Earth and Planetary Science Letters 307 (2011) 501–516

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

journal homepage: www.elsevier.com/locate/epsl

Differentiation of the continental crust by relamination

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ARTICLE INFO

Article history:
Received 14 February 2011
Received in revised form 12 May 2011
Accepted 13 May 2011
Available online 2 June 2011

Editor: T.M. Harrison

Keywords:
continental crust
relamination
differentiation
subduction erosion
subduction
continental refinery

ABSTRACT

Crust extracted from the mantle in arcs is refined into continental crust in subduction zones. During sediment subduction, subduction erosion, arc subduction, and continent subduction, mafic rocks become eclogite and may sink into the mantle, whereas more silica-rich rocks are transformed into felsic gneisses that are less dense than peridotite but more dense than the upper crust. These more felsic rocks rise buoyantly, undergo decompression melting and melt extraction, and are relaminated to the base of the crust. As a result of this process, such felsic rocks could form much of the lower crust. The lower crust need not be mafic and the bulk continental crust may be more silica rich than generally considered.

1. Introduction: differentiation of the continental crust

The origin and composition of continental crust—particularly the lower crust—remain enigmatic. The principal conundrum to be resolved is how an andesitic to dacitic continental crust has formed when most mantle-derived magmas are basaltic. This differentiation has been explained as the result of lower crustal foundering (Arndt and Goldstein, 1989; Kay and Kay, 1991), crustal formation from primary mantle-derived andesitic magmas (Kelemen, 1995), or the mixing of basaltic rock with silicic magma derived by partial melting of mafic, subducting crust (Martin, 1986).

In their seminal papers, Herzberg et al. (1983) and Ringwood and Green (1966) introduced the idea that igneous processes can lead to crustal differentiation by lower crustal foundering if mantle-derived basaltic magma intruded into the crust forms a buoyant differentiate that is retained in the crust, plus a dense, olivine- and pyroxene-rich residue that sinks into the mantle (Fig. 1A). Kay and Kay (1991) expanded this idea by postulating that differentiation and lower crustal foundering might also be driven by the formation of metamorphic garnet in mafic rock (Fig. 1B). Jull and Kelemen (2001) quantified aspects of lower crustal foundering, and noted that buoyancy and viscosity requirements restrict significant lower crustal foundering to relatively warm environments such as rifts or active volcanoplutonic arcs. Though foundering of dense garnet granulites and pyroxenites probably is recorded in some arc sections (DeBari and Sleep, 1991; Kelemen et al., 2003a), loss of these rocks still yielded a mafic arc crust very different from continental crust (DeBari and Sleep, 1991; Greene et al., 2006). This is so because garnet-free mafic rocks that are either density-stable or too viscous to founder remain in the cold, upper and middle crust.

Whereas foundering of dense material could potentially produce a differentiated continental crust, two other tectonic processes—subduction erosion (Fig. 1C) and sediment subduction (Fig. 1D) (von Huene and Scholl, 1991)—are usually presumed to work in the opposite sense, by returning differentiated crust to the mantle. The most recent calculations (Scholl and von Huene, 2007) suggest that this process recycles continental crust back into the mantle at the same rate that continental crust is created. This could produce a steady-state crustal volume (Armstrong, 1981) and a constant composition.

This paper investigates another paradigm for differentiation of the continental crust: *The mantle produces differentiated crust in intra-oceanic arcs. This raw crustal material is subsequently subducted, devolatilized, and melted, and separated into a mafic residue that returns to the mantle and a felsic fraction that is relaminated to the base of the crust in the upper plate. This process will be most efficient in arcs where upper mantle temperatures are sufficiently high at the base of the crust* (Kelemen et al., 2003b) *to permit vertical viscous flow due to lithologic buoyancy of the felsic fraction* (Jull and Kelemen, 2001). This 'continental refinery' makes continental crust. We envision that this refining of raw crustal material into continental crust can take place via relamination during four subduction-zone processes (Fig. 2): i) sediment subduction, ii) arc subduction, iii) subduction erosion, and iv) continent subduction.

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doi:10.1016/j.epsl.2011.05.024

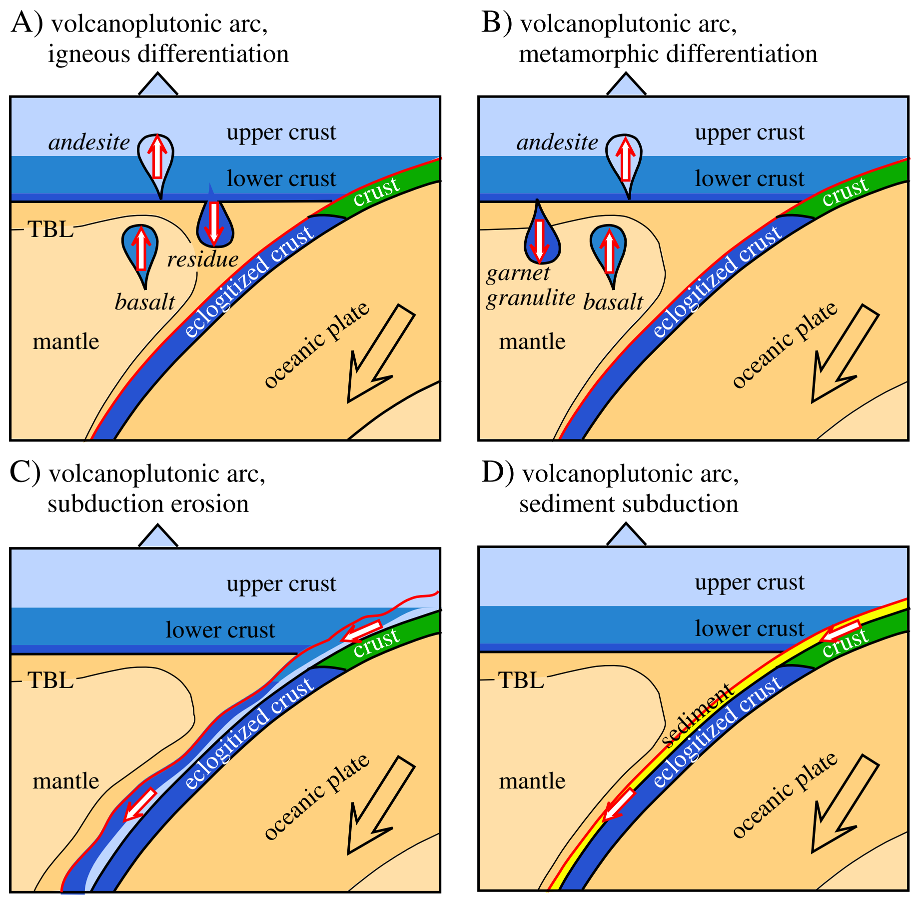

Fig. 1. Long-term change in the composition of the continental crust has conventionally been viewed as the result of two major "subduction factory" processes. A) Mantle-derived magma introduced into volcanoplutonic arcs differentiates into an andesitic fraction that is retained in the crust and an ultramafic cumulate that becomes part of the mantle (Arndt and Goldstein, 1989). B) Mafic rock at the base of a thick volcanoplutonic arc is converted into garnet granulite and sinks into the mantle (Herzberg et al., 1983). Two other major subduction-related processes are envisioned to work in the opposite sense, by removing differentiated material from the crust and returning it to the mantle. C) Crustal material ablated from the upper plate of a subduction system is returned to the mantle by subduction erosion (Scholl and von Huene, 2007; von Huene and Scholl, 1991). D) Trench sediments are returned to the mantle by subduction (Hilde, 1983). TBL: thermal boundary layer in mantle.

The relamination process can take the form of a) imbrication of material beneath the crust in the upper plate (Kimbrough and Grove, 2007), b) buoyant ascent from mantle depths to the base of the crust along a "subduction channel" (Gerya et al., 2007; Li and Gerya, 2009; Warren et al., 2008), and/or c) ascent of buoyant diapirs through the mantle wedge to the base of the crust (Behn et al., in review; Currie et al., 2007; Gerya and Meilick, 2011; Gerya and Yuen, 2003; Gorczyk et al., 2006; Kelemen et al., 2003a; Yin et al., 2007; Zhu et al., 2009). As discussed below, these processes may be more efficient than lower crustal foundering at generating large volumes of material with the major- and trace-element composition of continental crust, by relaminating the base of the crust with buoyant felsic rocks, and by purging the crust of eclogitized mafic rocks and dense residues produced by melting.

2. The composition and physical properties of continental crust

Earth's continental crust is distinct from the underlying mantle in that it is andesitic to dacitic (rather than ultramafic), has slower seismic velocities (V_P ~6–7 km/s, rather than >7.5 km/s) and is less dense (~2600–3000 kg/m^3, rather than >3300 kg/m^3) (Christensen and Mooney, 1995). It is typically subdivided into two or three discrete layers (Fig. 3A) on the basis of seismic velocities (Holbrook et al., 1992; Smithson, 1978), and considerable work has gone into inferring the compositions of these layers. Dividing the crust into three compositionally distinct layers on the basis of seismic velocity may be unwarranted because of the poor correlation between velocity and composition (Behn and Kelemen, 2003); the velocity of the lower crust could be higher than the mid crust due to mineralogical differences, such as the presence of garnet in the lower crust, rather than to a systematic compositional difference. Thus, here we make the simplifying assumption that there are just two layers: an upper crust and a lower crust (Fig. 3B).

The composition and physical properties of the upper continental crust are reasonably well known from exposures and from the composition of fine-grained clastic sediment such as shale and loess (e.g., the upper crust averages ~67 wt.% SiO_2; Rudnick and Gao, 2003). The composition of the lower crust, however, is more enigmatic. The principal difficulty is that, while there are many metamorphic terrains that record peak pressures of 8 to 12 kb, corresponding to lower crustal depths in cratons and mid-crustal levels of orogenic plateaus, there is no consensus that these are representative of typical or "average" lower crust. This problem applies to inferred "mid-crustal" exposures as well. Similarly, xenoliths erupted from lower crustal depths may be atypical because the basaltic lavas that host most xenoliths may not erupt through felsic lower crust (Jaupart and Mareschal, 2003) or may assimilate felsic xenoliths.

Physical properties (i.e., velocity, gravity, and heat flow) provide indirect constraints on the composition of the lower crust (Rudnick and Gao, 2003). For instance, the measured P-wave velocity of the lower crust is typically 6.7–7.1 km/s (Christensen and Mooney, 1995; Rudnick and Fountain, 1995), most likely corresponding to densities of 2900–3200 kg/m^3 (Christensen and Mooney, 1995). This has been