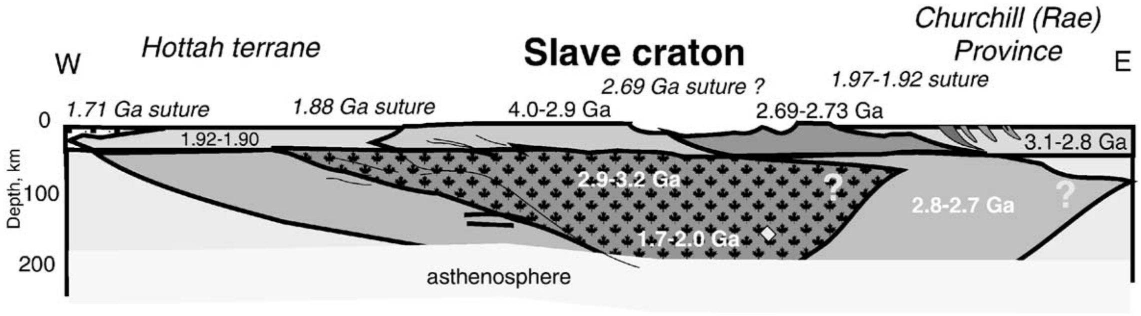


Fig. 8. Lithopsheric cross section of the Slave craton. Geometry in the western half is defined as discussed in this paper, those in the east are unconstrained. Crustal ages and structure are from Bleeker et al. (1999). Mantle ages are from Re–Os studies on xenoliths (Kopylova and Russell, 2000; Aulbach et al., 2001).

tory, the context of their formation in the Archean is not strictly proper plate tectonics as we know it today (e.g. Hamilton, 1998). If this is indeed true, modern examples are useful as crude analogs, but inadequate in critical details so that these analogies should not be taken too far.

All of the cross sections discussed in this paper have structural geometries constrained by seismic reflections, reflections interpreted as shear zones, mylonites or intrusions along shear zones. Perhaps the most surprising observation is the strong similarity of lithospheric-scale structures that were separated by thousands of kilometers when they formed 1.90–1.85 Ga ago and that these geometries are readily explained using modern analogues. Although we have relatively few quality seismic profiles across Archean convergent zones, those available reveal reflectors penetrating at most 10 km into the modern mantle (e.g. Calvert et al., 1995).

Constraints on the downward growth of cratons remain more elusive. The use of teleseismic energy from distant earthquakes has provided regional maps of mantle structures (e.g. Jordan, 1975; Grand, 1994; Bostock, 1998; Fouch et al., 2000). Isotope geochemistry and age dating of xenoliths typically brought to the surface in kimberlites (e.g. Kopylova and Russell, 2000) can provide key information on the ages of mantle rocks within the layers of a craton (Fig. 8). When this deep lithospheric information is combined with the more detailed geometries in the uppermost 100 km such as that described here, a crude picture of craton shape and growth begins to emerge (Fig. 8).

Cratons apparently endure for several reasons. Thick, cool mantle keels provide overall greater strength than that of younger converging lithosphere. This strength and relative buoyancy cause the last increment of convergence to occur via inward subduction that typically is insufficient to produce voluminous arc magmatism. It is the modest evidence for arc magmatism that provides a basis for preferring a shear deformation origin to a magmatic enhancement of impedance contrasts for the ‘bright Moho’ reflector observed on the BABEL and SNORCLE sections.

Deep seismic reflection profiles collected across Proterozoic–Archean margins are now sufficiently numerous to provide collectively a picture of how continental nuclei grow laterally to form cratonic shields. This picture is made possible only because the great lengths of these profiles span the entire orogenic sequence of each particular cratonic margin. It is not a complete picture because of the known great degree of along-strike variability of orogens and continental margins. These same profiles also provide key information of how cratons form and evolve, but the seismic profiles require supplementary information from teleseismic-based studies and isotope geochem-

Fig. 7. Cartoon suggesting, based on numerical modeling and observed structural geometries from seismic sections, evolution of the lithosphere along craton margins during convergent tectonic events, earliest at top (A). Annotations are as in Fig. 3. Striped part of the mantle represents material that is transferred from one plate to another as the convergence zone evolves.

ical studies. This process will undoubtedly prove to be complex at all scales; only the broadest architectural elements discussed here are apparent at present.

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