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Heterogeneity in the mantle—its creation, evolution and destruction

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Abstract

Small-scale seismic heterogeneity exists at different levels in the lower mantle, and is detected by methods that analyze scattered–not direct–energy from natural and artificial sources. Its vertical distribution, association with subduction, and its ≤10-km characteristic scale length strongly suggest that it is chemical/petrological in nature and originally created by melting and differentiation during mid-ocean ridge formation. What is of interest is that the scale lengths of both upper and lower mantle seismic heterogeneity are similar, which supports the view of a common origin explored here. Unlike the lower mantle however, which is broadly homogeneous in structure, the upper mantle contains things that trap and impede the dispersal and re-mixing of heterogeneity: continental crust, lithosphere and cratonic roots. These probably control the depths, the longevity and the age of heterogeneities at shallow mantle levels, and suggest that heterogeneities observed in continental mantle lithosphere are probably old, trapped by the process that grows continental roots. Alternatively, if crustal heterogeneity is controlled by the details of a magmatic process, it must either be somehow continually renewed, for which there is no recognizable surface expression, or it must be depleted over time and the present is a time when, by luck, we may still witness it.

Keywords: Seismology; Scattering; Mantle structure; Mantle evolution

1. Introduction

The earth differentiated from material of approximately chondritic composition into the stratified state that we recognize at present–core, mantle and crust–through a sporadic sequence of processes occurring on different time scales. The core's separation from the silicate earth took place ~50 Ma after accretion in the solar nebula (Halliday et al., 1996) based on anomalies in the W–Hf isotope system, and the main stage in extracting the continental crust from the remaining silicate progressed over the subsequent 1–2 Ga (Rudnick, 1995; Reymer and Schubert, 1984). Separation of the core from the approximately chondritic initial composition of the Earth (Halliday et al., 1996; O'Neill and Palme, 2000) separated the siderophile elements from lithophile ones that make up the rocky parts of the Earth: the mantle and crust. As the early Earth cooled, the crust gradually formed through retention at the surface of buoyant melting products from early earth magmatism (Carlson et al., 2005). For the past 2 Ga or so, these processes have been either inactive or of secondary importance to plate-tectonic processes (Allégre, 1987), of which, at present, the volumetrically most important component is the formation of oceanic crust generated by ~10% melting of peridotitic mantle (Hofmann, 1997).

Because mid-ocean ridge basalt (MORB) is the most common rock at the Earth's surface, its trace element and isotopic makeup is of key interest to geochemists. It reflects a 200 million-year-long, widespread, homoge-

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neous sampling of the shallow mantle and thus contains information about the long-term evolution of the mantle from its initial differentiated state into core, mantle and continent (Zindler and Hart, 1986; Allégre, 1987; Hofmann, 1997). Geochemists have a "standard model" of mantle evolution derived from the isotope ratios of lead, neodymium and strontium present in MORB (Allégre and Lewin, 1995; Hofmann, 1997). The model assumes that subduction has been going on throughout Earth history and uses the fact that the isotopic parents of the radiogenic isotopes of the previously mentioned elements, uranium, thorium, samarium and rubidium, partition differently into the melt that crystallizes at the surface as MORB: U and Th are strongly concentrated there and depleted from the solids remaining after melting. In particular, a component that is rich in radiogenic lead (called high-μ), present in all MORB, is assumed to represent subducted, recycled oceanic crust that has been in the mantle for about 1.5 Ga before being sampled in MORB (Hofmann and White, 1982). Recycled oceanic crust is therefore an element of the "standard model." Forging an observational link between this inferred process and the objects that carry the isotopic signal would physically validate the chemical inference. Seismologists need a way to track oceanic crust throughout the mantle in order to do this.

The basaltic crust's composition differs significantly from the peridotite from which it formed. Relative to peridotite, it is richer in silica, calcium and aluminum (Ringwood, 1975). The different mineral assemblages this entails leads to it being denser–garnet rich–and potentially elastically distinct from its surrounding mantle, even after thermal equilibration (Kesson et al., 1994). Provided this component of the subducted plate retains its coherence, it may potentially contribute to the chemical and elastic heterogeneity in the mantle as a whole.

The purpose of this report is to summarize the key observations supporting the notion of subduction-related heterogeneity in the mantle, and to speculate on how it evolves over time. Earlier work on this topic covers different aspects of this view, to which the reader is directed for more information (Kaneshima and Helffrich, 1999; Helffrich, 2002; Helffrich and Wood, 2001). The focus here will be on the possibility that widespread, small-scale mantle heterogeneity contributes to the small-scale structure of the continents and the oceans that is observed in active source experiments. It is not a view advocated in this contribution because the idea is not a complete explanation of the observations and it lacks a clear mechanism by which mantle material could be incorporated into the continents. Rather, it is a discussion of the observations that support the existence of dispersed mantle heterogeneity and how mantle heterogeneity might be linked to heterogeneity in the continental lithosphere.

2. Scattering characteristics

Scattering is a term with different meanings in different seismological contexts. Consequently, some definitions will help to clarify the underlying concepts and highlight their similarities.

In active source studies, scattering is a term applied to observational characteristics in the data (Nielsen et al., 2001, 2002; Louie et al., 2002). A typical active source study consists of a few hundred receivers recording many fewer sources (explosions, airguns, or mechanical) over roughly linear sections. An active source record section might resemble the sketch in Fig. 1. There are two major arrivals from top-side reflections from layers at different depths in the ground. The later arrival is continuous over the range it is observed in contrast to the earlier reflector, which is not. In one range interval it is delayed relative to other ranges, and in another range interval it is weak or absent. Both of these phenomena are termed scattering in the active source context (Thybo and Perchuæ, 1997; Nielsen et al., 1999). Here, scattering refers to the fact that the energy radiating from the source is diverted away from its most direct path to the line of sensors. The explanation for these features lies in discrepancies between the fundamental assumptions of an active source study and the structure in the ground. One typically assumes that contrasts in material elastic properties are horizontal and laterally extensive, or, in other words, the contrasts arise from horizontal layers in the medium. If the layers are located deeper at different ranges, then a delayed arrival will result. If the layers pinch out in some range, or over some area, making a hole in it, reflections may arise from places where the layer exists away from the direct path between source and receiver. This leads to delayed arrivals. If the layer pinches out, on the other hand, the arrival will disappear over some range interval. Thus the basis of both explanations is a lack of continuity in the layers existing in the earth. Dramatic examples of lateral changes in the nature of layering are evident in, for example, the Abitibi belt of the Canadian Shield (Grandjean et al., 1995) and the BABEL profile across the Tornquist Zone, Fennoscandia (BABEL Working Group, 1991).

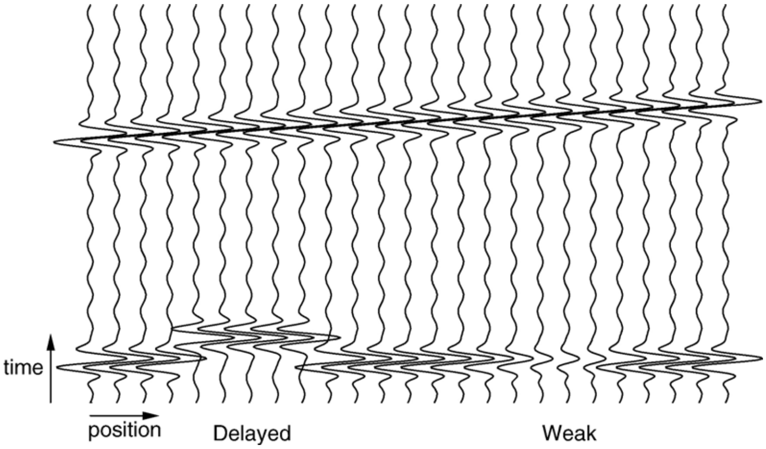

Fig. 1. Observational characteristics in an active source study showing features due to scattering. Horizontal axis is distance, vertical axis is time. Each line represents a seismogram recorded at some position in an active source experiment. Two prominent arrivals feature in the suite of seismograms. The later one is continuous through the observational range, whereas the earlier one is not. The delays and gaps in continuity are attributed to scattering. The figure is schematic because in reality, transitions between regions with delayed arrivals and normal ones would be more gradual due to diffraction or wavefront healing effects.

Scattering in the context of natural source studies has different characteristics, shown by the sketch in Fig. 2. Teleseismic studies usually focus on a particular clear arrival from the earthquake isolated in time from others. This main arrival might have additional features that precede or follow it. There might be higher frequency precursory energy in advance of the main arrival (Cleary and Haddon, 1972; Doornbos and Vlaar, 1973). The arrival might decay unusually slowly, reducing its clarity in the seismogram (Fehler and Sato, 2003). It might also be preceded or followed by a completely unexpected, or rogue arrival in the seismogram (Kaneshima and Helffrich, 1998). The figure illustrates each of these cases. Similar to the active source case, the explanation for these features lies in the deviation of the energy path for the main arrival away from the expected one. In contrast, there is no assumption of layering. The diversion arises from wavefield interactions with individual, small-scale objects embedded in the earth, or regions containing many small objects. The wavefield interaction with these objects results in them acting as secondary (Huygens) sources that re-radiate the energy. Thus the scattered arrival does not obey geometric optics (Baker and Copson, 1950; Chernov, 1960; Aki and Richards, 1980; Wu and Aki, 1985).

The common feature in each of these definitions is that there are structures that contrast significantly with the elastic properties of the surrounding medium. In the active source case, the structures are layers that are discontinuous in space. In the natural source case, the structures are individual objects that are dispersed in the

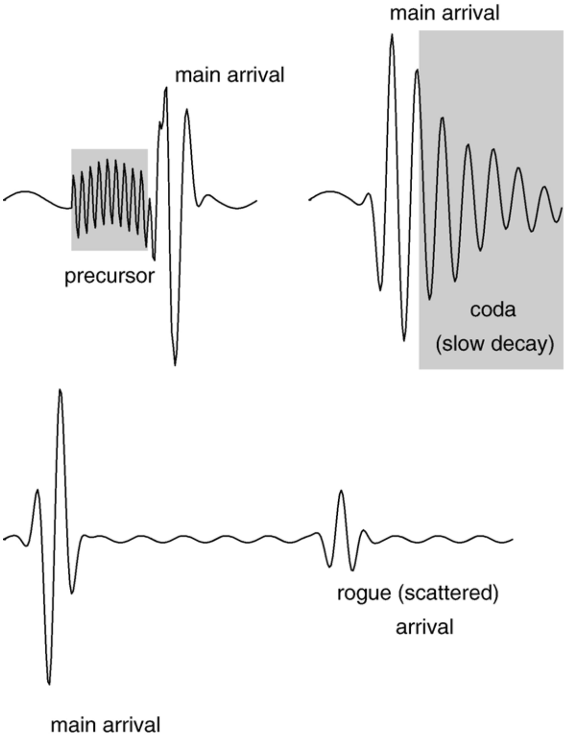

Fig. 2. Observational characteristics in a natural source study showing features due to scattering. High frequency energy may precede the main arrival (it may also follow, but if so, it is obscured by the coda of the main arrival and is thus more difficult to observe). The main arrival may decay uncharacteristically slowly, leading to an extended coda not usually observed. The main arrival may be preceded or followed by an unexpected, additional arrival. These features are attributed to scattering in the natural source context.

crust or mantle. Another common feature is that to observe these arrivals, a large number of sensors are required. See, for example, Helffrich (2002) for a description of methods used for teleseismic scattering work, or Thybo and Perchuæ (1997) for active source configuration and analysis methods.

3. Heterogeneity creation in the mantle

The major active differentiation source at present is the formation of oceanic crust at mid-ocean ridge spreading centers (Allégre and Turcotte, 1986; Hofmann, 1997), where about 18 km^3 of material is formed per year. Ridges are 4 times more productive than volcanic arcs (Crisp, 1984). Arc volcanism products do not geochemically imprint the mantle (Allégre, 1987; Hofmann, 1997) and there is little evidence of sediment subduction in arcs (von Huene and Scholl, 1991). Therefore, the volumetrically dominant source of input into the mantle is oceanic lithosphere. The lithosphere is a layered package whose topmost layer is dominantly basaltic in composition and about 6 km thick. The basalt is mineralogically different than the underlying harzburgitic and peridotitic lithospheric mantle, leading to seismic wavespeeds that are slower than the mantle's: around 6.4 km s^{-1} as compared to around 8.0 km s^{-1} (Stein and Wysession, 2003).

There is little doubt that the oceanic crust is subducted. On the basis of seismologically observed layering in subducted lithospheric slabs in subduction zones, the layering persists to depths of at least 200 km, beyond depths where it could be plausibly disrupted by processes related by arc magmatism (Matsuzawa et al., 1986; Helffrich and Abers, 1997). Slab layering is commonly observed in subduction zones around the Pacific: Tonga-Kermadec, Japan, Kamchatka, the Aleutians, and Alaska (Abers and Sarker, 1996; Abers, 2000). While its properties vary, its thickness is everywhere less than 10 km thick, strongly implicating subducted oceanic crust. There is, moreover, evidence that packets of material this thick also get into the lower mantle. Scatterers in the top and middle of the lower mantle (700 and 1600–1800 km deep) explain rogue arrivals following the P-wave arrival in teleseismic observations from earthquakes in the Mariana Islands (Kaneshima and Helffrich, 1998, 1999; Krüger et al., 2001; Kaneshima, 2003). Scattering regions containing material about 1 km in size exist at the bottom of the mantle where plate reconstructions place Cretaceous subduction, suggesting that subduction deposits crustal material at great depths in the mantle (Braña and Helffrich, 2005). There are also anomalous structures 100–300 km above the core–mantle boundary attributed to slab material accumulation there (Freybourger et al., 2001; Thomas et al., 1999, 2002). High-frequency precursors to PKP seem to be caused by distributed small-scale heterogeneity in the lower mantle. Hedlin et al. (1997) (following Cleary and Haddon, 1972) modeled the precursors as due to dispersed elastic heterogeneity <8 km in size and $<1\%$ in strength in the lowermost 1200 km of the lower mantle. Margerin and Nolet (2003) concluded that the strength was probably lower, but agreed that they were dispersed. In further work, Hedlin and Shearer (2000, 2002), extended their earlier analysis to assess the regional variation in lower mantle scattering and to include the coda to PKP arrivals. They found regional differences in scattering strength and, using PKP coda, confirmed their earlier results using precursors, but were unable to deliver a verdict on scattering at shallower mantle levels.

While there is persuasive evidence for regions of elastic heterogeneity related to subduction from the top to the bottom of the mantle, there are also some caveats for particular regions. In the middle mantle studies deducing scatterer size from the range dependence of precursor strength (Hedlin et al., 1997; Hedlin and Shearer, 2000; 2002; Margerin and Nolet, 2003), there are tradeoffs between scatterer size, scattering strength, scattering region thickness, and the possibility of multiple versus single scattering. For this type of study, scatterer sizes might be only weakly constrained. Near the core–mantle boundary, anomalous structures might be due to a post-perovskite phase transformation (Murakami et al., 2004; Hernlund et al., 2005). While the observations summarized here appear to be localized spatially, there might be abrupt spatial temperature variations that induce topography on a transformation surface rendering it patchy. Thus scattering might not be continuous from the top to the bottom of the lower mantle, but there is clear evidence for it at the top, in the middle, and at the bottom.

Because there appear to be no unequivocal barriers to subducted material reaching the bottom of the mantle, a plausible view is that the heterogeneity is deposited at many levels in the mantle where subducted material buoyancy becomes neutral. At this point, whole-mantle convection begins a long and inefficient (Allégre and Turcotte, 1986; Gurnis and Davies, 1986; Ferrachat and Ricard, 1998) process of disaggregating and dispersing the heterogeneity throughout the mantle, which ultimately leads to it re-appearing in the melting region underlying mid-ocean ridges, where it is re-

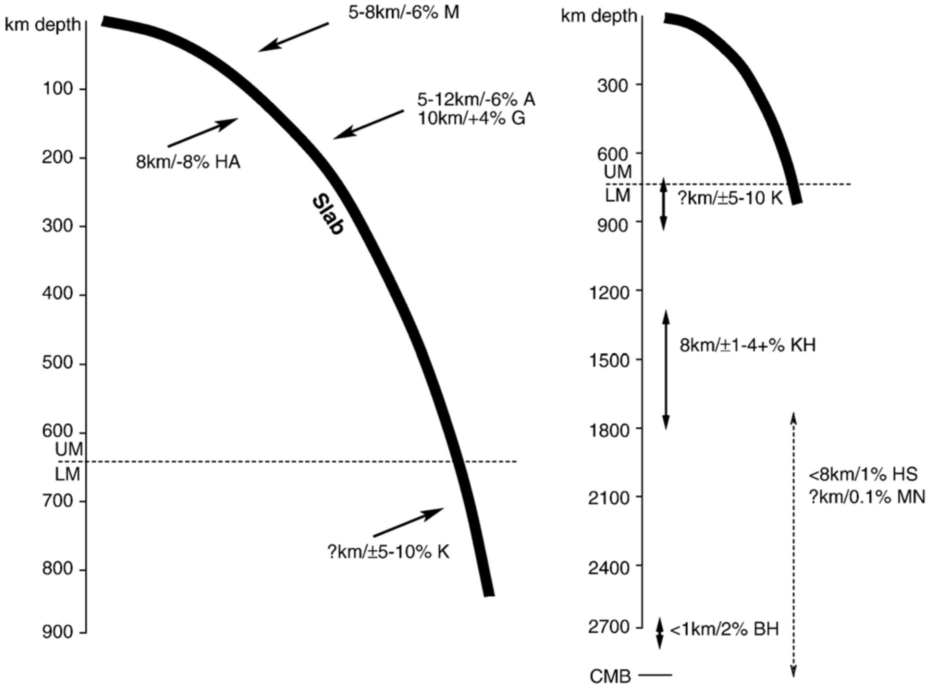

Fig. 3. Summary of evidence for subduction of oceanic crust and it reaching into the lower mantle. Figures give the characteristic dimension of the anomalous material and the contrast in elastic properties relative to the mantle, with "?" for indeterminate values, and "±" if the sign of the contrast is unconstrained. UM—upper mantle, LM—lower mantle, CMB—core–mantle boundary. References: M, Matsuzawa et al. (1986); HA, Helffrich and Abers (1997); A, Abers and Sarker (1996), Abers (2000); G, Ansell and Gubbins (1986); Gubbins and Snieder (1991); K, Krüger et al. (2001), Kaneshima (2003); KH, Kaneshima and Helffrich (1998, 1999, 2003); BH, Braña and Helffrich (2005); HS, Hedlin et al. (1997); MN, Margerin and Nolet (2003).

sampled in mid-ocean ridge basalt. It appears that the deeper, and "older" (in the sense of being in the mantle longer) material is characteristically smaller than shallower, "younger" material, suggesting that disaggregation and stirring by convection serves to reduce the size of the elastically distinct material and to disperse it (Gurnis and Davies, 1986; Christensen and Hofmann, 1994; van Keken and Zhong, 1999; Kaneshima and Helffrich, 2003; Xie and Tackley, 2004). The evidence is summarized in Fig. 3.

4. Properties of scattering in the shallow mantle

Active source studies in continental areas (Perchuæ and Thybo, 1996; Thybo and Perchuæ, 1997; Nielsen et al., 2001, 2002) generally show arrivals consistent with horizontal layering in the crust out to offsets of approximately 800 km. This range marks the onset of a region of incoherent arrivals with variable delays and amplitudes (Fig. 1), and long codas (Fig. 2). The end of the region of incoherence depends on the local tectonics. In

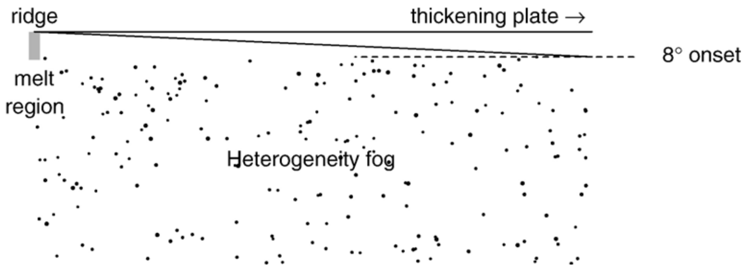

Fig. 4. Sketch of the development of the 8° discontinuity beneath oceanic lithosphere. Preferential melting of compositionally fertile heterogeneities beneath mid-ocean ridges homogenizes the newly created oceanic crust and the melt region. As the plate ages and thickens, the mechanical boundary layer at the lithosphere's base excludes further incorporation of heterogeneous material in the growing plate. The melt depletion region and the asymptotic plate thickness control the range onset of the scattering in active source profiles in tectonically active areas.

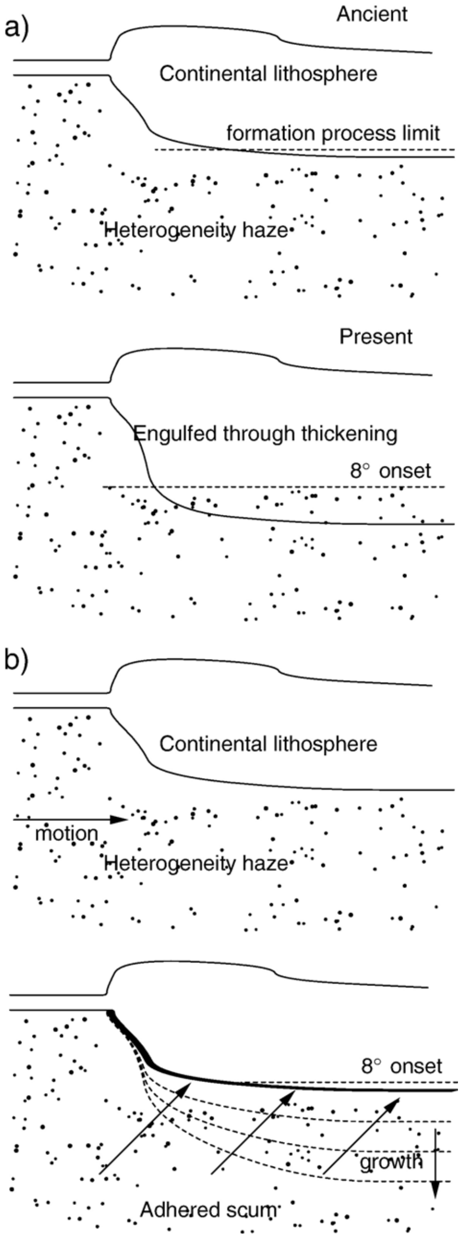

Fig. 5. Cartoons of processes that might lead to observed depth of 8° discontinuity. (a) Continental formation process might end with continental nuclei of uniform depth. Deepening of the continental root through cooling could engulf heterogeneity below this level, giving rise to the scattering features observed. (b) Similar to (a), but motion of the continental keel through the mantle embeds heterogeneities on the continental keel. As the keel thickens with time, the heterogeneities collect in the root, concentrating them.

tectonically dormant or stable areas, the incoherent range extends to around 1300 km, whereas in tectonically active areas it extends to around 1700 km and the arrivals are delayed with respect to the layer reflections at shorter ranges. Local velocity variations between 100 and 180 km depth, whose strength is ~2% relative to ambient, explains the observations in one of the profiles in a tectonically stable area (Nielsen et al., 2002). The base of the heterogeneous region corresponds to the Lehmann discontinuity, a discontinuity in continental structure at around 200 km depth (Lehmann, 1959,1964). In contrast, the depth range of variable velocity required to yield the profile characteristics seen in tectonically active areas is 100–400 km (Thybo and Perchuæ, 1997). In at least one longer period study of continental lithosphere, there is no evident structural change at ~200 km (Gaherty et al., 1999), suggesting that small-scale heterogeneities cause the scattering.

The combination of the frequency used and the spatial extent in the profiles of the incoherent waveforms provide constraints on the dimensions of the vertical and horizontal scales of the heterogeneities in the mantle. They are 5–10 km laterally, and <5 km vertically (Nielsen et al., 2002). Because the recording geometry is linear in these studies, the lateral resolution may be biased to larger values.

5. Synthesis

A compelling concordance between the scale lengths of scatterers in the mantle and scatterers seen in active source studies–<8 km vs. 5–10 km horizontally and <5 km vertically–invites attributing them to the same cause: elastic heterogeneity in the mantle caused by recycled subducted material. With this as a working hypothesis, are there further observational data to support or reject it?

A characteristic feature of active-source scattering is its onset around a range of 8° or ~800 km, which corresponds to turning depths of around 100 km. If the mantle is envisaged as containing widely dispersed heterogeneities such as the sketch in Fig. 4 shows, this onset may be linked to the thermally controlled asymptotic plate thickness in oceanic lithosphere. Studies place this at 95–110 km depth (Parsons and Sclater, 1977; Stein and Stein, 1992). The exclusion of the heterogeneities from the lithosphere is a consequence of the mid-ocean melting process which preferentially melted them, yielding a homogeneous lithosphere. The mechanical boundary layer that decouples plate motion from underlying mantle flow may inhibit further engulfment in oceanic settings because it implies stagnation in the vertical flow component at the base of the lithosphere.

Understanding the scattering features in continental lithosphere is more problematic. The original differentiation process that created the continents might have yielded continental nuclei that originally were equally thick (Fig. 5). These nuclei would have been barren of mantle heterogeneities because they would not have existed in large amounts then and because the melting processes would have homogenized any heterogeneity that existed then. With time, the continents cooled and developed the roots, of varying thickness, seen seismically (Grand, 1994; Carlson et al., 2005). As these roots grew, they might have engulfed the heterogeneity that existed subsequently in the mantle, leading to the structure seen in active source scattering: heterogeneity between 100 and 180 km depth. However, the seismological signature of continental roots varies, and extends down to depths as great as 350 km (Grand, 1994). This some process must limit the engulfment of heterogeneity to between 100 km (the hypothetical end-point thickness of the continent forming process) and 180 km. It is not obvious what this process would be, but may be related to the decorrelation of the rate of plate motion with cratonic root thickness in excess of 210 km, attributed to mantle viscosity layering (Stoddard and Abbott, 2003).

Rather than being a growth phenomenon of cratons, the range onset of scattering in active source profiles might be due to the solidus of a melting reaction being reached (Perchuæ and Thybo, 1996; Thybo and Perchuæ, 1997), or the level of neutral buoyancy of material injected into preexisting continental roots (Fig. 6). Both of these notions have difficulties. If this material is present everywhere under continents, it must not be buoyant enough to reach the surface, or else we would have some type of omnipresent volcanism on continents. This is not characteristic of the present earth. In continents, the most prominent density boundary is the top of the lower crust, at around 40 km, the provenance of the crust's more mafic component (Rudnick, 1995). This is significantly shallower than the 100-km depth onset of scattering structures. Alternatively, that depth may represent the crossing of the continental geotherm with a melting reaction solidus. Strongly curved solidi, convex toward lower temperatures, are characteristic of vapor-present melting reactions and generate excess gaseous fluid when crossed (Best, 1982). Olafsson and Eggler's, (1983) experiments show that if volatile-bearing melts (~1 wt.% H_2O+CO_2) intersect the peridotite solidus at ~100 km depth, an H_2O-rich fluid is formed. These do not dissolve many major elements (less than 10 wt.%), so their densities are not much more than supercritical fluid at those depths, about 1.2 Mg m^{-3} (Holloway, 1987), much less dense than rock. Thus there should be continual evolution of gaseous fluids under continents, for which, again, there is no evidence. CO_2-rich fluids are the causative agents of diatreme eruptions such as kimberlites and lamproites (Eggler and Wendlandt, 1979; Anderson, 1979; Wyllie, 1980), but they neither erupt frequently, nor everywhere on continents whereas the scattering structures are observed everywhere. For a solidus reaction to control the depth at which scattering begins in continents, a mechanism must be found to prevent catastrophic fluid evolution and loss.

The rate of ascent of bodies of fluids or fluid-rich magmas is rapid under crustal conditions. Spera (1987), and later Rubin (1998), analyzed the diking process for inviscid magmas and derived ascent times of tens of years for fluid viscosities around 10 Pa s from depths of ~100 km. This is so short a time, geologically, that there must either be a process of continuous magmatic fluid generation or there must be an ever-decreasing amount of seismic heterogeneity that we must be serendipitously observing today. Neither of these explanations is satisfying.

6. Conclusions

There is a striking similarity in scale between scatterers inferred in various active and passive source studies. Dispersed structures smaller than 10 km in

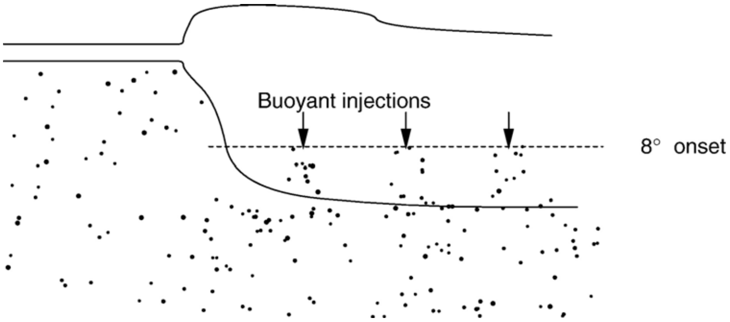

Fig. 6. Sketch showing how buoyant injections into cratonic roots might reach a level of neutral buoyancy and accumulate.

lateral and vertical extent plausibly explain either. While there is adequate observational evidence in support of a process that generates the scattering sources seen in natural source studies–ocean crust subduction–scattering seen in active source studies of continents may share a common origin if it represents engulfment of mantle heterogeneity during the growth of continental roots. Its apparent longevity, ubiquity and uniform depth of onset do not favor a magmatic origin. The least unsatisfactory explanation for scattering under continents is that it represents mantle heterogeneity incorporated into continents as they grew their roots.

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