Composition of the Earth's Crust

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Hypsography of Earth's Surface

In his book <The origin of continents and oceans>, Wegener wrote: "In the whole of geophysics there is hardly another law of such clarity and reliability as this—that there are two preferential levels for the world's surface which occur in alternation side by side, and are represented by the continents and ocean floors, respectively." Wegener was not the first person to have noted the bimodal hypsography of Earth's surface, but his appreciation of the underlying importance ultimately led to the discovery of two types of fundamentally different crust on Earth—the continental crust and oceanic crust (Fig. 1). Hypsography reflects the elevation of Earth's surface relative to sea level. The oceanic crust covers nearly two thirds of Earth's surface, and it sits low, averaging ~4 km beneath sea level. By contrast, the continental crust stands significantly higher and is mostly above sea level.

Earth's oceanic crust and continental crust have different chemical compositions and lithologies. The oceanic crust is mafic, meaning that it is rich in magnesium and iron. The continental crust, by contrast, is felsic with lower magnesium and iron contents but a higher silica content (Fig. 2). The most abundant rocks one can find in the oceanic crust are basalts, whereas the continental crust is dominated by granitic rocks. When silicate magmas differentiate, their compositions change as magnesium and iron are removed by early crystallizing minerals that fall out of the liquid. Thus, the oceanic crust is more primitive and the continental crust is more differentiated.

A number of space missions have launched in the last 50 years or so, tremendously enriching our knowledge of other bodies in our solar system. A major conclusion drawn from these missions is that Earth's oceanic crust is much like the crusts on other terrestrial planets, whereas the more differentiated continental crust is what makes Earth unique. No other terrestrial planets have large areas of highly differentiated crust like Earth, although evidence for evolved felsic materials have been uncovered on Mars (e.g., Ehlmann and Edwards, 2014; Wray et al., 2013) and potentially Venus (e.g., Hashimoto et al., 2008) on more local scales. Widespread exposure of granites distinguishes Earth's continental crust among planetary crusts. Table 1 lists the major element compositions of Earth's continental crust, oceanic crust, and the surfaces of other terrestrial planets in the solar system measured by various space missions.

Oceanic Crust

Extensive research on the oceanic crust started in the 1950s, made possible by the flourishing field of oceanic exploration at that time. The discovery of magnetic striping and polar reversals led to the proposal of seafloor spreading, which later became the backbone evidence for the plate tectonics theory. Spreading centers are the birthplace of oceanic crust. Beneath spreading centers, the asthenospheric mantle rises and undergoes decompression melting. As melting proceeds, oceanic crust is produced continuously, and early formed crust gets pushed away from the spreading centers. Because of convective upwelling of the mantle beneath, the spreading centers are uplifted and form underwater mountain ranges spanning tens of thousands of kilometers, known as the mid-ocean ridge system (Fig. 3).

The oceanic crust is relatively ephemeral, with an average age of 60 Ma (Cogné et al., 2006). The oldest oceanic crust is found in the west Pacific and north-west Atlantic and is dated at 180–200 Ma (Müller et al., 2008). Old oceanic crust is ultimately consumed through subduction at convergent plate margins (Fig. 3).

The oceanic crust is typically divided into three layers. The uppermost layer of the oceanic crust is composed primarily of basaltic lavas (with older sections covered by a veneer of pelagic sediment), which is then underlain by sheeted dikes. The lowermost oceanic crust consists of gabbroic rocks. The total thickness of oceanic crust is 6.5 km on average, but can vary locally as melting degrees and/or spreading rates change. Chemical variation is limited in the entire oceanic crustal column due to limited differentiation. Olivine, pyroxene, plagioclase, and Fe-Ti oxides are the major rock-forming minerals found in oceanic crust.

Trace element compositions are often regarded as the geochemical DNA of rocks. Trace element data are often presented in mantle-normalized diagrams, in which the elements are ordered by their relative compatibility, or the tendency of an element to remain in solid phases during partial melting. The oceanic crust has a trace element pattern that is distinct from that of the

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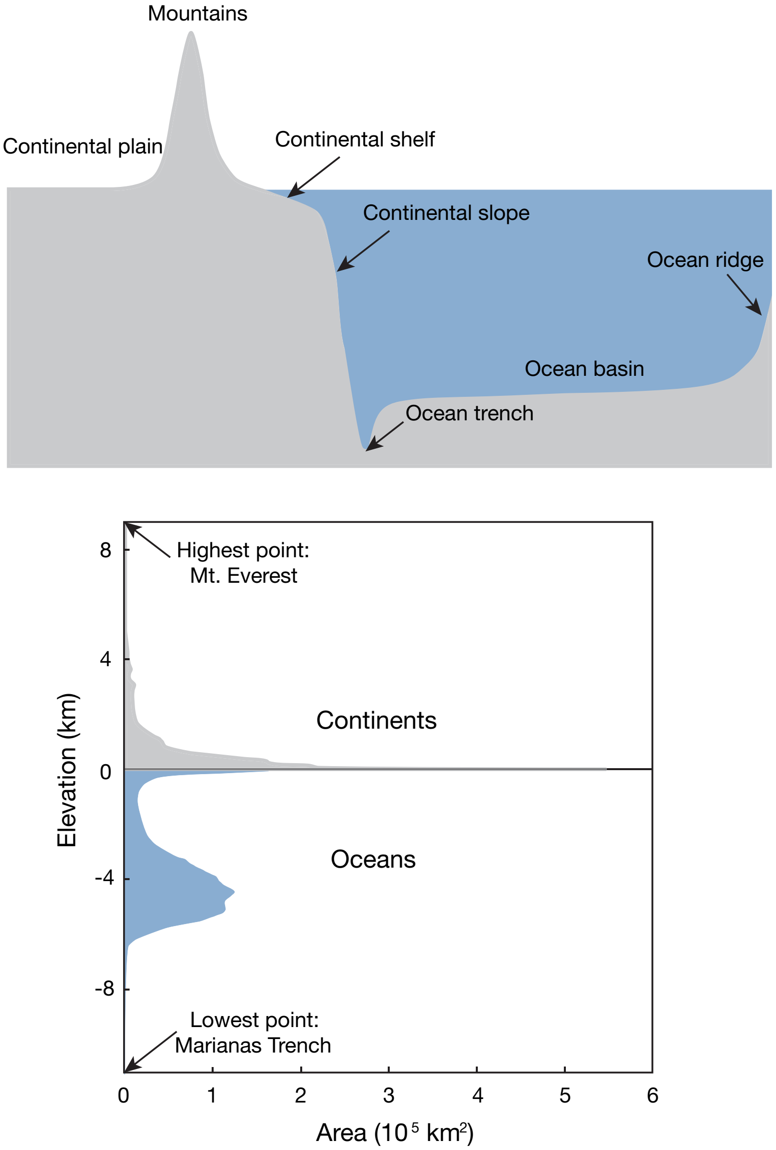

Fig. 1 Hypsography of Earth's surface. The cartoon on the top shows the basic topographic components of Earth's continents and oceans (not to scale). The bottom diagram plots the elevation distribution of Earth's surface based on the data from National Oceanic and Atmospheric Administration (NOAA). The continent-ocean contrast is clearly illustrated by the bimodal elevation distribution.

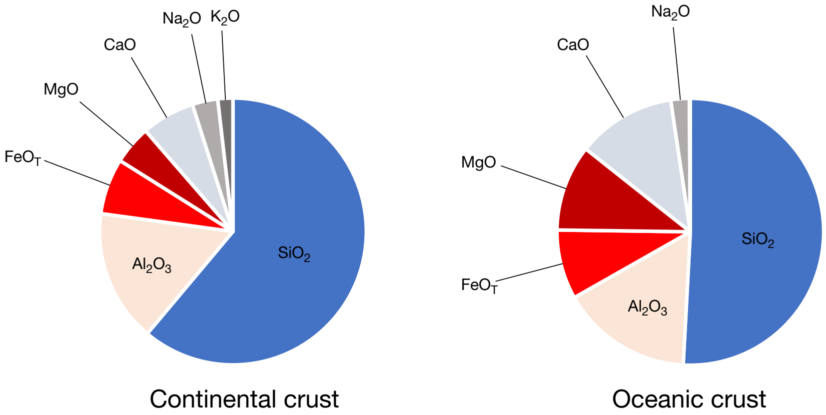

Fig. 2 Chemical compositions of Earth's continental crust and oceanic crust.

Table 1 Compositions of Earth's crust and the surfaces of other terrestrial planets in the solar system.

	Earth's continental crust[a]	*Earth's oceanic crust*[b]	*Mercury*[c]	*Venus*[c]	*Mars*[c]
SiO_2	60.6	50.1	54.2	45.6	49.3
Al_2O_3	15.9	15.7	12.8	16	10.5
FeO_T	6.71	8.3	1.7	7.74	18.2
MgO	4.66	10.3	18.4	11.5	9.06
CaO	6.41	11.8	5.8	7.5	6.92
Na_2O	3.07	2.21	4.1	n.a.	2.97
K_2O	1.81	0.11	0.16	0.48	0.45
P_2O_5	0.13	0.1	n.a.	n.a.	0.9

[a] Rudnick and Gao (2014).
[b] White and Klein (2014).
[c] Compiled by Taylor and McLennan (2008).

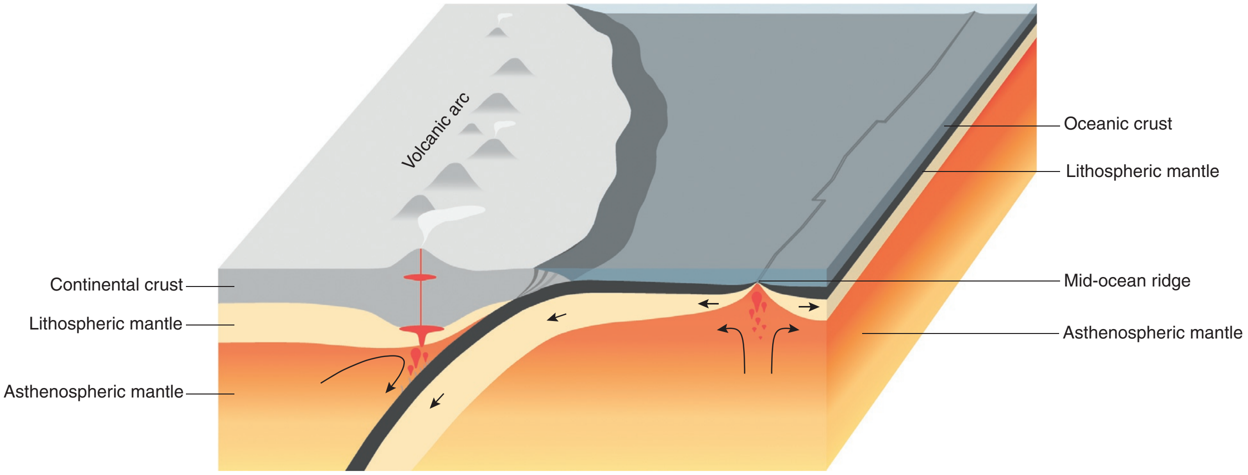

Fig. 3 Cartoon showing the formation of oceanic crust and continental crust. On modern Earth, the production of both continental crust and oceanic crust is driven by plate tectonics. New oceanic crust is produced at mid-ocean ridges and consumed at convergent margins through subduction. In subduction zones, magmatism and orogenesis together generate thick differentiated crust which eventually become part of the continental crust. The cartoon is not to scale.

continental crust. The oceanic crust is depleted in highly incompatible elements, such as Rb, U, Th, K, and light rare earth elements (Fig. 4). Because incompatible elements tend to enrich in the melt, the fact that these elements are depleted in the oceanic crust suggests that the source—the asthenospheric mantle—is even more depleted. There are profound implications behind this depletion. Of those incompatible elements, K, Th, and U are particularly important. K, Th and, U are called the heat producing elements. One or multiple isotopes of these elements decay and produce heat, which is a major source of energy in the interior of Earth. The depletions of K, Th, and U in the asthenospheric mantle of modern Earth suggests that crust formation has extracted most of these elements, which in turn cools the Earth's interior.

The depleted nature of the oceanic crust and its source, the upper mantle, is also reflected in the radiogenic isotopic composition of mid-ocean ridge basalts (MORB). Partial melting and crust extraction processes (e.g., magma mixing, crystal settling, etc.) fractionate the parent-daughter nuclides of radiogenic isotope systems, causing differing in-growth rates of daughter nuclides in the crust and residual mantle reservoirs. Nd, Sr, Pb, and Hf isotopes have been extensively examined by the geochemical community to quantify the degree of depletion/enrichment in the crust as a function of time. Taking the Sm-Nd system for example, ^{147}Sm decays to ^{143}Nd. Because Nd is more incompatible than Sm during mantle melting, the melt has a lower Sm/Nd ratio and the residual mantle has a higher Sm/Nd ratio. Over geologic timescales, the curst that formed from the melt develops a lower $^{143}Nd/^{144}Nd$ ratio than the residual mantle, which develops a higher $^{143}Nd/^{144}Nd$ ratio. The oceanic crust, as represented by MORB, has systematically more radiogenic Nd isotopic signatures (higher εNd values, $\varepsilon Nd = ((^{143}Nd/^{144}Nd_{sample})/(^{143}Nd/^{144}Nd_{chondrite}) - 1) \times 10{,}000$) and less radiogenic Sr isotopic compositions (lower $^{87}Sr/^{86}Sr$) than the continental crust (Fig. 5). An interesting observation is that oceanic basalts, including MORB and intraplate ocean island basalts derived from deep-rooted hotspots, though generally more depleted, display significant variations in their Nd and Sr isotopes (White, 2005). These isotopic variations are attributed to crustal recycling by either subduction or lower crust foundering.

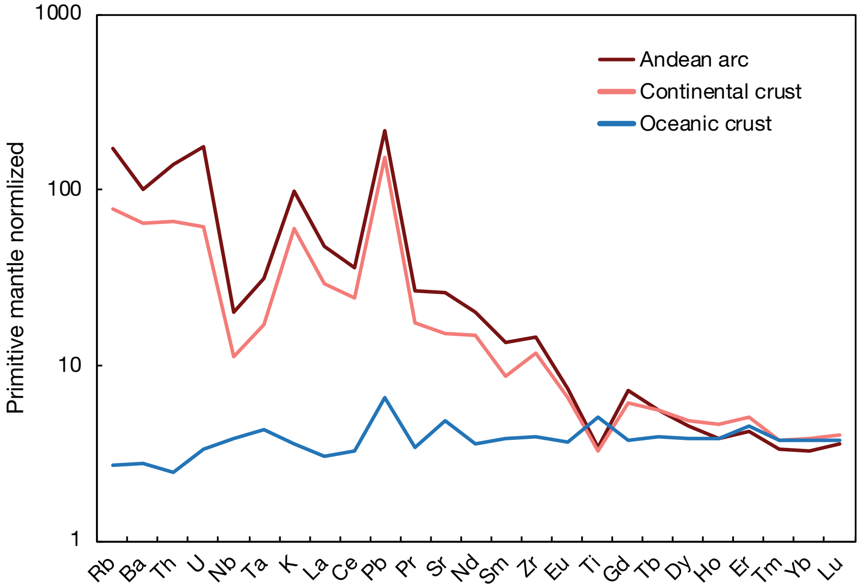

Fig. 4 Mantle-normalized trace element diagram of Earth's crust. Average elemental abundances in the oceanic crust (White and Klein, 2014), bulk continental crust (Rudnick and Gao, 2014), and Andean arc volcanics (Farner and Lee, 2017) are normalized to a compositional model primitive mantle, the assumed undifferentiated Earth's mantle (McDonough and Sun, 1995). The sequence of elements along the abscissa increases in compatibility during mantle meting (i.e., higher $D^{sol/liq}$) from left to right. The pattern of the continental crust is easily distinguished from that of the oceanic crust, but resembles that of Andean arc magmas.

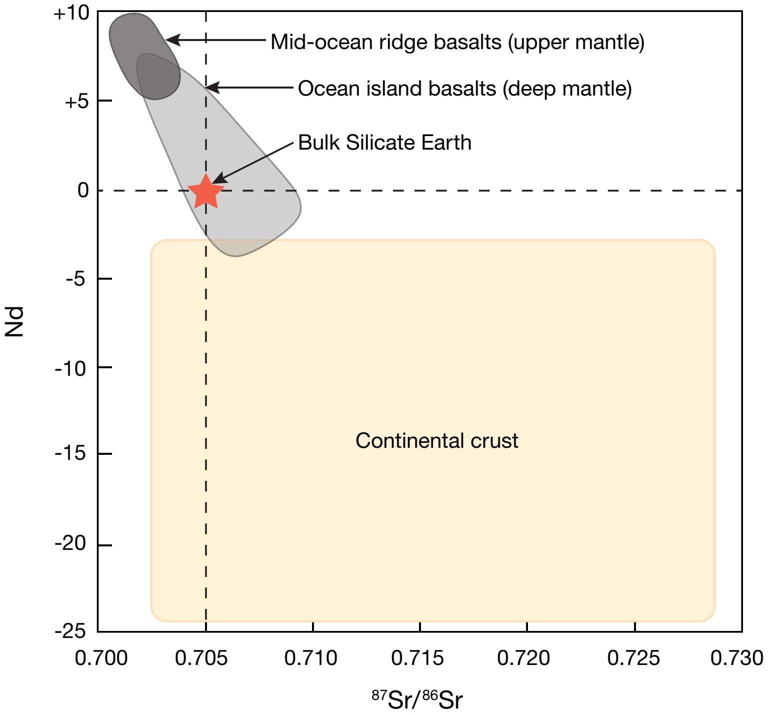

Fig. 5 Sr-Nd isotope compositional fields of the oceanic crust (mid-ocean ridge basalts and ocean island basalts) and continental crust. Modified from White, W (2005) *Geochemistry. An On-Line Textbook*. Cornell University, 701.

Continental Crust

Systematic research on the chemical composition continents started about a century ago. In 1889, Frank W. Clarke published the first study on the composition of the continental crust (Clarke, 1889). Since then, numerous efforts have been made to further understand the chemistry and physical properties of the continental crust. On average, the continental crust is ~40 km thick, and may be conveniently divided into the upper, middle, and lower continental crust based on seismic velocity. The upper continental crust is about 12 km thick, the middle continental crust about 11 km thick and lower continental crust roughly 17 km thick (Rudnick and Gao, 2014).

In his pioneering work in the 19th century, Clarke derived the composition of the upper continental crust by averaging hundreds of samples of the exposed rocks (Clarke, 1889). Thirty years later, Clarke revised his original estimate of the crustal composition to incorporate a larger dataset, although the numbers did not change much (Clarke and Washington, 1924). In the 1960–80s, this surface averaging method was used to determine the crustal composition of the Canadian, Baltic, and Ukrainian shields. Despite the different places these studies were centered on, they yielded consistent average major element compositions for the upper crust across the continents (Fahrig and Eade, 1968; Ronov and Yaroshevskiy, 1976; Shaw et al., 1967). These early surface sampling studies provide the foundation for progressive studies of crustal chemistry, and serve as the anchors for major element compositions of the upper continental crust even in the latest models.

The surface averaging approach, though effective and straightforward, is rather inefficient as the technique requires a massive amount of sampling and extensive analytical work. A new methodology emerged in the 1980s which utilizes shales and loess to determine globally-averaged compositions of exposed crust that undergoes erosion and weathering (Taylor and McLennan, 1985). This sedimentary approach, developed by Ross S. Taylor, Scott M. McLennan, and contemporary workers, allows nature to do the heavy lifting, including sampling and mixing/homogenizing, and has been very successful in determining the concentrations of insoluble trace elements, such as rare earth elements, in the upper continental crust. In addition to shales and loess, glacial deposits have also been used to constrain the composition of the exposed continental crust. The idea of using glacial diamictites originated from Victor M. Goldschmidt, the father of geochemistry (Goldschmidt, 1933). Glacial diamictites form from physical erosion of Earth's surface by glaciers as they slide across large tracts of the upper continental crust.

Our knowledge of crustal composition becomes progressively obscured with increasing depth because the deep crust is far less accessible. Direct samples of the deep continental crust come from metamorphic terrains exhumed by tectonic activities and xenoliths brought to the surface by violent volcanic eruptions. The middle crust is dominated by amphibolites while the lower crust mainly consists of granulites (Rudnick and Gao, 2014). The exposed metamorphic samples reveal a highly heterogeneous deep crust whose composition may vary depending on tectonic setting. Geophysical data have also been used to constrain the compositions of the deep crust. Mafic rocks tend to propagate seismic waves faster than felsic rocks. This correlation between lithology and seismic velocity allows researchers to use seismic velocity profiles to reconstruct the composition of the deep crust, but this method also suffers from great uncertainties due to the significant overlap in seismic velocities between mafic and felsic lithologies (Huang et al., 2013).

Specifically, views on the composition of the deep continental crust are divided into two camps. One group of researchers suggest that the crust becomes more mafic with increasing depth, and propose that the lower continental crust is largely basaltic (Gao et al., 1998; Rudnick and Fountain, 1995). The other group of researchers hold that the lower continental crust may not be that different from the upper continental crust, and thus may be largely felsic (Hacker et al., 2011). This ongoing debate has profound implications for the formation of the overall highly differentiated continental crust.

In contrast to the oceanic crust, the continental crust is strongly enriched in highly incompatible elements, and its trace element pattern shows much resemblance to those of volcanic arc magmas. This similarity in trace element patterns leads to the widely accepted hypothesis that, at least in the Phanerozoic, most of the continental crust may have been produced in subduction zones where two plates meet, and one subducts beneath the other. The subducting oceanic plate undergoes dehydration, which extracts fluid mobile elements from the subducted sediments and altered oceanic crust. These elements are then transferred to the sub-arc mantle—the source region of arc magmas. Most of the incompatible elements, those on the left side of mantle-normalized diagrams (Fig.3), are fluid mobile, so this process may explain the enrichments of these elements in primary arc magmas. Two elements, Nb and Ta, behave differently. Nb and Ta are highly insoluble, and they remain in the subducting slab during dehydration, making a trough in the trace element patterns of continental crust and arc magmas (Kessel et al., 2005; Tang et al., 2019a).

The subduction zone model for generating continental crust is attractive also because it solves the water problem (Arndt, 2013; Campbell and Taylor, 1983). The continental crust, particularly the upper part of it, has massive amounts of granitic rocks. To generate these granitic rocks requires extensive differentiation at low magmatic temperatures ($<1000\,^{\circ}\mathrm{C}$). Water, which significantly lowers the solidi of silicate minerals and magma viscosity and allows magmatic differentiation to proceed at much lower temperatures, is essential to this process. Dry magmatic systems, on the other hand, solidify at temperatures too high to support significant differentiation. In subduction zones, the down-going hydrated oceanic plate brings water directly to Earth's interior where melting and differentiation takes place. Indeed, most arc magmas are water rich.

However, the subduction model is not without problems in explaining continental crust production globally. It is well established that the continental crust has an andesitic average composition with $>60\%$ SiO_2 and <5 wt% MgO. Primary arc magmas, however, are generally basaltic with ~ 50 wt% SiO_2 and >10 wt% MgO. This compositional discrepancy between primary arc magmas and the continental crust presents a mass imbalance problem. Clearly, a component with a mafic to ultramafic bulk composition complementary to the felsic continental crust is now missing. What is the nature of this missing mafic component? When and how is this component removed from the continental crust? We do not yet have solid answers to these questions. One popular hypothesis is that magmatic differentiation produces mafic to ultramafic cumulates—the dance partners of the felsic differentiated melts—at the roots of volcanic arcs. Because their densities could be higher than the underlying mantle peridotite, these cumulates may eventually detach from the differentiated, less dense crust above, and sink into the mantle (Herzberg et al., 1983; Kay and Mahlburg-Kay, 1991). Alternatively, the continental crust may have formed by slab melting, particularly in the Archean. In this case, mafic residues may reside in the down-going slab (Moyen and Martin, 2012).

Canonical trace element ratios are particularly powerful tools in tracing crustal formation and recycling. The concept of canonical element ratios was first proposed by Albrecht Hofmann, who paired trace elements with similar bulk partition coefficients during mantle melting and used their ratios to determine the source composition. The continental crust often shows distinct canonical element ratios from the oceanic crust and depleted upper mantle. For example, the continental crust has a significantly lower distribution of Ce/Pb values than mid-ocean ridge basalts. Similarly, low Ce/Pb are also observed in arc magmas, which again points to the intrinsic relationship between arc magmatism and continental crust formation (Hofmann et al., 1986). The continental crust also has significantly lower Nb/U than the oceanic crust (Hofmann et al., 1986; Sylvester et al., 1997), which may be a signature inherited from arc magmas (Fig. 5). The continental crust and the upper mantle, as sampled by mid-ridge basalts, are often complementary in their compositions, but this is not always the case. Both the continental crust and mid-ocean ridge basalts have lower Nb/Ta and Ti/Eu ratios than the Bulk Silicate Earth, or primitive mantle (the right panel in Fig. 6) which suggests that either the Bulk Silicate Earth composition is poorly constrained or a reservoir with high Nb/Ta and Ti/Eu is missing (Arevalo and McDonough, 2010).

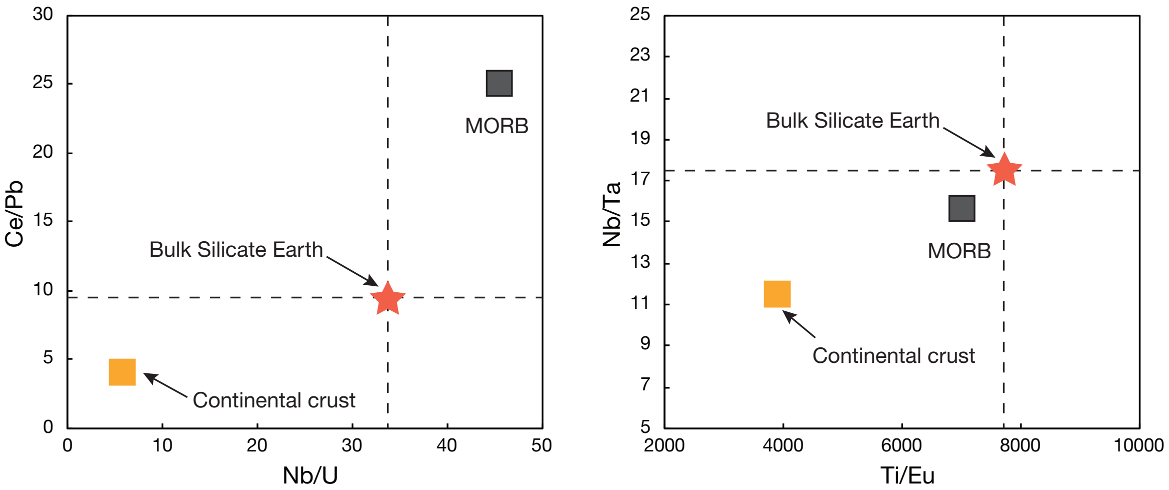

Fig. 6 Canonical trace element ratios of Ce/Pb, Nb/U, Nb/Ta and Ti/Eu in the continental crust and mid-ocean ridge basalts (MORB), compared to those of the Bulk Silicate Earth (Arevalo and McDonough, 2010).

Yet another important question concerns the differentiation process that generates the silicic continental crust. Basaltic, mantle-derived magmas, as they cool during ascent, may differentiate along two distinct pathways. One is termed tholeiitic differentiation and the other calc-alkaline differentiation. These two petrologic terminologies are not very intuitive. What these terms define is the relative Fe enrichment/depletion in early stage magma differentiation. Tholeiitic differentiation enriches Fe in the magma by precipitating minerals with low iron contents (leaving the residual melt more enriched in Fe), whereas calc-alkaline differentiation depletes the melt in Fe. Of these two differentiation series, calc-alkaline differentiation is particularly interesting and important because the continental crust is, on average, calc-alkaline with strong iron depletion (Fig. 7). Tholeiitic magmas are typically found in mid-ocean ridges while calc-alkaline magmas are mostly seen in subduction zones.

The conventional explanation for calc-alkaline differentiation is that subducting slabs introduce oxidized materials to arc magma sources. As a consequence, primary arc magmas are oxidized which prompts early saturation of magnetite—a mineral rich in ferric iron (Fe^{3+}) (Osborn, 1959; Zimmer et al., 2010). This magnetite model, however, cannot explain the fact that not all subduction zone magmas are calc-alkaline. In effect, some subduction zones, such as the Mariana arc, are predominantly tholeiitic. Interestingly, the calc-alkalinity, or the degree of iron depletion, of arc magmas strongly correlates with arc crust thickness (Fig. 7). The most Fe-depleted magmas are found in arcs built on extremely thick crust like the Central Andes in South America. Some researchers propose that calc-alkaline differentiation is driven by the fractionation of garnet, which is Fe rich and only stabilized at high pressure, and has nothing to do with magnetite (Alonso-Perez et al., 2008; Green and Ringwood, 1968; Tang et al., 2018, 2019b). If this is true, then the calc-alkaline nature of the continental crust would require orogenesis as a key process in its formation.

Continental Crust in the Past

Unlike the oceanic crust, the continental crust is old. The oldest rocks on the continents are the Acasta gneisses in Northwest Territories, Canada, which formed about 4 billion years ago. There are no rock records in the first ~500 Ma of Earth's history, but detrital zircons can take us back to as far as 4.4 billion years ago, just shy of the age of Earth (Fig. 8). The continental crust is a

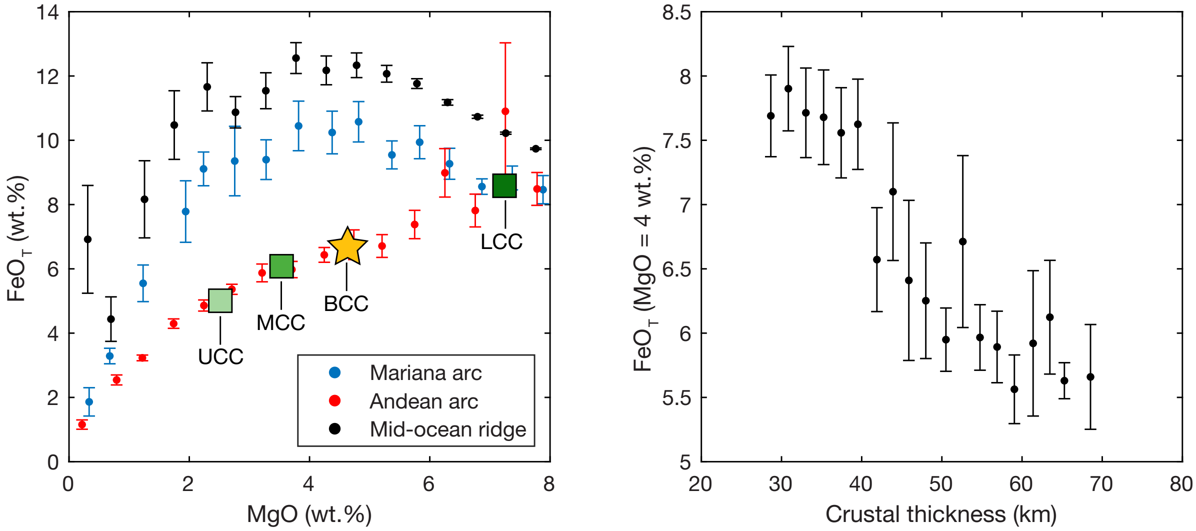

Fig. 7 Diagrams showing crustal thickness control on magmatic differentiation series. In mid-ocean ridges and arcs built on thin crust (e.g., Mariana arc), magmatic differentiation follows the tholeiitic series with initial Fe enrichment (total iron quantified as FeO_T), whereas in places built on thick crust such as the Andean arc, magmatic differentiation is marked by continuous Fe depletion (Farner and Lee, 2017; Tang et al., 2018). The continental crust plots on the Fe-depleting trend represented by Andean arc rocks. In the left diagram, UCC, MCC, LCC and BCC denote upper, middle, lower and bulk continental crust, respectively (Rudnick and Gao, 2014). The diagram on the right shows that magmas become progressively depleted in Fe with increasing crustal thickness.

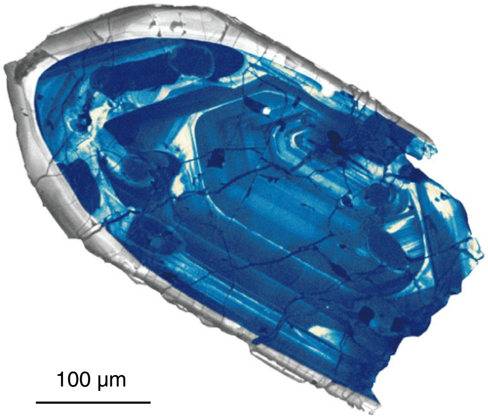

Fig. 8 False colored cathodoluminescence image of a Jack Hills detrital zircon crystal. With an age of 4.4 billion years, this crystal represents the oldest fragment of Earth's crust that has been dated. Image credit: John Valley (University of Wisconsin, Madison).

"history book" from which much our insights into Earth's past are gained. But at the same time, this "book" is poorly preserved, with missing pages here and there because the Earth keeps erasing its history as it evolves. Weathering, erosion, and tectonism have been reshaping Earth's surface for billions of years, which makes it very challenging to reconstruct crustal evolution in Earth's remote past.

How did the composition of continental crust evolve over Earth's history? Direct surface mapping of the preserved continental crust suggests little change in the last 3–4 billion years. Granitic rocks appear to be the dominant lithologies of subaerial crust since the early Archean (Condie, 1993). Today, only 50% of the exposed continental crust has Precambrian ages, and less than 5% is older than 3 billion years (Goodwin, 1996). This raises serious concerns whether the preserved continental crust, which we can sample, is representative of what it was billions of years ago if much of the ancient crust has been lost.

The detrital zircon archive has played a critical role in tracing early crustal evolution. Because zircon almost exclusively crystallizes from felsic magmas, the discovery of detrital zircons with Hadean ages has been used to argue for the formation of granitic rocks not long after Earth formation. A number of trace element geochemistry, isotope, and mineral inclusion studies of the Hadean detrital zircons from Jack Hills, western Australia further confirm the affinity of these zircons with highly differentiated magmas (e.g., Hopkins et al., 2008; Watson and Harrison, 2005). There is no question about the origin of these ancient detrital zircons, but their implications are strongly debated. Do they imply the existence of large areas of felsic continental crust, or a few felsic plutons scattered in a predominantly mafic crust?

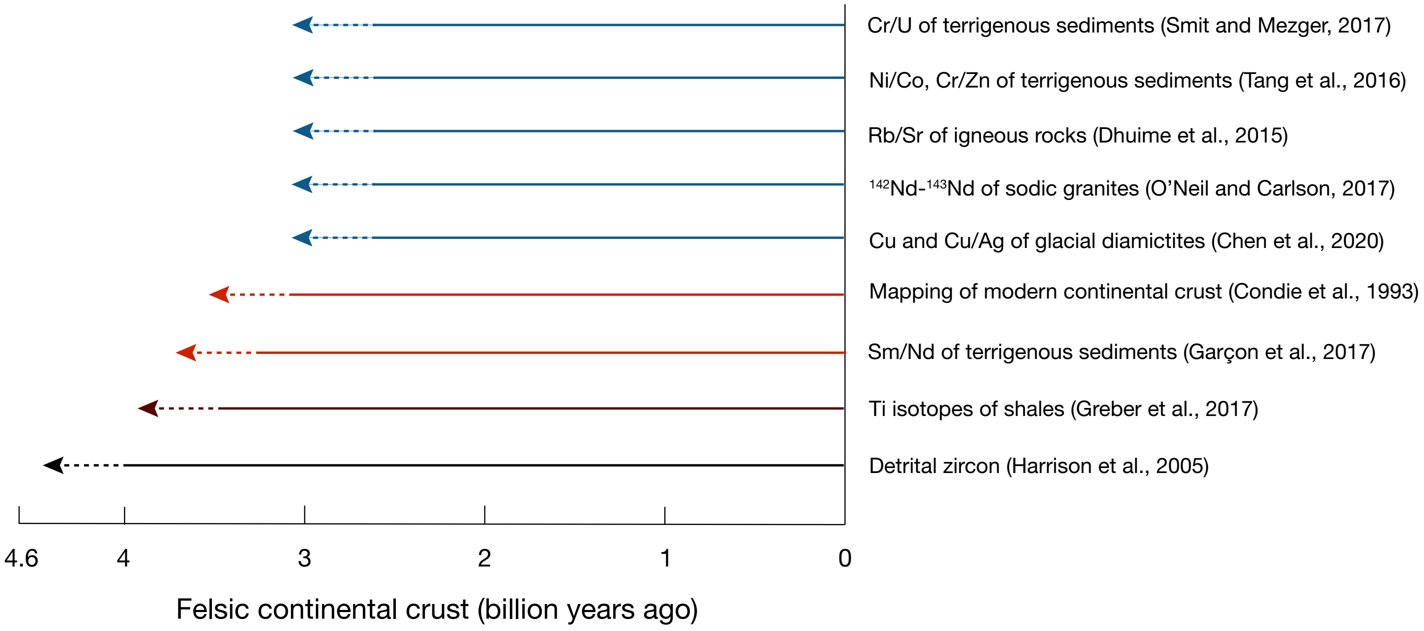

Fig. 9 Evidence for the emergence of felsic continental crust from different perspectives, as compiled from literature studies.

The latest studies of igneous records suggest that Earth had a vastly mafic crust and a stagnant-lid tectonic regime (as opposed to the plate tectonics regime of today) until the late Archean. In particular, the predominantly low Rb/Sr ratios of juvenile crust before 3 Ga, deduced from a global survey of Sr isotopes in igneous rocks, are consistent with lack of continent-scale granitic magmatism (Dhuime et al., 2015). The discovery of ^{142}Nd isotope anomalies in the Neoarchean sodic granites from Canada suggests that the mafic crust had been preserved for over 1 billion years before it was remelted to give rise to the Neoarchean granites (O'Neil and Carlson, 2017). This longevity of mafic crust would not have been possible if plate tectonics were operating before the Neoarchean.

Recently, terrigenous sediments with known depositional ages have been extensively examined to reconstruct the composition of continental crust in the past (Chen et al., 2020; Garçon et al., 2017; Greber and Dauphas, 2019; Greber et al., 2017; Tang et al., 2016). These sedimentary rocks are thought to provide snapshots of the average compositions of large areas of the subaerial crust at different times over Earth's history. Transition metals in the sedimentary records suggest a fundamental change in subaerial crust composition in the late Archean, from 3 to 2.5 billion years ago (Tang et al., 2016). Before 3 billion years ago, the subaerial crust seems to be highly mafic, similar to the oceanic crust and the crusts of other terrestrial planets. This crust appears to have been completely replaced by an overall felsic crust by the end of Archean. Titanium isotopes in these sedimentary rocks, however, tell a different story and suggest that there is no significant change in crustal composition since at least 3.5 billion years ago (Greber et al., 2017). This would mean that felsic continental crust already emerged within the first billion years of Earth's history. This debate has important implications for the evolution of our planet but is currently far from settled (Fig. 9).

Conclusion and Outlook

Earth owes much of its dynamic surface environment, including the complicated and diverse eco-systems, to its bimodal hypsography. This bimodal hypsography enables various forms of material cycling and energy transfer to happen continuously. A flat planetary surface would be silent, barren, and lifeless.

The bimodal hypsography of Earth is intrinsically related to plate tectonics and the presence of oceanic crust and continental crust. The most ancient oceanic crust is only 200 million years old because the oceanic lithosphere becomes colder and denser with age, ultimately subducting back into the mantle. Geologic records of the oceanic crust in the Precambrian are scarce and arguably absent in the Archean and Hadean. How did the composition of oceanic crust evolve over Earth's history? Was the oceanic crust thicker in the Precambrian?

The continental crust stands higher, in part, because it is less dense than the mafic oceanic crust, but more importantly because it is much thicker than the oceanic crust. Why is the continental crust so thick? What is the role of orogenesis in continent formation? Modern continental crust is felsic and depleted in magnesium and iron. But when did this felsic continental crust emerge globally on Earth? Subduction zone magmatism appears to be the dominant mechanism to form the continental crust on modern Earth. But how far can we extrapolate this mechanism back in Earth's history? The continental crust interacts with the oceans and atmosphere and exerts important influences on carbon, nitrogen and sulfur cycles and nutrient fluxes to the oceans. How did the evolving continental crust influence Earth's surface dynamics in the past? I leave this "conclusion" section less conclusive and hope that, in the next decade or so, when these subjects of Earth's crust are re-reviewed, we as a community will have deeper insights.

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