9.07 Mechanism of Continental Crustal Growth

M Stein, Geological Survey of Israel, Jerusalem, Israel
Z Ben-Avraham, Tel Aviv University, Ramat Aviv, Israel

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9.07.1 Introduction

The continental crust comprises the outmost 20–80 km (average thickness is about 36 km) of the solid surface of the Earth covering ∼41% of the Earth surface area. Most of this area (∼71%) is currently elevated above sea level, while the rest is defined by the topography of the continental shelves. The continental crust density ranges from 2.7 to 2.9 g cm^{-3} and increases with depth. The vertical extent of the continental crust is defined by the compressional seismic wave velocity that jumps from ∼7 to >7.6–8 km s^{-1} across the Mohorovičić discontinuity (or ‘Moho’). The Moho discontinuity discovered by the Croatian seismologist Andrija Mohorovičić is the boundary between the crust and the mantle, which reflects the different densities of the crust and the mantle, normally occurring at an ‘average’ depth of ∼35 km beneath the continental surfaces and about 8 km beneath the oceanic basins. The original recognition and definition of this boundary

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reflected seismic properties. However, in some regions, the Moho is not always well defined and appears to be transitional in its physical–chemical characteristics (cf. Griffin and O'Reilly, 1987).

The oceanic crust covering ~59% of the Earth surface is significantly thinner than the continental crust and is characterized by its distinct chemical composition and younger age (the oldest oceanic crust is Jurassic in age). Nevertheless, it appears that the growth of continental crust involves the accretion of thick magmatic sequences that were formed in the intraoceanic environment (e.g., oceanic plateaus); thus, the geodynamic evolution and geochemical evolution of oceanic and continental crusts are related.

The temperature gradient is typically less beneath continents than beneath oceanic basins, reflecting the thicker immobile regions underlying the continents. These regions are termed the lithospheric mantle, and they typically form a thick colder 'root' beneath ancient shields and a relatively thinner root beneath younger shields. Yet in intracontinental rifting regions, the asthenospheric mantle is rising and interacts with the lithospheric mantle and continental crust and replaces it with new mantle-derived material. Moreover, it appears that many of the current oceanic basins (and oceanic crust) commenced their history within the continental environment calling for some important relationship between stability and magmatic–thermal history of the continental lithosphere and the plate tectonic cycle. The relationship between asthenospheric mantle and lithospheric mantle and the questions concerning the growth, maturation, and fate of continental lithosphere and crust throughout geologic time are fundamental problems in Earth sciences that will be reviewed in this chapter.

The continental crust is of great antiquity and contains the record of most of the geologic (physical and chemical) evolution of the Earth. A major question in earth sciences is when and in what rates and modes the continental crust was formed and evolved. It is broadly accepted that most of the present-day continental masses are composed of rocks that were produced at the end of the Archean and the beginning of the Proterozoic, within the time period lasting from ~3.2 to ~2.0 Ga. The oldest surviving rocks were found in all continents and date from more than four billion years ago, a few hundred million years after the formation of the Earth (Taylor and McLennan, 1995). Yet although the continental crust covers about 40% of the terrestrial surface, rocks older than 2.5 Ga account for less than ~15% of the exposed continental area (Windley, 1995). Based on Nd model ages, the 'average' age of the continental crust was calculated as ~2.2 ± 0.1 Ga, which indicates that 50–60% of the continental crust was formed before 2.6 Ga (cf. DePaolo et al., 1991; McCulloch and Bennett, 1994; Nelson and DePaolo, 1985; Taylor and McLennan, 1995). These chronological determinations are critical to the long-standing debate on the history and mechanism of crustal formation, where models of very early creation and subsequent recycling of continental crust material contrast with continuous/episodic crustal growth (the 'Armstrong–Moorbath debate' elaborated later in the text).

Much of the present-day continental creation appears to occur at convergent plate margins mainly along the subduction zones; however, several studies indicate that large amounts of continent were created in the geologic past during short 'super events' at rates that are difficult to explain through 'typical' subduction activity (**Section 9.07.3.3**). This would imply that large portions of the continents were formed by other means than convergent margin magmatism, probably processes related to hot spot or mantle plume magmatism (e.g., oceanic plateau formation, accretion of juvenile mantle terrains to the continents, and basaltic underplating). How these accreted terrains were transformed into continental crust and how these retain geophysical properties of crustal material represent another central question that has been open to debate (the 'Ontong Java paradox' outlined later in the text). Crustal formation is related to heat generation in the Earth, which has clearly declined since early Archean time through the Proterozoic and Phanerozoic. What was the reflection of this change on the modes and mechanism of crust production, for example, intracrustal or lithospheric melting versus subduction-related magmatism and arc accretion?

In this chapter, we summarize some of the main results that emerge from the extensive efforts that were devoted over the past decades to determine the composition of the upper crust and lower crust and bulk continental crust (this subject and the relevant literature were thoroughly reviewed by Taylor and McLennan (1985, 1995, 1996) and more recently by Rudnick and Gao (2003)). Then, we go through the 'Armstrong–Moorbath debate' on early versus episodic crustal growth and the 'Reymer and Schubert dilemma' concerning arc–plume modes of crustal growth. We discuss mantle overturn and accretion models (cf. Ben-Avraham et al., 1981; Stein and Hofmann, 1994) that invoke episodic activity of large mantle plumes and accretion of juvenile mantle material to the continents and alternative arc-tectonics models (Patchett and Chase, 2002) or recent suggestions for continental preservation models (Condie et al., 2011; Hawkesworth et al., 2010). We discuss models of calc-alkaline and alkaline granitoids (the most important magma type comprising the upper continental crust).

Finally, we describe the production of juvenile continental crust in major segments of the continents (the 'major orogens'): the Archean Baltic Shield and Superior province, the Proterozoic Birimian orogen, and the late Proterozoic Arabian–Nubian Shield (ANS).

9.07.2 Structure and Chemical Composition of the Continental Crust

9.07.2.1 General

Based on seismic wave velocities, the continental crust can be vertically divided into two parts: the upper crust between the surface discontinuity and the Conrad discontinuity, which is poorly defined at 10–20 km from the surface, and the lower crust that principally extends from the Conrad discontinuity to the Moho discontinuity.

The problem in defining the location of the intracontinental crustal boundaries and obtaining an estimate of the chemical composition of the bulk continental crust reflects the complex history of the crust in different regions of the Earth. This evaluation requires knowledge on the type of the rocks comprising the upper crust and lower crust in various crustal domains. However, only a little portion of the continental crust is exposed (e.g., due to tectonic exhumation of mainly the upper crustal segments and deep erosion) and accessible for direct research. The composition and physical properties of the lower crust are mainly evaluated from geophysical data combined with information derived from xenoliths and outcrops of uplifted granulite terrains.

Nevertheless, many researchers devoted extensive efforts over the years to base an estimate of the bulk chemical composition of the crust. This was done by determining the distribution and chemical composition of the dominant rock types that are exposed at the surface (e.g., the pioneering studies of Clarke and his coworkers Clarke, 1889; Clarke and Washington, 1924) and recent works by Gao et al. (1998) (see the comprehensive summaries of this topic by Condie (1993) and Rudnick and Gao (2003)). Another approach was to use sediments as natural samplers of large areas of the upper continental crust. Goldschmidt (1933, 1958) introduced this approach in his pioneering studies on glacial sediments from the Baltic Shield.

Later, other researchers applied similar ideas and methodologies using other samplers such as fine-grained sediments such as desert dust (e.g., loess) or deep-sea terrigenous sediments. Important examples are the works of Taylor and McLennan (1985), Plank and Langmuir (1998), Gallet et al. (1998), Barth et al. (2000), and Hattori et al. (2003). The results of these and other related studies were used to estimate the chemical composition of the upper crust (e.g., Rudnick and Gao, 2003; Taylor and McLennan, 1995).

The estimates on the bulk composition of the continental crust require, however, knowledge on the composition of the deeper parts of the crust. This information is provided mainly by xenoliths of mafic granulites that are transported to the surface by intraplate alkali basalts (mostly in rift-related environments) and tectonically uplifted blocks that consist of granulite facies metamorphic terrains. The post-Archean metamorphic granulite terrains appear to represent the upper crustal segments or transitional zones between the upper crust and lower crust (e.g., depressed in Himalayan-type collision zones (Bohlen and Mezger, 1989; Mezger, 1992)). Xenoliths of mafic granulites are considered as representatives of the lower crust. The xenoliths were interpreted as cumulates from basaltic magmas that were rising to lower crustal levels and were later subjected to the granulite facies metamorphism (cf. Kay and Kay, 1981; Rudnick, 1992). Since the xenolith data are rather sporadic, Rudnick and Fountain (1995) combined it with seismic velocities to get an estimate of the bulk lower crust composition. Nevertheless, it should be noted that the xenoliths of mafic granulite were mostly transported to the surface by rift-related alkali basalts and they may be associated only with the particular tectonic–magmatic environment that also supports alkali basalt production. Rifting environments are associated with the rise of asthenospheric (mid-ocean ridge basalt (MORB)-like) mantle into the spreading lithosphere (see the example of the opening of the Red Sea later in the text), and thus, the production of the source lithologies of the mafic granulite xenoliths may be associated with additions of new material to an older continental lithosphere. This scenario is supported by younger Re–Os isotope ages of lower crustal xenoliths compared to the above-lying lithosphere (Rudnick, 1992).

Rudnick and Gao (2003) combined the estimates of the upper crust, middle crust, and lower crust composition to produce a bulk continental crust composition. Trace element patterns (normalized to primitive mantle values) of the lower crust, upper crust, and bulk crust are illustrated in **Figure 1**.

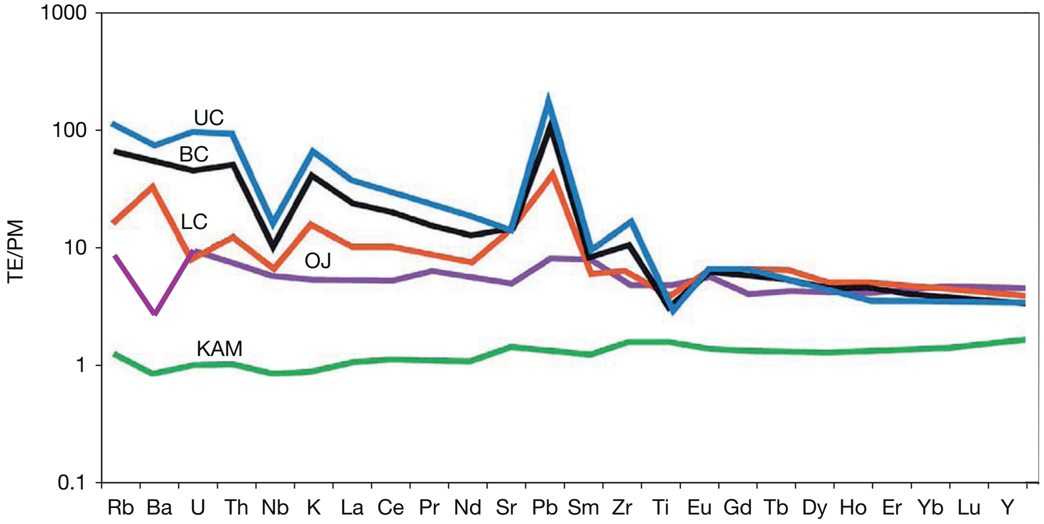

Figure 1 Primitive mantle-normalized trace element patterns of the upper, lower, and bulk crust estimates (UC, LC, and BC, respectively); the Cretaceous Ontong Java Plateau (OJ) basalt; and Archean Kambalda komatiite (KAM). Note the overall enrichment of the UC and BC crustal samples in the incompatible trace elements, the distinctive positive Pb and negative Nb anomalies in the crustal samples, and the flat patterns of the plateau and (almost primitive in KAM). A significant differentiation is required to transform OJ or KAM-type oceanic crust to the upper continental crust. The fractionation of trace elements like Nb and Pb could be furnished by processes in the subduction environment. Nevertheless, if accreted plateaus similar to OJ basalts comprise an important part of the continental crust, they either are not well represented by the bulk continental crust composition estimates or underwent (before or during accretion) internal magmatic differentiation (which are reflected by their continental-like seismic velocities; see **Figure 6**). Data sources: Rudnick and Gao (2003) and Mahoney et al. (1993a,b).

The order of appearance of the trace elements on the abscissa reflects the tendency of the incompatible trace element to move preferentially from the source to the melt during magma generation. This behavior can be applied to the processes that are involved in the production of continental crust from mantle sources (Hofmann, 1988). Noticeable features in this figure are the strong positive Pb anomalies and the negative Nb anomalies in the lower, upper, and bulk continental crust curves. These anomalies are probably related to mantle–crust differentiation processes that can fractionate Pb and Nb from the REE, Th, and U (cf. Hofmann et al., 1986). Such fractionation could occur in the subduction environment ('the subduction factory') along with the production of 'arc-type' calc-alkaline magmas (cf. Stein et al., 1997). The Mesozoic Ontong Java Plateau basalts and the Archean Kambalda komatiite display distinctly trace element patterns that are distinctly different from those of the 'lower, upper, and bulk' continental crust. These type of magmas show almost 'flat' primitive trace element patterns (although the Ontong Java sample displays small negative Pb and Ba anomalies that seem to oppose the strong positive Pb and Ba of the 'average lower crust'). If the Kambalda and Ontong Java type magmas represent important constituents of continental crust, they are not well represented by the 'bulk crust' patterns.

9.07.2.2 Composition of the Continental Crust: Open Questions

In the succeeding text, we outlined several topics and open questions that emerged from the extensive efforts to evaluate of the chemical composition of the continental crust.

9.07.2.2.1 Problems with the simple 'andesitic model'

The overall geochemical similarity of continental crust to arc-type magmas (e.g., the estimated average ~60% SiO_2 andesitic composition of bulk continental crust and similar values of indicative trace element ratios such as Ce/Pb and Nb/Th in arc–crust magmas) led many workers to suggest that the arc-subduction environment where andesitic magmas are produced is the main locus of juvenile crust production (the 'andesitic model' of continental crustal formation, e.g., Taylor, 1967) and that accretion of arcs at convergent margins is a major means of continental crustal growth. Transport and differentiation of melts and fluids that eventually control the composition of continental crust were associated with the subduction environment where mantle-wedge magmas and associated fluids with trace elements move upward while interacting and mixing with the bulk peridotitic assemblages (e.g., Kelemen, 1995). However, most arcs are too mafic in composition to build continental crust by simple accretion (cf. Anderson, 1982; Nye and Reid, 1986; Pearcy et al., 1990). Moreover, Taylor and McLennan (1985) pointed out several problems with a simplistic application of the andesitic model, such as the failure of this model to explain the abundances of Mg, Ni, and Cr and the Th/U ratio in upper crustal rocks. Rudnick (1995) proposed that the lower Sr/Nd and La/Nb ratios in continental crust compared to arc magmas are compatible with the involvement of intraplate magmatism in continental crust production. The andesitic magmatism and in a broader sense the intermediate 'granodioritic' bulk composition of the upper crust can be considered as a product of the differentiation processes that are involved in mantle–continental crust transformation. Taylor and McLennan (1985) suggested that only ~20–25% of the crust reflects the currently operating 'andesitic growth mode,' whereas the dominant mechanism that produced the Archean crust was the derivation of the bimodal basic–felsic magma suites from mantle sources (e.g., the formation of Archean tonalite–trondhjemite–granodiorite (TTG) magmas). It is argued later in the text that the production of thick oceanic crust and lithosphere by mantle plume activity and their accretion to the continents were an essential part of continental crust production throughout the past 2.7–2.9 Ga of the Earth history.

9.07.2.2.2 Plumes and arcs

The contribution of juvenile material from 'plume' or 'arc' sources to the continents can be assessed by using trace element ratios of Ce/Pb and Nb/Th that are distinctly different in arcs and plume-related mantle domains such as ocean island basalt (OIB) and oceanic plateaus (Hofmann et al., 1986; Kerr, 2013; Stein and Hofmann, 1994). Metatholeiites and greenstone sequences from major ancient orogens (e.g., the Superior, Birimian, and ANS) and plateau basalts such as the Ontong Java tholeiites display flat (chondrite-like) REE patterns (**Figure 2**) and where data exist show 'plume'-type Nb/Th ratios (**Figures 1** and **3**). It appears that these juvenile crustal units are not well represented by the sediment samplers. The upper crustal lithology and composition are largely dictated by the subduction and postaccretionary processes such as crustal melting and granite production, lithospheric delamination, and asthenospheric rising. These processes involved the preferential recycling of major elements (Mg and Ca) to the mantle at subduction zones and the removal of other major elements such as Si, Al, Na, and K to the continental crust (cf. Albarède, 1998). The subduction factory can be envisage as a big chromatographic column that fractionates the incompatible trace elements Nb, Pb, and Rb from REE and Th and U (Stein et al., 1997). Overall, these processes modified the

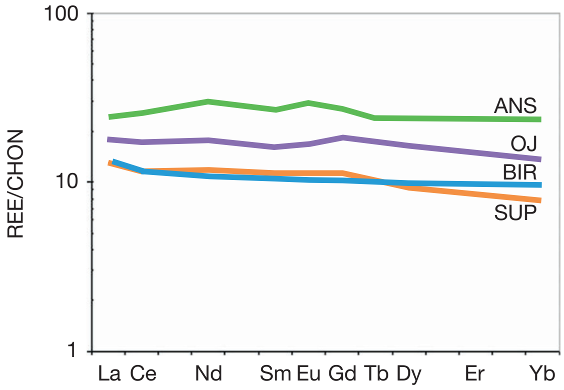

Figure 2 Chondrite normalized REE pattern in oceanic basalt from the Ontong Java Plateau (OJ) and several metatholeiites that were interpreted as plateau basalts from the Arabian–Nubian Shield (ANS), Superior province (SUP), and Birimian orogen (BIR). All these basalts were erupted rapidly and formed thick magmatic sequences, marking the early stage in a major orogenic cycle and production within oceanic basin. Data sources: Mahoney et al. (1993a,b), Abouchami et al. (1990), Reischmann et al. (1983), and Arth and Hanson (1975).

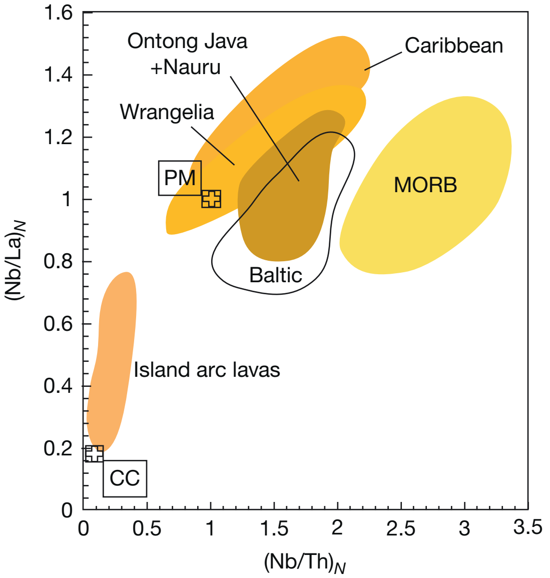

Figure 3 The location of basalts from several plateau basalt provinces on a $(Nb/La)_N$ versus $(Nb/Th)_N$ diagram (reproduced from Puchtel IS, Arndt NT, Hofmann AW, et al. (1998) Petrology of mafic lavas within the Onega plateau, central Karelia: Evidence for 2.0 Ga plume-related continental crustal growth in the Baltic Shield. *Contributions to Mineralogy and Petrology* 130: 134–53; Puchtel IS, Hofmann AW, Mezger K, Jochum KP, Shchipansky AA, and Samsonov AV (1998) Oceanic plateau model for continental crustal growth in the archaean, a case study from the Kostomuksha greenstone belt, NW Baltic Shield. *Earth and Planetary Science Letters* 155: 57–74). The Plateau basalts define fields that are distinctly different from island arc magmas and MORB and lie between primitive mantle (PM) compositions and Nb enriched that are similar to OIB and some rift-related alkali basalts (see **Figure 4**). Hofmann et al. (1986) attributed the high Nb/U and Nb/Th ratios to production of a 'residual' mantle after extraction of the low Nb/Th continental crust. Stein et al. (1997) proposed that Nb can be fractionated from REE, U, and Th due to production of amphibole 'front' in the mantle wedge, which they viewed as a giant chromatographic column. The Nb-rich zone is recycled back to the mantle or is frozen at the lower part of the lithospheric mantle after cessation of subduction. Could a similar process produce Nb/Th(REE) fractionation in the sources of the oceanic plateaus basalt? Does the convergence of several plateau basalts to primitive mantle ratios suggest that the plume head sample mantle with primitive Nb/Th–La ratios? In any event, Archean plateau magmas such as the Baltic Shield and the Phanerozoic magmas overlap to some extent in the diagram but are clearly not identical, suggesting some temporal changes in the Nb/Th ratios.

original geochemical signature of the juvenile mantle material and eventually shifted the upper continental crust to its average andesitic composition (Albarède, 1998; Rudnick, 1995; Stein and Goldstein, 1996).

9.07.2.2.3 *The Eu dilemma*

The application of REE to the study of the composition and evolution of the continental crust goes back to the works of Goldschmidt (1933), and the subject was thoroughly developed by Taylor and McLennan (1985). Most of the fine-grained sedimentary rocks that are used to estimate the bulk upper crust compositions typically show negative Eu anomaly (e.g., loess sample in **Figure 4**), pointing on significant intracrustal melting processes that require the existence of a residual reservoir with REE pattern showing positive Eu anomaly (Taylor and McLennan, 1995). However, such a reservoir remains largely unknown, because the xenoliths of mafic granulite that are considered as lower crustal samples and indeed show positive Eu anomalies are not interpreted as partial melting residues (cf. Rudnick., 1992; Rudnick and Taylor, 1987). It should be noted, however, that among the upper crustal rock suites, mainly the alkaline granites and related volcanics display distinctive negative Eu anomalies, while most of the calc-alkaline granites from juvenile crustal terrains display REE patterns with small or no Eu anomaly (e.g., the calc-alkaline batholiths of the Birimian and the ANS orogens; **Figure 4**). The alkaline granites and related rhyolitic volcanics typically characterize the closing stages of large orogenic cycles and their petrogenesis reflects fractionation of mafic magmas in shallow crustal levels (e.g., Mushkin et al., 2003, and see elaboration of this topic later in the text). These suites, however, are a rather small fraction of the total upper crust magmatic inventory that is probably irrelevant to the total crustal budget.

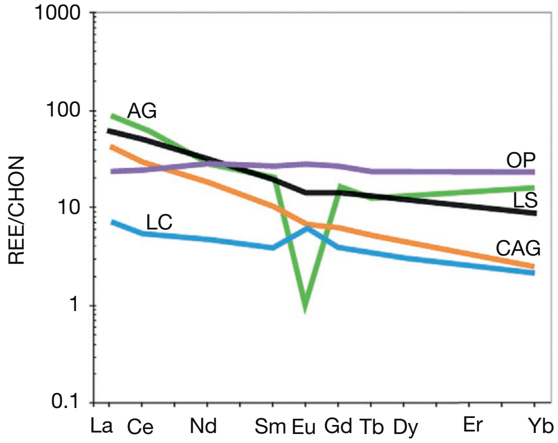

Figure 4 REE (chondrite normalized) pattern of magmas representing the main stages in the growth of a 'typical' orogen: tholeiitic magmas related to oceanic plateaus (OP), calc-alkaline granites (CAGs), and alkaline granites (AGs) as well as xenoliths of mafic granulites that are interpreted as lower crustal (LC) samples and late Pleistocene loess material that sample the exposed–eroded upper crust in the Sahara desert (LS). The pattern of the loess material is identical to bulk upper crust estimate (not shown). Note the appearance of a pronounced negative Eu anomaly related to plagioclase fractionation in the alkali granites and the almost smooth pattern of the CAGs. The production of the alkaline granites in the ANS was attributed to significant fractionation of a mafic assemblage that could be recycled to the mantle (Mushkin et al., 2003). The CAGs could be the product of midcrust (amphibolite-type) melting, which would produce residual lithology. The topic of production of vast calc-alkaline granitic batholiths is (surprisingly) not well understood. The production of granites requires water ('no water, no granites'), but the source of heat for the melting and the fate of the residual crust are not well known and the whole subject requires more studies.

9.07.2.2.4 *Crustal foundering*

The search after 'residual reservoir' is associated with models of crustal foundering. This topic was discussed by Plank (2005) in light of the high Th/La ratio in the continental crust (e.g.,

Figure 1). She argued that the high Th/La ratio is unlikely to reflect fractionation processes within the subduction environment and neither could it be related to processes of intraplate magmatism or to Archean magmatism (e.g., Condie (1993) showed that Archean crust was rather characterized by low Th/La). Alternatively, the Th/La continental crust ratio can be related to the production of lower crustal cumulates (with low Th/La ratios) and foundering of such cumulates and partial melting restites (both represent high-density heavy crust) into the mantle. This process would create over geologic time bulk continental crust with high Th/La ratio.

9.07.2.2.5 Archean TTG magmatic suites

Archean magmatic suites were characterized by the bimodal mafic–felsic compositions with scarce appearance of andesitic rocks (Taylor and McLennan, 1985). Thus, the simple 'andesitic model' cannot be applied to the production of the major inventory of continental crust, which is Archean in age. The felsic members of the TTG suites show fractionated HREE patterns with no Eu anomaly, indicating melting in the garnet stability zone and no evidence for intracrustal melting involving plagioclase fractionation. The felsic precursors of these sediments were interpreted to reflect partial melting products of basaltic or TTG sources. The TTG for themselves were interpreted as fractionation products of intermediate parental magmas that were derived from enriched and metasomatized mantle peridotite (Shirey and Hanson, 1984) or melting products of the subducting slab (Moyen and Martin, 2012). For example, high-Al TTG plutons that are characterized by high La/Yb ratios, like those exposed in the Superior province greenstone–granitoid terrains, were interpreted as melting of young, hot subducting oceanic slabs (Drummond et al., 1996). In this relation, the production of modern magnesian andesites, Nb-rich basalts, and adakites could be attributed to the subduction of hot oceanic slabs (e.g., Central Andes; Stern and Kilian, 1996). The processes involved with the TTG production required an environment with high heat flow (supporting the production of Mg-rich basalts and komatiites) and probably rapid stirring of the mantle. Taylor and McLennan (1985) envisaged the formation of the Archean continental nuclei in a process involving eruption piling and sinking of tholeiitic basalts followed by partial melting and formation of the felsic magmas. To a limited extent, this scenario resembles the descriptions of fast production of thick oceanic crust in relation to mantle plume activity and the subsequent processing of the juvenile-enriched crust by subduction and intraplate processes possible since late Archean time. The major tectonic–magmatic element in this description that apparently was not significant during the Archean is the 'subduction crustal factory' and the production of andesitic–calc-alkaline magmas.

9.07.2.2.6 Post-Archean granites

While the felsic members of the Archean bimodal suites show highly fractionated HREE, the Post-Archean granitoids typically show flat or slightly fractionated HREE patterns, indicating a shallower depth of source melting above the garnet stability zone. The depth of melting thus represents a fundamental difference between Archean and post-Archean crustal formations (Taylor and McLennan, 1985). It should be stressed that TTG magmas are petrogenetically different from the post-Archean granitoids. For example, if subducting plate melts in the eclogite stability zone, there is a possibility to produce TTG magmas and thus granitic rocks without water. The post-Archean granitoids are melting and differentiation products of water-bearing mafic sources at shallower depth of the crust. This melting involves fractionation of amphibole instead of clinopyroxene and orthopyroxene. Since the amphibole is low in SiO_2, the residual melt is more silicic, driving the differentiation from basalt melt (the 'normal' melt produced in subduction zones) to silicic melt all the way to granitic melt. The apex of this discussion is the requirement of water-carrying subduction processes in the formation of post-Archean granitic magmas.

Campbell and Taylor (1983) emphasized the 'essential role of water in the formation of granites' and, in turn, continents and introduced to the literature the important concept of 'no water, no granites; no oceans, no continents.' They argued that the Earth, which is the only inner planet with abundant water, is the only planet with granite and continents, whereas the Moon and the other inner planets have little or no water and no granites or continents. This concept could be extended to 'no water, no plate tectonics, no continents,' since with no water, plate tectonics is unlikely to work. Thus, there is a fundamental linkage between the formation of granitic (granodioritic) continental crust and plate tectonic mechanism.

9.07.2.3 The Lithospheric Mantle and Continental Stability

Beneath the Moho and the continental crust lies the lithospheric mantle whose thickness can reach 300–400 km beneath old continents and is relatively thin (up to 100–120 km) beneath young continents (e.g., beneath the Canadian and ANS, respectively). Subcontinental lithospheric xenoliths show large variations and heterogeneities in the trace element abundances that over time can 'incubate' large variations in the radiogenic isotope systems such as Pb, Nd, and Sr (cf. Hawkesworth et al., 1983; McKenzie and O'Nions, 1983; Stein et al., 1997). The magmatic and thermal history of the lithospheric mantle is related to that of the above-lying continental crust. Based on Pb, Nd, and Sr isotopes in ophiolites, galenas, and basalts, Stein and Goldstein (1996) suggested that the lithospheric mantle beneath the Arabian continent was generated during the events of the late Proterozoic crustal formation. The lithospheric mantle can be regarded as a 'frozen' mantle wedge, which previously accommodated the production of calc-alkaline magmas and fractionation–transportation processes of trace elements on route to shallower levels of the crust (the subject is elaborated in the succeeding text). After cessation of subduction, the lithospheric mantle (which also contains water) could become a source for alkali magmas that rose to the shallower levels of the continental crust (e.g., alkali granites) or erupt at the surface (cf. Mushkin et al., 2003; Weinstein et al., 2006). Thus, the lithospheric mantle not only is a potential source of information on the 'subduction factory' processes but also can be regarded as an important source of magmas that constitute a part of the continental crust inventory. Yet the source of heat and conditions of lithospheric melting is not obvious. One possibility is that the asthenospheric mantle that rises into the rifting continent and the thinning lithosphere supplies the heat for the melting. The production of magmas caused eventually the depletion of the lithospheric mantle from incompatible trace elements and basaltic components and eventually led to its exhaustion.

9.07.3 Models of Crustal Formation and Continental Growth

9.07.3.1 General

Models that describe the mechanism of continental crustal growth and the evolution of continental masses can be divided into two major groups: (1) models of early crustal growth and subsequent recycling and (2) models of continuous or episodic crustal growth.

The most prominent researcher that pushed the 'early crustal growth/recycling' model was Armstrong. He proposed that soon after the early mantle–crust differentiation and formation of continental crust, the Earth reached a steady state with accretion and destruction of continental masses occurring in approximately equal rate with essentially constant volumes of ocean and crust through geologic time (Armstrong, 1981a, 1991). The key process in this model is the recycling of the continental masses back into the mantle. Armstrong based his model on the principles of the constancy of continental freeboard and the uniformity of thickness of stable continental crust with age. These two critical parameters imply negligible continental crustal growth since 2.9 Ga BP. Defending his model, Armstrong addressed part of the arguments that were put against the steady-state model, mainly those that relied on the behavior of the radiogenic isotopes (e.g., Nd, Sr, and Pb; Armstrong, 1981b).

Among the pioneering researchers that developed the ideas of 'continuous/episodic crustal growth' were Rubey (who advocated the underplating theory as well), Engel, Hurley, and Taylor. The prominent researcher of this school of thinking was Moorbath who pointed on the difficulty to subduct large amounts of continental crust due to its buoyancy and argued that the chronological evidence derived from continental crustal rocks suggests the creation of juvenile continental crust throughout the Earth history. Moorbath also developed the concept of continental accretion as a major building process of continental crust (Moorbath, 1975, 1978).

The steady-state recycling theory of crustal growth requires evidence for substantial sediment recycling. Sediments are clearly recycled in the subduction environment. Various geochemical tracers of arc magmas demonstrated sediment involvement in subduction: for example, the radiogenic isotope ratios of Nd, Pb, Sr, and Hf (cf. Patchett et al., 1984; White et al., 1985), ^{10}Be isotopes (cf. Tera et al., 1986) and trace element fluxes (Plank and Langmuir, 1998). Plank (2005) introduced the Th/La ratio as a tracer of sediment recycling in subduction zones. Th/La in the subducting sediments reflects the mixing between terrigenous material with high 'upper crustal' Th/La ratio (0.3–0.4) and metalliferous sediments and volcaniclastic sediments with low Th/La ratios (<0.1). White and Patchett (1984) argued that a significant but small (at least 1–2%) contribution of older continental material could be potentially recycled into new continents. Nevertheless, based on mass–age distribution and Nd isotope data of sediments, McLennan (1988) estimated the mass of sediment available for subduction to be $<1.6\times10^{15}$ g year^{-1} and argued that that is insufficient to support a steady-state crustal mass according to the Armstrong model (see also Taylor and McLennan, 1995).

Hofmann et al. (1986) suggested that the Nb/U ratio in mafic–ultramafic magmas can be used to deduce the history of continental crustal growth because Nb/U ratio changed from the primitive mantle ratio of ~30 to a higher ratio of ~47 in the 'residual' mantle due to extraction of crust with Nb/U of ~10. Some of the Archean komatiites (e.g., samples from Kambalda and Kostomuksha provinces) show high Nb/U ratios of ~47 (Puchtel et al., 1998a,b; Sylvester et al., 1997) that may support the Armstrong steady-state model. Yet other komatiites and early Proterozoic tholeiites show Nb/U ratios that are similar to the primitive value (**Figure 1**). Puchtel et al. (1998a,b) commented on this topic that "the Nb/U data alone cannot unequivocally resolve this important controversy."

Although the continents appear to have undergone episodic changes throughout all of geologic time, the available geochronology of crustal formation shows time periods when large areas of continental crust were formed at a fast rate, alternating with apparently more quiescent periods of low crustal formation rates (marked in **Figure 5**). It may be that these quiescent periods merely represent missing continental material because the crust was destroyed and recycled into the mantle (according to the Armstrong model) but actual evidence for this process is indirect at best.

9.07.3.2 Timing and Rates of Crustal Growth

9.07.3.2.1 General

Crustal formation ages were determined by direct dating of major crustal terrains (numerous works applying the Rb–Sr, Sm/Nd, and U–Pb dating methods) and by using the concept of Nd – crustal model ages that mark the time of major chemical fractionation and the Sm/Nd ratio change accompanying the extraction of melts from the mantle and their incorporation into the continental crust (e.g., DePaolo, 1981; DePaolo et al., 1991; McCulloch and Wasserburg, 1978; Nelson and DePaolo, 1985).

The Sm/Nd crustal formation ages suggest that 35–60% of the currently exposed crustal masses were produced in the Archean (while actual exposed Archean crust accounts only for 14%; Goodwin, 1991). **Figure 5** shows that the most dramatic shift in the generation of continental crust happened at the end of the Archean, 2.7–2.5 billion years ago. The late Archean early Proterozoic pulse of crustal growth is represented in all continents (Condie, 1993). Before 3 Ga, very little continental crust had been preserved. The oldest preserved terrestrial rocks are the 3.96 Ga Acasta gneiss in the Northwest Territories of Canada (Bowring et al., 1990), and detrital zircons from the Yilgarn block, Western Australia, were dated to a much older age of 4.4 Ga (Wilde et al., 2001). The evidence from Hf and O isotopes in zircons on the oldest continental crust is discussed in the succeeding text.

9.07.3.2.2 Ages of the major orogens

The available geochronology of crustal formation shows time periods when large areas of the continental crust were formed

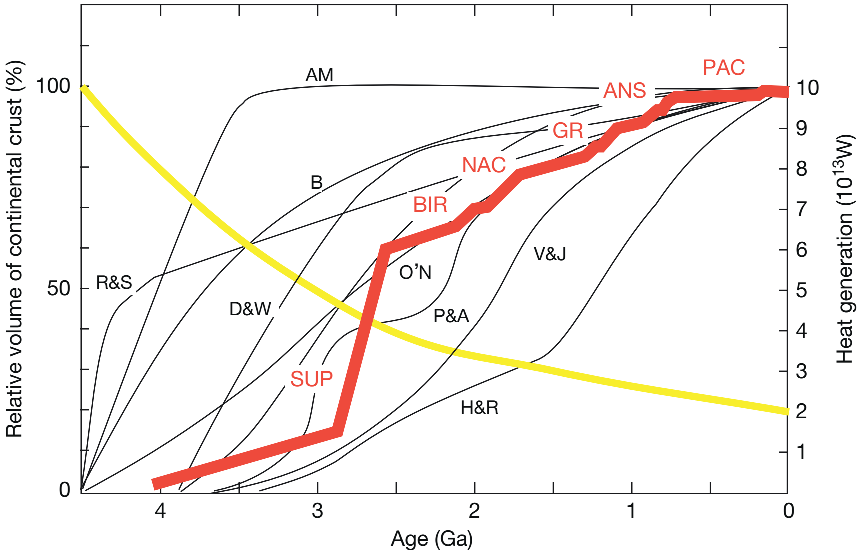

Figure 5 Models of continental crust (cumulative) growth and heat generation throughout the Earth history (reproduced from Reymer A and Schubert G (1984) Phanerozoic addition rates to the continental-crust and crustal growth. *Tectonics* 3: 63–77; Taylor SR and McLennan SM (1985) *The Continental Crust*: *Its Composition and its Evolution*. Oxford: Blackwell; Taylor SR and McLennan SM (1995) The geochemical evolution of the continental-crust. *Reviews of Geophysics* 33: 241–265; Condie, 1990; Patchett PJ (1996) Crustal growth – Scum of the Earth after all. *Nature* 382: 758–759). Crustal curves: R&S, Reymer and Schubert (1984); AM, Armstrong (1981a,b); B, Brown (1979); D&W, Dewey and Windley (1981); O'N, O'Nions et al. (1979); P&A, Patchett and Arndt (1986); V&J, Veizer and Jansen (1979); H&R, Hurley and Rand (1969). The thick red curve is after Taylor and McLennan (1995), with marks of the major orogenic episodes that were related by Stein and Hofmann (1994) to major upwelling events and plume head uprise in the mantle (the MOMO model illustrated in **Figure 9**). SUP, Superior province; BIR, Birimian orogeny; NAC, North Atlantic Continent; GR, Grenville orogeny; ANS,Arabian–Nubian Shield; PAC, Pacifica 'superplume.'

in a fast rate, alternating with apparently more quiescent periods of low crustal formation rates. The recent advances in U–Pb dating of zircons provided extensive sets of data that indicate the times of rapid growth of continental crust. For example, Condie and Aster (2010) and Condie et al. (2011) compiled numerous U–Pb ages of detrital zircons from all continents and whole rock granites and showed clustering of the ages at prominent peaks at 2.7, 2.5, 2.1, 1.9, 1.1, and 0.6 Ga. According to the Moorbath episodic growth model, these age peaks describe the timing of the major crustal formation events that are termed here as 'the major orogens' (**Figure 5**). Armstrong would interpret the quiescent periods between the intervals of the 'major orogens' as representing missing continental material because the crust has been destroyed and recycled into the mantle. Another view that emerged in the last decade relates the age peaks to the times of collision events of the continents and enhanced preservation of continental crust during the assembly of major continents (e.g., Hawkesworth and Kemp, 2006; Hawkesworth et al., 2009, 2010; Kemp et al., 2006). Yet, the detailed histories of the major orogenic cycles show that juvenile crust addition to the crust from the mantle occurs in the early stage of the cycle during the production of oceanic plateaus (which can accrete to the older continents) or during the time interval (e.g., >200 Ma) of subduction-related calc-alkaline magmatism. These processes are illustrated later in the text by the history of the late Proterozoic ANS, which is possibly the best-exposed and preserved juvenile crustal terrain on Earth and is described in some details later in the text. Moreover, it was argued by Stein and Goldstein (1996) that all major orogenic cycles such as the Superior province, the Birimian orogen, and the ANS evolved through similar histories that begin with oceanic plume-related magmatism and continued with the development of subduction margins and related calc-alkaline magmatism followed by anatexis of the crust and production of calc-alkaline and alkaline granites. Most of the zircon ages of the ANS orogeny mark the time of granitoid production by anatexis of the previously formed juvenile crust (calc-alkaline granites) or lithospheric mantle (alkaline granites).

9.07.3.3 The Reymer and Schubert Dilemma

Reymer and Schubert (1984, 1986) evaluated the rate of growth of major continental crustal segments (e.g., the Superior province in North America and ANS) and showed that they significantly exceed the rate of continental addition that prevailed along the subduction margins during the Phanerozoic time ($\sim$1 km^3 year^{-1}). The Phanerozoic rate was based on estimates of crustal additions along Mesozoic–Cenozoic arcs, hot spots, and some other additional sources (e.g., underplating). They calculated the total addition rate (mainly along the arcs) of 1.65 and total subtraction rate 0.59 km^3 year^{-1}, yielding a net growth rate of 1.06 km^3 year^{-1}. In addition, Reymer and Schubert calculated a growth rate by an independent model based on the constancy of freeboard relative to the mantle with declining radiogenic heat production (Schubert and Reymer, 1985).

The term freeboard was derived from civil engineering, describing the additional height above a normal operating water level and the top of the water-holding structure. The geologic–geophysical use of this concept encompasses the complicated relation between continental crustal thickness, volume, mantle temperature, and the Earth's heat budget. Wise (1974) tied the freeboard concept to crustal growth rates, by suggesting that approximately constant continental crustal volumes and areas pertained since the Archean–Proterozoic boundary, thus maintaining approximately the same elevation or freeboard of the continents above mean sea level. The freeboard calculation of Reymer and Schubert yielded a Proterozoic–Phanerozoic growth rate of 0.9 $\mathrm{km}^3\ \mathrm{year}^{-1}$, very similar to the calculated value in the preceding text. The Phanerozoic growth rate is three times less than the average Archean growth rate. Assuming formation between 900 and 600 Ma during the Pan-African orogeny, Reymer and Schubert showed that if the ANS was generated by convergent margin magmatism, it would require an addition rate of 310 $\mathrm{km}^3\ \mathrm{km}^{-1}\ \mathrm{Ma}^{-1}$ of convergence, compared with a global total of ~40 $\mathrm{km}^3\ \mathrm{km}^{-1}\ \mathrm{Ma}^{-1}$ (**Figure 6**). At the very least, the results of Reymer and Schubert indicate that the local crustal formation rates of the major continental shields have as high as or higher than the present-day rate averaged over the entire globe. As a consequence of their analysis, Reymer and Schubert proposed that juvenile additions to continental crust require additional mechanism besides the arc magmatism and this mechanism could involve activity of hot spots or mantle plumes. The geodynamic conditions during these intervals of juvenile crust creation may resemble to some extent the Archean conditions.

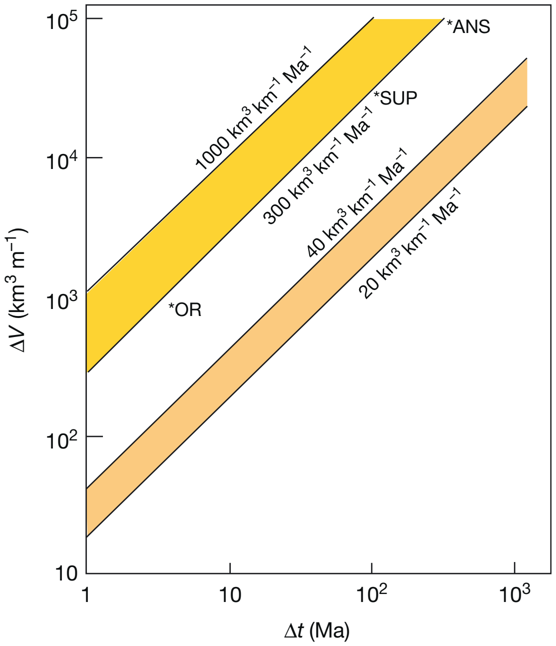

Figure 6 Arc crust (volume) addition curves (reproduced from Reymer A and Schubert G (1984) Phanerozoic addition rates to the continental-crust and crustal growth. *Tectonics* 3: 63–77) showing the large difference between Phanerozoic arc activity (20–40 $\mathrm{km}^3\ \mathrm{km}^{-1}\ \mathrm{Ma}^{-1}$) and the growth of some major orogens (e.g., SUP (Superior province), ANS (Arabian–Nubian Shield) ~300 $\mathrm{km}^3\mathrm{km}^{-1}\ \mathrm{Ma}^{-1}$ OR (Oregon Coastal Range)). The figures demonstrate the 'Reymer and Schubert dilemma' that points on the necessity to invoke additional sources and mechanism to support the production of continental crust during the episodes of major orogen production.

Galer (1991) performed another evaluation of the interrelationships between continental freeboard, tectonics, and mantle temperature. He concluded that before ~3.8 Ga, the potential temperature exceeded 1600 °C in the shallow mantle and therefore little or no hypsometric or tectonic distinction existed between 'continental' and 'oceanic' regimes. Thus, the pre-3.8 Ga period was subjected to tectonic and sedimentary processes that were distinctly different to those characterized by the Earth surface since mid-Archean time. An important component in his evaluation is the assumption that the early Archean oceanic crust was significantly thicker than typical present crust. The Reymer and Schubert (1984, 1986) assessment indicates that mantle plumes could play an important role in post-Archean crustal history of the Earth. Later in the text, we discuss the possible role of thick oceanic crust (e.g., the oceanic plateaus) in continental crustal growth. We can ask the question whether post-Archean episodes of crustal growth have some important components that 'mimic' to some extent the early Archean conditions.

9.07.3.4 Continental Growth and Heat Production

The heat production in the Earth, which is the main driving force for mantle convection and upwelling processes, has declined by a factor of 5 since the early Archean time (see yellow curve in **Figure 5**). This decrease reflects the decay of the long-living radiogenic isotopes. **Figure 5** indicates that continental crust accumulation does not reflect the Earth thermal history very well particularly in its earliest Archean history only since the late Archean a rough correspondence appears between the heat generation and crustal growth (Patchett, 1996). The heat engine of the mantle should have supported extensive mantle movements such as plume head upwelling in the Archean. Yet the low cumulative crustal growth in the Archean may indicate that the system was as efficient at destroying continental crust as making it (Taylor and McLennan, 1995).

The intensive pulses of continental crustal formation in the late Archean and early Proterozoic probably took place in a mantle that convected less vigorously than at earlier times. One possibility is that the tectonic regime became more similar to modern plate tectonics, where water played an essential role. By late Archean and early Proterozoic times, we might enter the regime of 'water, plate tectonics, continents.'

9.07.4 Oceanic Plateau, Accreted Terrains and Juvenile Crust Additions

9.07.4.1 General

With the advances made in geophysical techniques over the last 50 years, a different and new picture of the Earth began to emerge. For the first time, it was possible to image and sample the planet's crust and even layers deeper down. During the 1970s, it started to become clear that the ocean's floor is not homogenous, but contains areas of significantly thicker crust than the norm. The discovery of one such area, the Ontong Java Plateau with a crustal thickness of over 30 km, gave rise to the term 'oceanic plateau' (Kroenke, 1974). Today, about 100 such anomalous regions ranging in size from 1000 km to a few kilometers have been documented (**Figure 7**).

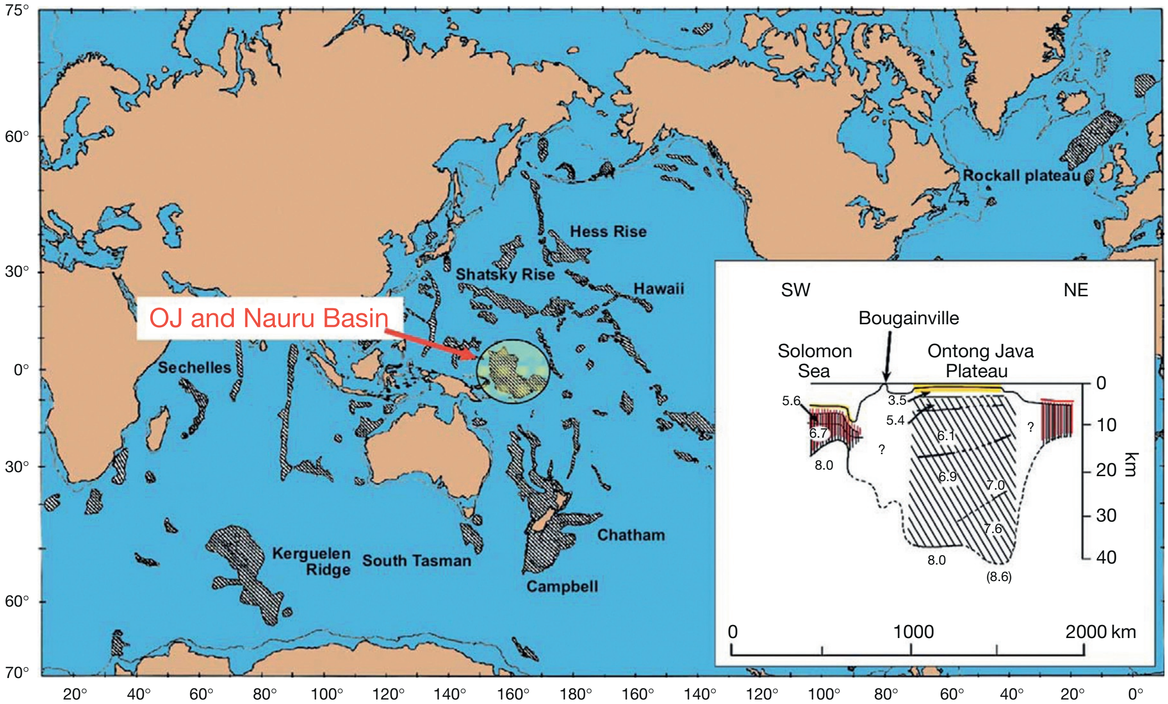

Figure 7 Distribution of oceanic plateaus and location of the Ontong Java Plateau and Nauru Basin in the Pacific. The Mesozoic Pacific was the locus of enhanced magmatism that was related to plume activity ('The latest pulse of Earth,' Larson, 1991). It also appears that shortly after the production of the thick oceanic plateaus, subduction zones were developed on their margins. The Nauru Basin comprised oceanic crust that erupted in ocean spreading environment but show geochemical similarities to the adjacent Ontong Java Plateau. Thus, it appears that both regions derived their magmas from similar enriched sources. This configuration supports the existence of an enriched upper mantle beneath the Pacific. Stein and Hofmann (1994) argued that the Nd–Sr isotopic composition of this mantle is similar to the PREMA isotopic composition (e.g., ϵNd $\sim$+6 and ^{87}Sr/^{86}Sr $\sim$0.7035 as defined by Wörner et al. (1986)) for various volcanic rocks around the world. It appears that the Pacific–PREMA composition characterized the entire upper mantle during the time of the production of the Ontong Java Plateau and Nauru Basin basalts and thus could mark the overturn or plume uprising events according to the MOMO model. Anderson (1994) proposed an alternative interpretation to the production of the Mesozoic Pacific plateau that requires no plume activity. He suggested that the upper mantle of the Mesozoic Pacific and the Indian Ocean is hot because this region has not been cooled by subduction for more than 200 Ma. Anderson argued that the timing of formation and location of the plateaus are related to the organization of the tectonic plates. This would require that the PREMA-type enriched isotopic compositions characterized the upper mantle rather than MORB, but magmatism in evolved rifting environments (e.g., Ross Sea–Antarctica and Red Sea–Arabia) clearly shows the transition from enriched isotopic composition to typical depleted MORB (e.g., Rocholl et al., 1995; Stein and Hofmann, 1992, and see **Figure 13** and 'Red Sea model' in **Figure 14**). (b) Seismic velocities across the Ontong Java Plateau. Surprisingly, the velocities suggest 'continental crust' composition and structure. This observation illustrates a kind of 'paradox' since it is expected that Ontong Java Plateau will show seismic structure of a thick oceanic crust. Does it mean that 'crustal formation' processes operate in the mid-oceanic environment? We regard the 'Ontong Java paradox' as a major open question that should be addressed by future studies.

The formation of these plateaus is still not clearly understood. They were considered to represent remnants of extinct arcs, abandoned spreading ridges, detached and submerged continental fragments, anomalous volcanic piles, mantle plume head traces, and uplifted oceanic crust. However, both isotope dating and isotope modeling support the theory that they formed rapidly, often in $<$2–3 My (Richards et al., 1989), with the majority forming at or near mid-ocean ridges (Kerr, 2013). These areas are conductive to large decompression melting (Eldholm and Coffin, 2000), providing a source of magma needed to form these features.

At least from a geophysical point of view, values of crustal seismic velocities, V_{p}, in the upper 5–15 km (where V_{p} ranges from 6.0 to 6.3 km s^{-1}; insert **Figure 7**), together with the anomalous thickness, relief, and gravity data, would indicate a continental structure for some of these plateaus (Ben-Avraham et al., 1981; Carlson et al., 1980; Nur and Ben-Avraham, 1977, 1978). Other plateaus are from clear oceanic origin, probably the result of continuous extrusion of basalts, probably from an active hotspot or mantle plume head.

Nur and Ben-Avraham (1977) and Ben-Avraham et al. (1981) suggested that the plateaus with the 'crustal seismic velocities' (e.g., Ontong Java Plateau) represent continental fragments rifted away from a parent continent that they named Pacifica. Stein and Hofmann (1994) and Abbott and Mooney (1995) on the other hand suggested that the plateaus were first extracted from the mantle within the oceanic basins above mantle plumes and were later accreted to the continents. In this context, it is interesting to note the coappearance of the basaltic sequences of the Ontong Java Plateau and those of the adjacent Nauru Basin in the Pacific Ocean (cf. Mahoney et al., 1993a,b). The tectonic setting of the Nauru Basin is clearly of a mid-oceanic spreading center type, with the typical appearance of magnetic anomalies and eruption of tholeiitic basalts.

The important point is that the Ontong Java Plateau and Nauru Basin basalts display similar geochemical characteristics such as Nd and Sr isotope ratios that are enriched relatively to the depleted MORB-type mantle (e.g., the basalts from the East Pacific Rise). Thus, it appears that the basalts erupted in the Nauru Basin and the Ontong Java Plateau represent a similar uppermost mantle that is enriched relative to the depleted (MORB-type) asthenospheric mantle. This enriched asthenosphere could be related to a large plume head (or a mantle upwelling) event that brought enriched material to the shallow mantle.

Richardson et al. (2000) produced a three-dimensional tomographic model of the seismic structure beneath the Ontong Java Plateau that indicated the existence of a low-velocity mantle 'root' reaching the depth of ~300 km. This was interpreted as a remnant of the Cretaceous Ontong Java plume that was attached to the plateau. Ishikawa et al. (2004) addressed the question of this seismically anomalous low-velocity root beneath the Ontong Java Plateau and its lithospheric mantle composition and structure by studying suite mantle xenoliths (peridotites and pyroxenites) from Malaita, Solomon Islands. The shallower mantle (Moho to 95 km) is composed of variably metasomatized peridotite with subordinate pyroxenite derived from metacumulates, while the deeper mantle (95–120 km) is represented by pyroxenite and variably depleted peridotites. The shallower and deeper zones are separated by a garnet-poor zone (90–100 km), which is dominated by refractory spinel harzburgites. Ishikawa et al. attributed this depth-related variation to different degree of melting for a basalt–peridotite hybrid source at different level of arrival depth within a single adiabatically ascending mantle plume: the lack of pyroxenites at shallower depths was related to extraction of hybrid melt from completely molten basalt through the partially molten ambient peridotite, which caused the voluminous eruption of the Ontong Java Plateau basalts. The authors concluded that the lithosphere forms a genetically unrelated two-layered structure, comprising shallower oceanic lithosphere and deeper impinged plume material, which involved a recycled basaltic component, now present as a pyroxenitic heterogeneity. The possible relevancy of this model to the shallower seismic structure of the Ontong Java Plateau (**Figure 7**) could be that evolved magmas were produced within the shallower layers.

Regardless of the mechanisms responsible for the formation of oceanic plateaus, they are assumed by many researchers to have an important role in the formation of new continental crust. Because they are part of moving plates and are embedded in them, they are destined to arrive at subducting plate boundaries and to accumulate, at least in some cases, onto the continental margin as accreted allochthonous terrains.

The potential of oceanic crust to be accreted to the continents rather than being subducted depends on its magmatic and thermal history and is reflected in its buoyancy. During 'normal seafloor spreading operation,' the oceanic lithosphere begins its history as a buoyant hot plate that cools with time and becomes susceptible for subduction. The buoyancy of the oceanic lithosphere depends on its age and density distribution (Oxburgh and Parmantier, 1977). The density distribution reflects the composition and the thickness of the crustal and mantle layers of the lithosphere, which in turn are controlled by the mantle temperature at place of crustal formation. Hotter mantle will produce thicker oceanic crust with more depleted lithospheric mantle, which can become less dense than more fertile mantle and, thus, more buoyant (Langmuir et al., 1992; McKenzie and Bickle, 1988; Oxburgh and Parmantier, 1977). This is probably the case in the production of oceanic plateaus by rising plume heads. The plumes are ~200–300 °C hotter than ambient mantle and can produce 15–40 km thick oceanic plateaus (compared with ~7 km thickness of normal oceanic crust). Therefore, some oceanic plateaus are too buoyant to subduct, and they can either be obducted into the continent (e.g., Caribbean and Wrangelia; Kerr et al., 1997; Lassiter et al., 1995) or, when arriving to the subducting margins, start subduction in the opposite direction (e.g., Ontong Java Plateau; Neal et al., 1997). The Archean mantle whose temperature was a few hundred degrees higher than the post-Archean mantle could produce thicker oceanic crust of 20–25 km (Sleep and Windley, 1982) and the plume-related plateaus could reach an average thickness of ~30 km (e.g., Puchtel et al., 1997). Some of these thick oceanic plateaus might be too warm and too buoyant when they reach the subduction margins and remain susceptible to subduction. Cloos (1993) and Abbott and Mooney (1995) argued that oceanic plates with crust thickness over ~25 km are unsubductable regardless of their age.

Nevertheless, several oceanic plateaus are currently being consumed, either by collision or by subduction. Among these are the Nazca and Juan Fernández Ridges off South America and the Louisville and Marcus–Necker Rises in the western Pacific (Cross and Pilger, 1978; Nur and Ben-Avraham, 1981; Pilger, 1978). These plateaus, which are presently being subducted, can clearly be associated with gaps in seismicity of the downthrown slab (e.g., Nur and Ben-Avraham, 1982). However, even more pronounced than these gaps are gaps in volcanism, associated with these plateaus. Close spatial association was found between the zones of collision or subduction of plateaus and gaps in volcanism in the Pacific (McGeary et al., 1985). Thus, these currently active areas of continental accretion are clearly identifiable.

The interaction of oceanic plateaus and other allochthonous terrains (e.g., island arcs, submarine ridges, and continental fragments) with convergent margins was recently evaluated by numerical models and experiments. For example, Mason et al. (2010) demonstrated that oceanic plateaus interacting with the trench of a subduction zone may alter trench behavior significantly. The plateau pins the trench, irrespective of slab and plateau rheology. Tetreault and Buiter (2012), using geodynamic numerical experiments, demonstrated how crustal properties of the allochthonous terrains impact the amount of the crust that is accreted or subducted, the type of accretionary process, and the style of deformation on the overriding plate.

9.07.4.2 Accretion of Allochthonous Terrains at the Pacific Margins

Large portions of the Pacific margins, especially the northeast margin, are made of accreted or allochthonous terrains (**Figure 8(a)**). The best understood accreted terrains are those in the northern cordillera of western North America, particularly in southern Alaska and British Columbia (Coney et al.,

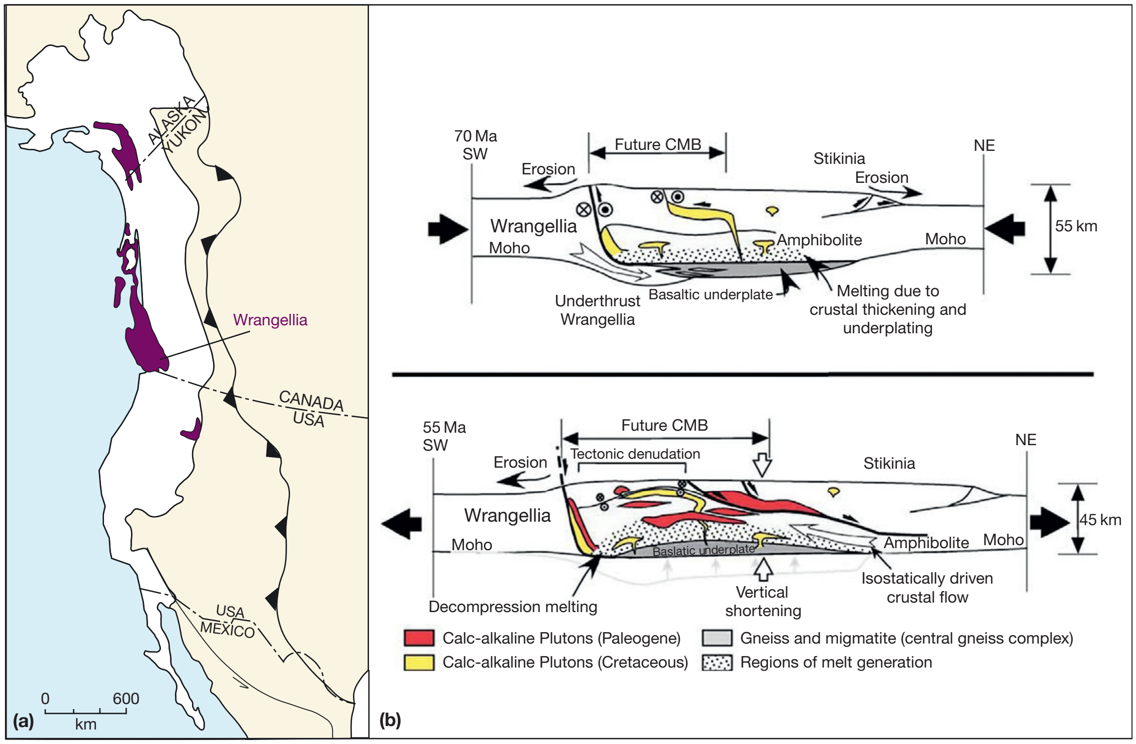

Figure 8 (a) Accretion plateaus along the western margins of North America and Alaska. The location of the Wrangellia oceanic plateau is marked in brown (reproduced from Ben-Avraham Z, Nur A, Jones D, and Cox A (1981) Continental accretion and orogeny: From oceanic plateaus to allochthonous terrains. *Science* 213: 47–54). (b) Model of plateau accretion and transformation of the oceanic crust to new continental crust and lithosphere (reproduced from Hollister and Andronicos, 2006). The figure shows processes of accretion, shortening and melting. Note the stratigraphic organization of Cretaceous and the Paleogene CAG and location of zones of melting due to crustal thickening and basaltic underplating. Amphibole appears above the Moho and its production could control Nb/Th(REE) fractionation (Stein et al., 1997).

1980; Monger, 1993). Paleomagnetic evidence indicates that many of the North Pacific accreted terrains in Alaska and northeast Asia migrated several thousand kilometers over periods of tens of millions of years prior to their accretion to the margins. The accreted terrains comprising the Canadian–Alaskan Cordillera are predominantly juvenile in composition (e.g., Patchett and Samson (2003) estimated that ~50% of the mass of the Canadian segment of the cordillera was juvenile crustal material). This evaluation is based on the initial ^{87}Sr/^{86}Sr and ϵNdt values of lithologic assemblages from both outboard and inboard terrains (e.g., Alexander, Cache Creek, and Slide Mountain as well as arc assemblages like Quesnel; Armstrong, 1988; Armstrong and Ward, 1993; Samson et al., 1989; 1990, 1991; and other references listed by Patchett and Samson (2003) in their recent review on this topic).

The Cache Creek terrane (CCT) of the Canadian Cordillera has an interesting history. It consists of accreted seamounts that originated adjacent to the Tethys Ocean in the Permian (Johnston and Borel, 2007). The paleogeographic constraints provided by the CCT indicate that much of the Canadian Cordilleran accretionary orogen is exotic. The accreting crustal block, a composite ribbon continent, grew through repeated collisional events within Panthalassa prior to docking with the North American Plate. Johnston and Borel (2007) suggested that Middle to Upper Triassic accretion of the Tethyan Cache Creek seamounts to Stikinia–Quesnellia and Lower Jurassic collision of Stikinia–Quesnellia with the combined pericratonic belt–Cassiar platform occurred >10 000 and >4000 km west of autochthonous North America, respectively. Most of the Cordilleran orogen is, therefore, exotic with respect to North America. According to their analysis, the development of the Cordilleran accretionary orogen was not, therefore, the result of sequential terrain accretion along the continental margin but was instead a two-stage process and resulted in a significant growth of the North American continent. Stage one involved the 230–150 Ma accretionary amalgamation of a ribbon continent within central to western Panthalassa. Stage two, from 150 to 55 Ma, consisted of collision, margin-parallel translation, and final coalescence of the composite ribbon continent with North America. The evolution and development of the Canadian Cordillera imply that accretionary orogens may, therefore, involve an offshore amalgamation stage that may take place far removed from the autochthonous continent.

In a detailed analysis of northern Cordilleran terrains, Colpron et al. (2007) suggested that although Cordilleran terrains are defined on the basis of their distinct tectonostratigraphic records, they are not necessarily limited to fault-bounded crustal blocks. They show that adjacent terrains can locally share depositional and geodynamic ties and that the nature of terrain boundaries evolves through time. A primary result of their analysis is that the Intermontane terrains represent one interrelated set of arcs, marginal seas, and continental fragments that once formed a Paleozoic to early Mesozoic fringe to North America, the peri-Laurentian realm. By contrast, the Insular terrains, along with the Farewell and Arctic Alaska terrains, include crustal fragments that originated from separate sites within the Arctic realm in Paleozoic time.

Future allochthonous terrains may be found in the oceans, in the various plateaus, which are present on the ocean floor (Ben-Avraham et al., 1981). The plateaus are modern accreted terrains in migration, moving with the oceanic plates in which they are embedded and fated eventually to be accreted to continents adjacent to subduction zones. The present distribution of oceanic plateaus in the Pacific Ocean and the relative motion between the Pacific Plates and the Eurasian Plate suggest that the next large episode of continental growth will take place in the northwest Pacific margin, from China to Siberia. Similar situations may have occurred in the past in other parts of the world.

Thus, it may be possible to identify ancient accreted terrains in the geologic record, based on chemical and geologic evidence. The oldest preserved oceanic plateau sequences have been dated to 3.5 Ga in the Kaapvaal shield, South Africa (De Wit et al., 1987; Smith and Erlank, 1982), and the Pilbara Craton in Australia (Green et al., 2000). Greenstone belts of the Canadian Superior province, ranging in age from 3.0 to 2.7 Ga, also contain lava groups that have been interpreted to be remnants of accreted oceanic plateaus (see recent review by Kerr, 2013). The evidence for an oceanic plateau origin is based on the occurrence of pillow basalts and komatiites without terrestrial sedimentary intercalations or sheeted dyke swarms, possessing the characteristics of Cretaceous oceanic plateaus. Later in the text, we elaborate on the examples of crustal growth in the ANS and the Baltic Shield where evidence was found for the formation of oceanic plateau and accretion of juvenile terrains to the existing older continents.

9.07.4.3 The Transformation of Oceanic Plateau to Continental Crust

The accretion of oceanic plateaus with a clear oceanic affinity to continental margins is of fundamental importance in the mechanism of crustal growth. The crustal structure of these plateaus, which was originally composed of basalts, is modified with time and a typical structure of upper continental crust is developed. The most dramatic example of this process can be seen in British Columbia, northwestern Canada. Here, many accreted (or ‘exotic’) terrains were added to the continent during lithospheric plate convergence from the Archean to the present. The tectonic evolution of northwestern Canada involved a series of accretionary events, alternating with periods of continental extension. Thus, it is tempting to suggest that the continent has ‘grown’ westward by the surface area of the accreted terrains (Cook and Erdmer, 2005). The large-scale geophysical and geologic transect - “The Slave-Northern Cordillera Lithospheric Evolution” was carried out in northwestern Canada and showed quite clearly that several of the large accreted terrains, which have traveled long distances embedded within oceanic plates before colliding with the continent, have now a continental crustal structure (Cook and Erdmer, 2005). The Wrangelia and Stikinia terrains, which were accreted during the Phanerozoic, and Hottah terrain, which was accreted during the Proterozoic, have continental crustal structure with an upper crustal layer having granitic V_{p} velocities (Clowes et al., 2005).

Hollister and Andronicos (2006) proposed that crustal growth in the Coast Mountains, along the leading edge of the Canadian Cordillera, was the result of processes associated with horizontal flow of material during transpression and subsequent transtension and the vertical accretion of mantle-derived melts. Their model has two distinct tectonic phases. The first occurred during a period of transpression when the continental crust was thickened to about 55 km, and mafic lower crust of the Wrangellia oceanic plateau was pushed under the thickened crust where basalt from the mantle heated it to temperatures hot enough for melting. The basalt and the melts mixed and mingled and rose into the arc along transpressional shear zones, forming calc-alkaline plutons. The second phase occurred as the arc collapsed when a change of relative plate motions resulted in transtension that accompanied intrusion of voluminous calc-alkaline plutons and the exhumation of the core of the Coast Mountains batholith (**Figure 8(b)**).

The calculation made by Schubert and Sandwell (1989) suggests that accretion of all oceanic plateaus to the continents on a timescale of 100 Ma would result in a high rate of continental growth of 3.7 $\mathrm{km}^3\ \mathrm{year}^{-1}$. This rate is much higher than continental growth rate based only on accretion of island arcs, which is 1.1 $\mathrm{km}^3\mathrm{year}^{-1}$ (Reymer and Schubert, 1986), thus providing an explanation to the previously mentioned crustal growth rate dilemma.

9.07.4.4 Mantle Overturn and Crustal Formation Episodes

In an attempt to link between various characteristics of mantle geochemistry and the dynamics and the apparent episodic mode of enhanced crustal growth (the Reymer and Schubert dilemma), Stein and Hofmann (1994) proposed that the geologic history of the mantle–crust system has alternated between two modes of mantle convection and dynamic evolution, one approximating a two-layer convective style when ‘normal mode’ of plate tectonics prevails (*Wilsonian tectonics*) and the other mode being characterized by significant exchange between the lower mantle and the upper mantle, when large plume heads form oceanic plateaus. The exchange periods apparently occurred over short time intervals – a few tens of million of years (as estimated from the chronology of magmatism that is involved in the production of the plume-related oceanic plateaus), while the Wilsonian periods extend over several hundreds of million of years (e.g., ~800 Ma in the case of the ANS; see later text). The idea is that during mantle overturn episodes (termed by Stein and Hofmann as *MOMO episodes*), a substantial amount of lower mantle material arrives to the Earth surface (mainly via plume activity), replenishes the upper mantle in trace elements, and forms new basaltic crust that eventually contributes juvenile material to the continental crust (via both subduction and accretion processes; **Figure 9**). Shortly after mantle upwelling and production of thick oceanic crust, new subduction zones are developed along the oceanic plateau margins as happened in the Mesozoic Pacific province. This mechanism views the formation of new subduction zones as a consequence of the production of thick oceanic crust and its cooling. Stein and Hofmann (1994) further proposed that

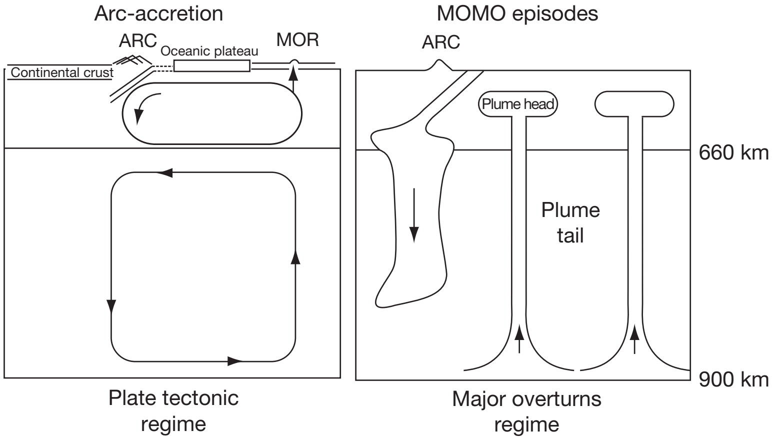

Figure 9 Mantle overturn and crust addition model (modified after the original MOMO model by Stein and Hofmann, 1994). The original MOMO model assumes that the mantle–crust system evolves through two modes of convection and dynamic evolution: one (MOMO overturn episodes) is characterized by significant exchange by the lower and upper mantle and crust and the other by two-layer convective style where typical plate tectonic Wilsonian cycle operates. The question of layered versus whole mantle convection has been continuously discussed in the literature and it is beyond the scope of this review. Here, we present a modified representation of the model where we stress the accretion of the oceanic plateau to the existing continent and development of subduction zones on the margins of the plateau (similar to the scenario shown by **Figure 8**). Most of the existing subduction zones in the world are associated with plateaus; a few subduction zones are not clearly associated with plateaus.

the mechanism responsible for the mantle overturns and rise of the plumes from the deep mantle is 'slab avalanches.' This mechanism describes the penetration of cold accumulated subducted material through the 660 km 'boundary' of the marginally stable two-layer convection configuration. It could also be that collapse of thick lithospheric roots that accumulated during the long processes of plate tectonics and subduction-related growth of continental crust (e.g., delamination or foundering models) could also trigger the collapse of the two-layer convection and rise of plumes from the deeper mantle.

The final product of the plume–thick oceanic crust-subduction system is a mass of continental crust that can be generated over a relatively short period of geologic time. The sequence of events involving the formation of anomalously thick, oceanic lithosphere, which is modified by subduction at its margin, explains the formation of both major continental segments during discrete episodes of time and their calc-alkaline affinities (a beautiful example for this evolution is described in the succeeding text for the growth of the late Proterozoic ANS).

In an alternative view of the Reymer and Schubert dilemma, Patchett and Chase (2002) and Patchett and Samson (2003) suggested that the evidence for enhanced crust production during discrete episodes can reflect the tectonics of accretion processes alone, arguing for the role of transform faulting, which serves to pile various terrains of juvenile crust into one restricted region (e.g., the Canadian–Alaskan Cordillera, where slices of juvenile accreted crustal material were piled up after northward along-margin transport associated with transform faulting; see **Figure 8**). The transport and accretion of juvenile mantle terrains are a central part of the plume-accretion model of crustal growth (**Figure 9**). Yet the additional important component in this model that is not required by the arc-accretion models alone is the evidence for the important role of oceanic plateau and enriched MORB crust as the nucleus of the juvenile continental crust and probably the locus of new subduction zones. Moreover, the crustal terrains that were formed during the episodes of 'major orogenic' production are not limited to geographically restricted region but rather are distributed globally. The best example is that of the late Proterozoic 'Pan-African' orogeny, when juvenile crustal terrains were produced in Arabia, Nubia (the ANS discussed later in the text) and North Africa, New Zealand, and Patagonia. All these geographic–crustal segments comprise the early Phanerozoic Gondwana. Considering a reconstruction of this old continent (**Figure 10**), it appears that continental segments within the Gondwana that can be identified as juvenile Pan-African crustal or lithospheric mantle terrains (see Stein, 2003, and caption of **Figure 10**) form a 'belt' along the possible margins of a mid or late Proterozoic continent. These segments are characterized by juvenile 'Pan-African' Nd, Sr, and Hf isotopic compositions that in turn are consistent with the plume ('MOMO')-type mantle (Stein and Hofmann, 1994, and see **Section 9.07.4.6**). In the following section, we discuss the isotope and chemical characteristics of the 'MOMO' mantle following the exciting recent ^{142}Nd data.

9.07.4.5 ^{142}Nd and Composition of the 'Juvenile Mantle'

The basaltic magmas that are the main samplers of the Earth mantle show no evidence for the existence of a 'primitive mantle' source. In this relation, it is interesting to return to the 'mantle array' that was first introduced by DePaolo and Wasserburg (D&W) (1976). D&W materialized the enormous potential in analyzing the ^{143}Nd/^{144}Nd and ^{147}Sm/^{144}Nd of various meteorites and determined these values for the chondritic meteorites, which were considered as samples of the 'primitive Earth' (the Chondritic Uniform Reservoir (CHUR) model) and then analyzed ^{143}Nd/^{144}Nd isotopic composition of oceanic and continental basalts and compared them to CHUR. Their achievement in the understanding of the

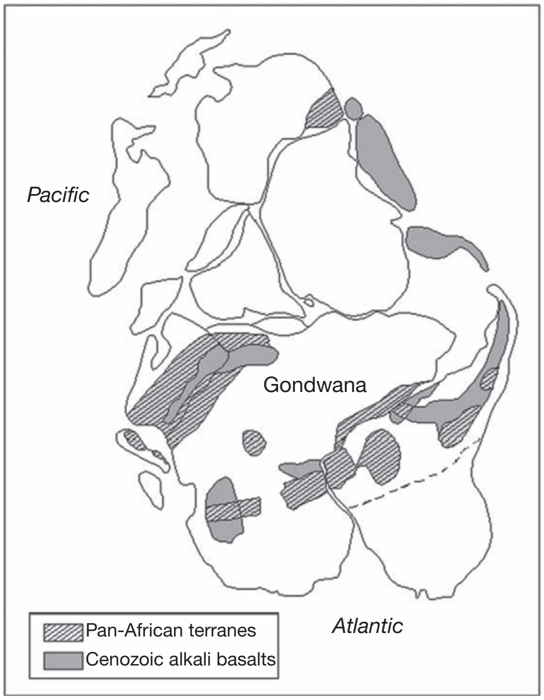

Figure 10 Distribution of regions that expose terrains of late Proterozoic Pan-African juvenile magmatic sequences and Cenozoic alkali basalts over a reconstructed map of Gondwana. The juvenile magmatic sequences are characterized by Nd and Sr isotopic compositions (e.g., $\epsilon\mathrm{Nd}=+5\pm1$ and $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}=0.7028\pm2$; Stein, 2003; Stein and Hofmann, 1994) or Phanerozoic volcanic fields of alkali basalts (the Gondwana basalts over Africa, Arabia, Antarctica, and South America; the Pb isotopic compositions of these basalts are marked in **Figure 11** that also shows the plume–lithosphere connection) that were derived from the juvenile Pan-African lithospheric mantle. The areas that are best documented are those of the ANS on both sides of the current Red Sea (closed in the reconstruction). The figure suggests that during the late Proterozoic Pan-African orogeny, juvenile terrains were accreted to an existing continental nucleus in a similar manner to the growth that was described for the North American continent. The distribution of the juvenile Pan-Africa terrains may mark the locus of the subduction zones that were developed at that time along the margins of the Pan-African oceanic plateaus.

evolution of the Earth mantle and crust emerged from the properties of the Sm and Nd that are both refractory and lithophile elements (as all REEs) and were probably not fractionated during processes such as accretion and core formation and appear in nearly constant proportions in different groups of chondrites (e.g., Jacobsen and Wasserburg, 1980; Patchett et al., 2004) and thus were not easily fractionated by 'nebular' processes. Thus, the long $^{147}\mathrm{Sm}$–$^{143}\mathrm{Nd}$ ($T1/2=106$ Ga) system comprise a powerful tool for tracing the long-term chemical evolution of the silicate Earth. The original 'mantle array' of D&W comprised several basalts representing the major tectonic–magmatic environments: mid-ocean ridge basalt (MORB), Hawaiian basalts that represent the hot spot or plume-related OIBs, and the Columbia River Basalt (BCR, which has been extensively used as international standard for Sr and Nd isotope analyses) that represents continental basaltic magmatism. The Nd isotopic composition of the MORB yielded $\epsilon\mathrm{Nd}=10$, while the BCR sample yielded $\epsilon\mathrm{Nd}=0$, which according to the CHUR model is consistent with bulk silicate Earth. Based on the 'mantle array,' D&W proposed the 'simple model' for the structure of the Earth mantle where the primitive lower mantle (sampled by the BCR plume) is overlain by the depleted (in incompatible trace elements) mantle (sampled by MORB), and the complementary trace element-enriched reservoir would be the continental crust. It is important to note that the change (relative to CHUR) in Sm/Nd of the mantle could reflect the extraction of continental crust over the Earth history or instead was caused by early global differentiation of the Earth mantle such as may have occurred during an early formed magma ocean (see succeeding text).

The simple D&W model was later challenged by the overwhelming sets of Nd–Sr–Hf–Pb isotope data that indicated on a more complex mantle composition with at least four end-members that define the extended mantle array (see Hofmann, 1988). It should be stressed that the isotopic variability exhibited by the basalts indicates the long-term preservation (billions of years) of chemical heterogeneities in the convecting mantle (see reviews of this topic in Albarède and Van der Hilst, 2002; Hofmann, 1988; van Keken et al., 2002).

Important clues on the early history of the mantle isotope heterogeneities come from several extinct isotopes. A critical isotope pair in this respect is the relatively short-lived $^{146}\mathrm{Sm}$ ($T1/2=103$ My) that decayed to $^{142}\mathrm{Nd}$ in the early history of the Earth. The importance of the analyses of $^{142}\mathrm{Nd}$ stems from its bearing on the $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}$ ratio that reflects the fractionation of the $^{147}\mathrm{Sm}/^{144}\mathrm{Nd}$ in the Earth reservoirs (relative to the CHUR chondritic ratio). Over the past two decades, several workers made outstanding efforts to determine accurately the very tiny deviation of $^{142}\mathrm{Nd}$ from CHUR.

Boyet and Carlson published a series of papers (e.g., Boyet and Carlson, 2005, 2006) showing a small, but significant, difference of ~20 ppm in the $^{142}\mathrm{Nd}/^{144}\mathrm{Nd}$ ratio between various types of meteorites and terrestrial samples. The deviation was identified in very old continental crust samples such as those from the Isua supracrustal belt (showing $^{142}\mathrm{Nd}/^{144}\mathrm{Nd}$ excesses of up to 17 ppm, e.g., Bizzarro et al., 2002). These results indicate that all terrestrial samples come from a mantle reservoir characterized by a superchondritic Sm/Nd ratio (e.g., **Figure 11**). The important implication of this result is that compared to chondritic meteorites (or the CHUR model), the elevated $^{142}\mathrm{Nd}/^{144}\mathrm{Nd}$ ratios of all terrestrial samples measured so far require that all these magmas were derived from a higher CHUR Sm/Nd ratio reservoir. This reservoir could reflect processes either within the solar nebula (namely, the excess in $^{142}\mathrm{Nd}$ is not the result of $^{146}\mathrm{Sm}$ decay) or in the mantle. The latter explanation implies that the silicate Earth has Sm/Nd ratio higher than chondrite due to an early differentiation (while $^{146}\mathrm{Sm}$ was still present), during the first few hundred million years of solar system history to higher and lower than CHUR Sm/Nd reservoirs.

The main samplers of juvenile mantle material are the oceanic plateaus that according to the MOMO model represent plume head material that rose from the deep mantle and are manifested by thick sequences of tholeiites that typically comprise the early phase in the evolutionary cycle of juvenile provinces of continental crust (see succeeding text). **Figure 11**

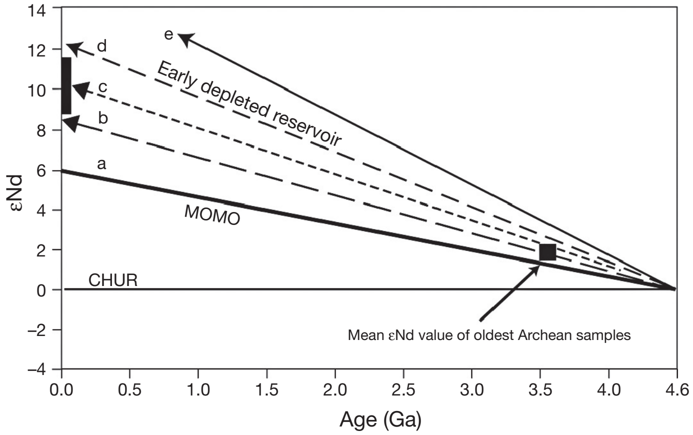

Figure 11 ϵNd evolution models of early depleted mantle. Line (a) comprises the 'MOMO–Nd evolution line' defined by the initial ϵNdt values of the major juvenile orogens (see Stein and Hofmann, 1994; **Figure 1**). The slope of the 'MOMO evolution line' corresponds to ^{147}Sm/^{144}Nd ~ 0.2. Lines (b–e) represent $^{\epsilon}$Nd evolution lines that were calculated by Boyet and Carlson (2005), reflecting the excess of 20 ppm for the ^{142}Nd/^{144}Nd ratio in the Earth mantle relative to chondrites. Each evolution line is defined by a specific slope dependent on the magnitude of the Sm/Nd fractionation and the age of the differentiation event: (b) $\Delta t = 5$ Ma and the ^{147}Sm/^{144}Nd slope = 0.209; (c) $\Delta t = 30$ Ma and the ^{147}Sm/^{144}Nd slope = 0.216; (d) $\Delta t = 30$ Ma and the ^{147}Sm/^{144}Nd slope = 0.216; and (e) $\Delta t = 100$ Ma and the ^{147}Sm/^{144}Nd slope = 0.222. Evolution lines (c) and (d) lead to the range of ϵNd values in MORBs. The MOMO evolution line could be slightly rotated towards CHUR by mixing with an enriched early basaltic reservoir (following the Galer and Goldstein (1991) model).

shows that the MOMO evolution line of the juvenile orogens is consistent with Sm/Nd ratio that is higher than CHUR but lower than MORB-type mantle. The Sm/Nd ratio of the juvenile orogen evolution line is consistent with the estimate of Boyet and Carlson for the 'depleted mantle reservoir' after the early differentiation event that caused the ^{142}Nd excess (e.g., MOMO line (a) and the Boyet and Carlson calculated line (b) in **Figure 11**). The important implication of this result is that the magmas forming the juvenile orogens were derived from a depleted mantle that preserved its chemical identity since the early history of the Earth. In the context of the MOMO model, the plumes and the major juvenile orogens sample the 'early depleted mantle' that is currently characterized by ϵNd = +6 and ^{147}Sm/^{144}Nd ~ 0.2. This mantle is represented by intraplate continental basalts that are erupted in all continents and was acronymed by Wörner et al. (1986) as the PREMA mantle reservoir or as the FOZO mantle reservoir (Hart et al., 1992). We prefer the acronym *MOMO* that provided also the geodynamics and the Earth history perspective of the term. As the MORB represents the depleted uppermost mantle and its tectonic environment, MOMO represents the connection to the mantle plumes and major orogens that were primarily evolved from the 'early depleted mantle.'

9.07.4.6 Hf in Zircons and Crust Recycling

The extensive works that were performed on zircons from granitoid terrains and detrital zircons (e.g., in Phanerozoic clastic (sandstones) sequences) provide rich data that are complementary to the information derived from Nd and Sr isotopes from the bulk magmatic rocks. Oxygen isotope ratios derived from the zircons are used to identify those that were crystallized in juvenile mantle magmas (e.g., 'mantle-type' δ^{18}O values of ~+6‰) or show significant recycled crust that contained surface sediments or was affected by seawater (e.g., δ^{18}O values higher than +7‰). Many of the initial ϵHf(t) detrital zircons and some of the granitoid zircon data lie below the 'primitive mantle' evolution line in **Figure 12** (detrital zircons that spread to low ϵHf(t) values (e.g., −10 to −30 during the past 2 Ga) are not plotted and are presented in several recent works, e.g., Iizuka et al., 2013), indicating contribution of recycled crustal material to the magmas. Yet a large number of the granitoid zircons and the detrital zircons converge to values that lie between the 'primitive mantle' and 'depleted MORB mantle' (**Figure 12**). They lie on an Hf evolution line defined by the 'juvenile orogens' similar in its concept to the 'MOMO–Nd evolution line' that was described for the initial Nd isotopes of the 'juvenile orogens.' The extensive set of oxygen and zircon isotope data from late Proterozoic ANS granitoids that are exposed in the Sinai Peninsula allows us to plot the field of the juvenile ANS on the 'MOMO–Hf evolution line.' The ANS–MOMO–Hf field is defined according to zircons with mantle-like δ^{18}O values. Similarly, Stein and Hofmann (1994) defined the MOMO–Nd evolution line of the juvenile orogens according to the ^{87}Sr/^{86}Sr and δ^{18}O values that were available for the magmas. We note that again similar to the 'MOMO–Nd evolution line,' the 'MOMO–Hf' evolution line is very close to the line described for subduction zones (see the 'arc mantle' in Dhuime et al., 2011). This reflects the composition of the arc volcanics that were derived from the MOMO mantle during the long interval of subduction-related magmatism that processed the MOMO – mantle to calc-alkaline magmas that comprise substantial parts of the upper continental crust.

9.07.5 The Production of Calc-Alkaline and Alkaline Granites and Related Rocks

9.07.5.1 General

The average composition of the upper continental crust is granodioritic (Taylor and McLennan, 1985), reflecting the

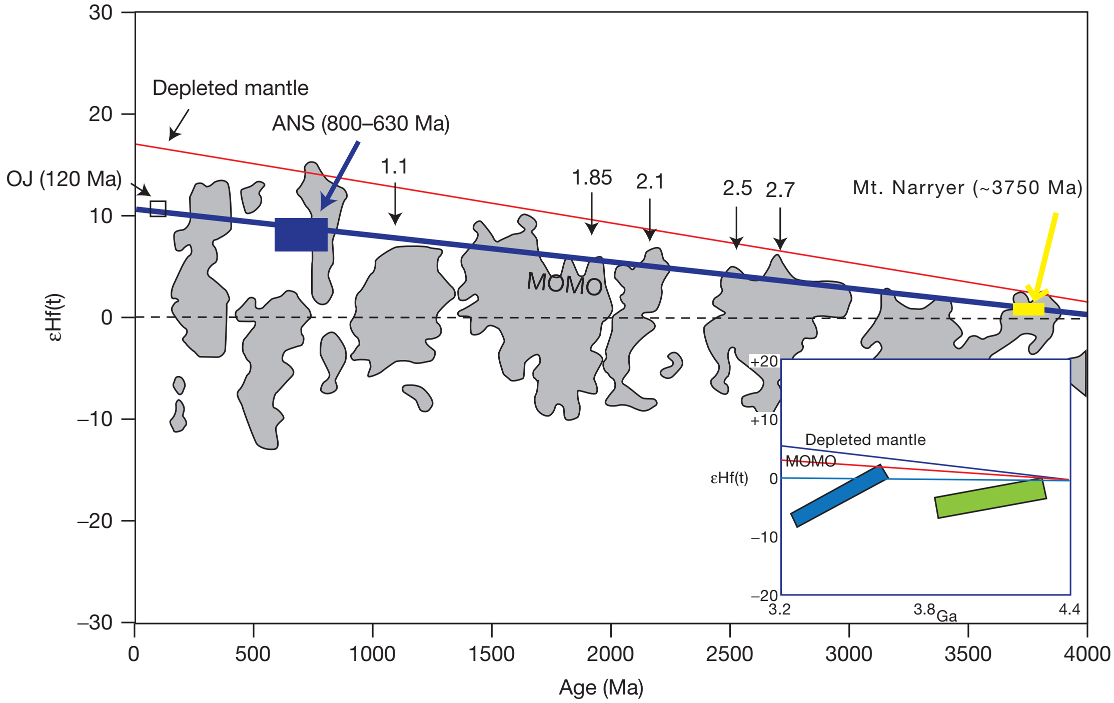

Figure 12 εHf isotope evolution diagram of primitive mantle (εHf = 0), depleted mantle, and major continental crustal segments (the 'major orogens'). The diagram shows Hf isotope data of zircons from granitoid terrains against their U–Pb crystallization ages (reproduced from Guitreau M, Blichert-Toft J, Martin H, Mojzsis SJ, and Albarede F (2012) Hafnium isotope evidence from Archean granitic rocks for deep-mantle origin of continental crust. *Earth and Planetary Science Letters*. 337/338:211–223; Arndt NT (2013) Formation and Evolution of the continental crust. In: Elliott T (ed.) *Geochemical perspectives*, vol. 2, No 3, and references there). The ages of the 'major orogens' are marked. The MOMO evolution line is defined by eNd(t) values of Ontong Java basalts (OJ) (data from Tejada et al., 2004), zircons from the juvenile ANS granitoids that are filtered by their mantle-type $\delta^{18}O$ values (data from Morag et al., 2011) and the Hadean Mount Narryer zircons (see text). Most of the Hf zircon data form fields that lie below the MOMO evolution line marking crustal recycling. The inset shows the εHf(t) values in early earth zircons (reproduced from Bell EH, Harrison TM, McCulloch MT, and Young ED (2011) Early Archean crustal evolution of the Jack Hills zircons. *Geochimica et Cosmochimica Acta* 75: 4816–4829). See text for further discussion of these data.

important role that calc-alkaline granitic magmas take in the construction of the continental crust besides the subduction-related basaltic–andesitic magmas and the tholeiitic oceanic plateau-type basalts. Yet the petrogenetic conditions and geodynamic relation of the calc-alkaline granites still comprise open issues, and surprisingly, a limited number of geochemical–petrological works were devoted to the understanding of the mechanism and geodynamic environment of production and emplacement of the granitic magmas (e.g., Borg and Clynne, 1998; Chappell et al., 1987; Green and Ringwood, 1968; Smithies et al., 2011; Wyllie, 1984; Wyllie et al., 1976). Unresolved issues include the composition and location of the sources of the calc-alkaline magmas, the sources of heat that are required for the melting, the mechanism of fractionation that forms the calc-alkaline series (e.g., from gabbro, diorite, tonalite, to granodiorite and granite), the mechanism of emplacement of vast amounts of granitic plutons, and their place in the chronology of events during the formation of juvenile segments of continental crust. This section discusses several topics in the broad field of petrogenesis of calc-alkaline (I-type) and alkaline (A-type) granites and related rocks. Here, we describe two recent works on the petrogenesis of calc-alkaline granites from the Elat massif (Weismann et al., 2013) and A-type granites (and other magmas) from the Amram massif (Mushkin et al., 2003). Both massifs are located at the northern uplifted edge of the ANS. The big advantage and beauty of exploring the calc-alkaline and alkaline massifs at Sinai Peninsula and Elat area lie in their unique 'desert clean and fresh' exposures and the variety of the rock types from mafic to felsic. The massifs were uplifted 'recently' during the Miocene to Pleistocene tectonic events that are associated with the breakup of the African plate and opening of the Red Sea and formation of the Suez Rift and Dead Sea Transform. The Elat massif comprises felsic calc-alkaline rocks, mafic xenoliths, and intermediate host rocks that were all emplaced during the calc-alkaline phase of the ANS history ~630–600 Ma (Weismann et al., 2013, and references on the chronology there). This association in space and time is supported by their systematic and continuous variation in major element concentrations and their similar initial Sr isotope ratios, suggesting a genetic link between all magma types. In the section later in the text, we discuss several models that were attributed to explain the petrogenesis of calc-alkaline magmas and apply the results from the Elat massif suite to infer the model of mafic crustal anatexis.

9.07.5.2 Models of Calc-Alkaline Granite Production

Three general processes can be considered for the production of this calc-alkaline association: (1) fractional crystallization of mantle-derived magma similar in composition to the mafic xenoliths towards the formation of the intermediate and felsic host rocks, with possible involvement of crustal assimilation; (2) mixing between mafic and felsic magmas; and (3) melting of crustal rocks by emplacement of mantle-derived basaltic magma in the presence of various amounts of water.

Fractional crystallization of a mantle-derived magma similar in composition to the mafic xenoliths requires high degrees of fractionation, that is, only small volumes of felsic rocks will form from a given volume of mafic magma in such a process. It is unlikely that such a mechanism produced such a large volume of felsic plutons that comprise most of the exposed surface of the northern segments of the ANS. In several cases, fractional crystallization accompanied by assimilation of crustal rocks (AFC, assimilation–fractional crystallization) is the suggested mechanism for the formation of I-type granites (DePaolo, 1981). This model implies that mafic magma, sourced from the mantle, is modified during its ascend and emplacement at crustal levels due to assimilation of crustal material during fractional crystallization, leading to the formation of felsic rocks. The heat required for assimilation of the crustal rocks is provided by the latent heat of crystallization of the magma.

9.07.5.3 The Petrogenesis of Calc-Alkaline Granites and Related Rocks from the Elat Massif

The calc-alkaline granites in the Elat area were indeed emplaced into metasedimentary rocks (e.g., the Elat schist), which could be regarded as the possible crustal component assimilating the primitive basaltic magma. Bielski (1982) reported initial $^{87}Sr/^{86}Sr$ ratio (ISr) of 0.7030 ± 6 for the Elat schist, suggesting that these rocks and the calc-alkaline granitic suite (ISr value of 0.7034; Weismann et al., 2013) were derived from young crustal rocks. Be'eri-Shlevin et al. (2010) performed a multi-isotope study of the calc-alkaline phase of the ANS in the Elat area and observed high $\delta^{18}O$ values for some of the Elat calc-alkaline granites, associated with initial ϵNd (T) lower than the 'juvenile values' (inferred as $\sim$+4; Stein and Goldstein, 1996) that were uncorrelated with variations in the major element chemical composition. Such a correlation would have been expected if AFC process had been a main mechanism associated with the formation of the calc-alkaline granites.

Basaltic mantle-derived melts ascending to crustal depths can induce partial melting of crustal rocks ('crustal anatexis') of felsic compositions, leaving behind a hydrous (amphibole-bearing) mafic residual rock (e.g., Bergantz, 1989; Droop et al., 2003; Huppert and Sparks, 1988; Sparks et al., 1977; Wyllie et al., 1976; Wyllie, 1977, 1984). The partial melting of the crust is enabled due to the heat and water supplied by the intruding basaltic melt. Various degrees of mixing of the mantle-derived mafic magma and the crustal felsic magma can lead to a wide range of magma compositions. Mafic xenoliths or xenocrysts surrounded by felsic magmas could be the products of such 'mingling.'

A common characteristic of calc-alkaline granitic plutons formed from magma mixing is the production of chemical zoning within the plutons (Zorpi et al., 1989). Since all mafic and felsic calc-alkaline rocks in the Elat massif lie on the same isochron converging to low ISr value of 0.7034, different sources (which evolved separately) for the mafic and felsic magmas are less likely. If mixing or mingling mechanism led to the formation of all calc-alkaline rocks in the area and mafic magmas intruded a felsic magmatic cell, both magmas must have been derived from the same source. Radiogenic isotope ratios (Nd–Sr–Pb) from the ANS core region were previously interpreted to show limited involvement of pre-Neoproterozoic crust in its formation (Be'eri-Shlevin et al., 2009, 2010; Stein, 2003; Stein and Goldstein, 1996).

Several studies advocated the 'restite unmixing model' to explain the production of suites of rocks of felsic compositions (e.g., Clemens, 1989; White and Chappell, 1977; Wyborn and Chappell, 1986). In this model, the rocks represent various degrees of separation between the residual source material and the melting phase. A possible petrogenesis scenario of Elat massif includes melting of the continental crust composed of rocks similar to Roded quartz diorite. The calc-alkaline rocks represent various degrees of melt separation (leading to the formation of the intermediate to felsic magmas) from the residual source (mafic xenoliths). The lack of linear correlation among the trace elements of the Elat suite and the common poikilitic texture argue against the restite unmixing model and rather indicate the formation of the calc-alkaline suite via crystallization from melt.

9.07.5.4 Crustal Anatexis and the Role of Water

Experimental studies have shown that water has a profound effect on melt compositions and residuum mineralogy during partial melting of mafic rocks (e.g., Beard and Lofgren, 1989; Holloway and Burnham, 1972; Rushmer, 1991, Wolf and Wyllie, 1994). In this model, crystallization of mantle-derived basaltic magma near the base of the colder crust provides the heat and, possibly, the hydrous fluids required for crustal anatexis. The introduction of water and heat leads to melting of the crustal rocks, but differences in fH_2O can account for differences in the resultant magma compositions and residual rock. In cases where the only source of water is the breakdown of hydrous minerals in the crustal rocks (dehydration melting), a tonalitic melt composition is formed, leaving behind a dry residuum composed of plagioclase, pyroxene, and Fe–Ti oxides (Beard and Lofgren, 1989; Wolf and Wyllie, 1994). When water is available as an external phase, vapor-saturated melting of the same crustal rock produces high silica and alumina felsic melts coexisting with an amphibole- and plagioclase-bearing restite assemblage (Beard and Lofgren, 1989; Helz, 1976).

The evolution of continental crust in the ANS spanned more than 250 Ma of subduction-related calc-alkaline volcanism before the time of production of the calc-alkaline granites and diorites. The subduction-related volcanics comprised the protolites of the thick sequences of metavolcanic and metapelitic rocks. The Elat amphibolite exposed in the Elat massif could represent the potential source for the calc-alkaline granites. The hydrous–basaltic protolite of the amphibolite was produced during the calc-alkaline–arc volcanic phase and then underwent metamorphism. The high and uniform values of amphibole/melt partition coefficient for many incompatible trace elements imply that melting of amphibolitic source could produce the calc-alkaline granites with similar distribution of incompatible trace elements between the amphibolite and the magma. The hydrous–basaltic protolites of the amphibolites could penetrate into the lower crust and be metamorphosed there. *Intruding hydrous basalts could serve as a source for heat and water for partial melting of former amphibolitic rocks and the production of felsic magma.* The high-water content in the amphibolitic rocks resulted in vapor-saturated melting, producing felsic melts, as represented by Elat calc-alkaline granite, and an amphibole-rich residuum, as represented by the mafic xenoliths.

9.07.5.5 The Genesis of Alkaline A-Type Granites

Anorogenic alkaline granites (termed A-type granites) and related A-type alkaline magmas commonly mark the closing stages of a major orogeny and are related to postcollision and intraplate tectonic setting (e.g., Black and Liegeois, 1993; Eby, 1990; Turner et al., 1992). Several mechanisms were proposed for the formation of the A-type granites: (1) partial melting of crustal rocks (e.g., Collins et al., 1982; Creaser et al., 1991; Whalen et al., 1987) and (2) fractionation products from the differentiation of mantle-derived mafic magmas (e.g., Kessel et al., 1998; Mushkin et al., 2003; Stern and Gottfried, 1986; Turner et al., 1992; Volkert et al., 2000). Here, we briefly describe the work of Mushkin et al. (2003), who studied the beautifully exposed Amram massif, north to the Elat massif. The Amram massif comprises a suite of mafic to felsic A-type magmas: rhyolites, alkali quartz syenites, quartz syenites, monzonites, and comagmatic mafic to felsic alkaline dikes (45.6–78.8% SiO_2). The rocks were formed ~550–530 Ma, upon the closing stage of the Pan-African orogeny at the ANS and the transition from an orogenic to an intraplate tectonic setting in the northeastern ANS, and reveal a correlation between decreasing stratigraphic age and increasing silica content. The Amram mafic rocks ($SiO_2 = 45.6–49.5\%$) have high MgO and Fe_2O_3 concentrations (4.10–8.95% and 10.0–12.5%, respectively) and relatively flat REE patterns $(La/Yb)_N = 6.4 \pm 0.9$, suggesting derivation from relatively primitive, mantle-derived magmas. It is proposed that the mafic magmas were derived from the juvenile lithospheric mantle, underlying the ANS. The Amram mafic and felsic rocks define a continuous chemical evolutionary trend and display constant La/Nb and Y/Nb ratios (1.4 ± 0.3 and 1.6 ± 0.3, respectively). Hence, the evolution of the Amram suite is attributed to fractionation of parental mafic magmas with only minor incorporation of crustal material. Thermodynamic modeling (applying MELTS) relates the Amram high silica (>70%) rhyolites to extensive (>90%) fractionation under anhydrous conditions, with plagioclase, alkali feldspar, clinopyroxene, olivine, and minor Ti magnetite and apatite as the fractionating phases. This fractionation would require a much larger volume of unexposed cumulate rocks (composed of the fractionating mineral phases) and would imply that the parental mafic magmas were derived from a large source region in the ANS lithospheric mantle. The post-orogenic alkali magmatism represents juvenile addition to the upper continental crust, of a similar magnitude to that of the Cenozoic rift-related alkaline magmatism of the Arabian Plate (e.g., Weinstein et al., 2006). Yet all these alkali basalts are possibly derived from lithospheric mantle sources that were primarily formed during the late Proterozoic orogeny in the ANS. Thus, the 'net juvenile' contribution to the Arabian continent is small (see succeeding text).

9.07.5.6 Petrogenesis of Granites: Concluding Comments

The described studies on the petrogenesis of the late Proterozoic calc-alkaline and alkaline granites from the northern ANS put them in the context of the evolutionary cycle of the ANS continental crust. It was the long interval of subduction-related magmatism and arc volcanics (250 Ma, comparable to the duration of activity of subduction processes along the Japanese arc) that produced the juvenile addition to the new continent, leading to the accumulation of thick lithosphere and crust that eventually went through anatexis of the crust or melting of the subcontinental lithosphere and not only produced a significant amount of felsic magmas but also left behind residual lithologies that could be dropped back to the mantle. The previously described models of crustal anatexis or lithospheric mantle melting that produced the ANS granitic magmas place the 'granite factory' in the 'intraplate' tectonic environment. This is simply because subduction processes in the ANS ceased before the late orogenic and post-orogenic production of the felsic granitic batholiths. Yet granitic magmas can be produced in the subduction environment itself. The 'subduction factory' provides the basic conditions for granite formation: parental–basaltic magmas and presence of waters and accommodates processes of fluids release from the subducted slab due to the breakdown of hydrous minerals (e.g., Grove et al., 2006), production of hydrous–basaltic magmas from the melting of hot peridotite + fluids, and fractionation of the hydrous–basaltic magmas to produce tonalitic and eventually granitic magmas. Regarding the history of the ANS, granitic metagneisses are known from the early phase of subduction-related magmatism in the ANS (e.g., Bentor, 1985). Nevertheless, most of the granitic batholiths covering the northern ANS and granitic batholiths in other major juvenile crustal orogens (see succeeding text) were produced after the termination of subduction activity (see succeeding text).

The thick sequence of 'meta-arc' volcanics including hydrous–basaltic magmas that accumulated during subduction period comprises the potential source for the calc-alkaline granites. We reemphasize the critical role of waters in the 'granite factory.' All models that propose the production of granites from thick basaltic sequences require the supply of water to the melting environment (no water, no granites). This prime requirement of the presence of water in the production environment of granites brings us back to the role of oceanic plateaus in the growth of continental crust. Several workers suggested that the thick piles of Archean basaltic sequences (e.g., original plume-related picritic magmas) comprising the basal parts of oceanic plateau sequences were melted to produce crustal tonalitic–granitic magmas (e.g., Bédard, 2006; Van Kranendonk, 2010). The problem is to bring water to the basal parts of the plateaus, which appear to be dry (Arndt, 2013, and references there). Arndt argued that only the uppermost part (1–5 km) of the layered plateau sequences comprises lavas that could interact with seawater. The basal parts of the plateau comprise crystallized phases from the primary plume-related picritic melts and compact gabbroic layers that are less susceptible to water penetration and alteration. In this context, we return to the interesting earlier-mentioned observation from the Ontong Java Plateau where crustal seismic velocities were identified in the upper 5–15 km (**Figure 7**). This issue remains an open question that requires further attention.

9.07.6 Rapid Growth of Major Continental Segments (the 'Major Orogens')

9.07.6.1 General

In this section, we describe of the magmatic histories of several prominent crustal segments (termed as 'major orogens') that underline the history of the Earth continental crust. We first elaborate on the evolution of continental crust comprising the late Proterozoic ANS. Then, we describe the other major orogens. Overall, we show the general similarity in the evolutionary pattern of all these orogenic episodes. They all evolved through four major phases: the (I) eruption of thick sequences of tholeiitic magmas. (II) production of arc subduction-related calc-alkaline magmas, (III) production of calc-alkaline granitic batholiths, and (IV) post-orogenic production of alkaline (A-type) granitoids.

9.07.6.2 The ANS Orogeny (~0.9–0.6 Ga)

The excellent preserved exposures of the late Proterozoic crystalline basement of the ANS and the sequences of overlying Phanerozoic alkali basalts provide an opportunity to monitor the magmatic history of the ANS over the past ~900 Ma (Stein and Goldstein, 1996). The low initial $^{87}Sr/^{86}Sr$ ratios of the late Proterozoic magmas of Sinai, Jordan, northern Saudi Arabia, and the Eastern Desert of Egypt preclude significant involvement of an old pre-Pan-African felsic continental precursor in this part of the northern ANS, indicating that basement magmas were derived either from a preexisting mafic crust or directly from the mantle. The absence of older continental crust is further indicated by mantle-type oxygen isotope ratios (e.g., $\delta^{18}O = +5.5$, Bielski, 1982). Recent studies of 'magmatic detrital' zircons from the ANS granitoid plutons and the Phanerozoic sedimentary cover, respectively, confirmed the juvenile nature of significant areas of the ANS (e.g., Be'eri-Shlevin et al., 2009, 2011; Morag et al., 2011).

The late Proterozoic history of the ANS can be divided into four evolutionary phases (following Bentor, 1985):

Phase I: This phase is characterized by the production of thick sequences of tholeiitic during a very short interval of time (~900 ± 30 Ma). The (meta)tholeiites are characterized by chondritic REE patterns and 'mantle-type' Th/Nb ratios and were interpreted as oceanic basalts similar to the plateau basalts (Stein and Goldstein, 1996; Stein, 2003, and references within there). It is important to emphasize that along with the production of the plateau magmas, thinner sequences of metatholeiites were interpreted as 'normal' mid-oceanic tholeiites erupting along spreading ridges (the 'old metavolcanics' in Egypt, described by Stern (1981)). The two ANS metatholeiite suites resemble the magmatic–tectonic association of the Pacific Ontong Java Plateau–Nauru Basin basalts.

Phase II: Upon reaching a continental margin, the thick oceanic plateau lithosphere resisted subduction and plate convergence occurred on its margins, forming the ANS calc-alkaline magmas. The subduction activity lasted for >200 My (between ~870 and 650 Ma), similar in duration to the activity arc magmatism in the Japanese arc. The large amount of calc-alkaline magmatism over a short period of time may be partly a result of the thermal anomaly in the upper mantle caused by the plume head. The arcs and oceanic plateaus were accreted to the old Gondwanaland producing thick and mainly mafic crust and lithospheric mantle, which served later as sources for the calc-alkaline granitic batholiths, alkali granites, and Phanerozoic alkali basalts. The enriched plume–mantle of the early ANS was exhausted by the subduction processes. The Gabal Gerf ophiolites (~750 Ma; Zimmer et al., 1995), which are assumed to represent the arc environment, show isotope mixtures between the enriched ('plume–lithosphere mantle') and depleted ('MORB-type mantle') components (see evolution lines in **Figure 13**). A similar shift to more depleted

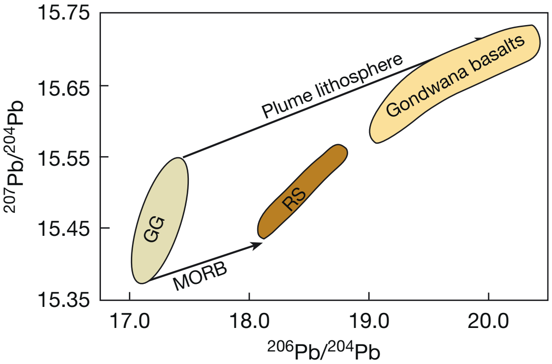

Figure 13 The distribution of late Proterozoic oceanic basalts (the Gabal Gerf (GG) ophiolites, Red Sea (RS) basalts, and Gondwana basalts in the Pb–Pb isotope diagram (reproduced from Stein M and Goldstein SL (1996)) From plume head to continental lithosphere in the Arabian-Nubian shield. *Nature* 382: 773–778; Stein M (2003) Tracing the plume material in the Arabian-Nubian Shield. *Precambrian Research* 123: 223–234). Stein and Goldstein proposed that the GG ophiolites lie in the diagram on a mixing trend between the asthenospheric MORB mantle and asthenospheric plume-type mantle (in similar tectonic–magmatic settings to the configuration of the Nauru Basin and EPR in the Pacific Ocean). The Gondwana basalts (location marked in **Figure 10**) lie on an evolution trend together with the late Proterozoic-enriched ophiolites and other magmas (e.g., galenas and K-feldspars not shown here; see Stein and Goldstein, 1996), suggesting that the lithospheric mantle beneath the Arabian continent was generated during the late Proterozoic crustal formation events. It can be regarded as a 'frozen' mantle wedge, which previously accommodated the production of calc-alkaline magmas and fractionation–transportation processes of trace elements on route to shallower levels of the crust (the subject is elaborated later in the text). The Red Sea basalts lie on a mixing trend between the lithospheric-derived basalts and the MORB-type asthenosphere. Stein and Hofmann (1992) noted that enriched-type Red Sea basalts erupt on the southern and northern edges of the Red Sea basin, while depleted MORBs erupt only in the central trough where 'real' spreading occurs. They regard this configuration as a strong evidence for the existence of the plume-type mantle above the asthenospheric MORB. The latter is rising into the rifting lithosphere and continental crust. This also provides a strong evidence for the MORB-type composition of the upper mantle. The Gondwana basalts show mixing relation with the Red Sea asthenosphere, suggesting that MORB is rising into the rifting lithosphere (e.g., in the Ross Sea rift, Ahaggar, and the Dead Sea rift). This rising has important implications for the heating of the lithosphere and the lower crust and for the production of basaltic melts from the lithosphere and provides evidence for asthenospheric underplating (Stein, 2006).

MORB values is observed also in Hf isotopes (eHf >+ 10) in zircons recovered from the Pan African magmas (Fig. 12)

Phase III: This phase constitutes the rapid production (∼630–600 Ma; Eyal et al., 2010) of vast amounts of the calc-alkaline granitic and dioritic magmas, which form batholiths that cover large areas, mainly in the northern ANS. The petrogenesis of the calc-alkaline granitoids (**Section 9.07.5.2**) was related by Weismann et al. (2013) to anatexis of metamorphosed mafic crust (e.g., the Elat amphibolite).

The production of the calc-alkaline granitic magmas certainly required the supply of 'heat and water,' a problem that is not clearly understood. One possibility is a relation between asthenospheric rise associated with delamination of a thick lower crust and lithosphere that were produced in the earlier evolutionary stage of the island arc magmatism.

Phase IV: This phase is represented by the orogenic cycle terminated by the production of alkali granites and related rhyolites (∼600–530 Ma; Bielski, 1982; Eyal et al., 2004; Mushkin et al., 2003; Morag et al., 2011). The parental magmas of the alkaline magmas were probably derived from the lithospheric mantle and underwent extensive differentiation in shallow crustal levels (Mushkin et al., 2003).

The transition from calc-alkaline magmatism to alkaline magmatism associated with the lithospheric mantle melting after 600 Ma reflects the ending of plate convergence. In the ANS, this transition is associated with a major uplift (Black and Liegeois, 1993). Similar rapid transitions in the stress field associated with continental collisions were described in other localities such as the Variscan province in Europe, the Basin and Range Province in the United States, and the Tibetan Plateau (Costa and Rey, 1995; Klemperer et al., 1986; Rey, 1993). In the Himalayas, major uplift and the appearance of alkaline volcanism have been related to the thinning and melting of the lithosphere after the ending of plate convergence.

The growth and fate of continental crust in the ANS are schematically illustrated in **Figure 14**. Overall, most of addition juvenile material to the ANS continental crust occurred during phases I and II during its early 200–250 Ma of plateau and arc formation and accretion. Magmas formed during phases III and IV comprise melting products of crust and lithospheric mantle that were formed in the earlier phases. Thus, the rate of juvenile creation of crust in the ANS (and possibly other 'major orogens') could be even faster than the Reymer and Schubert estimate.

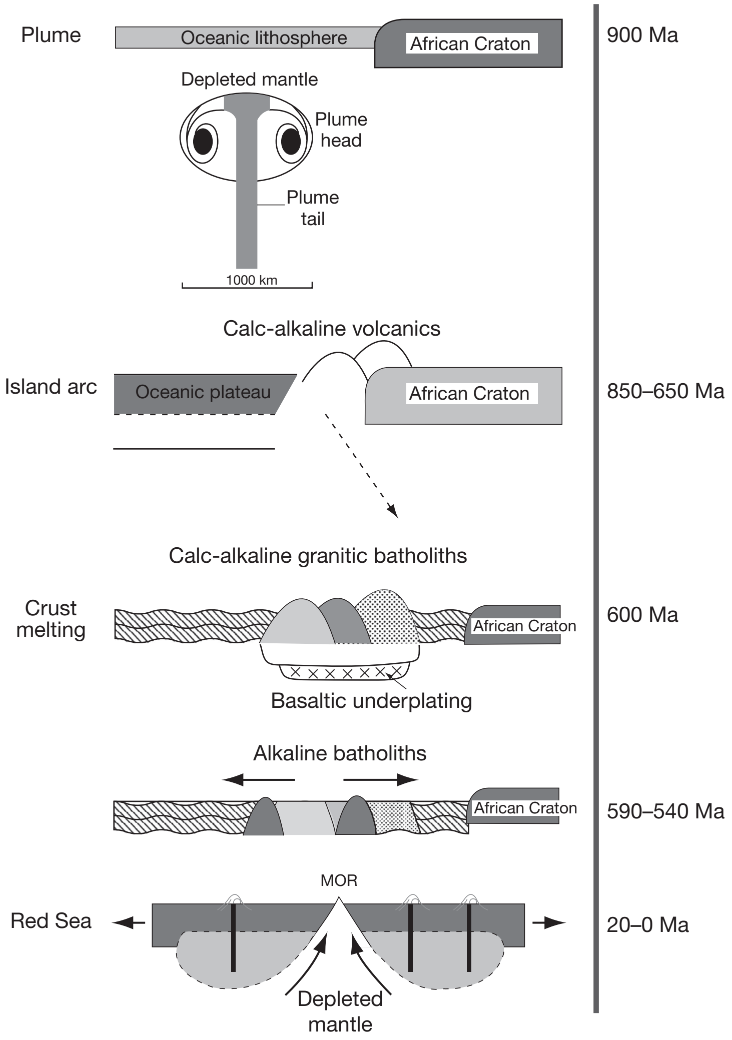

Figure 14 Schematic model illustrating the growth and fate of continental crust and lithosphere in the ANS. Similar (but clearly not identical) structure of magmatic histories can be ascribed to other major crustal segments (e.g., Canadian Shield and Birimian orogen the Mesozoic Pacific).

9.07.6.3 The Birimian Orogeny (~2.2–1.8 Ga)

Another well-studied case of episodic crustal formation is that of the Birimian orogeny that lasted between ~2.2 and ~1.8 Ga (Abouchami et al., 1990; Boher et al., 1992). The early stage in the growth of the Birimian juvenile crust was marked by eruption of thick sequence of basalts in oceanic basin that were interpreted as oceanic plateau (formed in an environment remote from any African Archean crust). Shortly after, calc-alkaline magmas were produced, probably in island arcs that were developed on the margins of the oceanic plateau, which then collided with the Man Archean craton.

While the magmatic–geodynamic history of the Birimian orogeny strikingly resembles that of the ANS and to some extent that of the Superior province, the growth rate calculated for the Birimian crust is ~1.6 $\mathrm{km^3\,a^{-1}}$, which is only ~60% higher than the Phanerozoic current rate (Reymer and Schubert, 1984) and slower than the mean growth rate of 2 $\mathrm{km^3\,a^{-1}}$ of the total continental crust from the mantle in 4 Ga (Turcotte and Schubert, 1982). Boher et al. argued that large part of the Birimian crust has been recycled into the mantle or incorporated into younger orogenic segments. They extended this line of argument to the Archean crust, suggesting that the apparent deficit in crustal budget is even more dramatic for the Archean crust. Thus, while the evidence from Birimian orogeny seems to support the model of episodic formation of juvenile continental crust in relation to large mantle upwellings, it also outlines the importance of recycling processes.

9.07.6.4 The Superior Orogeny (~2.7–2.5 Ga)

The Superior province, the largest Archean craton on Earth, comprises several continental and oceanic megaterrains that were formed and accreted rapidly (the ages of the various superprovinces lie in the range of 3.1–2.67 Ga and accretion–tectonics occurred between 2.74 and 2.65 Ga; Card, 1990; Percival et al., 1994).

Recent compilations of U–Pb zircon ages (e.g., Condie et al., 2009, 2011; **Figure 12**) indicate that the 2.7 Ga peak is the largest one and reflects a global event that was recorded on all continents: for example, Canada (e.g., Card (1990)), Zimbabwe (e.g., Bickle and Nisbet, 1993), Siberia (e.g., Puchtel et al., 1993), and Australia (e.g., Myers and Swagers, 1997), a picture that is consistent with the concept of the MOMO model on a global overturn event in the mantle.

The geologic history and magmatic–stratigraphy of the Superior province were divided by Arth and Hanson (1975) into four stages: (1) the production of tholeiitic basalts by shallow melting of mantle peridotites, followed by fractional crystallization that produced basaltic–andesites; (2) the formation of trondhjemite, tonalite, and dacites by melting of eclogites in mantle depth; (3) the intrusion of quartz monzonites; and (4) the intrusion of postkinematic syenites. The general pattern of this history is strikingly similar to the four-phase growth and magmatic evolution of the previously described late Proterozoic ANS or the Proterozoic Birimian orogeny.

In more recent studies, Polat and Kerrich (2001a,b) and Polat et al. (1998) described the formation of the 2.7 Ga Wawa and Abitibi greenstone subprovinces of the Superior province as an example of episodic continental growth, by lateral spread of subduction–accretion complexes. They recognized two principal volcanic associations: (1) tholeiitic basalt–komatiite and (2) tholeiitic to calc-alkaline bimodal basalt–rhyolite. Tholeiitic basalts of the former association are characterized by near-flat REE patterns and Th/U, Nb/Th, Nb/La, and La/Sm-pm ratios that span the primitive mantle values. Transitional to alkaline basalts and Al-depleted komatiites have fractionated REE patterns and OIB-like trace element signatures. Polat and his coauthors interpreted these assemblages as representing oceanic plateau derived from a heterogeneous mantle plume. The bimodal association has fractionated REE patterns and negative Nb, Ta, P, and Ti anomalies typical of arc magmas. Tonalite plutons derived from partial melting of subducted oceanic slabs intrude the subduction–accretion complex as the magmatic arc axis migrated towards the trench. The eruption of voluminous ocean plateau and island arc volcanic sequences and the following deposition of kilometer-thick siliciclastic trench turbidites and intrusion of the supracrustal units by syn- to postkinematic plutons occurred in the relatively short period of time of 2.75–2.65 Ga (a classic representation of the Reymer and Schubert superrapid crustal formation events). The earlier-mentioned events were accompanied by contemporaneous intense polyphase deformation, regional greenschist to amphibolite facies metamorphism, and terrain accretion along a north–northwest dipping subduction zone.

The description of the history of the Superior province is well fitted with the mantle plume upwelling–arc magmatism and terrain accretion models where the growth of the new continent and lithosphere involves accretion of oceanic plateaus, island arcs, continental fragments, closure of oceanic basins, rifting of magmatic arcs, and plume–arc interactions followed by intracrustal and intralithospheric extension-related melting. This comprises a complete MOMO–Wilsonian cycle that was repeated throughout the Earth history.

9.07.6.5 Early Precambrian Orogenies (~2.9–2.8 Ga)

The previous sections suggest that the crustal growth histories of the ANS and apparently the Superior and Birimian orogenies comprise complete MOMO cycles, illustrating a primary means of continental crustal formation and cratonization throughout the Earth history, and were particularly relevant in cases of rapid continental growth as demanded by the Reymer and Schubert dilemma. Evidence for the existence of magmatic provinces that resemble oceanic plateaus was found in older continental crust provinces.

The 2.9 Ga Sumozero–Kenozero greenstone belt in the SE Baltic Shield comprises several kilometer-thick lower unit that is made of submarine mafic–ultramafic units (with plume-type Nb/U ratios of 43 ± 6) that were interpreted as representing oceanic plateau magmas and the upper unit consists of arc-type magmas (Puchtel et al., 1999). The authors suggested that the overthickened plume-related oceanic crust and the overlying arc-type magmas were later accreted to the existing TTG-type older crust of the Vodla block.

The ~2.8 Ka Kostomuksha greenstone belt in the NW Baltic Shield consists of komatiitic–basaltic submarine lavas and volcaniclastics whose formation was attributed by Puchtel et al. (1997) to plume activity and production of thick oceanic crust–oceanic plateau. The plateau reached the Baltic continental margin but was too buoyant to subduct and became a new part of the continent. Using the example of the Cretaceous Caribbean plateau (Kerr et al., 1997), Puchtel and colleagues suggested that only the upper part of the thick komatiitic–basaltic crust of the proposed Baltic oceanic crust was imbricated and obducted on the ancient continent, whereas the deeper zones were subducted to the mantle. The subduction of this lower crust gave rise to subduction-related volcanism that erupted within the accreted sequences. This mechanism distinguishes the thick plateau-type oceanic crust from the thinner crust that is represented in the ophiolite sections. Moreover, it provides plausible explanation to the sequence of events that occurred within a 'cycle' of plateau formation–accretion–delamination–subduction–calc-alkaline arc-type magmatism.

9.07.6.6 Early (Hadean) Crust and the Initiation of Wilsonian Plate Tectonics–MOMO Cycles

The Nd and Hf isotope evolution trends (**Figures 11** and **12**) appear to deviate from the primitive (CHUR) mantle at the very early history of the Earth, calling for an early depletion event and possible formation of a complementary enriched reservoir.

The oldest zircons bearing evidence for early (Hadean) crust are the 4.4–4.1 Ga from Jack Hills, Australia (e.g., Peck et al., 2001). Other old zircons with ages lower than 4 Ga were found in the oldest remains of continental crust at Isua, Greenland (Nutman et al., 2009); Beartooth Mountain, the United States (Maier et al., 2012); and northern China (Cui et al., 2013; Geng et al., 2012). The interesting result that came from the Jack Hills zircons concerned their oxygen isotope values that are higher than the ~5–6‰ mantle value, indicating possible interaction with surface waters (Cavosie et al., 2005; Valley et al., 2002). This value indicates on a very early role of water at the Earth surface even before 4 Ga.

The series of works on the Hf and O isotopes in the Jack Hills and Mount Narryer in Western Australia reveal an exciting picture of mantle and crust evolution in the early Earth (e.g., Bell et al., 2011; Bell and Harrison, 2013; Blichert-Toft and Albarède, 2008; Harrison et al., 2005, 2008; Kemp et al., 2010, and see discussions on these results in Arndt, 2013). The zircons suggest a very early history of crustal formation on Earth that began by about 4.5 Ga (Bell et al., 2011). In the context of major themes discussed in this chapter review, they appear to lie on evolution trends that deviate from the MOMO evolution line (**Figure 12**). The oldest group appears to deviate at ~4.2 Ga and the younger one at ~3.7 Ga. The slope of the 'oldest ~4.2 array' (Lu/Hf~0.02) is consistent with mafic composition. The slope of the 'younger ~3.7 Ga array' appears steeper and points to an enriched reservoir possibly similar to HREE-depleted TTG (Blichert-Toft and Albarède, 2008; Harrison et al., 2005, 2008). The slight deviation of the 'oldest array' could be consistent with the ^{142}Nd excess, indicating the existence of an early fractionation event and formation of an early mafic crust possibly during the solidification of a magma ocean (Boyet and Carlson, 2006).

Galer and Goldstein (1991) proposed that the early differentiation and depletion event was accompanied by the production of enriched alkali basalt crust (similar to that produced in intraplate rift-related volcanism) that had been gradually reincorporated into the mantle.

Boyet and Carlson (2006) noted that variable excesses of ^{142}Nd/^{144}Nd in rocks from Isua indicate on a depleted Hadean mantle and on mixing back of the enriched 'primordial crust' into the mantle shortly after 3.8 Ga, producing a ^{142}Nd/^{144}Nd homogeneous reservoir. This description is consistent with the clear separation between the two groups of Western Australian Hadean zircons. The apparent appearance of the ~3.7 Ga zircons on the MOMO evolution line is consistent with early derivation of continental crust from the MOMO mantle.

9.07.7 Summary

The continents come from the mantle. Large submarine oceanic plateaus whose production was associated with mantle plumes may have formed the basis for the growth of continental crust, at least since the late Archean time. The chronological evidence suggests that plateau formation was rapid and episodic and that it was followed by enhanced activity of arcs and calc-alkaline magmatism. Thick oceanic plateaus are buoyant and resist subduction. Yet some plateaus were subducted, reflecting probably internal differentiation within the plateaus and the geodynamic conditions (e.g., thermal state of the mantle). Subduction of segments of plateaus can in turn enhance arc magmatism, because its altered parts can increase the water flux at depth of magma generation. It should be also emphasized that oceanic plateaus may well be an important component of current arc magmatism, as some of the currently active arcs are located close to anomalously thick oceanic crust (e.g., the central Aleutians and Lesser Antilles).

Along with the production of new crust, the lithospheric mantle is evolved. It probably represents a frozen mantle wedge where the production of magmas and the migration of fluids and incompatible trace elements occur; thus, both the continental crust and the lithospheric mantle preserved the complicated history of continental growth. Besides the plateau and arc-accretion and calc-alkaline magmatism, delamination of lithospheric mantle and lower crust and underplating by rising asthenospheric magmas, as well as lithospheric melting, are all important processes that lead to the magmatic and thermal maturation of the continents. The fate of the continent relates eventually to the geodynamics and thermal conditions in the mantle.

Many of the previously mentioned topics require further study. In particular, we emphasize the importance of understanding the origin of the 'crustal type' V_p velocities that indicate a continental structure for some of the oceanic plateaus. Are these velocities associated with significant magmatic differentiation before accretion of the plateau to the existing continents? The mechanism of production of the calc-alkaline granitic batholiths is not as well established as is the composition of 'midcrust.' The processes of asthenospheric underplating, crustal foundering, and crustal recycling and their relation to the plate tectonic cycles and mantle dynamics through geologic time require more attention.

Finally, among the numerous works and thorough reviews on continental crust composition and evolution, we consider and 'rephrase' the Taylor and Campbell statement 'no water, no oceans, no plate tectonics, no granites, no continents' as a major characteristic of the environment of production of the Earth continental crust.

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