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# LARGE IGNEOUS PROVINCES AND FERTILE MANTLE

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## ABSTRACT

If continental crust gets too thick, the dense eclogitic bottom detaches, causing uplift, asthenospheric upwelling and pressure-release melting. Delamination introduces cold low melting point blocks of lower crust into the mantle; these eventually also melt and rise to the surface. The mantle below 100-km depth is mainly below the melting point of peridotite but it is not necessarily subsolidus for recycled fertile components. When plates pull apart or delaminate, the mantle upwells; entrained crustal fragments are fertile and create melting anomalies. Eclogites associated with delamination are warmer and less dense than recycled oceanic crust and more susceptible to entrainment.

(keywords; LIPs, delamination, plumes, hotspots, lithosphere, eclogite)

## INTRODUCTION

Continental flood basalt provinces and oceanic plateaus occur at times of continental breakup and global plate reorganization. Geophysical and petrological evidence suggest that the local mantle was not hotter than normal while these piles of magma were erupting [Clift 2005, Korenaga et al. 2002, Green et al. 1999]. In extreme cases, the inferred temperature anomaly is +100°C but could be much less [Clift 2005]. The inferred temperatures of hotspots or ocean island basalts (OIB) are generally in the normal, MORB, range, and significantly less than temperatures in the deep mantle (Anderson 2000). These temperatures, and the temperatures required to form picrites, are well within the statistical variability of MORB mantle, even though ridge segments thought to be influenced by hotspots are generally excluded from the statistics; in the standard thermal models LIPs should be colder than OIB.

The largest igneous provinces, apart from the global ridge system, are the Siberian Traps and the Ontong Java Plateau. These were initially erupted at, below or near sea-level rather than at an elevation of 1 or 2 km above the surrounding terrain as predicted by thermal models. There is no indication from uplift, heatflow or tomography for high mantle temperatures, >100 C above the mean (Czamanske et al. 1998; Korenaga 2005; Roberge et al. 2005 ; Gomer and Okal, 2003). The crust under Large Igneous Provinces, LIPs, is thinner than average continental crust (Mooney et al. 1998). Many LIPs occur in backarcs or on old convergent margins. Their chemistry, although highly variable, is usually intermediate between ridge basalt and continental crust, and is not the same as OIB. Picritic melts are rare. These observations are all enigmatic in the context of the usual high-temperature explanations of LIPs. The alternate is that the mantle is compositionally heterogeneous on a bulk scale and eruptions are controlled by the lithosphere and mantle fertility rather than by active convective processes in the mantle. The tectonic and tomographic evidence is discussed below.

## GONDWANA, ATLANTIC AND INDIAN OCEAN LIPS

The breakup of Gondwana was preceded by extensive volcanism around the future Atlantic and Indian ocean margins (Figure 1). Plate reconstructions (Muller et al. 1993) show that the currently continent hugging (~1000-km offshore) plateaus were formed at ridges and triple junctions of the newly opened Atlantic and Indian oceans. They mostly formed in the middle of a 2000-3000-km wide ocean some tens of millions of years after breakup of the supercontinent. Some of these are Azores (1300 km), Bermuda (1100), Cape Verde (900), Crozet (1000), Discovery (2000), Iceland (1000), Jan Mayen (900), Madagascar (1200), Mozambique (800), Rio Grande rise (1200), Broken Ridge (1100), Kerguelen (1100) and Walvis ridge (1200), where the (number) is the approximate half-width of the ocean at the peak of volcanism based on magnetic anomaly maps and age-dating of the plateaus. The delay between continental break-up and plateau formation is usually about 20-50 Myr (Figure 1). Although some LIPs are currently intraplate, they formed, without known exception, at plate or craton borders, at triple junctions, or on a spreading ridge about 1000-km offshore from newly separated continents.

## THE PACIFIC PLATEAUS

The Pacific plate originated as a roughly triangular microplate antipodal to Pangea, surrounded by ridges (Natland and Winterer 2005). It grew by the outward migration of ridges and triple junctions (TJ). The growing Pacific plate may have been stationary because of the absence of bounding trenches. The great oceanic plateaus in the Pacific were being constructed at the boundaries of the expanding Pacific plate between the times of Pangea break-up and construction of the large igneous plateaus in Africa and South America and in the wake of the drifting continents. An unstable stress regime, plate reorganizations and complex triple junction jumps may be responsible for the formation of the Pacific plateaus [Natland and Winterer, 2005]. Korenaga (2005) suggested that the largest LIP of all, Ontong Java, formed by entrainment of recycled oceanic crust from deep in the mantle by a rapidly spreading ridge.

## CONSTRAINTS FROM TOMOGRAPHY

Some LIPs have small-diameter low seismic velocity zones, LVZ, in the upper 200-350-km, rarely deeper, of the underlying mantle [e.g. Allen and Tromp 2005 ; Christiansen et al. 2002]. It is natural to assume that these LVZ are related to the overlying volcanism and that they are thermal in nature. But some ancient LIPs such as Parana and Ontong Java Plateau (OJP) also have seismic low-velocity zones in the upper 200-300-km of the mantle (van Decar et al. 1995; Gomer and Okal 2003) even though they have traveled thousands of kilometers away from the putative source and the mantle has had more than 120-myr to cool. The OJP LVZ is not attenuating to seismic waves, implying that it is not hot (Gomer and Okal 2003). Compositional, rather than thermal, effects are implied [e.g. as in Figure 3]. Both upwelling asthenosphere and sinking eclogite can have low seismic velocities.

## CONTINENTAL CRUST IN THE MANTLE?

Is there any evidence that continental crust can get into the oceanic mantle? Fragments of continental crust have been found along the Mid-Atlantic Ridge (e.g. Bonatti et al.1996) and in hotspot and LIP magmas. Schaltegger et al. (2002) found continental zircon xenocrysts in basalts from Iceland and Mauritius. Continental crust is inferred to exist at Seychelles, Faeroes, Rockall Bank, Jan Mayen, Kerguelen, Ontong Java Plateau, Cape Verde and the Cameroon Line [e.g. Frey et al., 2002, Ishikawa and Nakamura 2003]. The widespread isotopic (DUPAL) attributes of Indian ocean basalts have been attributed to the presence of “lower continental crust entrained during Gondwana rifting” (Hanan et al. 2004) or “delamination of lower continental crust” (Escrig et al. 2004).

## THE DELAMINATION MECHANISM

The challenge is to find mechanisms that can explain the volume of basalt, the uplift history and the ubiquitous evidence for involvement of both continental and midocean ridge-type material in LIP magmas. Some igneous provinces are built on top of rafted pieces of microcontinents or abandoned island arcs but is there any mechanism for putting large chunks of continental material into the source regions of LIPs?
Lower crustal delamination appears to be such a mechanism although it has been basically unexplored in this context until recently.

The lower continental crust thickens by tectonic and igneous processes (Kay and Kay 1993; Rudnick 1995), including magmatic underplating. Presumably the same thing can happen at intraoceanic arcs. Below about 50-km, mafic crust transforms to garnet pyroxenite, hereafter referred to eclogite or arclogite. Histograms of the thickness of the continental crust have a sharp drop-off at a thickness of 50-km (Mooney et al. 1998). I suggest that this is controlled by delamination. The mean crustal thickness under continental LIPs is ~35-km, less than the continental average thickness in spite of the thick piles of basalt. Once a sufficiently thick eclogite layer forms [Figure 3], it will detach and founder because of its high density. This results in uplift, extension, and magmatism. Delamination of a 10-km-thick eclogite layer can lead to 2 km of uplift and massive melt production within 10–20 Myr (Vlaar et al.1994; Zegers and van Keken 2001). Lower-crust exceeds the mantle density by 3 to 10 % when it converts to eclogite. Density contrasts of 1 % can drive downwelling instabilities (Elkins-Tanton 2005). Delamination is a very effective and non-thermal way of thinning the lithosphere, extending the melting column and creating massive melting and uplift. In contrast to thermal models, uplift occurs during and after the volcanism and the crustal thinning is rapid.

Lee et al. [2005] estimated that it takes 10-30 Myr for a cumulate layer to reach critical negative buoyancy and for foundering to take place; the cumulate thickness at the time of foundering ranges between 10-35 km, resulting in significantly sized heterogeneities in the mantle. When the lower crust is removed, the underlying mantle upwells to fill the gap and melts because of the effect of pressure on the melting point. This results in a magmatic pulse superimposed on a background flux, and an episode of rapid uplift. The lower crust then rebuilds itself, cools and the cycle repeats. The delamination mechanism creates multiple pulses of magmatism, separated by tens of Myr, a characteristic of some LIPs. If the crustal thickening is due to compressional tectonics the time scales will be dictated by convergence rates. In a typical convergence belt I estimate that thickening and delamination may take 25-35 Myr.

Delamination may also be involved in the formation of oceanic plateaus such as Ontong Java (Korenaga, 2005). Korenaga, however, argues that OJP was built by entrainment of deeply subducted oceanic crust rather than involving delaminated lower crust. Eclogite that was sub-solidus at lower crustal depths can melt extensively when placed back into ambient mantle [Figure 2]. There are several ways to generate massive melting; one is to bring hot material adiabatically up from depth until it melts; the other is to insert low-melting point fertile material–delaminated lower arc crust, for example–into the mantle from above and allow the mantle to heat it up. Both mechanisms may be involved in LIP formation. The time-scale for heating and recycling of lower-crust material is much less than for subducted oceanic crust because the former starts out much hotter and does not sink as deep [Figure 3]. The total recycle time, including reheating, may take 30 to 75-Myr. If delamination occurs at the edge of a continent, say along a suture belt, and the continent moves off at 3.3 cm/yr, the average opening velocity of the Atlantic ocean, it will have moved 1000-km to 2500-km away from a vertically sinking root. One predicts paired igneous events, one on land and one offshore [see Figure 1].

## BROAD DOMAL UPLIFT

Broad domal uplift is a characteristic of delamination (Kay and Kay 1993). The magnitude is related to the density and thickness of the delaminating column. Modeling has shown that crustal domes of order 1000-km in extent and elevations of ~2-km above background, with no heat flow anomaly, can be explained with shallow processes [Petit et al. 2002]. The Mongolian dome, for example, is underlain by a modest (5%) tomographic anomaly of limited extent 100-200-km depth, and a density reduction of only 0.01 g/cc yet it has the same kind of domal uplift that has been assumed to require a large thermal perturbation. The removal of a dense eclogitic root and its replacement by upwelling peridotite creates both regional uplift and an underlying LVZ.

One of the best documented examples of delamination, uplift and volcanism is the Eastern Anatolia region [Keskin et al., 2003], which was below sea level between ~50 Ma and ~13 Ma. It was then rapidly elevated above sea level. Uplift was followed by widespread volcanic activity at 7-8 Ma, and the region acquired a regional domal shape comparable to that of the Ethiopian High Plateau. Geophysical, geological and geochemical studies support the view that domal uplift and extensive magma generation were linked to the mechanical removal of the lower crust , accompanied by upwelling of normal-temperature asthenospheric mantle to a depth of 50 km. The above examples are important in showing that well understood shallow processes can generate regional domal structures and large volumes of magma. The LVZ under some LIPs, including ancient ones, and domal structures, can be cold eclogite rather than hot upwellings [Figure 3].

**DO WE NEED TO RECYCLE OCEANIC CRUST?**

Recycled oceanic crust is often considered to be a component of ocean island and LIP magma, although this view is disputed. Once in the mantle MORB-eclogite reaches neutral buoyancy at depths of 500- 650-km [Anderson 1989b, Hirose 1999] [Figure 3]. Very cold MORB may sink deeper [Litasov et al. 2004]. If current rates of oceanic crust recycling operated for 1 Gyr [Stern 2005], the total oceanic crust subducted would account for 2 % of the mantle and it could be stored in a layer only 70-km thick. The surprising result is that most subducted oceanic crust need not be recycled or sink into the lower mantle in order to satisfy any mass balance constraints (see also Anderson 1989a). The standard geochemical model for recycling assumes that oceanic crust, recycled to the base of the mantle, is the source of eclogite in LIP basalts. The MORB-like component in some LIPs may simply be due to passive asthenospheric upwelling, as in the delamination model; eclogite has a variety of protoliths.

The recycling rate of lower crustal cumulates (Lee et al. 2005) implies that about half of the continental crust is recycled every 0.6 to 2.5 billion years. In contrast to oceanic crust one can make a case that eroded and delaminated arc and continental material is not stored permanently or long-term or very deep in the mantle; it is re-used and must play an important role in global magmatism and shallow mantle heterogeneity.

**MELTING OF ECLOGITE**

Geophysical estimates of the potential temperature of the mantle are about 1350-1400 C (Anderson 2000) with statistical and geographic variation of at least 100 C; this permits partial melting of peridotite, along with extensive melting of eclogite [Figure 2] and the formation of high-MgO magmas.  Melting experiments (e.g. Yaxley 2000) suggest that 60-80% melting of eclogite is required to reproduce compositions of some LIP basalts [James Natland, personal communication]. Figure 2 shows that this is plausible and that lherzolite will start to melt under these conditions. The interaction of melts from eclogite and lherzolite is implied and this may be required to generate picritic melts and cumulates, and the trace element patterns of LIP magmas.

## THE NEUTRAL DENSITY PROFILE OF THE MANTLE

Figure 3 shows the materials of the crust and mantle arranged mostly in the order of increasing density. A" is the region of over-thickened crust that can transform to eclogite and become denser than the underlying mantle. Region C' is the top part of the transition region. Eclogites having STP densities between 3.6 and 3.7 g/cc, may be trapped in C'. Eclogites and peridotites have similar densities in this interval but different seismic velocities. Region C" is where MORB- and low-MgO-eclogites reach density equilibration. Note that trapped eclogite and dense eclogite sinkers can be LVZ.

## DISCUSSION

Delaminated lower crust sinks into the mantle as eclogite where it has relatively low seismic velocities and melting point compared to normal mantle peridotite. Although delaminated continental crust enters the mantle at much lower rates than oceanic crust, the rates are comparable to LIP production volumes. I speculate that the large melting anomalies that form on or near ridges and triple junctions may be due to the resurfacing of large fertile blobs, including delaminated continental crust. Ponded melts may contribute at new ridges and TJ. Delaminated arclogites may form a unique component of hotspot and ridge magmas (Lee et al. 2005) but I suggest that lower continental crust is not just a contaminating agent; blocks of it are responsible for the melting anomalies themselves, including Kerguelen and Heard and other features in the Indian ocean. The usual story is that upwellings at Kerguelen and Heard from the deepest mantle are responsible for polluting the Indian ocean. The massive plateaus, such as OJP, may be involve some combination of underplating, delamination, excess mantle fertility, entrainment, slightly higher than average mantle temperatures (~100 C), lower melting temperatures (~200 C) and focusing of magma.

The crustal delamination, variable mantle fertility model combined with passive asthenospheric upwelling has the potential to explain the tectonics and compositions of LIPs including heatflow and uplift histories. Apparently, no other model explains the formation of LIPs and uplifted domes so elegantly, with so few contradictions. But the model needs to be tested further and quantified.

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[Current information on the subject matter of this article can be found at www.mantleplumes.org ]

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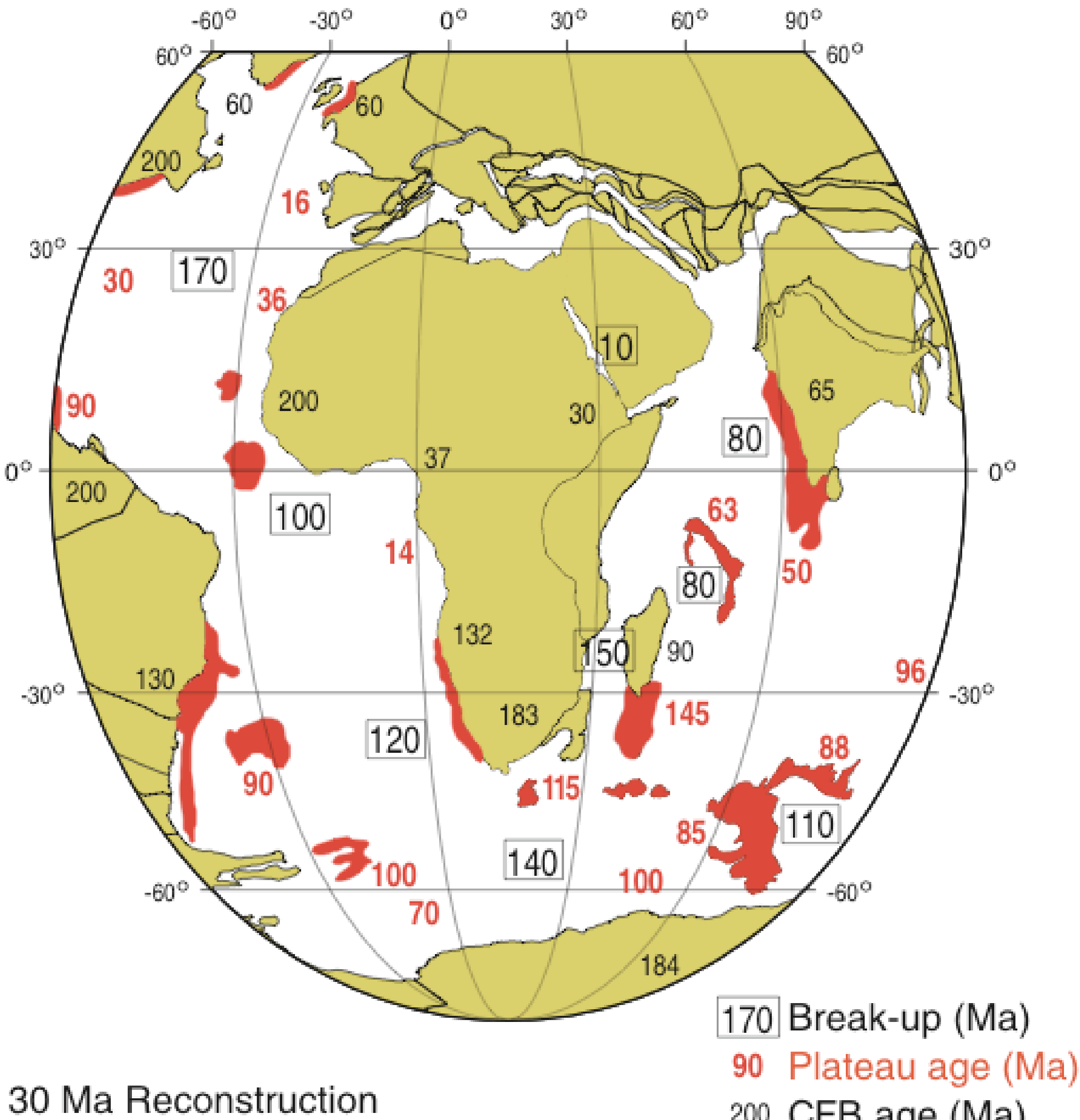
**FIGURES**

Figure 1. Distributions and ages of LIPs in the Gondwana hemisphere. The ages of continental breakup and the ages of volcanism or uplift are shown. Delamination of lower crust may be responsible for the LIPs in the continents, which usually occur along mobile belts, island arcs and accreted terranes. If the continents move away from the delamination sites, it may be possible to see the reemergence of fertile delaminated material in the newly formed ocean basins, particularly where spreading ridges cause asthenospheric upwellings.

Figure 2. Melting relations in dry lherzolite and eclogite based on laboratory experiments. The dashed line is the 1300-degee mantle adiabat, showing that eclogite will melt as it sinks into normal temperature mantle, and upwellings from the shallow mantle will extensively melt gabbro and eclogite. Eclogite will be about 70 % molten before dry lherzolite starts to melt [compiled by J.Natland, personal communication].

Figure 3. Density and shear-velocity of crustal and mantle minerals and rocks at STP, from standard compilations plus Lee et al. (2005) and Anderson (1989a). The ordering approximates the situation in an ideally chemically stratified mantle. The materials are arranged in order of increasing density, except for the region just below the continental moho where the potentially unstable lower crustal cumulate material is formed. The STP densities of peridotites vary from 3.3 to 3.47 g/cc; eclogite densities range from 3.45 to 3.75 g/cc. The lower density eclogites (high-MgO, low-$SiO_2$) have densities less than the mantle below 410-km and will therefore be trapped at that boundary, even when cold, creating a LVZ. Eclogites come in a large variety of compositions, densities and seismic

velocities. They have much lower melting points than peridotites and will eventually heat up and rise, or be entrained. If the mantle is close to its normal (peridotitic) solidus, then eclogitic blobs will eventually heat up and melt. Cold oceanic crust can contain perovskite phases and can be denser than shown here.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200 CFB age (Ma)
30 Ma Reconstruction

Figure 1

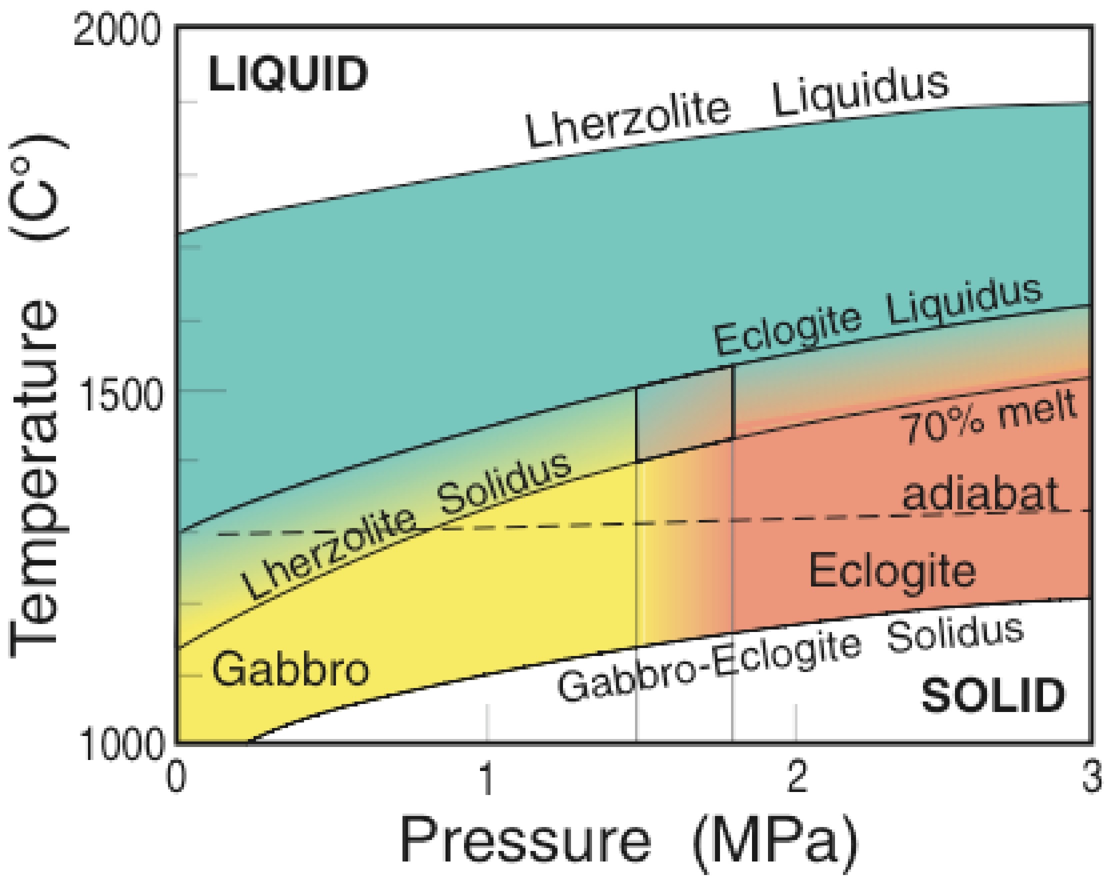
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Figure 2

Figure 3: Rocks and minerals arranged by density

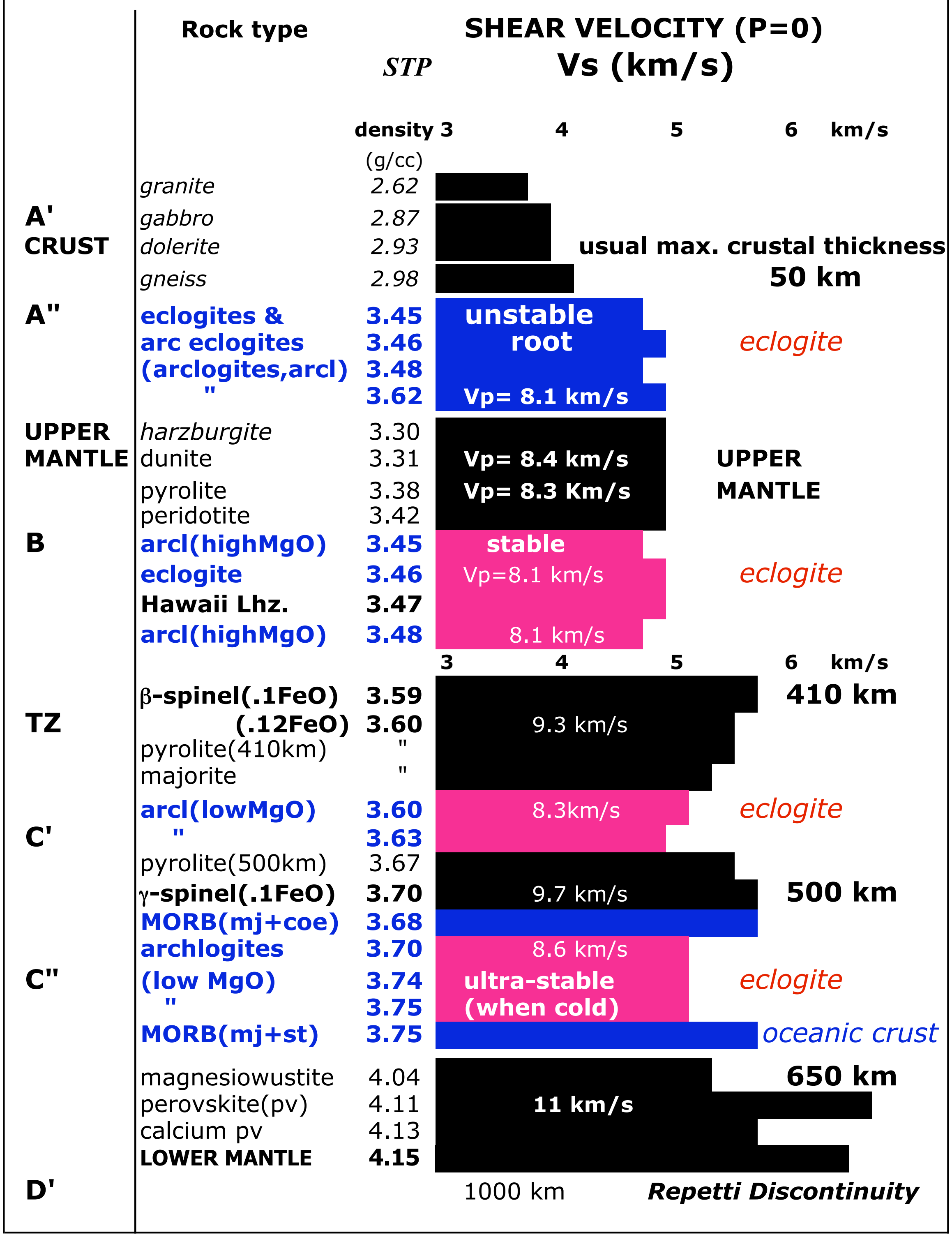


Figure 3