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Geological Constraints on the Origin of the Mantle Root beneath the Canadian Shield

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Geological constraints on the origin of the mantle root beneath the Canadian shield

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Cratonic North America is composed of a cluster of Archaean microcontinents centred on the Canadian shield, and juvenile Proterozoic crust that lies mainly buried beneath the sedimentary cover of the western and southern interior platforms. The shield is underlain by an anomalous low-temperature mantle root that is absent beneath the platform. As there appears to be no systematic difference in crustal thickness or density between the shield and the platform, the long-lived arching of the shield implies an intrinsic buoyancy imparted by the mantle root that more than offsets its colder temperature. Isotopic and seismic anisotropy data indicate an Archaean age for the mantle root, close to the time of formation of the overlying crust. The preferential development of the mantle root beneath Archaean crust is consistent with an origin by imbrication of partly subducted slabs of highly depleted oceanic lithosphere, assuming that buoyant subduction was more common in the Archaean. Formation of the mantle root was not dependent on collisional orogenesis, as has been suggested, but the Archaean cratonic mantle was sufficiently buoyant and refractory to survive later tectonic thickening. The mantle root persists beneath Archaean crust that was transected by mafic dyke swarms and subjected to short-lived episodes of post-orogenic crustal melting, but the root is reduced at mantle plume initiation sites. The partitioning of Archaean and Proterozoic crust between the shield and the platform, respectively, causes the shield to misrepresent Precambrian crust as a whole. Studies of the shield falsely conclude that a high percentage of Precambrian crust formed in the Archaean, and that the Proterozoic was characterized by epicontinental volcanism and sedimentation, and crustal 'reworking'. Furthermore, the isotopic ratios of detritus eroded from the craton may tend to overestimate the mean age of continental crust.

1. Introduction

Shields are arched areas of continental crust that expose Precambrian igneous and metamorphic rocks. Areas where Precambrian crystalline rocks are hidden by little-deformed sedimentary or volcanic cover are called continental *platforms*. *Cratons* encompass shields and contiguous platforms.

For obvious reasons, shield areas provide most of our geological knowledge of Precambrian crust. The largest shield, the Canadian shield (figure 1), is composed 84% of crust that separated from the mantle before 2.5 Ga (McCulloch & Wasserburg 1978; Patchett & Arndt 1986; Hoffman 1989; E. Hegner, personal communication 1989). This fact has contributed to the notion that most Precambrian crust originated in the Archaean (4.0–2.5 Ga), and that Proterozoic (2.5–0.57 Ga) tectonism was dominated by 'reworking' of Archaean crust, and by epicontinental sedimentation and volcanism (see, for example, Windley 1984). The validity of this generalization depends on the assumption that shields are representative of all Precambrian crust.

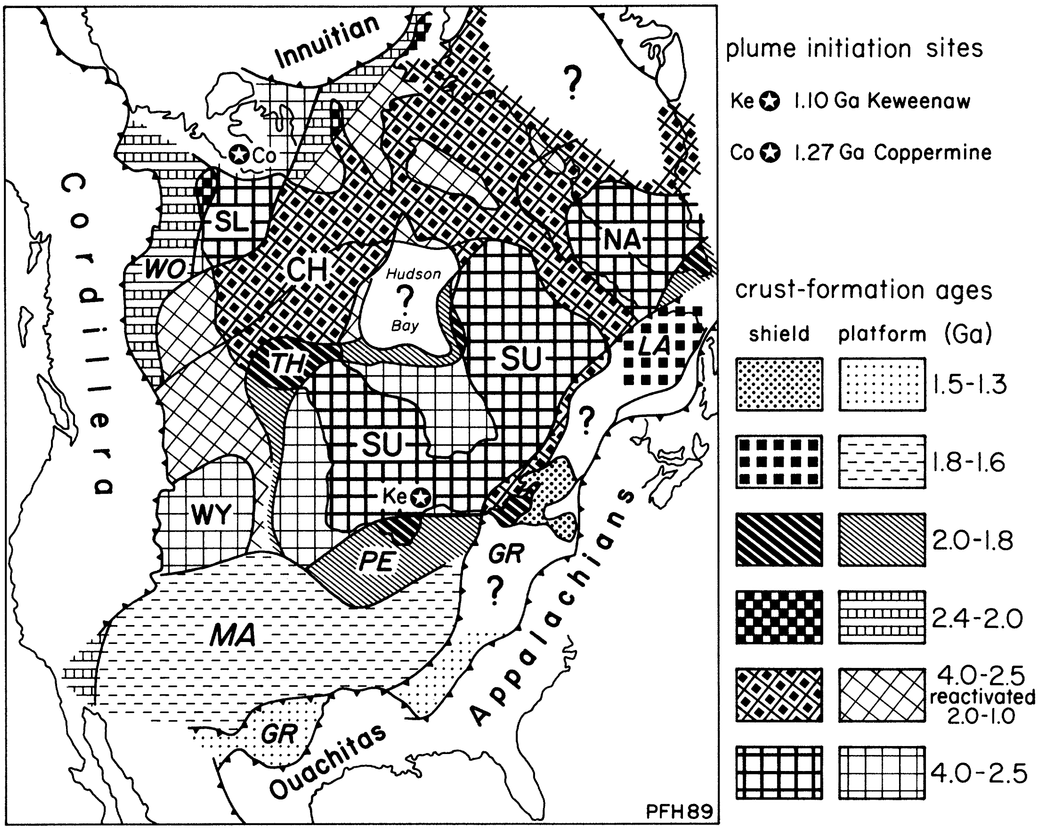

Figure 1. Crust-formation age map of the North American craton, based on Sm–Nd, Pb–Pb and U–Pb geochronology of samples from the shield and the subsurface (data from McCulloch & Wasserburg 1978; Nelson & DePaolo 1985; Patchett & Arndt 1986; Bennett & DePaolo 1987; Patchett & Ruiz 1989; E. Hegner, personal communication 1989; and other sources cited in Hoffman (1988, 1989)). Note the concentration of Archaean crust in the shield. Abbreviations: CH, Churchill hinterland; *GR*, Grenville orogen; *LA*, Labradorian orogen; *MA*, Mazatzal orogen; NA, Nain province; *PE*, Penokean orogen; SL, Slave province; SU, Superior province; *TH*, Trans-Hudson orogen; *WO*, Wopmay orogen; WY, Wyoming province. Breaks in pattern indicate possible cryptic sutures within the Churchill hinterland. Greenland is positioned in a pre-drift reconstruction after Roest & Srivastava (1989).

Recent work shows that, unlike the Canadian shield, the North American platform contains a high proportion (59%) of juvenile Proterozoic crust (figure 1). This conclusion is based on Sm–Nd model mantle-separation ages (De Paolo 1981), amplifying earlier Rb–Sr and Pb–Pb data, of Precambrian inliers and scores of basement samples obtained by commercial drilling through Phanerozoic sedimentary cover (Nelson & DePaolo 1985; Bennett & DePaolo 1987; Patchett & Ruiz 1989). The Canadian shield is therefore not representative of the North American craton as a whole, but is strongly biased in favour of Archaean crust.

Maps of isopachs and lithofacies of sedimentary cover on the North American platform (Cook & Bally 1975) indicate that the Canadian shield has been an area of relatively elevated basement throughout the Phanerozoic. Presumably this reflects long-lived lateral heterogeneities in the crust and/or mantle which migrate with the lithospheric plate. In this regard, the Canadian shield is distinct from shields produced by active tectonics. Uplift of the Arabian–Nubian shield, for example, is probably a consequence of Neogene rifting in the Red Sea. Uplift due to the thermal and dynamic effects of rifting will be geologically short-lived,

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however, once rifting ceases. The only permanent component of uplift adjacent to the rift zone would be that due to subsurface addition of basaltic melts to the crust (cf. White & McKenzie 1989).

Relative to the rest of the North American craton, the Canadian shield is not an area of unusually thick crust but coincides with a region of anomalous upper mantle. Crustal thickness appears not to vary systematically between the shield and platform (Mooney & Braile 1989), so that relative uplift of the shield is not simply an isostatic consequence of a thicker crust. The shield is, however, underlain by an anomalous mantle 'root', which is indicated by seismic shear velocities (figure 2) that are faster than those beneath the platform to depths exceeding 200 km (Grand 1987). The higher velocities signify colder temperatures within the mantle root relative to the adjacent asthenosphere, the implications of which are discussed in detail by Jordan (1988). To resist convective erosion, the mantle root must be more refractory than the adjacent asthenosphere. To ensure gravitational stability, the root must be composed of intrinsically less dense material to offset its lower temperature. Otherwise, the formation of a cold mantle root would result in subsidence equivalent to a sedimentary basin over 15 km deep or, alternatively, would generate a large positive gravity anomaly, neither of which are observed on the scale of the shield. The twin requirements of intrinsic buoyancy and elevated solidus temperature are met by mantle material that is highly depleted in the components extracted by partial melting. The extraction of basaltic melt depletes the mantle residuum in iron, thereby decreasing its density by reducing its capacity to form garnet. The fact that a depleted mantle root (the *tectosphere* of Jordan 1988) coincides roughly with the area of the

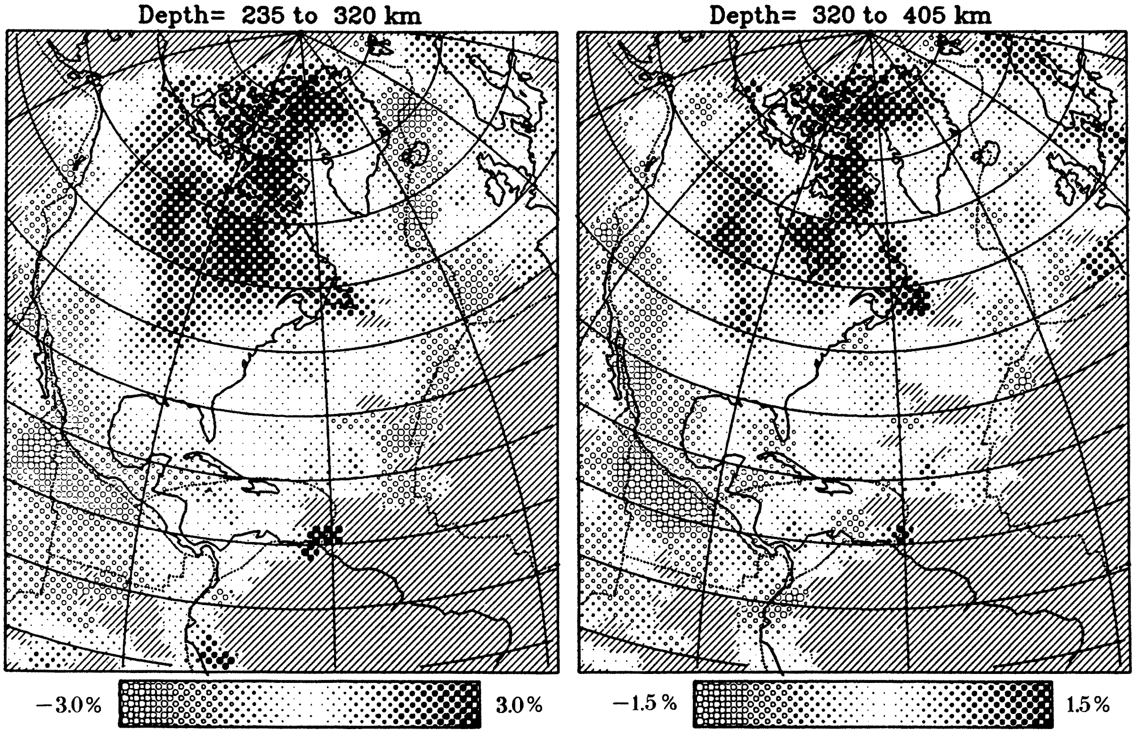

FIGURE 2. Results of tomographic inversion for shear velocity for planar depth sections beneath the North American plate according to Grand (1987). Hatching indicates unresolved areas. Note that the velocity perturbation scale changes as a function of depth. Compare the location of the high-velocity mantle root with the area of the shield in figure 1. Note the present-day position of Greenland, unlike that in figure 1.

Canadian shield (Grand 1987) implies that the mantle root has a net buoyancy and is responsible for the arching of the crust.

Different causal mechanisms for cratonic mantle roots have been advanced. Jordan (1988) proposes a two-stage process. First, subcontinental mantle is depleted by partial melting at an Andean-type magmatic arc. Then, it is advectively thickened during collisional orogenesis. This model implies that depleted mantle roots should preferentially underlie crustal regions that have experienced arc magmatism and subsequent collisional orogenesis. Conversely, Ashwal & Burke (1989) argue that collisional orogenesis leads to delamination or convective erosion of the tectonically thickened mantle lithosphere, whereupon it is replaced by fertile asthenospheric mantle (cf. England & Houseman 1988). They view continents as aggregates of island arcs having roots of depleted mantle that are preserved only in regions that have not experienced subsequent collisional orogenesis. Neither Jordan (1988) nor Ashwal & Burke (1989) predict a secular control on the formation of mantle roots.

In contrast, Helmstaedt & Schulze (1989) envision cratonic mantle roots as being formed of imbricated slabs of partly subducted oceanic lithosphere. Their model, which is based on the study of xenoliths of Archaean age contained in kimberlites intruding the Kaapvaal craton of southern Africa, is particularly relevant to the Archaean. It presupposes a buoyant mode of subduction, which would have been more common at that time. Oceanic lithosphere entering Archaean subduction zones would have been relatively young and warm because of higher global spreading rates (Bickle 1986). Furthermore, the oceanic crust would have been relatively thick and the suboceanic mantle strongly depleted because of the large volumes of melt produced at Archaean spreading ridges (Bickle 1986). Density-driven subduction of Archaean oceanic slabs would have been dependent on the formation of eclogite within the oceanic crust.

The association of mantle roots and Archaean crust may also be a result of selective preservation. Presuming a secular decline in mean mantle temperature, the Archaean mantle would have convected rapidly due to its relatively low viscosity. Richter (1988) suggests that mantle convection was so vigorous as to cause recycling of Archaean crust unprotected by refractory mantle roots.

In summary, different genetic models predict that the tectosphere should occur either in regions that have experienced collisional orogenesis (Jordan 1988), regions that have escaped collisional reactivation (Ashwal & Burke 1989), or regions that have been mechanically underplated by partly subducted oceanic slabs (Helmstaedt & Schulze 1989). The purpose of this paper is to evaluate these models in light of the distribution of the mantle root with respect to segments of the North American craton having different tectonic histories.

2. Extent of the mantle root beneath the North American craton

Cratonic North America is composed of a cluster of Archaean microcontinents, centred on the Canadian shield, and juvenile Proterozoic crust that mainly underlies the western and southern interior platforms (figure 1). Hoffman (1988, 1989) documents that aggregation of the craton in detail and those works should be consulted for references concerning the geological and geochronological information outlined below. Aggregation of the Archaean microcontinents occurred in a series of collisions between 1.97 and 1.82 Ga. Proterozoic arc terrances built on crust having mantle-separation ages of 2.4–2.0 Ga were accreted to the western margin (Wopmay orogen) of the Archaean protocraton between 1.90 and about 1.8 Ga. Juvenile (i.e. newly extracted from the mantle) Proterozoic crust was accreted to the southern margins of the Superior and Nain provinces (Penokean and Ketilidian orogens, respectively) between 1.90 and 1.80 Ga. More juvenile crust was accreted to the southern margin of the protocraton (Mazatzal and Labradorian orogens) between 1.80 and 1.60 Ga. Finally, crust having mantle-separation ages of 1.5–1.3 Ga was accreted in parts of the Grenville orogen between 1.2 and 1.0 Ga.

The ratio of Archaean to Proterozoic crust is almost 6:1 for the shield but only 0.66:1 for the platform. Exceptions to the general association of Archaean crust with the shield and Proterozoic crust with the platform may be short-lived. They include the Proterozoic crust of the Laurentian highlands (Grenville orogen) adjacent to the St Lawrence rift system, and Cretaceous–Tertiary downwarping of Archaean crust in the foreland of the Rocky Mountains in west-central North America (Mitrovica *et al.* 1989).

The Superior and Slave provinces (figure 1) are composed mostly of 3.0–2.7 Ga island arcs and relatively small fragments of older continental crust. Amalgamation of the island arcs of the Superior province occurred between 2.73 and 2.70 Ga, and was immediately followed by widespread crustal melting between 2.69 and 2.67 Ga. The Slave province experienced a broadly similar scenario that was delayed by about 50 Ma relative to the Superior province. Significant post-Archaean tectonic shortening is limited to within 100 km of the margins of both provinces, except for a WNS-dipping intracratonic thrust in the central Superior Province (Percival *et al.* 1989). Both provinces are transected by Proterozoic mafic dyke swarms (Fahrig & West 1986) but were spared the mid-Proterozoic (1.8–1.1 Ga) crustal melting that affected other parts of the North American craton.

High-velocity mantle roots underlie both the Slave and Superior provinces, with the latter having the highest velocities and deepest root in North America (figure 2). The difference in velocity structure may reflect the small area of the Slave province, which approaches the horizontal resolving power (400 km) of the tomographic inversion (Grand 1987). If real, the difference might signify the partial destruction of the mantle root beneath the Slave province during an episode of subduction (1.88–1.86 Ga) along its western margin. There is no geological evidence for subduction beneath the Superior province.

Seismic anisotropy data provide a potential key to the age of mantle roots. In at least one area of the Superior province, vertically travelling seismic waves have an ENE azimuth of fast polarization that parallels the island arcs within the province and lies within the bulk flattening plane developed during their amalgamation (Silver & Chan 1988). The seismic anisotropy presumably reflects a strain fabric within the mantle root and the magnitude of the anisotropy implies that the strain fabric likely persists through a depth range on the order of 200 km (Silver & Chan 1988). The anisotropy data, although limited in areal extent, are none the less important because, if confirmed, they imply that the mantle root formed in the Archaean. Certainly, the province underwent no significant bulk strain after intrusion of the NNW-trending Matachewan dyke swarm at 2.45 Ga. The inferred age of the mantle root accords with evidence from diamond inclusions, xenocrysts and mantle xenoliths contained in kimberlites intruding the Kaapvaal craton, which unequivocally indicate an Archaean age for the tectosphere in southern Africa (Boyd & Gurney 1986). The persistence of a depleted mantle lithosphere of Archaean age beneath the Superior province is also supported by Nd and Sr initial isotopic ratios in carbonatite intrusions ranging in age from 2.7 to 0.11 Ga (Bell &

Blenkinsop 1987). The apparent Archaean age of the mantle root is compatible with the model of Helmstaedt & Schulze (1989), although they do not explicitly address the problem of the origin of the strain fabric responsible for the seismic anisotropy.

Mantle roots are conspicuously absent beneath the Archaean Wyoming and Nain provinces (figures 1 and 2). Both contain early–middle Archaean gneiss terranes that were thoroughly reactivated when each province was amalgamated in the late Archaean. This accords with the Ashwal & Burke (1989) model, in which mantle roots are destroyed by collisional orogeny. Alternatively, destruction of a mantle root beneath the Wyoming province may be related to Laramide horizontal subduction and crustal shortening (Bird 1988). Moreover, the Iceland plume may have eroded a former mantle root beneath the Nain province during rifting of the northern North Atlantic (White & McKenzie 1989). Accordingly, the absence of mantle roots beneath the Wyoming and Nain provinces may be related to Mesozoic–Cenozoic tectonism rather than Archaean collisional orogenesis.

The middle–late Archean provinces of the Churchill hinterland (the Rae, Hearne and Burwell provinces of Hoffman (1989), figure 1) were variably reactivated as a result of collisions with the Slave, Superior and Nain provinces between 1.97 and 1.82 Ga. As a result of crustal shortening, early Proterozoic sedimentary cover is preserved in cuspate synclinoria and Klippen between broad basement antiforms. West of Hudson Bay, crustal shortening in the Churchill hinterland was succeeded by extensive alkalic magmatism and associated normal faulting at about 1.85 Ga, widespread crustal melting (rapakivi-type granite and rhyolite) at 1.76 Ga, and development of cratonic basins about 1.7 Ga. On southern Baffin Island, northeast of Hudson Bay, an enormous charnockite-granite batholith, emplaced at 1.90–1.85 Ga, is flanked by high-grade early Proterozoic fold belts. Nevertheless, both regions are underlain by high-velocity mantle roots (figure 2). An Archaean mantle root under the Churchill hinterland may have been sufficiently refractory and buoyant to survive tectonic thickening, contrary to the Ashwal & Burke (1989) model, but how it could have survived advective heating sufficient to promote extensive crustal melting is problematic. Sm–Nd model ages of the 1.85 Ga alkaline rocks west of Hudson Bay are most compatible with melting of an Archaean cratonic mantle source (Esperança & LeCheminant 1986), but isotopic evidence bearing on the age of the mantle root that survived the 1.76 Ga crustal melting event is lacking. Seismic anisotropy data might potentially resolve the problem of the age of the extant mantle root west of Hudson Bay. If the root post-dates the crustal melting event, it should have no azimuthal anisotropy because the resulting granite–rhyolite suite remains undeformed. On the other hand, if the root predates the crustal melting event, an azimuthal anisotropy related to the late Archaean and early Proterozoic NW–SE shortening events would be expected.

Mantle roots are not strictly limited to Archaean cratons, as implied by Richter (1988) and Hawkesworth *et al.* (1990). The Penokean, Trans-Hudson and Wopmay orogens (figure 1) incorporate crust that was extracted from the mantle in the early Proterozoic. In the Wopmay orogen, 1.95–1.85 Ga magmatic arcs, built on 2.3–2.0 Ga crust, were accreted to the Archaean Slave province between 1.90 and about 1.8 Ga. In the Trans-Hudson orogen, juvenile 1.91–1.85 Ga island arcs are sandwiched between the Archaean Superior and Hearne provinces southwest of Hudson Bay. In the Penokean orogen, 1.89–1.84 Ga island arcs, in part built on Archaean crustal slivers, were accreted to the Superior province between 1.85 and 1.84 Ga. All three orogens are underlain by high-velocity mantle roots, although the roots are less well developed than beneath the adjacent Archaean provinces (figure 2).

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Sites of profuse basaltic volcanism associated with the initiation of mantle plumes (cf. Richards *et al.* 1989) correlate with areas of reduced mantle shear velocities beneath Archaean crust, apparently signifying significant erosion of the mantle root (figure 2). This is observed in the northern Slave province (figure 1), the site of a 1.27 Ga mantle plume that was responsible for the Coppermine plateau basalts and the enormous Mackenzie dyke swarm (LeCheminant & Heaman 1989). The Keweenaw (Midcontinent) rift coincides with a corridor of lower-velocity mantle between the Penokean orogen and the Superior province (figure 1). The rift, which overlies a mafic crustal underplate and contains up to 20 km of basalt erupted between 1.10 and 1.09 Ga, developed above a mantle plume (Nicholson *et al.* 1989). Near the Grenville orogen, the NW–SE trend of the rift parallels the direction of contemporaneous thrusting in the orogen, consistent with the 'impactogen' model of Burke (1980). Away from the orogen, the rift-trend is deflected southwestward, tracking the Superior–Penokean boundary zone, implying that the rift was unable to propogate into the rigid interior of the Superior province. The lower-velocity corridor beneath the rift is compatible with the suggestion that channels of relatively 'fertile' mantle may replace depleted mantle lithosphere during intracratonic rifting (Phipps 1988). Erosion of the Archaean mantle root by the Keweenaw plume may be compared with the postulated destruction of an Archaean mantle root beneath the Nain province by the Iceland plume.

Mantle roots are absent or poorly developed beneath the Proterozoic crust on the southern and southeastern margins of the craton (figures 1 and 2). The Mazatzal orogen is composed of 1.80–1.70 Ga juvenile crust that was reactivated by NNW-directed thrusting between 1.69 and 1.65 Ga. Protracted anorogenic magmatism including widespread crustal melting occurred between 1.54 and 1.32 Ga. Proterozoic crust in the southwestern United States was reactivated again during Neogene Basin-and-Range extension. The Grenville orogen experienced northwest-directed crustal-scale thrusting between 1.2 and 1.0 Ga. South of the Superior province, Grenvillian thrusting involved parautochthonous Archaean and Penokean (*ca.* 1.9 Ga) crust, and allochthonous terranes having 1.5–1.3 Ga model ages (figure 1). Near the Atlantic coast, Grenvillian thrusting involved mainly of 1.70–1.65 Ga (Labradorian) crust. Both the Labradorian and the Penokean zones of the Grenville orogen were intruded episodically by associated anorthositic and granitic batholiths between 1.65 and 1.15 Ga. Mantle shear velocities beneath the Grenville orogen are higher in the area of the Canadian shield than the buried platform, consistent with the association of the mantle root with crustal arching, but the reason for the difference in mantle structure cannot be assessed until the buried part of the Grenville orogen is better known.

3. Conclusions and discussion

The Canadian shield is not representative of the North American craton as a whole. Crust that evolved from the mantle in the Archaean (before 2.5 Ga) makes up 84% of the shield but only 55% of the entire craton. The shield gives a misleading impression that little new crust evolved from the mantle during the Proterozoic.

The area of the Canadian shield coincides closely with the area underlain by a high-velocity mantle root, or tectosphere, that extends to depths of at least 200 km. The mantle root must be composed of relatively refractory material of low intrinsic density to offset its lower temperature. The arching of the shield, which was located in the same general region throughout the Phanerozoic, may result from a net buoyancy of the mantle root.

The mantle root is not limited to areas of Archaean crust but is best developed there. It is less well developed beneath crust extracted from the mantle in the early Proterozoic, and least well developed beneath Middle Proterozoic and younger crust. The secular control on the development of the mantle root is compatible with the Helmstaedt & Schulze (1989) model, assuming that buoyant subduction has become less common over geologic time. If the arching of the shield is caused by a buoyant mantle root developed preferentially beneath Archaean crust, this would account for the observed partitioning of Archaean and Proterozoic crust between the shield and the platform respectively.

Isotopic and seismic anisotropy data suggest that the mantle root beneath the Archaean provinces formed in the Archaean, close to the time of crust formation, rather than developing progressively over subsequent geologic time.

Development of the mantle root is not dependent on collisional orogenesis, as implied by Jordan (1988). The mantle root is best developed under the Archaean Superior province, which is composed of island arcs that underwent little tectonic shortening after their initial aggregation.

On the other hand, collisional orogenesis does not always destroy a mantle root, as inferred by Ashwal & Burke (1989). A mantle root persists beneath the Archaean crust of the Churchill hinterland, which was reactivated during early Proterozoic collisions with the Slave, Superior and Nain microcontinents. Yet, mantle roots are conspicuously absent beneath the Wyoming and Nain provinces, which experienced late Archaean collisional orogenesis. However, destruction of their mantle roots may have occurred in the Mesozoic–Cenozoic, as a consequence of the Laramide orogeny in the Wyoming province and the Iceland plume in the Nain province.

The efficacy of mantle plume initiation in eroding mantle roots beneath Archaean crust is also shown by areas of reduced shear velocity near the sites of the Coppermine plume (1.27 Ga) in the northern Slave province and the Keewanaw plume (1.10 Ga) in the southern Superior province.

Mantle roots beneath Archaean crust survived the emplacement of extensive mafic dyke swarms, and also crustal underplating by mafic melts presumed responsible for short-lived post-orogenic crustal melting events (e.g. 1.76 Ga rapakivi-type granite and rhyolite suites in the Churchill hinterland west of Hudson Bay). However, little or no mantle root is present beneath the early Proterozoic crust of the southern United States, which was subjected to repeated anorogenic melting between 1.5 and 1.3 Ga.

The Archaean crust of the shield has been exposed to erosion for much of Phanerozoic time. The Proterozoic crust of the platform has been largely protected from erosion by sedimentary cover since the early Palaeozoic. As a result, the Archaean crust has contributed disproportionally to the detritus eroded from the North American craton, including modern river sediments. Consequently, the mean age of continental crust, which is used to constrain models of chemical cycling between the crust and mantle (see, for example, Galer *et al.* 1989), will tend to be overestimated by the isotopic ratios of particulate and dissolved material in rivers draining the North American craton (cf. Goldstein *et al.* 1984; Goldstein & Jacobsen 1987). This should also be true of ancient sediments of cratonic derivation deposited after the early Palaeozoic transgression of the platform.

If mantle roots developed preferentially beneath Archaean crust are responsible for long-lived shields, then the spatial association of shields and Archaean crust should be observed on continents other than North America. The largest shield area in Australia (Western Australian shield) is composed almost entirely of Archaean crust. Except for the Archaean Gawler craton of southern Australia, most of the rest of the pre-Palaeozoic craton of Australia is composed of crust having Proterozoic model ages (McCulloch 1987). For other continents, crust-mantle extraction ages are poorly known, especially in platform areas, and upper mantle shear velocity structures remain to be worked out.

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References

Ashwal, L. D. & Burke, K. 1989 African lithospheric structure, volcanism, and topography. *Earth planet. Sci. Lett.* **96**, 8–14.

Bell, K. & Blenkinsop, J. 1987 Archean depleted mantle: evidence from Nd and Sr initial isotopic ratios of carbonatites. *Geochim. Cosmochim. Acta* **51**, 291–298.

Bennett, V. C. & DePaolo, D. J. 1987 Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. *Bull. geol. Soc. Am.* **99**, 674–685.

Burke, K. 1980 Intracontinental rifts and aulacogens. In *Continental tectonics, studies in geophyusics* (ed. B. C. Burchfiel and others), pp. 42–49. Washington, D.C.: American Geophysical Union.

Bickle, M. J. 1986 Implications of melting for stabilization for the lithosphere and heat loss in the Archaean. *Earth Planet. Sci. Lett.* **80**, 314–324.

Bird, P. 1988 Formation of the Rocky Mountains, western United States: a continuum computer model. *Science, Wash.* **239**, 1501–1507.

Boyd, F. R. & Gurney, J. J. 1986 Diamonds and the African lithosphere. *Science, Wash.* **232**, 472–477.

Cook, T. D. & Bally, A. W. 1975 *Stratigraphic atlas of North and Central America*. Princeton University Press. (272 pages.)

DePaolo, D. J. 1981 Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. *Nature, Lond.* **291**, 193–196.

England, P. C. & Houseman, G. A. 1988 The mechanics of the Tibetan plateau. *Phil. Trans. R. Soc. Lond.* A **326**, 301–320.

Esperança, S. & LeCheminant, A. N. 1986 Isotopic evidence for multiple enrichment events from mica-lamprophyre dykes in the District of Keewatin, Canada. *Geol. Soc. Am. Abst. Programs* **18**, 595.

Fahrig, W. F. & West, T. D. 1986 *Diabase dyke swarms of the Canadian shield*. Geological Survey of Canada Map 1627A, scale 1:4873900.

Galer, S. J. G., Goldstein, S. L. & O'Nions, R. K. 1989 Limits on chemical and convective isolation in the Earth's interior. *Earth planet. Sci. Lett.* **75**, 257–290.

Goldstein, S. J. & Jacobsen, S. B. 1987 The Nd and Sr isotopic systematics of riverwater dissolved material: implications for the sources of Nd and Sr in seawater. *Chem. Geol.* (*Isotope Geosci. Section*) **66**, 245–272.

Goldstein, S. L., O'Nions, R. K. & Hamilton, P. J. 1984 A Sm–Nd isotopic study of atmospheric dusts and particulates from major river systems. *Earth planet. Sci. Lett.* **70**, 221–236.

Grand, S. P. 1987 Tomographic inversion for shear velocity beneath the North American plate. *J. geophys. Res.* **92**, 14065–14090.

Hawkesworth, C. J., Kempton, P. D., Rogers, N. W., Ellam, R. M. & van Calsteren, P. W. 1990 Continental mantle lithosphere, and shallow level enrichment processes in the Earth's mantle. *Earth planet. Sci. Lett.* **96**, 256–268.

Helmstaedt, H. & Schulze, D. J. 1989 Southern African kimberlites and their mantle sample: implications for Archaean tectonics and lithosphere evolution. In *Kimberlites and related rocks, vol. 1. Their composition, occurrence, origin, and emplacement* (ed. J. Ross). *Geol. Soc. Australia, Spec. Publ.* **14**, pp. 358–368. Carlton, Australia: Blackwell.

Hoffman, P. F. 1988 United plates of America, the birth of a craton: Early Proterozoic assembly and growth of Laurentia. *A. Rev. Earth planet. Sci.* **16**, 543–603.

Hoffman, P. F. 1989 Precambrian geology and tectonic history of North America. In *The geology of North America – an overview* (ed. A. W. Bally & A. R. Palmer). *Geol. Soc. Am.*, *The geology of North America vol. A*, pp. 447–512.
Jordan, T. H. 1988 Structure and formation of the continental tectosphere. *J. Petrol.*, *Spec. Lithosphere Issue*, pp. 11–37.
LeCheminant, A. N. & Heaman, L. M. 1989 Mackenzie igneous events, Canada: Middle Proterozoic hotspot magmatism associated with ocean opening. *Earth planet. Sci. Lett.* **96**, 38–48.
McCulloch, M. T. 1987 Sm–Nd isotopic constraints on the evolution of Precambrian crust in the Australia continent. In *Proterozoic lithospheric evolution* (ed. A. Kröner). *Am. Geophys. Union*, *Geodynamics Ser.* **17**, 115–130.
McCulloch, M. T. & Wasserburg, G. J. 1978 Sm–Nd and Rb–Sr chronology of continental crust formation. *Science*, *Wash.* **200**, 1003–1011.
Mitrovica, J. X., Beaumont, C. & Jarvis, G. T. 1989 Tilting of continental interiors by the dynamic effects of subduction. *Tectonics* **8**, 1079–1094.
Mooney, W. D. & Braile, L. W. 1989 The seismic structure of the continental crust and upper mantle of North America. In *The geology of North America – an overview* (ed. A. W. Bally & A. R. Palmer). *Geol. Soc. Am.*, *The geology of North America vol. A*, pp. 39–52.
Nelson, B. K. & DePaolo, D. J. 1985 Rapid production of continental crust 1.7 to 1.9 b.y. ago: Nd isotopic evidence from the basement of the North American mid-continent. *Bull. geol. Soc. Am.* **96**, 746–754.
Nicholson, S. W., Shirey, S. B. & Schulz, K. J. 1989 1100-Ma Keweenaw hotspot: Nd and Pb isotopic evidence for a Proterozoic mantle plume in the Midcontinent rift, U.S.A. *Eos* **70**, 1357.
Patchett, P. J. & Arndt, N. T. 1986 Nd isotopes and tectonics of 1.9–1.7 Ga crustal genesis. *Earth planet Sci. Lett.* **78**, 329–338.
Patchett, P. J. & Ruiz, J. 1989 Nd isotopes and the origin of Grenville-age rocks in Texas: implications for Proterozoic evolution of the United States mid-continent region. *J. Geol.* **97**, 685–695.
Percival, J. A., Green, A. G., Milkereit, B., Cook, F. A., Geis, W. & West, G. F. 1989 Seismic reflection profiles across deep continental crust exposed in the Kapuskasing uplift. *Nature*, *Lond.* **342**, 416–420.
Phipps, S. P. 1988 Deep rifts as sources for alkaline intraplate magmatism in eastern North America. *Science*, *Wash.* **334**, 27–31.
Richards, M. A., Duncan, R. A. & Courtillot, V. E. 1989 Flood basalts and hot-spot tracks: plume heads and tails. *Science*, *Wash.* **246**, 103–107.
Richter, F. M. 1988 A major change in the thermal state of the earth at the Archean–Proterozoic boundary: consequences for the nature and preservation of continental lithosphere. *J. Petrol.*, *Spec. Lithosphere Issue*, pp. 39–52.
Roest, W. R. & Srivastava, S. P. 1989 Sea-floor spreading in the Labrador Sea: a new reconstruction. *Geology* **17**, 1000–1003.
Silver, P. G. & Chan, W. W. 1988 Implications for continental structure and evolution from seismic anisotropy. *Nature*, *Lond.* **335**, 34–39.
White, R. & McKenzie, D. 1989 Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *J. geophys. Res.* **94**, 7685–7729.
Windley, B. F. 1984 *The evolving continents*, 2nd edn. New York: Wiley. (399 pages.)