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Introduction

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1.1 Rationale

Understanding the evolution of the continental crust poses many fundamental geological questions that are being addressed currently by several different groups within the community of solid earth scientists. The general approach is one in which the aim is to understand the processes of generation, modification and destruction of continental crust in relation to tectonics on modern Earth, and then to apply this understanding to the formation and evolution of the continental crust throughout Earth's history. However, the Earth is a self-organized body with an irreversible evolution dissipating energy into space, so that applying what we learn from modern Earth to the past must be moderated by a consideration of secular evolution. One way to do this is by tracking geological variables as a function of time, which is referred to as "secular analysis." For example, Earth's radiogenic heat production has declined exponentially with time. If this evolution translates into a warmer mantle in the past, which is a reasonable inference, this will have had an effect on mantle dynamics and degree of melting during decompression, which, in turn, has implications for the formation and evolution of continental crust. For this reason, the full characterization of the continental crust as it is preserved in the exposed geology of the continents remains an important area of research, for without these data we cannot undertake a complete secular analysis using, for example, proxies for subduction- or plume-related activities.

New advances in geophysics and geochemistry have led to ever more detailed information concerning the structure and composition of the continental crust, which, in turn, has shed light on additions and losses of mass to the continental crust during subduction, the nature of the Moho, the role of crust–mantle interactions, and the processes involved in crust–mantle evolution. Research concerning the mechanisms of chemical and physical

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differentiation of the continental crust has been invigorated by integrative studies that combine field observations with laboratory experiments and numerical modeling. In particular, new results from such studies address crustal melting, melt and fluid extraction and transport through the crust, and the effect of melt and fluid generation and migration on crustal rheology. However, even with this renewed attention on the continental crust, basic questions continue to linger in regard to many vital processes, particularly with respect to secular evolution, and it is these topics that are addressed in this book.

There are three fundamental questions that drive research into the origin and evolution of Earth's continental crust. First, by what process or processes has the continental crust been extracted from Earth's mantle, how have these processes changed through time, and has extraction been a continuous or episodic activity? Second, how much of the continental crust has been recycled back into Earth's mantle, by what processes has this recycling taken place, and what has been the net rate of continental growth through time? Third, in stabilized continental crust, upper, middle and lower crust (and lithospheric mantle) are distinguished on the basis of chemical composition and geophysical properties, but by what processes has the continental crust been differentiated, have these processes changed with time, and what are the consequences for evolution of the Moho?

We have made significant advances in characterizing the petrological and geochemical composition of the mantle-derived products that form the primitive continental crust. However, determining when the bulk of the continental crust was generated and what was the balance between extraction from the mantle in subduction settings versus plume activity in the past remain largely unresolved. Arc and plume magmatism contrast not only in the composition of the primary addition to the continental crust (predominantly andesite in continental arcs versus basalt above plumes), but also because subduction is an ongoing process that is argued to produce essentially quasi-continuous additions to the continental crust, whereas superplume events are inferred to be rare global-scale episodes that imply non-continuous additions to the continental crust.

Arcs are traditionally viewed as sites of crustal growth, and in many models of crustal evolution the subduction factory is regarded as the principal site of production of continental crust. Even in modern arcs, though, it is challenging to quantify the mass of material being transferred from mantle to crust, and the mass of material as sediment or crust being transferred back to the mantle by sediment subduction and by subduction erosion and delamination. Furthermore, although we make a conceptual distinction between recycling crust into the mantle and reworking crust leading to differentiation, it remains problematic in ancient crust to determine the relative importance of these processes in the generation of particular rock suites exposed at Earth's surface.

Alternative models for crustal growth place greater importance on basaltic magmatism related to superplume events and the accretion of oceanic plateaus to continents. Oceanic plateaus cover about 3% of modern Earth's sea floor, and if the Ontong Java Plateau collision with the Solomon Islands Arc is typical, about 80% of the thickness of the plateau is subducted and recycled into the mantle (Mann & Taira, 2004). Although crustal growth by this mechanism appears minimal on modern Earth, it is interesting to speculate whether superplume events were more important earlier in Earth history, and this is one question that will only be answered by full characterization of Earth's continental crust and a careful secular analysis of appropriate proxies for mantle plume magmatism. For example, with higher degrees of mantle melting earlier in Earth history, oceanic plateaus may have been thicker and more buoyant, and consequently could have made a greater contribution to the mass of the continental crust, particularly if subduction was absent from the tectonics of early Earth.

With respect to differentiation of primitive crust that has been extracted from the mantle, we have a good understanding of the melting relations of crustal protoliths (Chapter 9) but we need to develop a better understanding of the dynamics of partial melting in the crust, and to characterize the rheological response of the crust to partial melting and melt transfer. Sources of heat to drive crustal melting processes and the specific links between the petrologic and structural, and the kinematic and dynamic expressions of crustal differentiation by intra-crustal magmatism, continue to be highly debated topics in which it is common for case studies to reach as many different interpretations as there are tectonic settings on modern Earth. As a result, numerical modeling has been used increasingly in crustal studies to determine the primary drivers and elemental properties of melt flow through the crust and magma emplacement in the upper crust.

In this first chapter, we outline briefly our understanding of the structure of the continental crust and its chemical composition, and we consider the distribution of heat sources and their role in crustal evolution. We speculate about the extraction and turnover of crust, and the generation of an evolved "continental" crust on early Earth, and we consider the subduction factory as the primary source of continental crust production on modern Earth. Thus, we recognize that secular change has been important, and we touch upon the contrasts between modern arc magmatism and magmatism in the Archean. We introduce convergent margin processes and accretionary versus collisional orogenesis, and this leads into a discussion about the geologic materials that melt; we consider outstanding questions in regard to melt segregation and transport through the crust. We discuss the driving forces for melt migration in relation to different tectonic regimes, because these are the physical controls on crustal differentiation. Finally, we review the important issue of fluids in the crust, both aqueous and silicate-melt, and we introduce recent advances in modeling the modes of transport of fluids and mechanisms of magma ascent and emplacement.

1.2 Structure, composition and heat production in the continental lithosphere

The continental crust is highly heterogeneous, both in terms of chemical composition and geophysical properties (Chapters 2–8). Indeed, the heterogeneity of the continental crust–mantle lithosphere system itself is one of its most important properties. Lithospheric heterogeneity is described and documented by geophysicists and geologists alike who have studied the seismic structure and the potential strength during large-scale tectonic deformation of exposed lower crustal sections and crust–mantle sections reconstructed from xenolith suites (e.g., Rudnick & Fountain, 1995; Karlstrom & Williams, 1998). This heterogeneity is probably a product of the buoyancy forces associated with Earth's convection cycle, heat and mass transfer associated with plumes, and the large-scale horizontal translation of crustal plates and their interactions during convergence (Davies, 1999; Turcotte & Schubert, 2002). These geodynamic processes have led to redistribution of mass and differentiation of crust from mantle.

Horizontal translation of crustal material has become increasingly identified as of fundamental importance in the development of the overall heterogeneity of continental crust, mainly through integrated seismic studies such as Lithoprobe, INDEPTH and the US Continental Dynamics Working Groups (e.g., Cook, 1995; Brown *et al.*, 1996; Fliedner *et al.*, 1996; Karlstrom & CDROM Working Group, 2002). One conclusion derived from interpretation of these data sets is that whole crustal detachments are common, even in cratonic portions of the continents, which suggests that metamorphic and igneous rock packages are thrust up from lower crustal depths to become interlayered with more recently deposited sedimentary rocks, thereby increasing local crustal heterogeneity (Chapter 2). Indeed, recently tectonic interleaving by ductile thrusting of oceanic and continental materials has been identified as an important process in the Isua Greenstone belt of west Greenland (Fedo *et al.*, 2001; Hanmer & Greene, 2002), which suggests that the deformational behavior, rheological constitution and overall strength of Paleoarchean and modern continental crust were similar.

It is also clear that crustal heterogeneity and variation in seismic character are functions of continental antiquity and recent tectonic regime. For example, shields and platforms, such as those present in North and South America, Eurasia and Africa, contrast significantly with Phanerozoic orogenic belts and convergent margins with accretionary orogenic belts. Orogenic belts undergoing net contraction, such as those in Tibet, the Altiplano–Puna and the Canadian Cordillera, show variations in crustal structure, including bright middle and lower crustal reflectivity and deformation fabrics, in comparison with those belts undergoing extension and collapse, such as the Basin and Range and the Colorado Plateau in the southern Rocky Mountains. Variation in seismic character also applies to rifted margins such as North America and Europe, and South America and Africa, and to the significant, but smaller-scale examples of rifting, such as the Rio Grande Rift and the North Sea, where ocean basin formation processes apparently have stalled (Burke, 1977; Klemperer *et al.*, 1986). Considering the heterogeneity observed both compositionally and structurally in the continental crust, it may be surprising that estimates of the average chemical composition of continental crust derived from seismic velocity variation and thicknesses of upper, middle and lower continental crust are in reasonable agreement with estimates derived from other approaches to assessing the average chemical composition of continental crust (Taylor & McLennan, 1981, 1985; Rudnick & Fountain, 1995).

Determining the bulk composition of the crust is a formidable, but important, task because the composition and element distribution in the crust may be used to develop models of crust–mantle evolution, and to test models of crustal production and crustal evolution through time. The crust is about 0.6% by mass of the silicate Earth, but it is the major reservoir for the incompatible elements (e.g., Taylor, 1992; Taylor & McLennan, 1985). There are several methods to estimate upper crustal elemental abundances. One successful approach that has been used by several researchers is the chemical composition of well-mixed clastic sedimentary rocks. The natural sampling of the exposed continental crust of different ages provided by erosion, transport and deposition of sediments allows the composition of upper crust to be estimated over geological time, because there is a sedimentary record dating back to at least 3.8 Ga (Taylor & McLennan, 1981; Chapter 4). With this approach, constraints may be placed on the composition of the bulk continental crust and possible recycling of continental crust. The chemical composition of the sedimentary rock record supports growth of the continental crust in an episodic manner, but with a major increase in the growth rate in the Late Archean (Chapters 4 and 6). Continental crust generated during the Archean has been suggested to be more mafic in overall composition compared to the composition of younger crust, but the difference may not be as profound as once thought (Rudnick & Gao, 2003). On modern Earth, the crust continues to grow mainly by island-arc volcanism and related magmatism (Chapters 4 and 6), but today this appears to be approximately balanced by crustal recycling through sediment subduction and subduction erosion (Scholl & von Huene, 2004).

Crustal differentiation is mainly achieved through partial melting processes and segregation of more felsic melt from the mafic residue, which means that heterogeneity in the crust, both local and regional, is an inevitable result. Thus, magmas that crystallize after migration to shallower levels of the crust contribute to a more evolved upper crust, whereas the lower crust becomes dominated by residue. However, the process by which sufficient heat is introduced into the crust to promote partial melting is a major area of research, because the thermal regimes for the crust calculated using numerical models (e.g., Connolly & Thompson, 1989; Jamieson *et al.*, 1998) at present do not achieve temperatures required for extensive melting of crustal protoliths as inferred from experiments (Chapter 9).

One significant source of heat in addition to underplating of mafic magma to the base of the crust is the presence and distribution of heat-producing elements (U, Th, K). A better understanding of crustal differentiation and the origin of crustal heterogeneity may be obtained by investigating the relationship between observed heat flow and possible heat sources and crustal heat production. Modern heat-flow observations suggest that heat-producing elements in the crust contribute on average about 50–66% of the observed surface heat flow and that the modern continental crust is strongly differentiated with respect to the heat-producing elements (McLennan & Taylor, 1996; Chapters 3 and 4). The observed distribution of crustal heat sources in stable continental crust may be understood in a similar way to explaining crustal structure and compositional heterogeneity, in that deformation, magmatism, and erosion redistribute the heat-producing elements. In general, these tectonic and petrologic processes increase the long-term thermal and mechanical stability of the continental crust by moving the heat-producing elements upwards in the crust through magmatism and reducing the total budget of heat-producing elements in the lithospheric column (Jaupart, 1983; Chapters 3 and 4). This process was particularly important in the evolution of cratons in the Archean, where tectonic processes ultimately achieved a stable ordering of the heat-producing elements.

1.3 Generating continental crust

It is of fundamental importance to identify when crust was first differentiated from the mantle and whether oceans were present at the same time, but this is a challenging task, for the evidence is rare and fragmentary and our knowledge of the earliest differentiation processes on Earth is limited because information retrieved from the earliest crust is punctuated by large gaps. Earth's earliest primitive crust most probably was mafic, and formed on top of a previously convecting magma ocean of uncertain depth (Boyet *et al*., 2003). However, no outcrop evidence of this earliest primitive crust is known to have survived, probably due to the intense meteor bombardment that affected Earth between its formation and *c*. 4.0 Ga, the age of the oldest known components in outcrops of the Acasta gneisses of northwestern Canada (Bowring & Williams, 1999). Thus, the discovery of detrital zircons with U–Pb ages that are older than 4.0 Ga and that are characterized by high $\delta^{18}O$ isotopic compositions provides evidence that both continents and liquid water were surface features of the earliest Earth (Wilde *et al*., 2001; Mojzsis *et al*., 2001), and it is now considered possible that differentiation processes that produce a felsic evolved crust have been active since very close to the birth of the planet (e.g., Amelin *et al*., 1999). This requires the planet to have formed an embryonic, differentiated, silicic crust during the Hadean (the time period between the formation of the Earth at *c*. 4.56 and *c*. 4.0 Ga, corresponding to the first preserved terrestrial rocks (Gradstein *et al*., 2004)), and has reinvigorated the discussion on continental growth through time (e.g., Armstrong, 1991; Chapter 6).

Archean Earth was a different place from modern Earth, and the formation and evolution of the lithosphere and the tectonic interactions between segments of lithosphere will have been affected by secular change due to cooling from the Hadean magma ocean to an Earth at *c*. 2.5 Ga with a significant proportion of the volume of continental crust that we have today. Herein is one of the important questions in Earth Science: was crustal growth progressive and stepwise through time, or was it primarily an Archean phenomenon with significant crustal recycling since that time?

One view from isotope geochemistry has been summarized recently by Kramers *et al*. (2004). These authors consider it unlikely that before 4.0 Ga there was much continental crust, and whatever continental crust that may have existed most likely was largely recycled into the mantle so fast that with present techniques we cannot identify any isotopic trace of it. However, we do have those enigmatic detrital zircons! These authors argue that from *c*. 4.0 to *c*. 2.0 Ga, net growth of continental crust was rapid, resulting in about 75% of the present mass at 2.0 Ga, and from *c*. 2.0 Ga to the present, net growth of continental crust has continued at a slower pace. Kramers *et al*. (2004) argue that rates of recycling by continental erosion have remained approximately proportional to continent mass throughout Earth history.

This view is broadly consistent with the data of Scholl and von Huene (2004), who argue that on modern Earth crustal recycling to the mantle at subduction zones and new additions from the mantle at arcs are similar at approximately 70 km^3 Myr^{-1}/km. By uniformitarian extrapolation this implies that the mass of recycled continental crust since the beginning of the Proterozoic is approximately equivalent to the mass of the present continental crust, which is less than 1% of the mass of the mantle. However, in an alternative view, Condie (2000) argues for episodic crustal formation with significant peaks in production at 2.7, 1.9 and 1.2 Ga for periods up to 100 Myr long related to probable superplume events. These peaks appear to correspond to periods of crustal amalgamation in the supercontinent cycle. Thus, the increased rate of crustal production and/or growth may reflect the mantle dynamics responsible for supercontinent formation (Condie, 2004). Condie (2002) argues that growth of juvenile crust occurred chiefly in the form of new arc systems accreted to continents during collision, but net growth may have been increased by reduced sediment subduction rates due to higher sea levels during these periods. According to Scholl and von Huene (2004), about 30 km^3 Myr^{-1}/km of crustal recycling is accomplished by sediment subduction on modern Earth, so that any reduction in this rate in the past is likely to have led to a significant increase of continental mass.

Currently, magmatism at arcs is viewed as representative of the main long-term flux of material from the mantle to the crust, but plume activity and construction of oceanic plateaus may have been more significant in the past (Chapter 6). As a result, the continental crust that is being formed today is generated in arc settings. However, assessing how important this process has been throughout geological time also addresses whether or not the plate tectonic paradigm for modern Earth is an adequate tectonic model for the generation and evolution of continental crust throughout Earth history (DePaolo, 1988). A comparison of estimated average compositions of the continental crust with the compositions of material associated with modern mantle–crust arc fluxes will enable an evaluation of arc magmatism in the generation of continental crust earlier in Earth history. Evaluation of data from specific subduction zones shows that primary arc magmas are high MgO basalts, and that the composition of magmas emplaced in the near surface environment (volcanic and plutonic crust) is actually a reflection of protracted intra-crustal assimilation and differentiation (Davidson, 1996).

But, what happened in the Archean? Although it is debated whether or not the Archean crust is more mafic than modern-day crust (Hamilton, 2003), studies of Archean crust have led many workers to the conclusion that the mechanisms by which the Earth's continental crust formed during the Archean were fundamentally different than those processes forming the continental crust today (e.g., Condie, 1981, 1990, 2000). Contrasts exist between the average composition of the continental crust, the estimated contemporary fluxes from the mantle via multistage evolution in arcs on modern Earth and typical Archean felsic crust. Models based on modern Earth and extrapolation of present-day arc volcanic processes to a hotter early Earth have not adequately explained the observations in these terranes, particularly the predominance of the tonalite–trondhjemite–granodiorite (TTG) suite of rocks and high-grade (amphibolite and granulite facies) metamorphism.

Zegers and van Keken (2001) have suggested that the earliest continental crust may have been differentiated and stabilized by delamination of the lower part of an oceanic plateau-like protocrust equilibrated at eclogite facies. Such delamination could have resulted in uplift, extension and the production of TTG suites as recorded in Archean cratons. Indeed, this process may not be that dissimilar to the process of foundering of a continental arc root that has been proposed recently to have occurred beneath the southern part of the Sierra Nevada in California (Ducea, 2002; Saleeby *et al.*, 2003; Zandt *et al.*, 2004). The removal of the root is hypothesized to have occurred by a Rayleigh–Taylor-type instability, with a nearly horizontal shear zone accommodating the detachment of the ultra-mafic root from its overlying granitic crust, and such a process could have been more common in Archean time. Ultimately, discerning the balance of contribution among melts derived from over-ridden "oceanic" lithosphere (so-called "slab" melts), mantle that might separate over-ridden "oceanic" lithosphere (so-called mantle "wedge") from continental lithosphere, mafic underplate and older continental crust to the process of Archean TTG suites and crust-formation, is of prime importance if we are to understand Archean geodynamics (Kramers, 1987; Kramers & Tolstikhin, 1997; Chapter 6).

An evaluation of modern arc magmatism suggests that either arc magmatism is not representative of the process that has generated the bulk of the continental crust in the past, or if it is an important crust-building process, it must be accompanied by an additional differentiation process that returns mafic materials to the mantle (Arculus, 1999). Initial mass additions to the crust through arc magmatism are basaltic. These compositions generate the distinctive trace element signatures that are observed in all continental crust by subsequent modification of this primary arc material through intra-crustal differentiation or contamination by the deep mafic lower crust (Chapter 5).

Differentiation may involve the formation of cumulates derived from fractional crystallization of magma located close to the Moho or residues derived from later crustal melting (Rudnick, 1995). Partial melting residues and cumulates from the original mantle influx may have been recycled into the mantle (Jull & Kelemen, 2001) or reside below the Moho (e.g., Ducea & Saleeby, 1998; Cook & Vasudevan, 2003), and this suggests that the Moho itself changes position (Arndt & Goldstein, 1989; Chapter 5).

1.4 Intracrustal differentiation at convergent margins

Studies of modern convergent plate margins have led to a better understanding of tectonic settings associated with most observed crustal melting (Chapter 10). In general, convergent margins generate two types of orogen. Accretionary orogens are produced along convergent plate margins characterized by long periods of ocean plate subduction (e.g., the Phanerozoic–Mesozoic–Cenozoic evolution of the Pacific Margin, e.g., the Japanese Islands, Tasmanides of eastern Antarctica and Australia). They form by creation and destruction of large arc systems, with growth of accretionary wedges in the fore arc, and extension and sedimentation in the back arc during prolonged slab roll-back. Episodic basin inversion occurs during short-lived events, probably driven by subduction of ocean floor features such as plateaus (Collins, 2002). Shortening and thickening of behind-arc basin sequences formed on thin lithosphere characterized by high heat flow give rise to typical low-pressure–high-temperature metamorphism, with counterclockwise pressure–temperature–time paths that may involve melting at the metamorphic peak and synchronous granite magmatism (e.g., Johnson & Vernon, 1995; Brown & Solar, 1999; Johnson *et al.*, 2003; Brown, 2003). Additionally, subduction of an active ocean ridge may be an important component of the thermal evolution of some accretionary orogens (e.g., Brown, 1998).

In contrast, collisional orogens form by closure of an ocean basin (e.g., the Cenozoic Himalayas of Asia, the Paleozoic Variscides of Europe). Collisional orogenesis involves a period of ocean plate subduction followed by an arc or continent collision, so that in most circumstances the effects of collision will be superimposed on an older accretionary orogen. The geotherm and the rheology of the lower crust, the convergence rate and any metamorphic changes that occur in the crust if it is subducted determine what happens during the collision period (e.g., Toussaint *et al.*, 2004). Arc or continent subduction may occur if the lithosphere is strong and the convergence rate is high, in which case the trench absorbs the convergence until it locks, after which ongoing convergence is accommodated by internal deformation.