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Multi-genetic origin of the continental Moho: insights from LITHOPROBE

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ABSTRACT

This paper reviews four hypotheses for the origin of the continental crust–mantle boundary and discusses seismic parameters with which these hypotheses might be tested. The *relict Moho* hypothesis posits that the oceanic Moho is preserved during continental assembly; the *magmatic underplating* hypothesis posits formation of a new Moho by episodic emplacement of sill-like intrusive bodies; the *metamorphic* (*or metasomatic*) *front* hypothesis posits that the Moho is overprinted by a phase transformation; and the *regional décollement* hypothesis posits that the Moho behaves as a structural detachment. These hypotheses are not mutually exclusive, and examples from the Canadian LITHOPROBE program suggest that all four may be applicable in different regions of North America. Comparison of seismic images from a fossil subduction zone with modern subduction at Cascadia suggests that serpentinization of the forearc mantle, a previously unrecognized mechanism for overprinting and erasing the reflection Moho, may have occurred in the Proterozoic.

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Introduction

Nearly a century after its discovery by Andrija Mohorovčiči in 1910, our understanding of the Mohorovičič discontinuity (a.k.a. the Moho) remains incomplete. The defining characteristic of the Moho – an abrupt increase in *P*-wave velocity to ≥ 7.6 km s^{-1} (e.g. Giese, 2005) – enables its identification and mapping by seismological methods in all parts of the world. Beneath the oceans, the Moho occurs at a nearly uniform depth of 5–8 km under the seafloor, where it coincides with the transition from cumulate mafic to cumulate ultramafic rocks (White *et al.*, 1992). The seismologically defined continental Moho is considerably deeper (20–85 km) and, although it is an almost universally mappable feature, there is still no scientific consensus about its origin, petrologic significance and structural context (Jarchow and Thompson, 1989).

A better understanding of the origin of the continental Moho could provide insights into processes of formation of continental crust and material exchange between the crust and mantle (Nelson, 1991; Rudnick, 1995; Albarède, 1998). Such discussions, however, are often fraught with methodology- and resolution-dependent semantic issues. By definition, the Moho is a seismic-velocity boundary or transition zone (Jarchow and Thompson, 1989). The use of different geophysical techniques to identify the Moho, however, has spawned a variety of labels, including the *refraction Moho* (Steinhart, 1967), the *reflection Moho* (Klemperer *et al.*, 1986) and the *electric Moho* (Jones and Ferguson, 2001). The emergence of teleseismic receiver-functions techniques for mapping the Moho (e.g. Zhu and Kanamori, 2000) augurs the creation of a new label, the *teleseismic Moho*. Occasional discrepancies in Moho depths obtained using different techniques largely reflect intrinsic differences in their spatial resolution and underlying physical basis. More importantly, the seismological Moho is not always equivalent to the petrologic crust–mantle boundary (Griffin and O'Reilly, 1987a,b).

Although it is the shallowest global manifestation of a differentiated Earth, a major impediment to understanding the nature of the continental Moho is its paucity of exposure. Regional granulite terranes are dominantly Precambrian and may not be representative of lower crustal conditions (Nelson, 1991). On the contrary, uplifted lower crustal exposures are rare (Fountain and Salisbury, 1981) and may have been modified by tectonic processes during emplacement. Although xenoliths from the lower crust and upper mantle can provide considerable information, individual samples are small, contacts between different rock types are rarely preserved, and sampling beneath cratonic regions is sparse (Griffin and O'Reilly, 1987b). We are therefore largely reliant on a growing body of geophysical data to furnish structural observations with which to test hypotheses for the formation and evolution of the continental Moho.

This paper reviews four hypotheses for the origin of continental Moho (Fig. 1) and discusses several observable parameters (mainly seismic) that might be used to test them. The examples are taken from seismic reflection and refraction surveys recorded as part of the Canadian LITHOPROBE program (Fig. 2), which completed its 20-year research mission in 2004. The hypotheses and examples presented here are intended to be illustrative, rather than exhaustive. Indeed, other major deep-seismic programs have yielded high-resolution observations of the continental Moho, including pioneering studies by COCORP (e.g. Klemperer *et al.*, 1986; McBride and Knapp, 2002), BIRPS (e.g. Klemperer and Hobbs, 1991; Chadwick and Pharaoh, 1998) and DEKORP (e.g. Meissner, 2000), as well as more recent investigations such as INDEPTH (e.g. Hauck *et al.*, 1998) and CROP (e.g. Finetti *et al.*, 2001). The LITHOPROBE data set is particularly exemplary for Precambrian regions, which in North America encompass both the Canadian Shield as well as contiguous areas of the platform, comprising the largest Precambrian craton on Earth. Earlier

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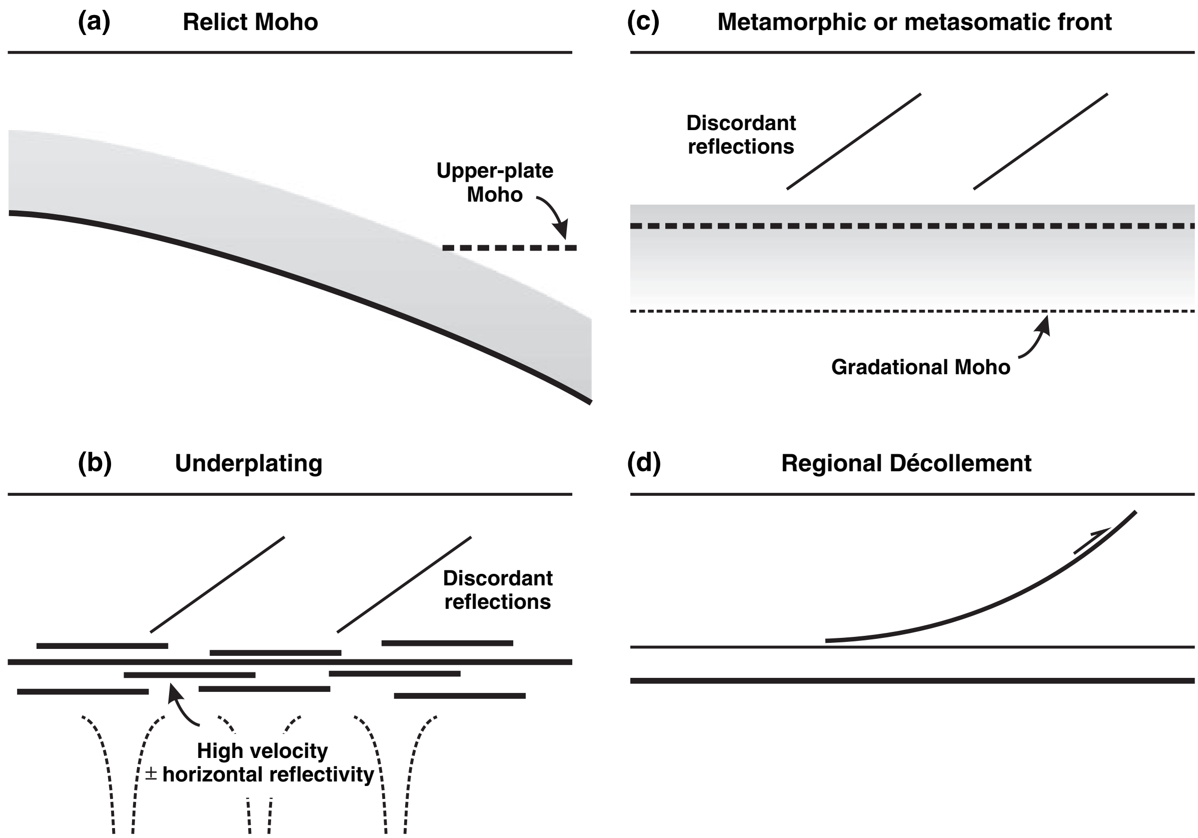

Fig. 1 Cartoon illustrating four hypotheses for formation of the continental crust–mantle boundary, by: (a) preservation of old (oceanic) Moho during island arc assembly (relict Moho); (b) creation of a new Moho by magmatic underplating; (c) establishment of a new Moho along a metamorphic or metasomatic front; (d) localization of deformation along a regional décollement at (or near) the Moho.

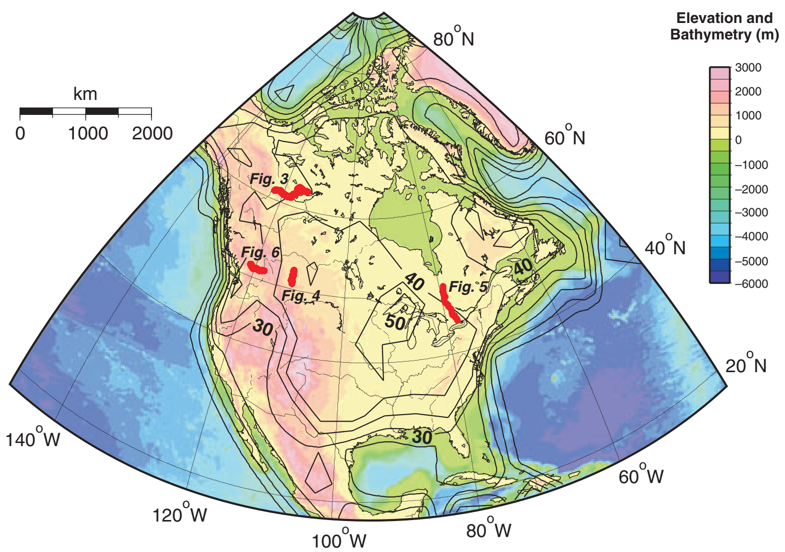

Fig. 2 Elevation and bathymetry map of North America (from model etopo5; NOAA, 1988), with contours of crustal thickness in km, based on model Lith5.0 (Perry *et al.*, 2001).

studies suggesting significant differences between Precambrian and modern lower crustal reflectivity patterns (e.g. Gibbs, 1986) have been supplanted by newer results from LITHOPROBE (Hammer and Clowes, 1997), which provide strong evidence that tectonic processes which created and modified the ancient Moho are similar to those that operate at the present time.

Hypotheses for formation of the continental Moho

Four hypotheses for formation of the continental Moho are shown schematically in Fig. 1 and listed in Table 1. Each hypothesis is classified as either igneous or reworked in character. Observable seismic parameters that are deemed to be diagnostic for each type of Moho are also given, based on the interpretations below. The first hypothesis (*relict Moho*) posits that

Table 1 Hypotheses for the origin of the continental Moho

Classification	Hypothesis	Seismic expression
Igneous	1. The continental Moho is an inherited old (oceanic) Moho, assembled by imbrication of old crust (island arcs)	Fossil subduction with continuous lower-plate reflection Moho (Fig. 3)
	2. The continental Moho is formed by magmatic underplating	High-velocity lower crust (Fig. 4) Down-dip truncation of lower-crustal reflections
Reworked	3. The continental Moho is a metamorphic or metasomatic front (a) Eclogite phase transition (b)Serpentinized upper mantle	(a) Relict layering of the upper mantle observed at wide-angle; preserved Moho topography without reciprocal surface topography (Fig. 5) (b) Demonstrably transparent Moho
	4. The continental Moho (or lower crust) is a regional décollement	Dipping reflections in upper and middle crust that are listric into subhorizontal reflectivity in the lower crust; flat, strong reflection Moho (Fig. 6)

the present continental Moho is inherited from the base of pre-existing crustal blocks. According to this model, the present Moho became frozen (Cook, 2002) early in its development, and thus faithfully records terminal processes of continental assembly without overprinting by post-collisional processes. A variant of this model is implicit in some crustal interpretations, including those that invoke palaeo-subduction to explain observed dipping seismic reflection at or beneath the Moho (van der Velden and Cook, 2005). One implication of this model is that most of the lithological contrasts in the lowermost crust and upper mantle are preserved, in spite of the long history. Carried to its logical extreme, this hypothesis implies that parts of the continental Moho represent a relict oceanic Moho. A challenging implication of this model, if it applies to large areas, is that thickening and development of an andesitic bulk composition of the continental crust (Rudnick, 1995) are achieved without apparent disruption of the Moho.

The second hypothesis, *magmatic underplating* (McKenzie, 1984; Furlong and Fountain, 1986) has been invoked by a number of authors to explain a thick (> 10 km) high-velocity layer and/or strong horizontal reflectivity in the lower crust (Holliger and Levander, 1994; Thybo *et al.*, 2000; Clowes *et al.*, 2002; McBride *et al.*, 2004). In this scenario, the continental Moho is located near the base of an intrusive complex that is, for the most part, younger than the overlying crust. Dipping reflections in the upper and middle crust that are truncated in the lower crust can provide seismic evidence for a process such as this, which has destroyed pre-existing Moho structure (e.g. McBride and Knapp, 2002). Substantial thickening of continental crust by magmatic underplating is interpreted to have occurred during the Archean (Fyfe, 1973) and the mid-Proterozoic (Musacchio and Mooney, 2002). Nelson (1991) proposed that given sufficient time, magmatic underplating of continents is virtually inevitable, and suggested that: (1) mafic underplating could result from either lithospheric delamination or passage of a continent overtop a mantle upwelling; (2) mafic dike swarms, which abound in ancient continental crust, are a surface manifestation of this process; and (3) although modest mafic magmatic addition to the crust in the form of discrete sills produces a reflective lower crust, massive magmatic addition leads to a seismically transparent lower crust (cf. McBride *et al.*, 2004).

The next two hypotheses involve non-igneous origins of the Moho. The *metamorphic or metasomatic front* hypothesis invokes phase changes that modify the seismic wavespeed and density of rocks near the crust–mantle boundary. For example, the transformation of mafic rocks into eclogite (O'Connell and Wasserburg, 1967) can increase their *P*-wave velocity to > 8.1 km s^{-1}, a value that is typical of the *P*-wave velocity for upper mantle peridotite (Holbrook *et al.*, 1992). Granulite facies mineral assemblages are metastable under dry conditions to depths of more than 50 km (Bjornerud *et al.*, 2002), but their sudden transformation to eclogite can substantially weaken crustal support of surface topographic loads (Jackson *et al.*, 2004). Baird *et al.* (1995) appealed to this process to suggest that a remnant crustal keel beneath the Williston Basin underwent eclogite facies metamorphism, overprinting the Moho and inducing basin subsidence. Conversely, serpentinization of mantle rocks can lead to a reduction of upper mantle *P*-wave velocity to a value less than that in the lower crust, possibly resulting in inversion of the continental Moho (Bostock *et al.*, 2002). In either case, the typically gradational nature of metamorphic fronts implies that direct seismological detection of the Moho may be difficult (Hurich *et al.*, 2001). In addition, like the magmatic underplating hypothesis, this can lead to discordance between the reflection patterns of the upper and lower crust.

The fourth hypothesis (*regional décollement*) posits mechanical decoupling of the crust and uppermost mantle as a result of structural detachment at (or near) the Moho. Depending on crustal composition and thermal conditions, decoupling can occur at rheological weak zones in the lower crust or the uppermost mantle (Reston, 1990; Meissner and Mooney, 1998). Under exceptionally hot conditions, lower-crustal channel-flow behaviour can result in nearly complete decoupling of the upper crust from the upper mantle (e.g. Royden *et al.*, 1997). Based on BIRPS reflection data around the British Isles, Chadwick and Pharaoh (1998) suggested that development of a Moho detachment surface can tectonically smooth the Moho and thereby markedly increase its reflectivity. Lower crustal reflections that are listric into the reflection Moho in both extensional and compressional regimes have been interpreted to represent localization of deformation along a rheological boundary near the crust–mantle transition (Cook, 2002; McBride and Knapp, 2002).

Example 1: Relict Moho

Figure 3(a) shows one of the most definitive available seismic images of

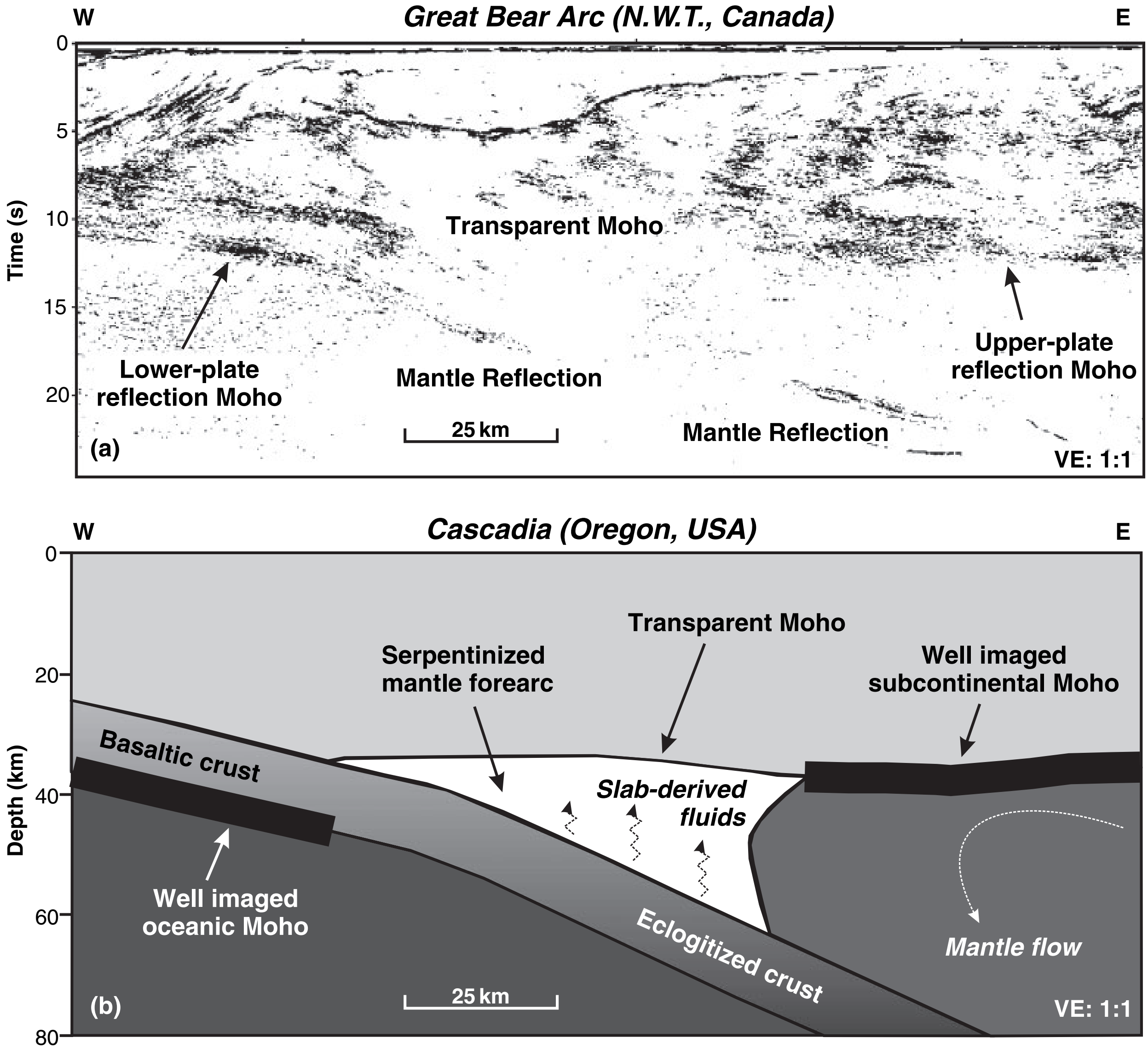

Fig. 3 (a) Example 1: migrated vibroseis profile (SNORCLE line 1) across the Great Bear Arc, Northwest Territories. East-dipping mantle reflections, interpreted to image a fossil subduction zone (Cook *et al.*, 1999) can be followed to more than 20 s two-way time (~66 km depth). (b) Simplified cross-section of the modern Cascadia subduction zone (Oregon, USA) based on migration of teleseismic scattered waves (Bostock *et al.*, 2002). Note geometrical similarity with the inferred fossil subduction zone in (a). In both cases a zone of transparent Moho is sandwiched between adjacent areas where the Moho is well imaged.

inferred frozen subduction (Cook *et al.*, 1999). In this example, the continental magmatic arc (Great Bear Arc) that developed in the upper plate of this system is an episutural batholith that formed between 1.88 and 1.84 Ga (Hoffman and Bowring, 1984). The arrested subduction apparent in this image implies that the lower-plate Moho is a relict feature that formed earlier than terminal collision (1.84 Ga). Coupled with geological evidence that young oceanic lithosphere was consumed in this subduction zone (Hoffman and Bowring, 1984), this age constraint suggests that the relict lower-plate Moho may be of oceanic origin. Indeed, the striking similarity of the Great Bear Arc with the modern Cascadia subduction zone (located *c.* 1600 km SW of the Great Bear Arc), as imaged using teleseismic methods (Fig. 3b; Bostock *et al.*, 2002), reinforces this interpretation.

This example supports the first hypothesis for the origin of the Moho, as it indicates that relict oceanic Moho may be preserved, at least locally, at the base of shield-type continental crust after collisional assembly. Low Moho temperatures near a subduction zone could enhance the preservation of relict Moho, in the absence of subsequent thermal effects or deformation (Cook, 2002). Near the west end of SNORCLE line 1 (Fig. 3a) it is worth noting that both the reflection Moho, which flattens out and coincides with the base of a subhorizontal reflectivity, and the refraction Moho (Fernandez-Viejo *et al*., 1999) appear to have characteristics that are typical of the continental Moho. It therefore may be difficult, on the basis of seismic characteristics alone, to determine if relict oceanic Moho exists as a widespread feature of the continental crust–mantle boundary.

In the case of the Cascadia subduction zone, Bostock *et al.* (2002) showed that where the top of the slab lies between 35 and 65 km deep (Fig. 3b), the continental Moho atop the forearc mantle wedge is transparent to scattering of teleseismic *P* waves. They attributed this transparent Moho, sandwiched between well-imaged Moho segments, to hydration of the forearc mantle from de-watering of the slab. The formation of serpentinite minerals in mantle peridotite can reduce the bulk density and of the upper mantle and eliminate acoustic impedance contrasts at the Moho (Bostock *et al*., 2002). Similarly, in the case of the Great Bear Arc no reflection Moho is apparent above the shallow part of the inferred subducting slab (Fig. 3a). The disappearance of the reflection Moho cannot be ascribed to inadequate signal penetration (Eaton and Wu, 1996), as deeper mantle reflections are still visible along part of the segment where the reflection Moho is absent. The loss of Moho reflectivity could be caused, however, by the elimination of impedance contrasts between mafic and ultramafic rock units associated with serpentinization of the forearc lithosphere, in the same manner as in the modern Cascadia subduction zone. Although additional work is necessary to test this hypothesis, it provides a novel explanation for the absence of a reflection Moho along this part of the seismic profile.

Example 2: Thick magmatic underplating

Figure 4(a) shows a LITHOPROBE seismic-reflection profile (line SALT-25) across a buried Precambrian structure in the subsurface of western Canada, where Phanerozoic sedimentary rocks of the western Canada sedimentary basin overlie the Precambrian crystalline basement. This feature, known as the Vulcan structure, is an inferred 1.8 Ga suture (Villeneuve *et al*., 1993) interpreted as the northern boundary of the Archean Wyoming craton (Eaton *et al*., 1999). The Vulcan structure coincides with a distinct change in Moho reflectivity. North of the suture, beneath the 1.78–2.71 Ga Loverna Block, the reflection Moho is a distinct, broadly undulating contact between reflective lower crust and non-reflective upper mantle. South of the suture, the reflection Moho is indistinct and the lower crust is characterized by weakly coherent panels of dipping reflections that resemble imbricated, north-verging thrust sheets (Fig. 4a).

The Deep Probe experiment (Gorman *et al*., 2002) comprised a major long-range refraction profile extending from north-western Canada to the south-western United States. Part of the Deep Probe deployment coincided with a shorter, more densely instrumented crustal refraction profile (the SAREX experiment; Clowes

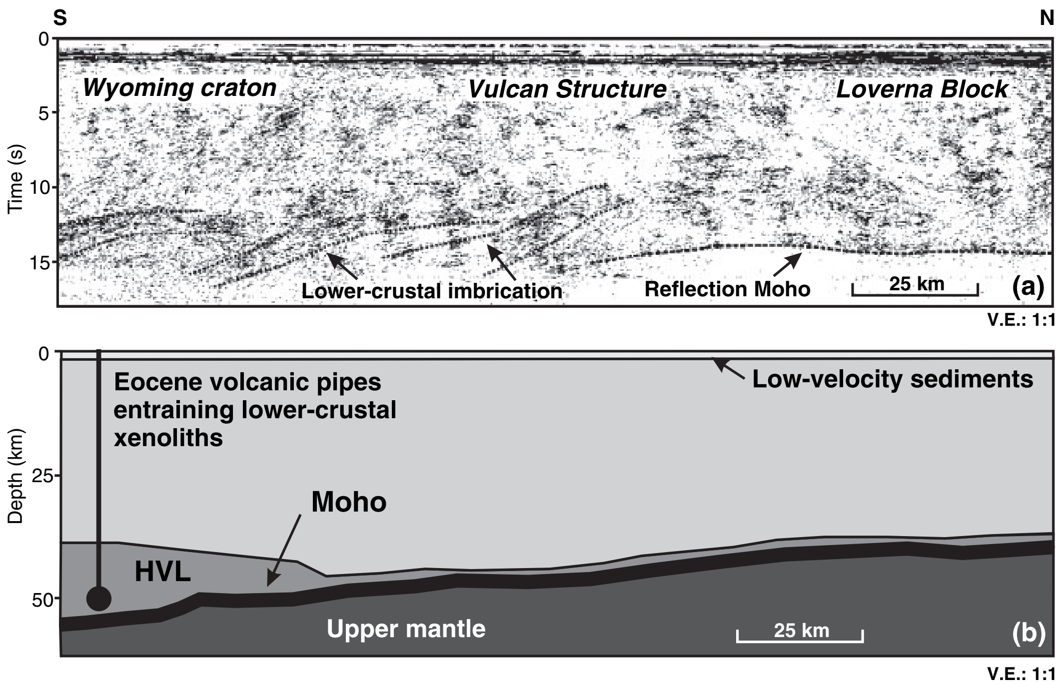

Fig. 4 (a) Example 2: migrated vibroseis profile (SALT line 25) across the Vulcan Structure, a Proterozoic collisional belt in southern Alberta (modified from Eaton *et al*., 1999). (b) Simplified crustal model based on results of the Deep Probe long-range refraction experiment (Gorman *et al*., 2002), located *c*. 90 km east of SALT line 25. A lower-crustal high-velocity layer (HVL) at the south end of this profile extends for hundreds of km beneath the Wyoming craton and thickens to 25 km. Lower crustal xenoliths from nearby Eocene volcanics indicate that the HVL represents underplated mafic material (Davis *et al*., 1995).

et al., 2002) parallel to and *c*. 90 km east of line SALT-25. The most prominent crustal feature evident in both data sets is a thick (10–25 km) lower crustal layer underlying the Archean crust south of the Vulcan structure, characterized by unusually high *P*-wave velocities (7.5–7.9 km s^{-1}; Gorman *et al*., 2002). Based on the high seismic velocities and analysis of lower-crustal xenoliths collected near line SALT-25, this lower-crustal layer has been interpreted as a mafic underplate (Clowes *et al*., 2002). Lower-crustal xenoliths comprise samples of 1.75–1.81 Ga garnet–kyanite paragneiss that equilibrated at 1240 MPa, and samples of 1.70–1.75 Ga mafic granulite that equilibrated at 1350 MPa (Davis *et al*., 1995). An underplating event inferred from the texture and composition of the mafic granulites (Davis *et al*., 1995) therefore post-dated formation of the Vulcan collisional suture, and occurred more than 800 Ma after crystallization of Archean rocks in the upper crust (Villeneuve *et al*., 1993).

Taken together, evidence from roughly co-located crustal refraction, reflection and xenolith data lends convincing support for the hypothesis of thick magmatic underplating in this area. The underplating event occurred long after the late Archean formation of upper crustal rocks (Davis *et al*., 1995). Where underplated material is present, lower crustal reflectivity diminishes gradually with depth and no distinct reflection Moho is discernible. Seismic evidence for imbrication of the lower crust (Eaton *et al*., 1999) suggests that underplated material deformed as coherent blocks, at scale lengths of *c*. 25 km, during post 1.70 Ga brittle deformation.

Example 3: The role of eclogitization in the preservation of Moho relief

Figure 5(a) shows a residual velocity model obtained by Winardhi and Mereu (1997), derived from line MDG of the 1992 LITHOPROBE crustal-refraction experiment in the Grenville Province of south-eastern Canada. Two significant features of this model are an unusual thickness of the Moho transition zone (up to 8 km), and a large (> 10 km) variation in Moho depth. The thickest crust occurs near the Grenville Front, where high-grade gneisses and migmatites were exhumed along a major crustal ramp (Green *et al*., 1988) during the *c*. 1.0 Ga Grenville orogeny. Recent studies have revealed that this high-grade terrane contains localized exposures of rocks with relict high-pressure (eclogite facies) mineral assemblages (Ludden and Hynes, 2000). Pressure–temperature estimates for eclogite facies conditions in well-preserved assemblages are about 1800 MPa and 850 °C (Rivers *et al*., 2002).

The Moho topography partially preserves a crustal root that formed beneath a *c*. 1.0 Ga mountain belt of Himalayan proportions and/or a late Precambrian extensional overprint (Eaton *et al*., 1995). However, this region has little surface relief (< 400 m), implying that classical Airy-type isostasy, in which surface topographic loads are balanced at

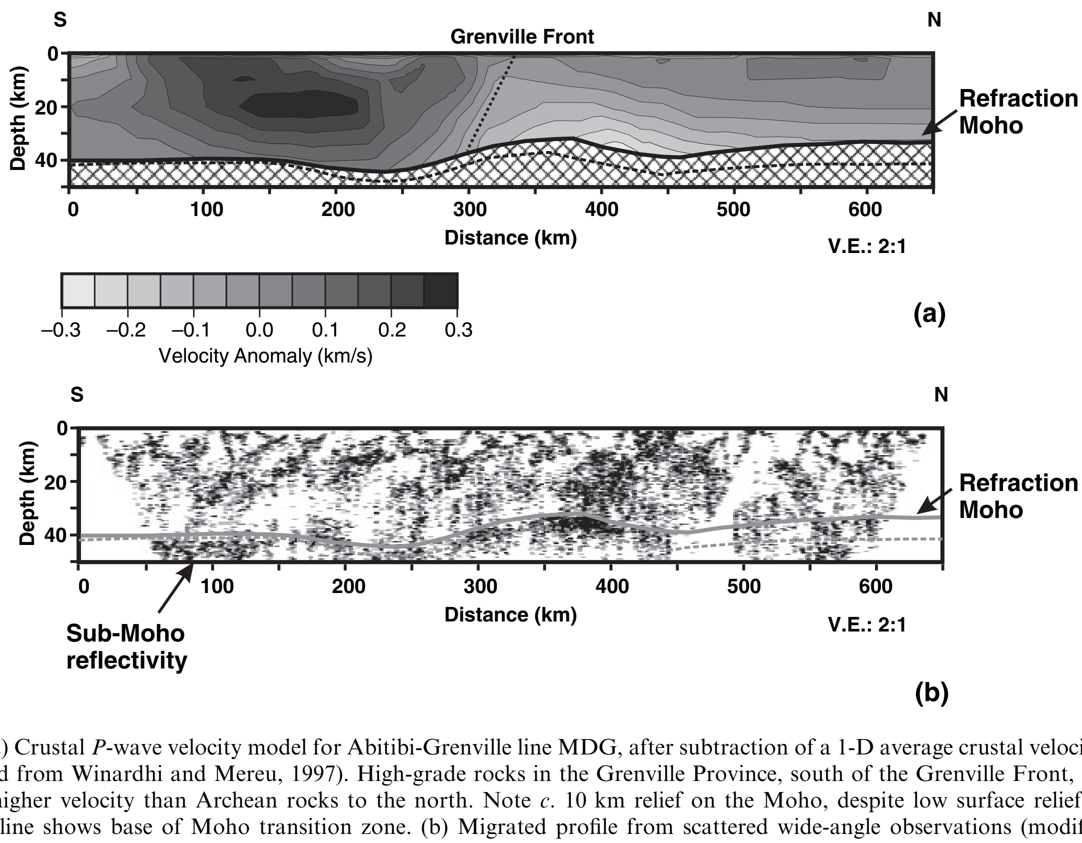

Fig. 5 (a) Crustal *P*-wave velocity model for Abitibi-Grenville line MDG, after subtraction of a 1-D average crustal velocity model (modified from Winardhi and Mereu, 1997). High-grade rocks in the Grenville Province, south of the Grenville Front, generally have a higher velocity than Archean rocks to the north. Note *c*. 10 km relief on the Moho, despite low surface relief (Fig. 1). Dashed line shows base of Moho transition zone. (b) Migrated profile from scattered wide-angle observations (modified from Mereu, 2000). Note apparent increase in wide-angle reflectivity below the Moho in the southern half of the profile.

depth by mass deficiencies associated with reciprocal Moho topography, is not applicable at present. Approximate isostatic balance could nevertheless be maintained if the density contrast between deep crustal roots and the underlying mantle has been reduced by partial transformation of lower crustal rocks to ecologite, as proposed by Fischer (2002). The existence of exhumed rocks with a relict high-pressure signature provides circumstantial support for this interpretation, as it demonstrates that rocks that were once deeply buried beneath the Grenville orogen contained eclogite facies mineral assemblages that formed under peak metamorphic conditions. It is worth emphasizing that this scenario does not imply that lower crustal densities are equal to (or greater than) the upper mantle, as the transformation to eclogite is a self-limiting and spatially heterogeneous process that can leave significant masses of granulite-grade rocks unaffected (Bjornerud *et al*., 2002).

The reflection Moho from near-vertical incidence profiling in this area is generally weak (White *et al*., 2000; O'Dowd *et al*., 2004). However, Mereu (2000), who performed a line-drawing migration of wide-angle reflections to construct a reflectivity section from the LITHOPROBE refraction data, has obtained a wide-angle reflection image of the Moho. In contrast to the usual case for near-vertical incidence data, where the reflection Moho coincides with the base of crustal reflectivity (see Figs 3 and 4), the migration of scattered wide-angle events reveals a somewhat reflective upper mantle beneath a seismically unreflective lower crust (Fig. 5b). Consistent with the previous discussion, the sub-Moho wide-angle reflectivity could represent previously laminated lower-crustal material that was tectonically buried and subsequently transformed to eclogite (cf. Hynes and Snyder, 1995; Eaton *et al*., 2000). Thus, the Moho in this area could be interpreted as a metamorphic front associated with a phase transformation to eclogite that has overprinted an older Moho. If the metamorphic front is gradational in character, this would also provide a plausible explanation for the indistinct reflection Moho and inferred thick Moho transition zone and in this area.

Example 4: Role of the Moho in crust–mantle decoupling

Figure 6 shows a migrated seismic profile constructed by combining lines 7–10 of the LITHOPROBE southern Cordillera transect (Cook *et al*., 1992). These lines are located in a modern back-arc setting within the Omineca crystalline belt, where the metamorphic and plutonic hinterland of the Canadian Rockies is spectacularly exposed in the Selkirk Mountains. A panel of prominent, west-dipping reflections, extending with nearly uniform dip from close to the surface to at least 9 s two-way time (*c*. 27 km depth), correlates with a zone of high-grade mylonites that are prominently developed in a thrust zone (the Monashee décollement; Cook *et al*., 1992). These mylonites formed in Middle to Late Jurassic time, accommodating ductile eastward transport of the Selkirk allocthon over the Monashee complex (Brown and Read, 1983). West-dipping reflectivity in supracrustal rocks of the Selkirk allochthon shows a listric geometry and flattens at *c*. 8 s two-way time (*c*. 24 km depth). The reflection Moho is imaged as a *c*. 1s band of subhorizontal reflections, at the base of moderately reflective lower crust.

The absence of coherent reflectivity in the mantle, coupled with pronounced discordance between dipping reflectivity in the top *c*. 27 km of the crust and horizontal reflectivity near the Moho, indicates that deformation in the crust is effectively decoupled from the upper mantle in this region (Cook *et al*., 1992). Furthermore, some reflections are clearly listric into subhorizontal reflection fabrics in the lower crust, suggesting that the lower crust behaved as a zone of weakness into which upper crustal detachments soled (Cook, 2002). Observations such as these provide support for the fourth hypothesis for the origin of the continental Moho in this area – namely, that the Moho is a predominantly structural/tectonic boundary located at the base of a weak lower crust.

Despite significant (> 2 km) surface relief and high topography in the Selkirk Mountains, the crust is thinner (34–35 km) than the continental average (38 km; Mooney *et al*., 1998) and

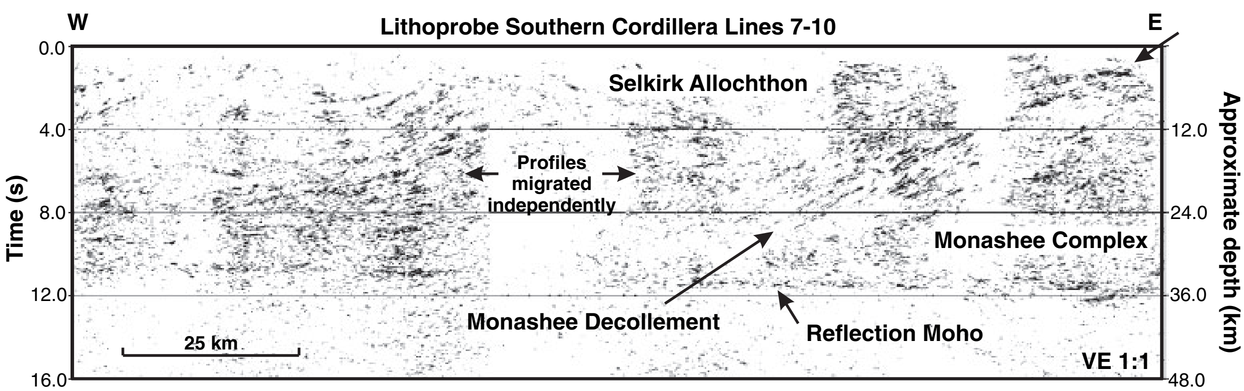

Fig. 6 Composite profile (Southern Cordillera lines 7–10) in the Omineca Crystalline Belt of the Canadian Cordillera. The reflection Moho is clearly imaged as a discrete, *c*. 1 s package of subhorizontal reflectivity below a highly reflective crust. The depth to the Moho decreases slightly to the west. Prominent reflections associated with major structural elements, such as the Monashee Décollement (arrows), extend into the lower crust but do not cross the Moho (Cook *et al*., 1992).

the reflection Moho is remarkably flat. Thermal and rheological properties of the crust may explain this deviation from classical Airy isostasy. High surface heat flow in the Omineca belt is probably being advected from the mantle by convective circulation in the asthenosphere (Davis and Lewis, 1984), resulting in high Moho temperatures (800–900 °C) and weak (ductile) rheology of the lower crust. An almost identical thermal environment characterizes the northern Canadian Cordillera where, like the southern Cordillera, high surface topography may be isostatically supported by elevated temperatures in the crust and mantle (Lewis *et al.*, 2003).

Discussion and conclusions

Motivated by examples from Canada's LITHOPROBE program, four hypotheses for the formation of the continental crust–mantle boundary are considered here: (1) the Moho was inherited from a pre-existing (e.g. oceanic) regime; (2) the Moho was created by magmatic underplating; (3) the Moho represents a metamorphic or metasomatic front; (4) the Moho represents a regional décollement. As summarized below, observations of Moho characteristics from multichannel seismic reflection profiling, wide-angle refraction observations and xenolith studies, indicate that the continental Moho may have different origins in different parts of North America.

1. A remarkable similarity in Moho configuration beneath a fossil subduction zone (the Proterozoic Great Bear Arc in northern Canada) and a modern subduction zone (Cascadia) argues against substantial post-collisional modification of the Moho beneath the Great Bear Arc. In particular, continuity of the lower-plate Moho with dipping mantle reflections favours the hypothesis that, in some areas, the oceanic (island arc?) Moho forms the present-day continental Moho.
2. In southern Alberta, lower-crustal xenoliths confirm that a high-velocity layer (7.5–7.9 km s^{-1}) in the lower crust represents a thick, mafic underplate that was emplaced more than 800 Ma after crystallization of the upper crust. In the underplated region, lower crustal reflectivity diminishes gradually with depth and no distinct reflection Moho is discernible.
3. Near the Grenville Front in south-eastern Canada, substantial (*c.* 10 km) Moho topography is preserved beneath an area of low surface relief. Underneath the Moho, a zone of enhanced wide-angle reflectivity has been observed (Mereu, 2000). The recent recognition of relict high-pressure (eclogite facies) mineral assemblages in high-grade terranes exhumed near the Grenville Front implies that deeply buried crustal rocks underwent phase transformation to eclogite as a result of crustal thickening during the Grenville orogeny. Such dense, eclogitic material in (and beneath) lower-crustal roots could lead to a Pratt-style, rather than Airy-style, approximate isostatic balance long after erosion of high surface topography (Fischer, 2002). These arguments lend support to the hypothesis that the continental Moho forms, at least in some areas, by widespread eclogitization of the lower crust.
4. In the metamorphic and plutonic hinterland of the southern Canadian Cordillera, the reflection Moho is imaged as a nearly horizontal, *c.* 1s package of reflections at the base of subhorizontal lower-crustal reflectivity. These subhorizontal reflections separate strong dipping reflection fabrics in the middle and upper crust from unreflective upper mantle, suggesting decoupling of the upper crust from the mantle during deformation. Under high-temperature conditions, such decoupling could be achieved by lower-crustal channel flow. This example supports the hypothesis that the lower crust can be a zone of weakness, localizing deformation such that the overprinted Moho serves as a subhorizontal regional décollement (Meissner and Mooney, 1998; Cook, 2002).
5. In the inferred fore-arc region of the Great Bear Arc, the reflection Moho is transparent. Lack of signal penetration can be discarded as an explanation for this, as prominent dipping mantle reflections are visible. Comparison with the Cascadia subduction zone suggests that the transparent Moho could be caused by elimination of physical-property contrast between the lower crust and mantle due to serpentinization of the forearc mantle (Bostock *et al.*, 2002). This lends support to the notion that the Moho can be destroyed (as well as created) by metamorphic and/or metasomatic phase changes.

This list is not exhaustive; in addition to the processes considered here, seismic observations elsewhere in the world suggest other important mechanisms for formation and modification of the continental Moho. For example, Reston (1990) interpreted well-developed horizontal reflectivity that characterizes the lower crust around the British Isles to represent distributed deformation that accommodates the transfer of shear strain between the upper crust and the mantle. Meissner (2000) argued that a strong heat pulse due to a delamination process or plume in an extensional or collapse regime could destroy a pre-existing Moho. In the case of a persistent source of heat, Meissner (2000) argued that this mechanism could lead, through an ordering process, to development of horizontal lamellae in the lower crust and invoked this model to explain enhanced lower-crustal reflectivity and thin post-Variscan crust of central and western Europe. Doglioni (1991) proposed that in the Apennines and other retreating subduction zones, slab roll-back leads to the creation of a new Moho through a shallow delamination process. Taken together with the examples considered here, these models strongly support the concept of a multi-genetic origin for the continental Moho.

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