Evolution of early continental crust

R. S. Sharma* and M. K. Pandit

Department of Geology, University of Rajasthan, Jaipur 302 004, India

The present article reviews the evolution of continental crust since the time the earth began to inscribe a permanent history in rocks of the cratonic nuclei. The existence of a sialic crust prior to 4200 Ma ago, soon after the permobile stage of the earth, is documented by detrital zircon in the Precambrian metaconglomerate of Neyerer Complex, Western Australia. The evolution of Archaean crust (> 2500 Ma) is discussed in terms of currently used Nd model-age calculations, based on a depleted mantle evolutionary model. The model fits the generally accepted assumption that LREE depletion of the upper mantle commenced very early in the earth's history and that the present-day MORB is the best representative for the Nd-isotopic composition of today's depleted mantle. Finally, the mechanisms for growth or accretion of the continental crust and the incompatibility of thickened crust during Archaean time are discussed.

THE problem of origin of the early continental crust, which forms 0.4% of the earth's volume, can only be judged from the time when the earth began to inscribe a permanent history in the rocks. It is thus important to consider the nature of the Archaean crust through the constituent rocks. A survey of Archaean cratons[1] reveals that all the Archaean terranes show greenstone–gneiss association. In these Archaean terranes the greenstones are represented by amphibolites, whereas the gneisses are characterized by tonalite–trondhjemite–granodiorite (TTG). This twofold rock-assemblage seems to represent vestiges of ancient mafic and sialic crust. This geological revelation raised two important questions. One relates to the source, which formed the continental crust, and the second to the composition of the first crust – whether mafic or sialic.

The early Archaean record

Archaean gneisses of ages exceeding 3.8 Ga are reported from several continents, e.g. Wyoming, Nain and Slave cratons of North America[2], West Greenland[3], China[4], Antarctica[5] and western Australia[6]. This suggests that the early Archaean crust was once widespread, but now occurs as fragments, mainly within the central stable portions (cratons) of the continents. The oldest continental crust thus formed in great volume at about 4.0 Ga ago, but we have no direct record of the earth's first 500 million years of evolution (accepting the age of the earth as ~ 4.5 Ga). There could have been several reasons which may have destroyed the early crust. These may include rifting, delamination or continental subduction, erosion, covering by younger sediments and even meteorite bombardment. It should be borne in mind that if the earliest crust was completely destroyed, the oldest rocks preserved now probably represent a fairly advanced stage of crustal evolution.

*For correspondence. (e-mail: ramss4@sify.com)

Features of the Archaean crust

Isotopic and geochemical characteristics of Archaean crustal rocks (TTG) are characterized by the following features:

(i) The TTG series is restricted to central portions of continents in which the growth rate has been maximum between 3.0 and 2.5 Ga.
(ii) The Archaean crust is a bimodal suite: 80% tonalite, 20% basaltic and no intermediate rocks.
(iii) The TTG rocks are characterized by SiO_2 = 60–75%, MgO = 0.5–2.5%, $Na_2O/K_2O > 1$.
(iv) Tonalitic gneisses have low initial $^{87}Sr/^{86}Sr$ ratio in the range of 0.700–0.703 and thus are close to or slightly higher than the presumed ratio in the upper mantle at the corresponding age.
(v) Tonalitic gneisses are strongly enriched in incompatible elements (LIL and LREE) and depleted in HREE.
(vi) Exposed cross-sections through continental crust reveal a vertical zonation. Upper crust (one third) is granodioritic and lower crust (two-third) is silicic granulite with mafic granulites.
(vii) Upper crust is enriched in heat-producing radioisotopes (K, Th, U) and in certain LIL elements.

Continent formation and growth

Considering the given compositional characterstics, the Archaean continental crust has obviously formed from the mantle which constitutes nearly all of the silicate part of the earth[7]. However, Archaean TT rocks cannot be the result of direct partial melting of the mantle due to its inability to produce melts with major and trace element characteristics of the Archaean TT series. Experiments have shown that basaltic composition is required for the generation of these silica-rich rocks that occupy the bulk of the shield areas on all the continents[8]. The basalt generated from peridotite mantle is emplaced at different depths and crystallized with increasing depth as garnet–amphibolite, garnet–granulite or eclogite (Figure 1). When these metabasalts undergo melting, they give rise to a composition akin to the TT series[9]. A high $(La/Yb)_N$ ratio (15 to 50) and depletion in HREE in these TTG rocks distinguish them from the TTG rocks of more recent times. When it was recognized that the bulk composition of continental crust is not basaltic, i.e. not primary mantle melts[10], two views were proposed about continental development. The first view is by Armstrong[11], who conceived that the present volume of continental crust formed in a 'big-bang', early in the earth's history with a modification by crustal additions and subtractions ever since. This view involves geochemical differentiation of the crust as a major event, very early in the earth's history. This also implies that crustal recycling was an important process and that ages of rocks in the continental crust are the record of crust preservation rather than crust formation. Armstrong's model was a challenge to many geologists who held the crust to be indestructible and too buoyant to be dragged down into the mantle. A year later, another view was proposed by Hurley and Rand[12]. On the basis of quantification of available database, they argued that the distribution of ages of rocks in continents (corrected for intracrustal processes such as re-melting, metamorphism, erosion and re-deposition) reflects the growth rate of continents. Their calculations suggested that continents have been extracted from the mantle progressively with time. This view involves continuous geochemical differentiation of crustal components from the mantle as a secondary process. When the present areal distribution of continental crust is used to constrain the rate of continental crustal growth, a strong episodicity in rates of crust formation is seen[13]. Most geoscientists have proposed crustal growth models in which total volume of continental crust has increased with time at the expense of the primitive mantle, leaving a complementary depleted mantle. Also, models for formation of intermediate composition TT gneisses, characterizing Archaean terrains, have been proposed. These include, (i) partial melting of a subducted slab of garnet–amphibolite, garnet–granulite or eclogite[14] (Figure 1), (ii) intracrustal melting of mafic or sedimentary rocks[13], and (iii) arc magmatism and magmatism associated with rising plumes[15].

Geochemical models and early crust

Geochemical models for the development of the earth's early crust involve study and interpretation of Sm–Nd isotopic compositions of crustal rocks. This is because ^{147}Sm and its decay product, ^{143}Nd, fractionate during differentiation of mantle melt and the continental crust that is derived from it. Because the continental crust is enriched in Nd compared to Sm (atomic radius of Nd being greater than Sm), the Sm/Nd ratio in the crust is lower than that in the mantle reservoir. The mantle is therefore depleted in Nd and has a high Sm/Nd ratio. The enriched crust and depleted mantle (DM) are therefore complementary to each other. Mantle reservoirs having a high Sm/Nd ratio, such as MORB, are called depleted

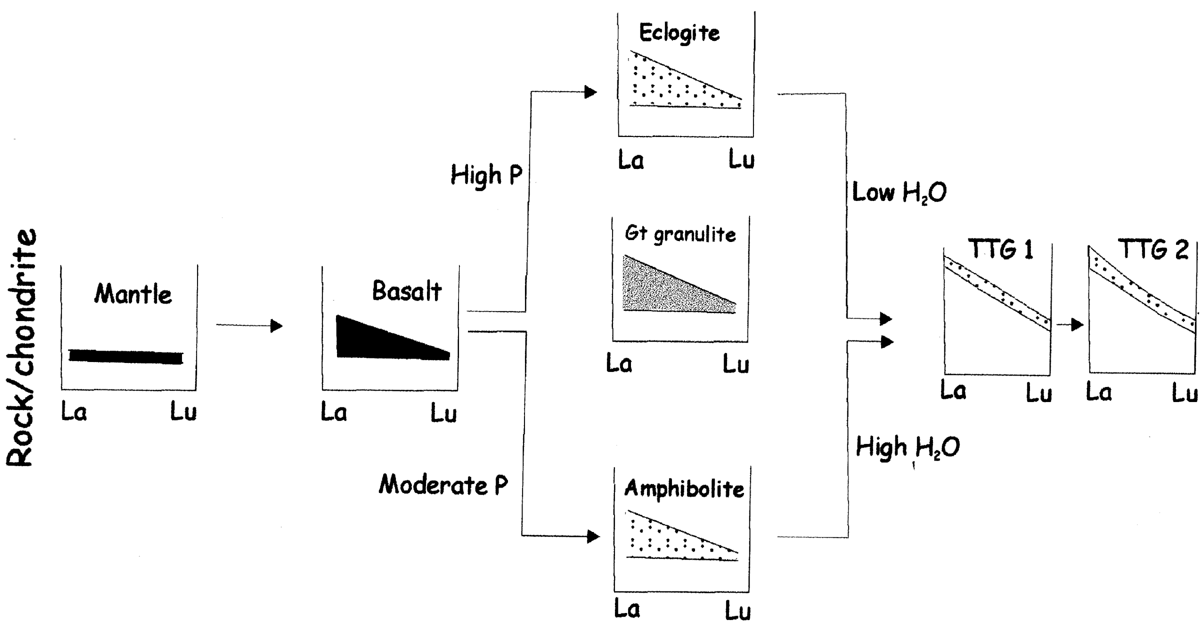

Figure 1. Schematic illustration showing origin of Archaean TTG.

and evolve towards a positive e_{Nd} with time. Crustal rocks that contain similar isotopic ratios as the DM are called juvenile, while rocks enriched in initial isotopic ratios are classified as evolved and contain a component of the older crust. The Nd-isotopic composition of Archaean rocks can thus help in constraining the geochemical characteristics of reservoirs (sampled by crystallized magmas) in the earliest part of the earth's history.

On the basis of Sm/Nd–isotopic characteristics, two possible models for the extraction of continental crust from the mantle reservoir have been suggested.

Model 1: Continental crust derived by melt extraction from an undepleted mantle; taking the DM reservoir as the source for today's MORB[16]. This becomes clear from the plot of the initial Nd isotopic ratios ($^{143}Nd/^{144}Nd$) available for Archaean tonalitic gneisses against their corresponding age (Figure 2 *a*). We notice that all the data plot on or very close to the chondrite growth curve[17] for $^{143}Nd/^{144}Nd$. This suggests that the precursor magmas for these gnesisses were generated from the undepleted chondritic mantle source region[18]. This conclusion is in agreement with the data from Sr and other isotopic systems[19]. Because the undepleted mantle is supposed to have bulk earth Nd isotopic composition, Nd model ages (corresponding to this model) can be calculated using the bulk earth isotopic evolution. The best approximation for the bulk earth isotopic composition is given by the so-called Chondrite Uniform Reservoir (CHUR).

Model 2: Model of depleted mantle: Continental crust formed by repeated extraction from a mantle which became increasingly depleted with time. When we plot the published Nd isotopic data of various rocks of different ages, they yield positive e_{Nd} initial values[5]. This implies that these rocks were derived from the sources with $^{143}Nd/^{144}Nd$ ratios higher than CHUR. This means that the DM is the source of continental crust[20,21] (Figure 2 *b*).

Accordingly, Nd model ages corresponding to model 1 can also be calculated using the bulk earth isotopic evolution (T_{CHUR}). For model 2, the model age calculations are based on the DM evolutionary model, because the continental crust is considered to be derived from the DM source.

The e_{Nd} value represents the deviation of the initial Nd-composition of a sample from CHUR. It is calculated as:

$$\sum \mathrm{Nd}(T)\mathrm{sample} = \left[\frac{(143_{\mathrm{Nd}} / 144_{\mathrm{Nd}})_{T_{\mathrm{sample}}}}{(143_{\mathrm{Nd}} / 144_{\mathrm{Nd}}) T_{\mathrm{CHUR}}} - 1 \right] \times 10^4,$$

$$e_{\mathrm{Nd(Today)sample}} + 10\ \mathrm{MORB} = \%\ \mathrm{Nd\ of\ present\text{-}day\ DM}.$$

Thus, we see that when the Nd–isotope composition of the crust was identical to that of its assumed mantle source, we can theoretically deduce the age of crustal differentiation from the mantle. The Nd model ages indicate the time when the mantle differentiated into the crust. The Nd model age is deduced by calculating the age for which the initial $^{143}Nd/^{144}Nd$ ratio of a sample is identical to that of its source: ($^{143}Nd/^{144}Nd$)[T] sample = ($^{143}Nd/^{144}Nd$)[T] source.

The model age variation can be appreciated from the typical model age diagram for the Sm–Nd system (Figure 3). The granitoid sample with measured $e_{Nd} = -8$ and known $^{147}Sm/^{144}Nd$ ratio must have evolved along the growth curve with time (Figure 3). If the sample was derived from CHUR, then the separation event occurred at 1.5 Ga ago. If the source was a DM, the separation took place 2.0 Ga ago. If the granite source formed at 0.8 Ga ago from a crustal source separated from the DM 3.2 Ga ago, which seems the likely origin, both T_{CHUR} and T_{DM}

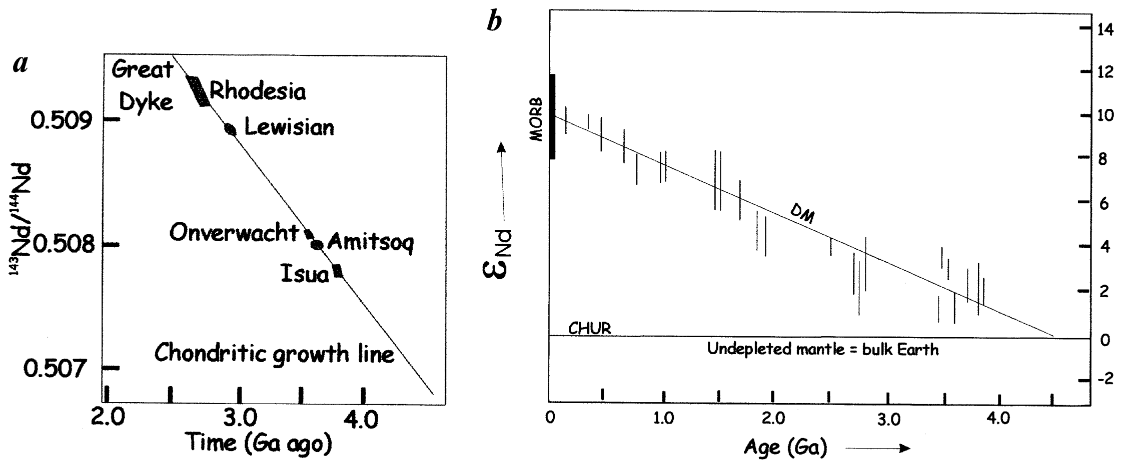

Figure 2. *a*, Growth of initial $^{143}Nd/^{144}Nd$ ratio against age for Archaean rocks. Diagonal line represents the growth of $^{143}Nd/^{144}Nd$ in a chondritic reservoir which had a $^{143}Nd/^{144}Nd$ ratio of 0.50682 at 4550 Ma ago (see text); ***b***, Initial e_{Nd} values for different rocks (after Galer *et al.*[18]). Solid bar represents present-day MORB values (see text).

ages for the granitoid are incorrect, consequently. There are uncertainties of model age values due to the controversies[20–27] with regard to: (i) the value of $^{143}Nd/^{144}Nd$ at present time; (ii) the age of intersection of DM and CHUR, and (iii) the shape of the evolutionary path of DM, as shown in Figure 4.

In the earlier Nd-isotopic studies it was found that most Archaean rocks have a positive e_{Nd} (between + 4 and + 7)[13], indicating their derivation from the DM. This, together with the absence of rocks with negative e_{Nd}, was taken as firm evidence that there was no older continental crust prior to 4 b.y. Recent isotopic data from Acasta Gneisses and other Archaean cratons exhibiting a wide range of e_{Nd} (+ 3.5 to – 4 at 4 Ga and + 4 to – 7 and 3.6 Ga)[13], as well as the discovery of 4.3 to 4.1 Ga detrital zircons derived from enriched continental crust[28], clearly indicate that an older continental crust once existed. The data led to the conclusion that the earth differentiated early in its history and that the record of the differentiation was largely obliterated by subsequent recycling of crustal material back into the mantle. It is a matter of conjecture only as to how much of the earth's mantle had participated in the formation and recycling of

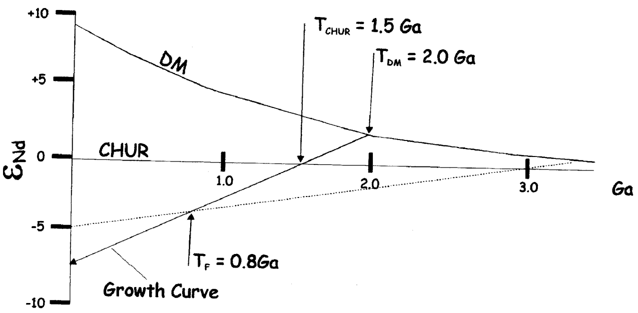

Figure 3. Typical model age diagram for Sm–Nd system.

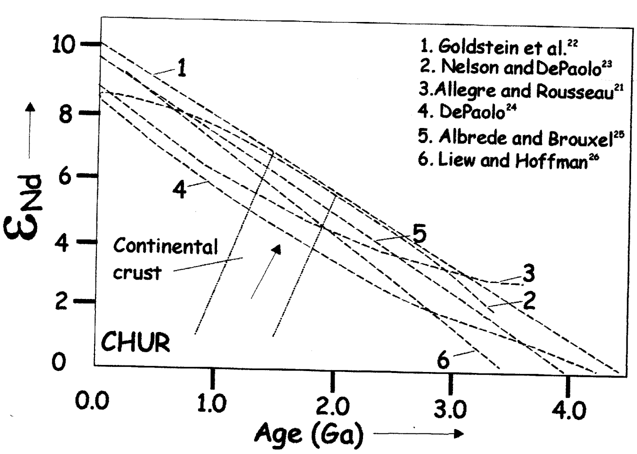

Figure 4. The e_{Nd} evolution for depleted mantle as proposed by different workers.

the continental crust. It is an important question whether a peridotite composition, representative of the upper 150 km, can also be assumed to represent the remainder of the mantle down to 2900 km depth. Most geochemical data do not suggest that this is so. Seismic studies show two major discontinuities in the mantle, at 410 and 660 km depths. These discontinuities are due to chemical layering of the mantle. According to the standard models, the chemical structure of the mantle can be considered a two-layered feature (Figure 5). Small-scale heterogeneities in the lower mantle can be attributed to subduction of lithospheric mantle and whole convective currents in the mantle[7].

The upper mantle is depleted in incompatible elements (Zr, Hf, Ti, Nb, Ta, etc.) and having its chemistry complementary to that of the continental crust. The DM is continuously sampled by mid-oceanic ridge (MOR) volcanism. The return flow (subduction) does not penetrate the 660 km boundary which is, therefore, a pronounced chemical boundary.

The lower mantle being undepleted, is also called primitive. Relatively small amounts of this primitive material rise (plume) through the depleted layer and form Ocean Island Basalt (OIB).

As stated earlier, the basalt generated from the peridotite mantle is emplaced at different depths and crystallized with increasing depth as garnet–amphibolite, garnet–granulite and eclogite. The melting of these mafic basalts gives a composition akin to the TT-series[9]. When sufficient water is present in these lower crustal amphibolite source rocks containing garnet, TT melts with characteristic major and trace elements would be generated. If sufficient water is not available, high pressures in excess of 10 kbar (> 30 km depth) would be required to satisfy the REE constraints, because of the positive slope of the plagioclase/garnet boundary. Such an environment demands tectonically thickened crust or a subducted oceanic crust so that eclogite, garnet–granulite or garnet–amphibolite becomes the source for TT melts. These TT melts would have highly fractionated REE patterns and, on crystallization at mid-crustal levels,

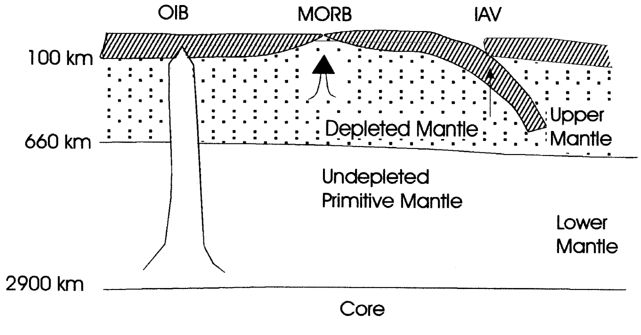

Figure 5. Standard model showing two-layered chemical structure of mantle.

would be tonalite–trondhjemite (TT). Subsequent melting of these TT rocks would generate melts with closely similar chemistry, inheriting the fractionated REE patterns of the source rocks (because neither plagioclase nor quartz significantly fractionate HREE from LREE). Thus, we would expect high negative slopes on chondrite-normalized REE plots for both I and II order trondhjemites, although second-generation TT will have higher REE abundances (Figure 1).

Nature and origin of early crust

The available radiometric data are not capable of resolving the argument as to whether the earliest crustal rocks were acidic or basic[29]. Two divergent hypotheses on the nature of the early crust are briefly discussed below:

The sialic crust

Considering the antiquity of the gneissic complex relative to the greenstone belts they enclose in the Archaean terranes, Fyfe[30] and others believe that most, if not all, continental crust was formed early in the history of the earth by rapid separation of core, mantle and crust about 4600 m.y. ago. However, this early crust may have been completely destroyed by events like intense meteoric bombardment (which terminated ~ 3.9 b.y. ago on the moon). Moreover, considering the high thermal regime (documented by high Mg komatiites) during early history of any sialic crust prior to 3800 m.y. ago, the oldest crust thus preserved would represent a fairly advanced stage of crustal evolution. The only dated material older than ~ 4.3 Ga are detrital zircons from metaconglomerate of Neyerer complex, western Australia, which support the existence of continental crust 4.2 b.y. ago[28]. The presence of 3960 ± 3 Ma old gneiss reported from Slave Province of Canada[31] and other Archaean provinces could be the product of (partial) melting of pre-existing tonalite gneiss. These pre-existing gneisses are not found in the exposed crust, either because of having been eroded away or of not being sampled.

The mafic crust

The enclaves of old orthogneiss (TT rocks) within the mafic suite in many Archaean terranes have led geoscientists to postulate early crust of mafic composition in which the plutonic gneisses (formerly TT rocks) intruded[32]. Because of its high density and low buoyancy, the mafic crust is being continuously recycled into the mantle, explaining the absence of Precambrian oceanic crust on the present-day ocean floors. Some proponents[33] of the early mafic crust regard the base of the greenstone belts as ‘primordial oceanic type crust’ (mantle-derived). It is proposed that this primordial oceanic type crust then fractionated to calc-alkaline and granitic rocks via some early analogues of island arc or subduction[19,34–36]. Based on geochemical data, it has been concluded that the earliest crust to have formed would have been predominantly basaltic and the low-density granitic crust was generated later by processes which involved thickening of oceanic crust by collisions or imbrications, whereby partial melting at depths produced TTG rocks[29]. It is, however, not possible to extract large volumes of tonalitic magmas from the primordial oceanic crust or from fractional crystallization of a basaltic magma[29]. The bimodality is against an origin by differentiation of basalts, because the intermediate compositions that would surely be produced are not found in the Archaean terranes. Again, hydrous melting of mantle pyrolite can yield liquids no more siliceous than andesite[37]. It is, therefore, difficult to generate continental crust with a bulk composition less siliceous than andesite by single-stage melting of mantle.

There is no conclusive evidence to suggest that processes in older times were basically different from those of modern plate tectonics. The operation of plate tectonics over much of the earth’s early history has been responsible for: (i) episodic assembly and dispersal of continental lithosphere, (ii) uplift and erosion of mountain belts, (iii) growth and thermal reworking of continental crust and convergent margins, and (iv) disposal of eroded continents into ocean basins. Obviously, no one knows just what did happen in those early days of the earth’s history. But we can only postulate what may have happened from the uniformitarian approach[13]. This is schematically illustrated in Figure 6. About 4000–4500 m.y. ago, there was a hot earth resulting from decay of short-lived isotopes. The core had already differenttiated, but violent convection currents existed in the peridotitic mantle (Figure 6, I). A thin primitive basaltic crust formed over the convective upwells (Figure 6, II). At convective sinks, the primitive basalt crust got re-melted, resulting in andesitic magmas, which erupted over the axis of the sink. Consequently, elongated volcanic chains developed (Figure 6, III). As the andesitic protocontinents were over convective downwellings, their position on the earth’s surface changed along with the convective patterns. The continents could have ‘skidded’ all over the surface, like molten slag at the top of molten iron (Figure 6, IV). The drifting masses of continental ‘slag’ collided with each other to form larger continental masses (Figure 6, V). This thin continental plate (andesitic), with a convection upwell beneath it, fractured and the pieces moved apart resulting in generation of new basaltic (oceanic) crust at the rift zones (Figure 6, VI). As the oceanic plates widened, the leading edges of the advancing continental margins encountered basaltic crust on an opposing convective current. A subduction zone formed and partial melting of the subducted continental plate produced the granitic (TTG) rocks for the first time (Figure 6, VII).

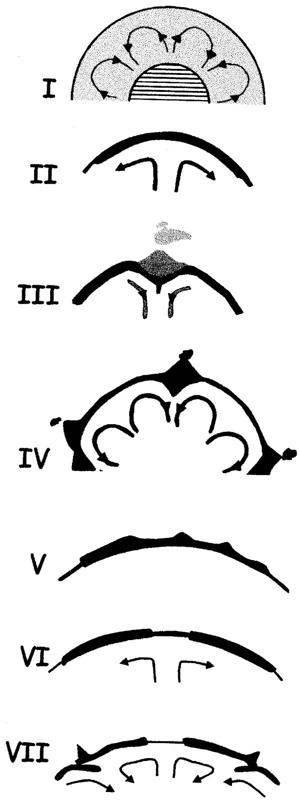

Figure 6. Cartoon illustrating different stages in the development of continental crust (see text for explanation).

The lack of plate tectonics on the moon resulted in the preservation of a record of early differentiation and crust formation. The earth largely eradicated the record of its earliest history as it was hotter, and hence more vigorously convecting, in which recycling and subduction may have played an important role.

A principal limitation in applying the Phanerozoic-type plate tectonic model for the evolution of Archaean TT crust is that there is an overwhelming dominance of TT in the Archaean crust compared to the relatively much subdued occurrences of this association in younger ocean–continental margin batholiths. Perhaps, high thermal gradient and coincidence of dehydration reaction boundaries with the wet solidus are the possible explanations for the situation.

Thickening of continents

A systematic radiometric dating of continental rocks revealed that the continents must have grown more or less continuously over the course of geological time. Average age of continental surface rocks is ~ 2 Ga. Details of growth are uncertain, but determination of crustal volume vs age is of considerable importance for understanding the earth's evolution.

Calculations show that the present volume of continents/age of the earth = average rate of continent growth (~ 2 km^3/yr)[38]. Following the uniformitarian approach, it seems that Arc volcanism may be the primary means by which the continents formed and grew, vertically as well as horizontally. Similar effects are also due to magma underplating the continental crust[39].

The constant recycling of oceanic crust (with superficial sediments) into the mantle causes melt formation from the mantle wedge and from the descending slab, which forms island arcs. Island arc volcanism is accompanied by igneous intrusions. If these arcs are swept together, the underlying intrusions could eventually form huge batholiths, like the ones that form the roots of the Cordilleran mountain ranges characterizing ocean–continent convergent plate boundaries. By this lateral accretion, the island arcs must ultimately become part of the larger continental blocks. Since island arcs are accreted laterally, they suffer intra-crustal melting at depth. Such melt would remove the radioactive heat-producing elements (U, K, Th) and LIL and LREE, and would be emplaced as granodiorite to granite melt in the shallower or higher levels of the crust, leaving behind a residual refractory lower crust of granulite (now seen depleted in LIL and other elements). It is this mechanism that perhaps differentiated the early andesitic continental crust vertically into upper granitic and lower granulite crust.

In summary, the growth of continental crust occurred dominantly by vertical as well as horizontal accretion, volcanic activity and plate tectonic processes. Structural duplication and underplating are important mechanisms by which a crustal segment gets thickened.

Thickness of continental crust during Archaean

In shield areas, continental crust above the Moho has thickness ranging from 35 to 40 km. The crust is divisible into upper and lower parts on the basis of seismic wave velocity. The lower continental crust is mainly granulitic and depleted in LIL and heat-producing elements.

In many Archaean terranes, 8 to 10 kbar pressure has been deduced by geobarometric calculations in surface samples, which indicates an overburden of 28 to 35 km. With a 35 km crust preserved beneath the sampled localities, total thickness of the Archaean crust may have been ~ 70 km, which is of considerable significance from the crustal evolution point of view. Such an estimate assumes that the present-day crustal thickness under these Archaean metamorphic provinces has not been appreciably augmented since the time the metamorphic assemblages were formed[40]. But, on the contrary, the above-stated accretionary processes suggest that the continental volume has been increasing and so also the thickness of the continents. This is in conformity with the decreasing geothermal gradient and general cooling of the earth since its origin. It seems that the maximum thickness of the sialic crust is constrained by its minimum melt temperature, roughly 750°C for water-rich systems. When temperatures exceed this value, the melting ensues and liquids get buoyed up, adjusting the base of the crust at 750°C isotherm. Because of a higher thermal gradient during Archaean times, this 750°C isotherm must have been shallower than at present. A thickened crust by collision with thickness up to 70 km would return to normal thickness of ca. 35 km by uplift, gravitational collapse, erosion and eventual exposure of lower crustal rocks[34]. The juvenile crust formed locally appears to have assembled to produce primitive continents[18,37]. There are also suggestions, rather imprecise, that these primitive continents may have coalesced to form still larger continents. But geoscientists are not sure about the processes by which continents have attained their present-day configuration.

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ACKNOWLEDGEMENTS. R.S.S. thanks CSIR, New Delhi for a grant under the Emeritus Scientist Scheme. We thank the anonymous reviewer for helpful comments which improved the manuscript. We acknowledge the facilities provided by the Head, Department of Geology, University of Rajasthan.

Received 11 April 2002; revised accepted 31 December 2002