MECHANISMS OF CONTINENTAL CRUST GENERATION THROUGH GEOLOGIC TIME AND ITS CHEMICAL COMPOSITION

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Abstract

The Earth formed approximately 4567 million years ago from the solar nebula. Although in theory planets should have similar compositions according to their formation time, they have experienced geochemical differentiation. In the case of Earth, this differentiation is manifested in its structure of core, mantle, and crust, resulting from the segregation of metallic iron and nickel from silicate material. This paper reviews the mechanisms of continental crust generation throughout geologic time, from the initial magma ocean to the establishment of plate tectonics. The geophysical and geochemical evidence of early differentiation, the record of Archean komatiites, the transition toward more evolved compositions in the Proterozoic, and the tectonic models proposed for the formation of granulites and anorthosites are analyzed. The integration of isotopic and trace element data allows reconstructing the compositional evolution of the crust and evaluating the role of processes such as subduction, mafic underplating, and crustal thickening in different geodynamic contexts. Recent studies on komatiite alteration and anorthosite complexes provide new constraints on Archean surface conditions and Proterozoic magmatic systems, reinforcing the operation of plate tectonic processes since at least 3.8 Ga.

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ABSTRACT

The Earth formed approximately 4567 million years ago from the solar nebula. Although in theory planets should have similar compositions according to their formation time, they have experienced geochemical differentiation. In the case of Earth, this differentiation is manifested in its structure of core, mantle, and crust, resulting from the segregation of metallic iron and nickel from silicate material. This paper reviews the mechanisms of continental crust generation throughout geologic time, from the initial magma ocean to the establishment of plate tectonics. The geophysical and geochemical evidence of early differentiation, the record of Archean komatiites, the transition toward more evolved compositions in the Proterozoic, and the tectonic models proposed for the formation of granulites and anorthosites are analyzed. The integration of isotopic and trace element data allows reconstructing the compositional evolution of the crust and evaluating the role of processes such as subduction, mafic underplating, and crustal thickening in different geodynamic contexts. Recent studies on komatiite alteration and anorthosite complexes provide new constraints on Archean surface conditions and Proterozoic magmatic systems, reinforcing the operation of plate tectonic processes since at least 3.8 Ga.

Keywords: continental crust, geochemical differentiation, komatiites, granulites, plate tectonics

1. INTRODUCTION

1.1 Early geochemical differentiation of the Earth

The Earth formed together with the solar system from a diffuse mass of interstellar gas and dust known as the solar nebula, which originated approximately 4567 million years ago (White, 2015). Although in theory planets should have similar compositions according to their formation time, they have experienced geochemical differentiation. In the case of Earth, geochemical differentiation can be visualized in the three layers that compose it: core, mantle, and crust. This process involved the separation of metallic iron and nickel from silicate material.

Geophysical records indicate an increase in density and seismic wave velocities with depth, which has allowed determining the geochemical differentiation of the planet, complemented by geochemical studies of xenoliths and primitive magmas. The Earth presents several discontinuities that separate different chemical compositions. The main ones are: the Mohorovicic discontinuity (Moho), located at approximately 40km depth, and the boundary between the core and mantle, called the Wiechert-Gutenberg discontinuity, at 2883km depth (Faure, 1998).

The fundamental question is: how did the crust evolve to its present state? Various models have attempted to explain this process. To address this, it is necessary to analyze the initial composition of the planet, which can be inferred from the most primitive meteorites. The Allende meteorite provides a formation age of 4567.32±0.42Ga by the Pb-Pb system and 4564.71±0.30Ga by $^{238}U/^{235}U$ ratios (White, 2015).

Studies of hafnium and tungsten isotopes have been fundamental to determine the extraction of hafnium into the core, given that the present crust presents higher concentrations of this element compared to chondrites. From these studies, ages for core formation have been estimated between 45 and 90 million years after the formation of the solar system. Specifically, variations in $^{182}W/^{183}W$ indicate that at least 45-90 million years elapsed between chondrite formation and Earth's core formation. Other authors have specified a minimum time of 62 million years for this process (Lee and Halliday, 1995 cited in White, 2015).

A widely accepted theory postulates that Earth's accretion and core formation were induced by a giant impact that also gave rise to the Moon. This event produced widespread melting of both celestial bodies, generating an extensive magma ocean that allowed the segregation of silicate material from iron, thus differentiating the mantle from the core (White, 2015).

Variations in $^{142}Nd/^{148}Nd$ isotopes and stable oxygen isotopes ($\delta^{17}O$ and $\delta^{18}O$) corroborate the chemical differentiation of Earth relative to chondritic composition (Fig. 1). This figure shows the terrestrial differentiation trend when comparing the concentrations of primitive chondrites (initial composition) with differentiated chondrites, which represent the early stages of differentiation. It is observed that Earth and the Moon have oxygen isotope patterns similar to those of eucrites (differentiated chondrites).

Additionally, metavolcanic rocks of 3.8Ga from the Isua area in Greenland present an excess of ^{142}Nd, with Nd concentrations equivalent to those of chondrite. This evidence has been interpreted as indicative that the magmatic reservoir had a high Sm/Nd ratio and formed early, within the first 100Ma of Earth's history (White, 2015).

1.2 The initial composition of the crust and the magma ocean

The initial composition of the crustal reservoir is related to matter differentiation and the cooling rate of the magma ocean. This process involved crustal stratification during cooling, its solidification, and subsequent remelting, with separation of residual magmas until complete crustal solidification was achieved. This solidification depended critically on forsterite formation, since peridotite is rich in this crystalline phase (Pilchin and Eppelbaum, 2012).

Under the prevailing thermal conditions, carbonate rocks were unstable and decomposed, injecting CO_2 into the atmosphere, which modified its composition and increased its density. Hydrated conditions were unlikely in this context. Some authors suggest that the crust may have experienced slab subduction to depths of 100km by the late Archean, and that this increase in crustal thickness was gradual and associated with temperature increase (Pilchin and Eppelbaum, 2012).

Under these conditions, the oceanic magma would have organized into layers of different density, where the denser ones tended to sink. Pilchin and Eppelbaum (2012) introduced fundamental physical considerations for this process: 1) magma from a dense layer within the ocean could not ascend through the melt if the overlying layers (magmatic slabs) already overlay it; 2) an intermediate magma layer could not erupt before the overlying felsic magma layers had solidified; 3) magma from a basic magmatic slab could not erupt to the surface until the overlying intermediate or felsic magmas had also solidified; and 4) ultramafic magmas could not erupt until these upper layers had solidified. The duration of this magma ocean is debated, with estimates ranging from 1-10Ma to 100-200Ma.

2. SCOPE AND METHODOLOGY OF THIS REVIEW

This paper presents a synthetic review of the mechanisms of continental crust generation from the Hadean to the Proterozoic. The review focuses on three key rock records that serve as proxies for geodynamic processes: (1) Archean komatiites and tholeiites (3.8–2.5 Ga) as indicators of mantle temperature and early tectonic settings; (2) Proterozoic granulite-facies metamorphic terrains (2.5–0.9 Ga) as records of crustal thickening and thermal regimes; and (3) massif-type anorthosite complexes (1.8–0.9 Ga) as markers of Proterozoic magmatic underplating.

A systematic, qualitative synthesis of the peer-reviewed literature was conducted. Primary sources were identified through searches in Web of Science, Google Scholar, and GeoRef using targeted keyword combinations, including "continental crust evolution," "Archean komatiite petrogenesis," "Proterozoic anorthosite," "granulite geodynamics," and "early Earth tectonics." Priority was given to studies published in the last two decades that present original isotopic (Sm–Nd, Lu–Hf, U–Pb, O) and trace element data, as these provide the most direct constraints on crustal sources and processes. Key historical papers (pre-2000) were included where they provide foundational petrological observations (e.g., komatiite spinifex textures) or introduce influential tectonic models (e.g., Newton's granulite scenarios) that remain central to current debates. The information is organized chronologically to trace the compositional and tectonic evolution of the crust. Tectonic models are evaluated comparatively against the geochemical and petrological constraints derived from the compiled dataset.

3. RESULTS

3.1 The Archean record: komatiites and tholeiites

Archean komatiites (3.4Ga to 2.7Ga) constitute a fundamental source of information about the processes of new crust generation. Their composition is characterized by the formation of MgO-enriched olivine crystals, which were fractionated from the liquid to produce the characteristic textures of spinifex lavas, while another fraction accumulated in cumulates. Elemental variations in komatiites reflect the compositions of the oldest magmas, characterized by high concentrations of alumina, titanium, and nickel, with linear relationships relative to olivine composition. These magmas are distinguished by their high CaO/Al_2O_3 ratios and low Al_2O_3/TiO_2 ratios, in addition to depletion in heavy rare earth elements (HREE), quantified by the (Gd/Yb)N ratio (Fig. 2). Recent studies on komatiites from the Barberton region confirm that these high-MgO lavas underwent extensive serpentinization near the Archean seafloor, with implications for the thermal and chemical evolution of the early crust (Tamblyn and Hermann, 2023).

The greenstone belts where these rocks were emplaced consist of supracrustal sequences approximately 5-10km thick. The emplacement mechanism included sill intrusions and lava flow extrusions. Another type of magmatism recognized in these belts is tholeiitic basalts, which exhibit pillow lava structures and accretionary lapilli indicative of shallow marine environments. Andesites occur in lesser proportion and, volumetrically even more reduced, lava flows and volcaniclastic deposits of silicic composition. In the latter, an evolutionary trend from basaltic compositions toward intermediate magmas during the Proterozoic is recognized.

In Archean rocks, pressure-temperature (P/T) gradients were low to intermediate. The oldest rocks with high P/T ratios correspond to greenschist to blueschist metamorphic facies, underlain by unmetamorphosed sedimentary rocks of 800Ma in northwestern China (Liou et al., 1989 cited in Best, 2003).

Trace element geochemistry in Archean tholeiites (including komatiites), normalized to mantle composition, shows low potassium contents and patterns reflecting enrichment in large ion lithophile elements (LILE) and negative niobium (Nb) anomalies. These patterns are not comparable with those of mid-ocean ridge basalts (MORB), showing greater similarity to island arc tholeiites (IAT) (Fig. 3).

Komatiites also appear associated with intermediate and felsic volcanic rocks, configuring a bimodal type volcanism. The intermediate and felsic compositions present trace element patterns typical of calc-alkaline magmas. The presence of associated shoshonitic, adakitic, and boninitic rocks suggests that plate tectonics, particularly in subduction environments, offers a plausible explanation for these processes already in the Archean. This interpretation is reinforced by recent arguments that stagnant lid models are not viable for the Archean because the lower oceanic crust is dry and lacks the water required for melting; instead, subduction likely operated from at least 3.8Ga, albeit transiently and at shallow depths (Arndt, 2023).

Supracrustal rocks of 3.8Ga have been documented in Greenland (Jacobsen and Wasserburg, 1979 cited in Best, 2003). In these sequences, banded iron formation (BIF) sediment layers appear intercalated with metaintrusive rocks. It is interpreted that these rocks precipitated in oceanic basins proximal to fumaroles, where iron enriched both mafic volcanic rocks and sediments. Additionally, evidence of oceanic basin closure has been identified, and the presence of Archean island arcs and continental shear zones has been inferred as generating mechanisms for volcanism in these belts (Fig. 4).

Thermobarometric estimates in Archean granulites indicate pressures close to 10kbar, which, considering the high thermal gradient, correspond to a minimum crustal thickness of 25km. An alternative mechanism of crustal generation, documented in the Kaapvaal Craton trondhjemite suite, involves convergent tectonism with formation of imbricated layers. These layers, due to their high buoyancy, did not subduct and adhered to mafic oceanic rocks and island arcs, generating crustal thickening that allowed dehydration and partial melting to form igneous bodies (Best, 2003).

3.2 The Proterozoic: granulites, anorthosites, and crustal generation models

Granulites are metamorphic rocks recrystallized at high temperatures in environments associated with the presence of anorthositic bodies with ages between 1.8 and 0.9Ga (Morse, 1992; Ashwal, 1993 cited in Cisneros, 2015). These anorthosites are accumulations composed of up to 90% plagioclase. In some cases, they show no evident relationship with gabbroic bodies, with anorthosites of this type being generally Proterozoic in age. However, more calcic compositions associated with banded mafic rocks of the Archean are also recognized. The architecture of large anorthosite suites, such as the Mesoproterozoic Kunene Complex in Angola/Namibia, reveals multiple magmatic pulses over tens of millions of years, supporting models of long-lived, multi-injection magmatic systems in the Proterozoic (Lehmann et al., 2023). Complementary geochemical patterns of anorthosites, such as Fe/Fe+Mg ratios and REE distributions, are shown in Fig. 7 (Best, 2003). Additionally, εNd values for Proterozoic anorthosites indicate mantle components with εNd around +1, trending toward more negative values (up to -4) due to assimilation of upper crustal rocks (Fig. 8; Best, 2003).

Newton (1987) synthesized four scenarios proposed by various authors to explain the generation of metamorphic complexes associated with granulite facies during the Proterozoic. Given that paleotemperatures were very high in the Archean, the emplacement mechanisms of these magmas required substantial heat sources, with partial melting and depletion being the predominant processes.

First scenario (Mantle plume with underplating): Magmatic anorthosites would come from a mantle plume that injected mafic magmas into the crust through underplating, associated with a thermal anomaly. This process originated a high degree of metamorphism by crustal thickening, with lateral increase of paleotemperatures that produced transition zones to granulite facies, without significant changes in paleopressure, and favored the emplacement of gabbroic bodies at greater depth (Fig. 5A).

Second scenario (Nappe-stacking): This model involved a compressive regime where tectonic wedges adhered to pre-existing crust (Fig. 5B). However, it did not satisfactorily explain magma generation at shallow depth, as it would require crustal thickening of at least 30km. Additionally, the increase in heat and pressure did not adequately support the origin of metamorphic rocks in granulite facies, and for anorthositic rocks, formation was postulated 300Ma prior to the metamorphic event.

Third scenario (Accordion-type thickening): Similar to current collision tectonics, this model proposed crustal thickening by accordion-type shortening, with magma ascent from a subduction zone and vertical control of metamorphism.

Fourth scenario (Continental underthrusting): This mechanism involved an increase in crustal thickness by subduction of one lithospheric mass beneath another (Fig. 5C). The lower plate recorded metamorphism in amphibolite facies, followed by post-orogenic exhumation associated with evaporites, interpreted as lubrication horizons for underthrusting. This model, documented in Oaxaca, satisfactorily explained metamorphism in granulite facies.

Subsequently, Shaw (1993 cited in Best, 2003) proposed a model for the generation of anorthositic magmas (Fig. 6), similar to scenario A of Newton (1987). This model involves underplating of basaltic magmas, where mafic crystals associate with plagioclase crystals that float in the melt. Progressive crystallization destabilizes the floating plagioclase, forming igneous diapirs that ascend. These diapirs separate from the residual mafic fraction and move toward upper crustal levels.

4. DISCUSSION

Magma generation mechanisms in the geologic past present fundamental similarities with current ones, although with significant differences derived from distinct thermal conditions. At the beginning of Earth's history, geothermal gradients were considerably higher due to the prevailing high temperatures. The primitive crust began as a magma ocean that recycled already cooled crustal fragments in a repetitive cycle of cooling, melting, and renewed cooling.

The dominant crustal generation processes were fractional crystallization and partial melting. In these processes, olivine crystallized early, together with plagioclase, giving rise to compositions similar to tholeiitic series. The geochemical evidence from Archean komatiites, with their high generation temperatures and trace element signatures suggesting subduction contribution, indicates that processes similar to those of modern convergent margins were already operating in the Archean, although probably with different geometries and rates due to higher thermal flow. The recent demonstration that komatiites underwent extensive serpentinization near the Archean seafloor (Tamblyn and Hermann, 2023) provides additional constraints on surface conditions and fluid-rock interactions during the early evolution of the crust.

The transition toward the Proterozoic marks the definitive establishment of plate tectonics as the dominant mechanism of crustal generation. As Arndt (2023) recently argued, models invoking a stagnant lid regime for the Archean face a fundamental problem: the lower oceanic crust is dry and lacks the water required to generate granitic melts through partial melting. This supports the interpretation that subduction, and therefore plate tectonics, has been operating since at least 3.8 Ga, even if in a transient or shallow form. In this period, tholeiitic rocks, although still present, begin to be accompanied by significant volumes of felsic and intermediate rocks of calc-alkaline series. The deposition of metasediments and banded iron formations, intercalated with basaltic lavas in marine environments, attests to the incorporation of erosion, sedimentation, and early biological activity processes into the crustal cycle.

The diversity of models proposed to explain the generation of Proterozoic granulites and anorthosites reflects the complexity of tectono-thermal processes in this period. The mantle plume underplating model (scenario A of Newton, 1987; Shaw, 1993) is particularly attractive because it coherently integrates: 1) an anomalous heat source (plume), 2) a crustal thickening mechanism (underplating), 3) generation of high-temperature metamorphism without need for extreme pressures, and 4) a specific petrogenetic process for anorthosite formation by plagioclase flotation and diapiric ascent. This model explains satisfactorily the temporal and spatial association of granulites and anorthosites in several Proterozoic cratons. Studies of large anorthosite complexes such as the Kunene Complex reveal that these systems were built by multiple magmatic pulses over tens of millions of years, consistent with long-lived underplating processes (Lehmann et al., 2023). These petrogenetic interpretations are supported by trace element and isotopic evidence from anorthosites, including positive Eu anomalies and LREE enrichment (Fig. 7), as well as Nd isotopic signatures that suggest variable crustal contamination (Fig. 8; Best, 2003).

On the other hand, tectonic stacking (nappe-stacking) and continental underthrusting models are more consistent with collisional compressive regimes, but require additional mechanisms to explain the high thermal flow necessary for granulite metamorphism. In these cases, it is probable that heat was supplied by subduction-associated magmatism or post-collisional lithospheric thinning.

The presence of evaporites associated with underthrusting terrains, as in Oaxaca, suggests that surface processes can influence deep tectonic dynamics, acting as lubricating agents that facilitate the overthrusting of large crustal masses. This interaction between surface and deep processes is a topic of growing interest in current geodynamics.

Overall, petrological and geochemical evidence indicates that continental crust has evolved from predominantly mafic-ultramafic compositions in the Archean toward more felsic and intermediate compositions in the Proterozoic and Phanerozoic. This evolution reflects not only the gradual cooling of the planet and the decrease in thermal flow, but also the establishment and maturation of subduction and crustal recycling cycles that characterize modern plate tectonics.

5. CONCLUSIONS

1. The early differentiation of Earth, occurring within the first 100 Ma of its history, established the core-mantle-crust structure, with evidence preserved in isotopic systems such as Sm-Nd, Lu-Hf, and O.
2. The initial magma ocean generated a primitive crust through fractional crystallization and partial melting, with a critical role of differential buoyancy of mineral phases in crustal stratification.
3. Archean komatiites (3.4-2.7Ga) document high generation temperatures and geochemical signatures (LILE enrichment, negative Nb anomalies) that suggest subduction processes already operative in the Archean. Recent studies confirm that these lavas underwent extensive serpentinization near the Archean seafloor, with implications for early crustal evolution (Tamblyn and Hermann, 2023).
4. The Archean-Proterozoic transition marks the establishment of modern plate tectonics, with generation of calc-alkaline magmas, crustal thickening, and

formation of granulites. As argued by Arndt (2023), stagnant lid models are not viable for the Archean due to the absence of water in the lower oceanic crust, reinforcing that subduction has operated since at least 3.8 Ga.

5. Proterozoic anorthosites (1.8-0.9Ga) formed preferentially by mafic underplating associated with mantle plumes, with diapiric ascent of floating plagioclase, although tectonic stacking and underthrusting models may also explain some complexes. The architecture of large anorthosite suites, such as the Kunene Complex, reveals multiple magmatic pulses over tens of millions of years, supporting long-lived underplating processes (Lehmann et al., 2023).
6. The compositional evolution of continental crust reflects planetary cooling and maturation of geodynamic cycles, with a trend from mafic-ultramafic compositions toward more felsic and intermediate compositions.

6. ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1. Oxygen isotope diagram ($\delta^{17}O$ vs. $\delta^{18}O$) showing the terrestrial fractionation trend (solid line) compared to different groups of chondrites. CO, CK: carbonaceous chondrites; H, L, LL: ordinary chondrites; HED: howardite-eucrite-diogenite meteorites (eucrites or differentiated chondrites). Earth aligns with the eucrite field, evidencing its early differentiation. Modified from White (2015).

Figure 2. (Gd/Yb)N vs. Al_2O_3/TiO_2 ratios for komatiites from the Barberton and Pilbara cratons. Low Al_2O_3/TiO_2 ratios correlate with high (Gd/Yb)N ratios, reflecting heavy rare earth element depletion in the mantle source. Modified from Arndt (1994).

Figure 3. Mantle-normalized multielement diagram for Archean tholeiites, compared with patterns of N-MORB, OIB (ocean island basalts), and IAT (island arc tholeiites). The pattern of Archean tholeiites, with LILE enrichment and negative Nb anomaly, is similar to that of IAT. Modified from Arndt et al. (2008).

Figure 4. Schematic section of Archean subduction in the southern-central Superior Province of the Canadian Shield. Modified from Hoffman (1989) in Best (2003).

Figure 5. Schematic models for the generation of Proterozoic granulite and anorthosite terrains. (A) Mantle plume underplating model. (B) Nappe-stacking model. (C) Continental underthrusting model. Modified from Newton (1987).

Figure 6. Model of anorthosite generation by mafic underplating and diapiric ascent of plagioclase. Modified from Shaw (1993) in Best (2003).

Figure 7. (A) Fe/Fe+Mg vs. SiO_2 diagram for anorthosites and associated rocks from the Morin Massif. (B) Primitive mantle-normalized REE patterns for anorthosites, showing positive Eu anomalies and LREE enrichment relative to HREE. Modified from Best (2003).

Figure 8. εNd values for Proterozoic anorthosites, showing mantle components with εNd values around +1, trending toward more negative values (up to -4) due to assimilation of upper crustal rocks. Fields for high-Al basalt parent magma, Proterozoic granitoids, and Archean greenstone are shown for reference. Modified from Best (2003).

Figure 1

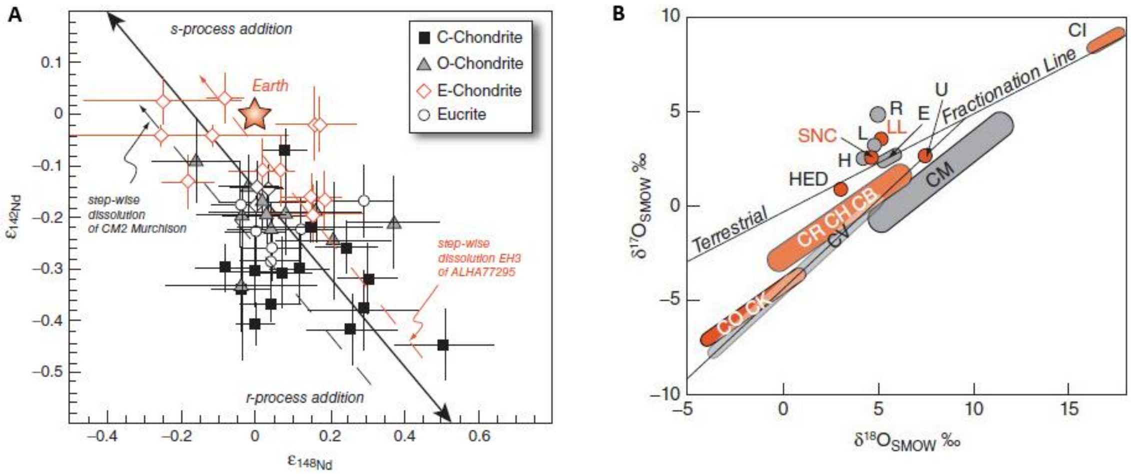
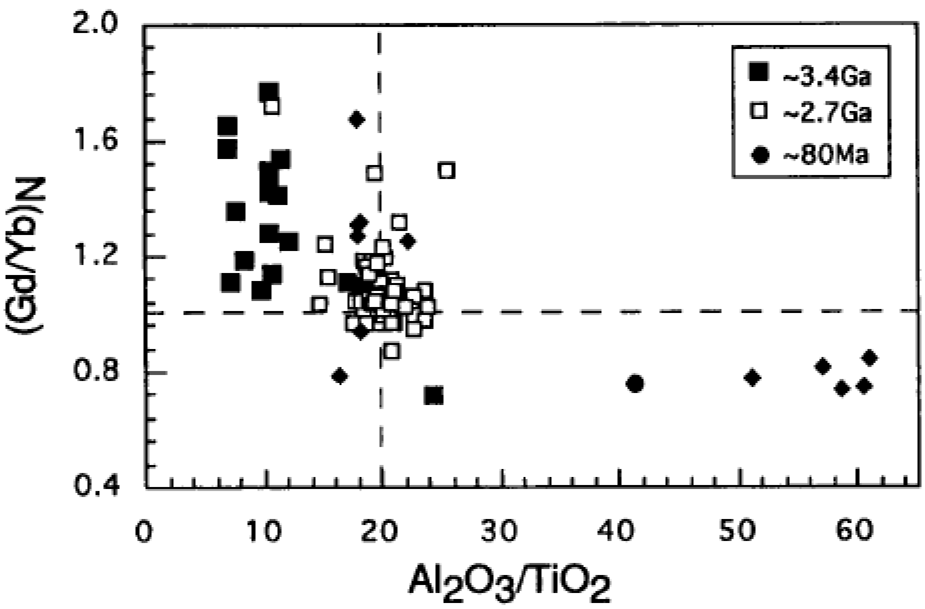


Figure 2



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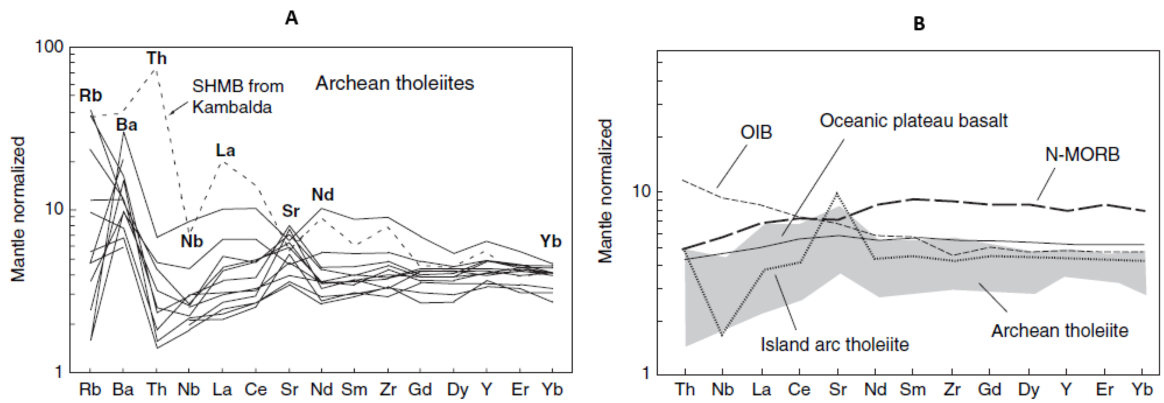

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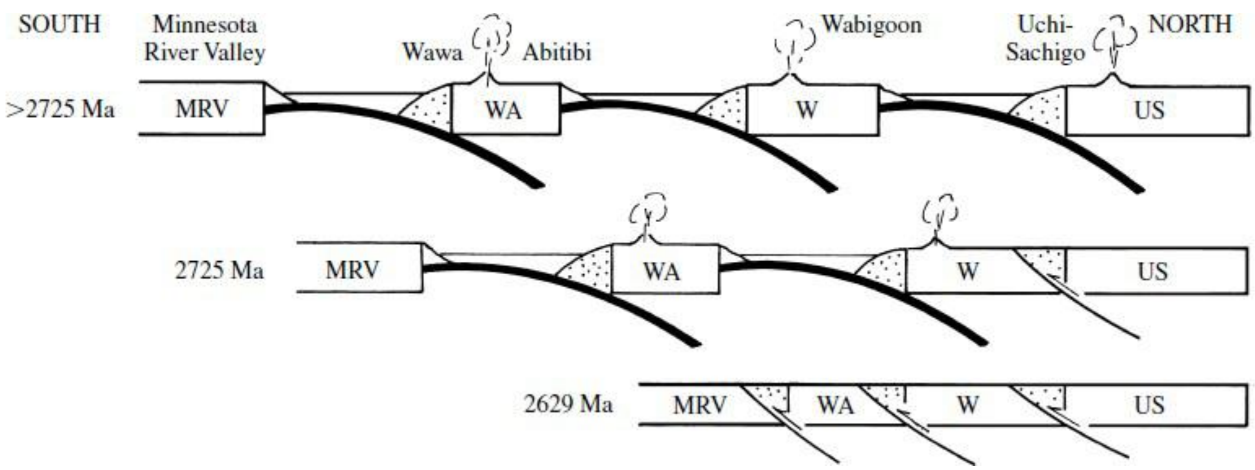

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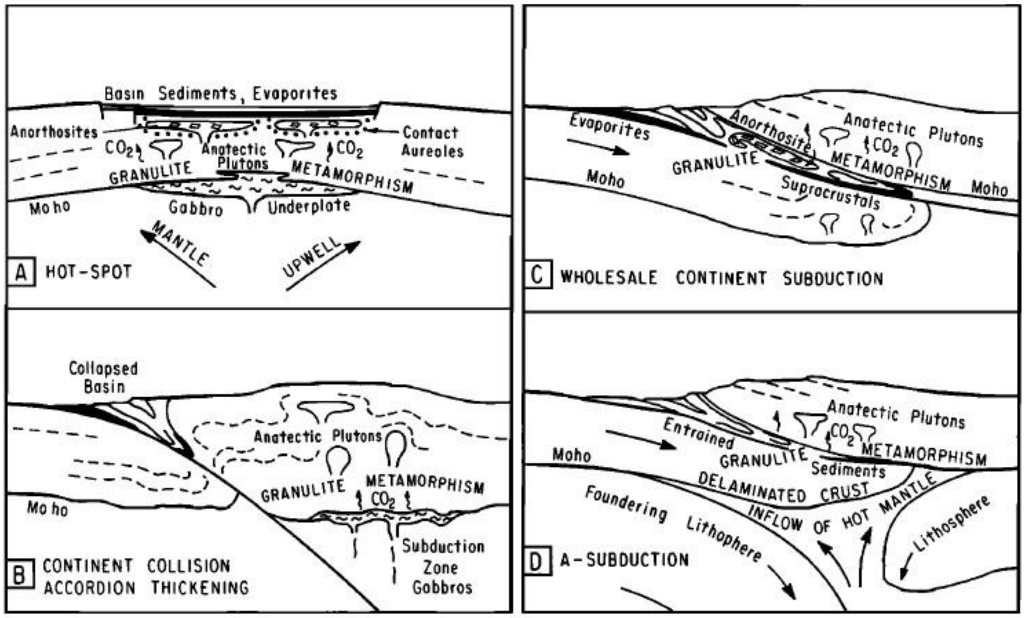

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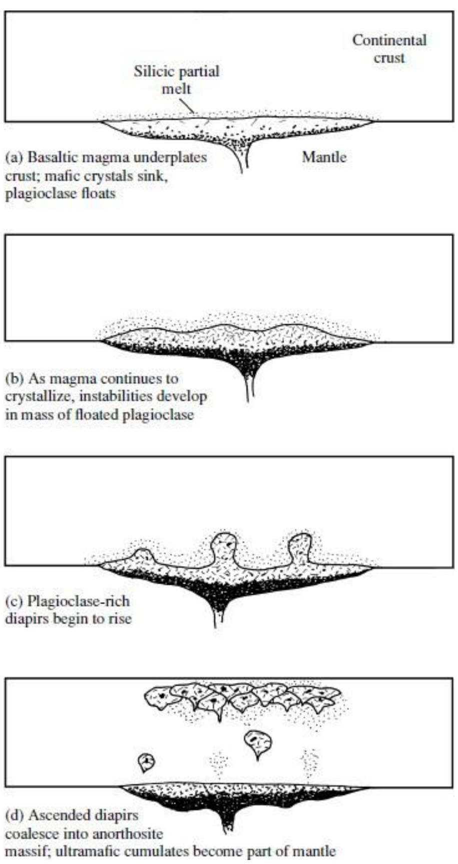
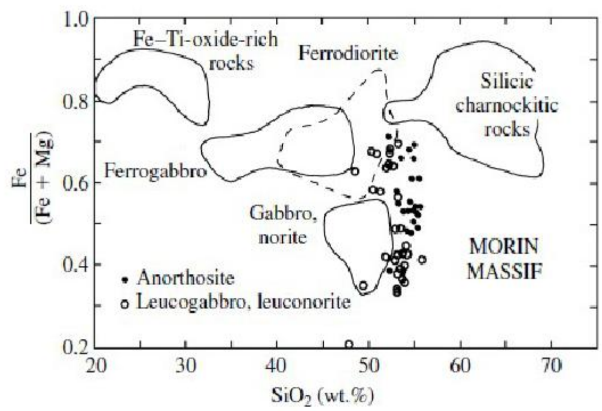


Figure 7

A



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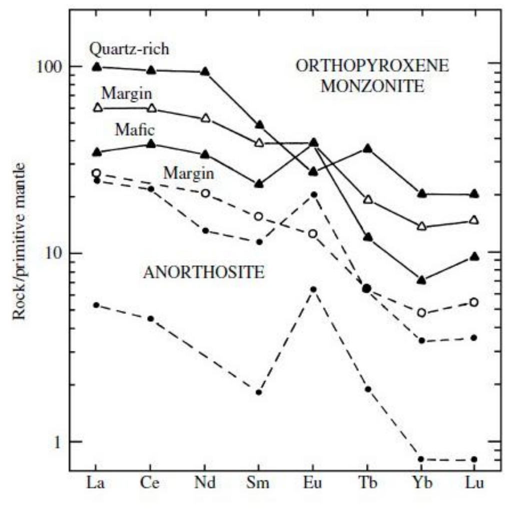

Figure 8