Evolution of the Archaean continental crust: Insights from the experimental study of Archaean granitoids

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Experimental petrology is a valuable tool to test different models proposed to account for the origin of Archaean granitoids. However, a feasible petrogenetic model needs to be supported by studies from different disciplines. Therefore, the present article is a synthesis of experimental studies on the origin of Archaean granitoids (TTG and K-rich granites). Besides, a review of the published work about their origin is briefly discussed. Finally, the experimental synthesis and new results, along with the review presented allow us to propose a model for the evolution of the early continental crust.

The petrogenetic evolution of the Archaean crust was catalysed by progressive decrease in geothermal gradients. The thermal structure of the early Archaean down-going plates was favourable for melting the oceanic crust at low depths ($P < 10$ kbar) in subducting slabs to produce TTG magmas, without interaction with the mantle during ascent. The progressive cooling of the earth produced an increase in the dip of the subducting slab, favouring partial melting of the basaltic rocks at higher depths ($P > 10$ kbar) and the interaction of TTG magmas with the overlying mantle wedge. Crustal evolution at the Archaean–Proterozoic boundary was dominated by the generation of different sort of voluminous K-granite batholiths, the origin of which is controversial. In this study, it is considered an origin of K-granites by interaction between hydrous sanukitoid magma and tonalitic crust.

Keywords: Archaean granitoids, continental crust, experimental petrology, K-granites, TTG complexes.

There are no continental rocks older than 4.0 Ga. This could be indicative either of the presence of unstable older continents subjected to an extreme extraterrestrial bombardment, or simply to the fact that continents were very rare at that time. The subsequent processes of continental crust formation were modulated by the decrease in heat production of the planet. It is broadly accepted that some form of plate tectonics operated during the Archaean, and the authors who support a model of Archaean plate tectonics often suggest that it must have been characterized by the presence of many small plates of basaltic or komatiitic composition. Therefore, the formation of a basaltic oceanic crust (4.5 Ga) preceded the formation of a felsic continental crust (4.0 Ga). Alternatively, other authors have proposed tectonic regimes for the Archaean, which differ qualitatively from those of post-Archaean times. On the other hand, different models of continental growth have been proposed, which were summarized by Taylor and McLennan. These models range from those that suggest an extremely early crustal growth (pre 4.0 Ga) followed by a simple recycling of the crust, to those that propose a continuous growth throughout the geological time. The Archaean–Proterozoic boundary is considered as a limit of prime geological relevance in relation to the growth of the continental crust. From a compositional point of view, the Archaean continental crust is made of Na-rich lithologies against the K-rich igneous rocks predominant in the post-Archaean crust. Consequently, understanding the origin, transport and emplacement of Archaean granitoids is essential with regard to the study of the evolving continental crust.

The Archaean continental crust is mainly composed of grey gneisses, collectively known as TTG (tonalite–trondhjemite–granodiorite) complexes, volcano-sedimentary basic rocks (greenstone belts), and GGM (granite–granodiorite–monzogranite) suite. The study of the GGM suite or K-granites has considerably increased during the last decade, and it has been possible to sort out different types of granites that also imply different sources and origin processes. The principal hypothesis proposes an origin of K-granites, referred to as Bt-granites by Moyen et al., by partial melting of older tonalitic gneisses, perhaps together with mixing with mantle-derived magmas. On the other hand, the Archaean continental crust is also characterized by the presence of mantle-derived igneous lithologies referred to as sanukitoids.

Background to the origin of Archaean granitoids

The TTG complexes were the embryos of the continental crust. Around 90% of the Archaean juvenile continental crust belongs to this suite. These lithologies are charac-
terized by high silica (> 64 wt.%), low K/Na ratio (< 0.48; average 0.36) and strong fractionated REE patterns with average (La/Yb)N of 38.4, but it can be higher than 150. Besides, TTG complexes show variable content in ferromagnesian components (Fe2O3 + MgO + MnO + TiO2 = 0.5–5 wt%), with an average Mg# of 0.43 (Mg# = MgO/[MgO + FeO], mol), and show average Ni and Cr contents of 14 and 29 ppm respectively. Unravelling their origin is the first step in the knowledge of crustal evolution. In this sense, many petrogenetic studies have focused on the generation of these Na-rich igneous lithologies and different studies have presented the main results of the experimental approach to this problem.

The different proposed processes for the origin of TTGs include fractional crystallization of basaltic magmas, mantle melting, re-melting of older tonalitic materials, partial melting of basaltic rocks or their metamorphic equivalents, and Na-metasomatism of pre-existing granites. The geochemical signatures of the TTG rocks are the main test for these models. The most significant feature of these rocks is their strongly fractionated REE patterns, which are depleted in HREE. This characteristic led to the evolution of the continental crust, as a compositional change took place in the continental crust at the Archaean–Proterozoic boundary. The origin of these K-granites constitutes one of the most important topics with regard to the evolution of the mantle wedge by ascending melts generated from the partial melting of subducting basalts.

Some K-rich granites appeared associated with sanukitoids at the end of the geological evolution of cratons showing syn- and post-kinematic characteristics. Therefore, sanukitoids and K-rich granites have been related to the process of craton stabilization. The origin of these K-granites is an important topic with regard to the evolution of the continental crust, as a compositional change took place in the continental crust at the Archaean–Proterozoic boundary. K-granites belong to the calc-alkaline series and show high K/Na ratio (commonly > 1), high Nb (150–250 ppm) and Sr (150–600 ppm). With regard to REE patterns, these lithologies show variable REE patterns and (La/Yb)N ratios [LaN/YbN = 38(±6) or 80(±24)]11; (LaN/YbN = 10–60)]12; (LaN/YbN = 6–64)]12. Generally, their REE patterns may show slight enrichment in LREE and slight depletion in HREE, compared with the patterns of TTG rocks and show negative Eu-anomaly (Eu/Eu* = 0.2–0.7, where Eu/Eu* is EuN/[15Sm5GdN]). There are many hypotheses concerning the origin of late-Archaean K-granites. These include partial melting of pre-existing tonalities, alkaline metasomatism, fractional crystallization of granitic or TTG magmas, derivation from the mantle, and mixing between sanukitoid magmas and anatectic melt derived from migmatization of TTG complexes. The partial melting of older tonalitic gneisses has been widely proposed to account for the origin of K-granites. The high 87Sr/86Sr initial ratio has been cited as evidence for the participation of older crustal rocks in their origin. According to Condie et al., the source rock of the K-granites is tonalite together with the participation of a fluid enriched in K, Rb, Ba and LREE. Other
authors proposed that K-granites are a product of the interaction between an old tonalitic crust and mantle-derived magmas. This association has been established on the basis of field and geochemical relations in late Archaean cratonic areas such as the Superior Province of Canada, the Dharwar Craton in India and the North Marginal Zone of the Limpopo Belt in Zimbabwe.

New experimental results

Methodology

Experiments were carried out in end-loaded, solid-medium piston-cylinder apparatus at the University of Huelva, Spain. NaCl–graphite cell assemblies of 12.7 mm diameter were used, wherein samples were contained in welded Au capsules of 2.4 mm inner diameter and with 0.3 mm wall. In hydrous experiments, the appropriated amount of water was added with a micro-syringe, in natural samples, or in the form of Al(OH)₃ in synthetic glass. Analyses were made by energy-dispersive spectrometry (EDS) attached to an SEM. Melt fraction and modal abundances were calculated by image analyses using compositional images (back-scattered electron images) and the NIHimage software.

Experimental generation of tonalites and trondhjemites

The chosen starting material is the Acebuches amphibolites from the Aracena metamorphic belt (Variscan massif, southwest Spain). These amphibolites have a MORB geochemical signature and represent an exhumed fragment of a Palaeozoic oceanic crust, subducted during the Variscan orogeny. Hornblende (49 vol. %), plagioclase (46 vol. %; An₆₂) and ilmenite (5 vol. %) characterize the modal composition of these rocks. The experimental study of fluid-absent melting of amphibolites has been carried out in an extensive range of pressure and temperature conditions, between 4 and 14 kbar as well as 725 and 950°C. These conditions cover the subsolidus and supersolidus fields. The melting reaction produced tonalitic melt and different peritectic phases (clinopyroxene, orthopyroxene, epidote and garnet) depending on experimental conditions, as will be described below.

Composition of melts obtained by dehydration partial melting of the Acebuches amphibolites is similar to that of natural TTG rocks with tonalitic composition. The experiments indicate a decrease in the FeO, MgO, CaO and TiO₂ contents in melts with increasing pressure (Figure 1); therefore, the composition becomes more trondhjemitic with increasing pressure, thereby confirming the observations of Winther and Newton. TTG magmas are typically depleted in HREE, which require the presence of amphibole and/or garnet as solid phases during their genesis, the presence of which has been confirmed experimentally.

The main conclusions from our previous studies were that at pressures lower than 10 kbar, clinopyroxene, amphibole and plagioclase (± Opx) dominate the experimental assemblage. However, at pressures higher than 10 kbar, the experimental assemblage is made up of clinopyroxene, garnet, plagioclase, amphibole and epidote at temperatures close to the solidus. Therefore, our experimental results show that at high pressures (>10 kbar), the melt composition tends to be trondhjemitic (Figure 1), with garnet appearing as a new peritectic phase.

On the other hand, as it was previously exposed, one of the most important features of TTG rocks is their depletion in HREE. To explain this feature, the REE content of the experimental melt has been calculated according to the batch melting equation:

\[
\frac{C_i}{C_0} = \frac{1}{[D_{RS} + F(1 - D_{RS})]}.
\]

where \(C_i\) and \(C_0\) are the concentration of the element in the melt and unmelted source (starting material) respectively, \(F\) is the weight fraction of melt produced and \(D_{RS}\) is the bulk partition coefficient obtained by the expression:

\[
D_{RS}^i = x_1K_{d1} + x_2K_{d2} + x_3K_{d3} + ...,
\]

where \(D_{RS}^i\) is the bulk partition coefficient for the element \(i\), \(x\) is the weight proportion of mineral and \(K_{d}\) the partition coefficient for the element \(i\) in that mineral.

The REE contents obtained by this procedure are shown in Table 1 and Figure 2. In the experiments with garnet as a peritectic phase of the partial melting process, the REE patterns obtained show higher HREE depletion and LREE enrichment, which is characteristic of TTG gneisses, and a slight positive Eu anomaly (Figure 2).

Experimental generation of K-granites

Most of the late Archaean K-granites belong to the Bt-granite type and they are considered as a product of partial melting of older TTG gneisses. In this sense, different experimental studies were carried out to determine the partial melting process of Bt-Hbl-bearing tonalite, similar to TTG gneisses. The partial melting of tonalitic material under fluid-present (hydrous partial melting) and fluid-absent (dehydration melting) conditions was carried out here at constant pressure and temperature. The chosen starting material is an Archaean tonalite from the Lewisian complex. In this process, it produced clinopyroxene and/or orthopyroxene depending on melt water content. The melt composition is tonalitic/trondhjemitic or granodioritic depending on melting degree (Figure 3).

The REE contents of experimental melts obtained by dehydration and hydrous partial melting of Archaean tonalite have been calculated according to the batch melting equation (Table 1) following the procedure previously explained in the amphibolite partial melting process. The REE patterns
Figure 1. Compositional variation (wt%) as a function of pressure of melts obtained by fluid-absent melting of amphibolite at 900°C. Compositions are normalized to sum 100 (wt%). Numbers in brackets are melt and garnet modal proportions as vol.% respectively.

Table 1. REE contents of experimental melts obtained by partial melting of amphibolite and tonalite

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Data obtained according to a batch melting partial melting process, as a function of REE contents of the starting material, partition coefficients and weight fraction of melt produced in the experiment. Mineral/melt partition coefficients (Kd) considered for dacitic and rhyolitic composition were for plagioclase and amphibole according to Arth and La values from Dudas et al. and Sisson, respectively. Kd considered for clinopyroxene is according to Fujimaki et al., ilmenite, orthopyroxene from Nash and CRECRAFT, and garnet from Irving and Frey. S.M., Starting material; A, Amphibolite; T, Tonalite; H2O%, Water added (wt %). Eu/Eu* calculated as Eu/Eu* = EuGd/(Sm*Gd)Gd.
Figure 2. a. Experimental melt REE pattern obtained according to a batch melting process of amphibole as starting material. Data normalized to Nakamura91. P, Pressure (kbar), T, Temperature (°C), Grt, Garnet proportion (vol.%); Liq, Melt proportion (vol.%). Grt-present, Garnet is a peritectic phase in the partial melting process; Grt-absent, Garnet is not a peritectic phase in the process. b. Close-up of the 1–100 range of sample/chondrite ratio showing details of the differences between garnet-present and garnet-absent experimental melts.

Figure 3. Ca–Na–K plot with average melt compositions, obtained in the interaction process of hydrous basic magma and tonalitic material (black diamonds). Grey circles represent experimental melts obtained in hydrous (Hy) and dehydration (Anh) melting of tonalite61,65–67. Ca, Calc-alkaline trend; Td, Trondhjemitic trend.

Figure 4. REE pattern of experimental melts obtained according to batch melting process of tonalite as starting material at 6 kbar and 950°C as a function of different added water contents.

of experimental melts show negative Eu-anomaly that decreases with increasing water (Figure 4). The dehydration melting of tonalite produces a 16 vol.% of granitic melt61, with a high negative Eu-anomaly and slight LREE enrichment (Figure 4). In contrast, the hydrous partial melting of tonalite with 10 wt% of added water produces a 93 vol.% of tonalitic melt61 with slight negative Eu-anomaly and REE content similar to that of the starting material (Figure 4).

Conversely, it has been suggested that a type of K-rich granites like the Closepet batholith in Dharwar Craton44, or the granodiorite in the northern region of the Lewisian Complex61,69, might have been generated by some kind of interaction between basic magmas of sanukitoid affinity and melts produced in the continental crust of dominantly tonalite composition. Two-layer experiments were designed to simulate the process of interaction between a hydrous basic magma and the tonalitic crust resulting in a granodioritic melt61. The starting materials were a hydrous (6 wt% of H2O) mafic synthetic glass with a representative composition of enriched (K-rich) basic lithology associated
with late Archaean batholiths, and a natural tonalite from the Lewisian Complex (NW Scotland). Therefore, the experimental study tried to simulate a process in which a type of late Archaean granodiorites could be the recycling product of older tonalite crust, with the intrusion of mantle-derived mafic magmas as a necessary step of the recycling process.

The experimental interaction process produces a similar melt proportion in the two layers, basic magma and tonalitic material, at given pressure and temperature conditions, and with a homogeneous granodioritic composition. The phase assemblage is characterized by the presence of pyroxene, biotite or/and amphibole as peritectic phases depending on experimental conditions.

Figure 3 represents the experimental melts obtained by interaction between a K-rich basic magma and tonalite, and those obtained by partial melting of tonalites at 6 kbar and 950°C under fluid-present and fluid-absent conditions. Experimental melts obtained by an interaction process show a K-enriched trend with regard to trondhjemitic trend. This is the main difference with Archaean TTG rocks, which are plotted along the trondhjemitic trend. As it was previously exposed, the partial melting of tonalitic starting material under fluid-absent conditions produces a calc-alkaline melt similar to those obtained by the interaction process (Figure 3). However, the melts produced under fluid-present partial melting of tonalite are plotted on the trondhjemitic trends with a low K/Na relation (Figure 3).

Discussion

Origin of Archaean igneous rocks

Origin of TTG rocks: The melts obtained by partial melting of amphibolite as starting material are plotted on the TTG field (Figure 5) defined by Moyen et al. The melt composition is similar to that obtained in experimental studies carried out with similar starting materials and natural TTG rocks (Figure 5). The most important difference between experimental melts and natural lithologies is observed in the Mg#. The experimental melts show a highly variable Mg#, ranging between 10 and 60 (Figure 5 b and d). Furthermore, some experimental melts show a high K/Na relation that is not characteristic of TTG magmas (Figure 5 c). Some of these experiments were carried out with Qtz-Ky-bearing eclogite as starting material with minor amounts of phengite, or with higher K2O contents than that of the starting materials in other experimental studies (K2O = 0.80 wt%)22. On the other hand, analytical difficulties to measure the Na content could explain the geochemical variations in the experimental melts with regard to TTG gneisses. Na-loss is a normal effect in the measurement of experimental glasses by electron bombardment. Therefore, Na contents of our experimental melts were corrected according to a factor obtained by regression curves of time vs Na-loss.

The major element composition of the experimental melts is similar to that of natural TTG rocks (Figure 5). However, one of the most characteristic features of the TTG lithologies is their REE patterns. The experimental results of this work suggest that the HREE depletion be directly related with the garnet proportion instead of melting degree (Figure 2). The HREE content decreases directly with increasing garnet proportion at runs with similar melt proportion (< 6 vol.%) and pressures (> 10 kbar). Therefore, and according to our experimental results, higher HREE depletion and more fractionated REE patterns can be obtained at higher pressure, where garnet is a stable phase. If the calculated REE patterns are compared to those of natural TTG, it is observed that our profiles are less fractionated (Figure 6). This difference could be explained by the chosen experimental pressure conditions (<14 kbar). The TTG rocks are characterized by negative Nb-Ta anomaly; therefore, rutile is a necessary residual phase in TTG magma genesis and this phase is stable at pressures higher than 15 kbar, depending on the starting material composition and water content72. Melts with garnet produced at higher experimental pressures in this study show a slight positive Eu-anomaly (Figures 2 and 6). This is a consequence of the decreasing plagioclase proportion and higher HREE depletion (Table 1). In the study of natural TTG gneisses, it is observed that the Eu-anomaly is variable (Figure 6). Samples with positive Eu-anomaly show higher HREE depletion and steeper patterns than those with negative Eu-anomaly (Figure 6). To analyse the fractionation between LREE and HREE, the (La/Yb)n ratio of the experimental melts has been plotted against Yb. The experimental melt produced with garnet as peritectic phase shows a slightly higher fractionation than those obtained without garnet, and the garnet modal proportion is directly related to the (La/Yb)n ratio (Figure 7).

The study of natural TTG rocks shows that trondhjemitic rocks show a higher HREE depletion and more fractionated profiles than tonalitic rocks (Figures 6 and 7). This is in agreement with our experimental results and those obtained by Winther. Therefore, trondhjemitic TTG could be generated from partial melting of basic protoliths at high pressures (> 10 kbar), with garnet as a peritectic phase. However, the geochemical comparison between natural tonalitic and trondhjemitic compositions presented in this study should be considered with caution because the number of analyses of natural trondhjemites is considerably lower than that of tonalites (Figure 7).

Therefore, the pressure conditions exert a strong control on the partial melting reaction that causes melt compositional changes (REE and major element contents). Experimental melts tend to trondhjemitic compositions with pressure (decrease in CaO, FeO, MgO and TiO2 content with pressure: Figure 1), with correspondingly higher depletion in HREE (Figures 2, 6 and 7), higher (La/Yb)n ratio...
Figure 5. Experimental melts synthesized in this work, expressed as average compositions, obtained by partial melting of amphibolite [66,70], partial melting of tonalite under fluid-present and fluid-absent conditions [65,68], and interaction between a basic magma and tonalitic crust (op. cit.), compared with Archaean granitoids (a and b) and with the experimental melts available from the literature (c and d). Archaean granitoids data: TTG (262 data) from Brazil [98,99], Greenland [100,102], Lewisian Complex [98-102], SWPS [5,39], Slave Province [103], Wyoming [11], Finland [9,106], South Africa [2], Aldan Shield [105], Kaapvaal Province [100], Kreevian terrane [107], India [108], Zimbabwe [59] and Australia [106], Bt-granites or granodiorites (228 data) from Brazil [98,99], Dharwar Craton [12,43,44], SWPS [39], Greenland [10], Slave Province [103], Wyoming [11], South Africa [2], Aldan Shield [105], Kaapvaal Province [100], Kreevian terrane [107], Madras Province [10], India [108]. Experimental melt data: melts obtained by partial melting of amphibolitic or eclogitic starting material [27,29,31,71,72]; melts obtained by partial melting of tonalitic starting material under fluid-absent [66,67] and fluid-present conditions [65,68]. Archaean granitoid fields according to the typology established by Moyen et al. [13].

(Figure 7) and slight positive Eu-anomaly (Figure 2). Therefore, it is possible to suggest a relation between REE pattern and depth of TTG magma source. TTG magmas with more fractionated REE profile, higher HREE depletion and slight positive Eu-anomaly, could have been generated at greater depths. It can be proposed that at high pressures (>10 kbar), the melting reaction consumes plagioclase, which favours slight positive Eu-anomalies, with peritectic garnet producing high HREE depletions. Instead, at low pressures (<10 kbar), the participation of plagioclase in the reaction is less important, and garnet is absent as a peritectic phase. This produces negative or no
Eu-anomalies and small HREE depletions. According to a previously published experimental study\textsuperscript{74}, plagioclase is a product ($P < 10$ kbar) or a reactant phase ($P > 10$ kbar) depending on the pressure conditions in the dehydration melting process of quartz amphibolite.

One of the most important topics with regard to the TTG origin is the geological setting in which the magmas originated. It is widely accepted that TTG magmas were formed by partial melting of a hydrated basic protolith. This process could be either by partial melting of subducting slab\textsuperscript{23} or melting at the base of a thickened crust\textsuperscript{38}. It has been concluded that TTG production became a dominant process in subduction slabs after about 3.2 Ga, explaining their low Nb/Ta ratio\textsuperscript{75,76}. According to these authors, in the early Archaean the crust was too thick to be subducted, and so the process was dominated by delamination and melting of the lower crust, a non subduction-like setting. In the same sense, the geochemical study\textsuperscript{77} of Whundo Group in the Pilbara Craton provides evidence about modern-style subduction process at least at 3.0 Ga. Therefore, the petrogenetic efficiency of subduction-related processes remains obscure for the Palaeoarchaean and Eoarchean (3.8–3.2 Ga). During the early Archaean, some kind of convergence by stacking or low-angle underthrusting is accepted. In this geological setting, non \textit{sensu stricto} subduction, the $P$–$T$–$t$ path could have achieved granulite facies conditions before eclogite conditions, explaining the rarity of Archaean blueschist and eclogite\textsuperscript{78}. Notwithstanding, crustal thickening by low-angle underthrusting, where eventually the mantle wedge could have overlaid the down-going sheet, can be considered like a protosubduction setting.

On the other hand, TTG rocks show geochemical variations with time that have been interpreted as a product of increasing interaction between magmas from the down-going slab and the mantle wedge\textsuperscript{25}. If TTG magmas are interpreted as due to partial melting of underplating basaltic magmas or of the base of a thickened crust, the geochemical variations of TTG with time are hard to explain, because this process does not allow interaction between the melts and the peridotitic mantle.

Consequently, to explain the origin of TTG rocks it is assumed that some type of plate tectonics operated on the earth during the Archaean\textsuperscript{2,3}, and the production of TTG magmas is placed in a protosubduction or modern-style subduction in the early and late Archaean respectively. Partial melting of Archaean subducting slabs was conditioned by the geothermal conditions along the subducting plate. Unfortunately, the thermal structure of Archaean subduction orogens remains poorly known, although it has been suggested that subducting plates were hotter than their modern analogues. Consequently, Archaean plate tectonics should have been dominated by smaller, faster, thinner and younger plates than those of the post-Archaean times\textsuperscript{79}. Results of thermal models of modern subduction zones vary according to the considered starting and boundary conditions\textsuperscript{80–84}. Models considering uniform viscosity in the mantle wedge\textsuperscript{82,83} indicate that the geothermal gradient along the Benioff plane is inversely proportional to the age of the subducting lithosphere (Figure 8). Therefore, only young (less than 20 Ma old) and slow (less than 20 km/Ma) slabs develop geothermal gradients that intersect the hydrous and anhydrous basaltic solidus (Figure 8). With small Archaean plates, the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure6.png}
\caption{REE patterns of tonalitic gneisses (grey gneisses) without Eu-anomaly (a), positive Eu-anomaly (b), negative Eu-anomaly (c) and REE pattern of trondhjemitic gneisses from the Lewisian Complex and Aldan Shield (d). Grey field, REE pattern calculated for experimental melt. Data normalized to Nakamura\textsuperscript{91}. Tonalite data from refs 10, 39, 40, 53, 55, 99–105, 107. Trondhjemite (s.s.) data from refs 100–101, 107.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{$(\text{La/Yb})_N$ against $\text{Yb}_N$ of tonalites (black circles) and trondhjemites (white squares), and experimental melts (white diamonds) in this study. Numbers in brackets are melt and garnet proportion as vol.% respectively. Grt and non-Grt. Experiments with and without garnet as peritectic phase, respectively. Archaean TTGs and post-Archaean granite fields according to Martin\textsuperscript{71}. Data normalized according to Nakamura\textsuperscript{91}. Tonalite and trondhjemite compositions are taken from the literature. For references, see Figure 6.}
\end{figure}
average age of down-going segments should be lower than that of modern plates. Consequently, the thermal conditions in Archaean subducting zones were favourable for melting of subducting slabs generating tonalitic and trondhjemitic magmas, in accordance with experimental results. Furthermore, this process was easier early in the Archaean than during the late Archaean25 (Figure 8).

**Origin of K-granites:** The younger Archaean granites referred to as K-granites or GGM suite have been interpreted as a product of partial melting of older TTG gneisses11,42,64. This interpretation is based on higher $^{87}$Sr/$^{86}$Sr initial ratios of K-granites with respect to the older tonalitic gneisses with which they are associated53,57. Partial melting of TTG gneisses gave rise to Bt-granites, according to the typology established by Moyen13. To test this process, different experimental studies about the partial melting of tonalite as starting material have been published65–68. The partial melting process produces melt compositions depending on the water present61. Melts obtained by simple dehydration melting of tonalite show a granitic and granodioritic composition and they are plotted on the Bt-granite field (Figure 5), but are generated in low proportion (< 10 vol.%). However, melts obtained by hydrous partial melting are produced in high proportions (75–93 vol.%), but their composition is tonalitic and trondhjemitic, similar to that of the starting material (Figure 5). With regard to REE content of late Archaean K-granites, it has been explained that they are characterized by a wide $(La/Yb)_N$ range that may show steeper patterns than those observed in the TTG. The calculated REE pattern of the experimental melts obtained by partial melting of tonalite with different water added contents overlap the K-granites field, with a negative Eu-anomaly similar to that of late Archaean K-granites (Eu/Eu* = 0.2–0.6) (Figure 9). However, the calculated REE profiles are less fractionated than those of natural lithologies, observing higher fractionation in the melt obtained by dehydration melting of Archaean tonalite with regard to those obtained with fluid-present condition (Figure 9). Therefore, dehydration melting of tonalites could explain the origin of late Archaean granites. However, dehydration partial melting is governed by the breakdown of the hydrous phases in the starting material, biotite and amphibole, which requires higher temperatures than those estimated for the Archaean crust and, therefore, addition of heat is required. Different possibilities have been proposed to explain the additional heating85 (i.e. radiogenic heating, extensional thinning of the crust and intrusion of basaltic melts, delamination, and extensional collapse).

Some late Archaean granites have been interpreted as a product of interaction between sanukitoid magma and anatectic granites from the TTG complexes, such as the case of the Closepet granite12,43,44 in India, or late Archaean granites in the Superior Province, which show a genetic relation between sanukitoids and older tonalites39. This process was also inferred from the field relationships observed in the Northern Region of the Lewisian Complex (NW Scotland), which strongly support the hypothesis of interaction between sanukitic magmas and anatectic tonalites

**Figure 8.** $P$–$T$ diagram showing water-saturated basaltic solidus109 and anhydrous solidi of amphibolites (LC01 (ref. 60) and WW93 (ref. 110)). Dashed lines indicate geothermal gradients along subducting slabs as a function of their ages of 4 Gya. Arrows indicate geothermal gradients along the Benioff plane for early Archaean (≈4 Gya), late Archaean (≈2.5 Gya) and actual8,11. Hbl-out (SP98) and (R91) according to Schmidt and Poli11 and Rushmer28, respectively.

**Figure 9.** Comparison between REE content of experimental melt, calculated according to batch melting process of a tonalite as starting material, and REE profile of natural K-granites (grey field). For references of natural K-granites see Figure 5.
to generate K-granites. K-rich veins and massive granodiorites appear with magmatic structures evidencing partial melting and melt segregation by in situ transformation of the pre-existing continental crust. A similar origin for K-rich granites has been proposed by Winther and Newton, which indicated that metasomatic redistribution of K$_2$O is a process that should be considered in a petrogenetic model of these rocks. On the other hand, K-granites that mark the Archaean–Proterozoic boundary also contain relatively higher contents of radio elements (U, Th, $^{40}$K), compared to TTG, possibly due to the migration of these elements from the mantle to the continental crust, resulting in higher radiogenic heating that could be a major source of the additional heating required for dehydration partial melting of tonalites. Therefore, it seems necessary to experimentally test this process of interaction between basic magma and tonalitic crust.

From an experimental point of view, the origin of granodioritic melts, quite similar to the late Archaean K-granites (Figure 5), by interaction between a basic hydrous magma and the tonalitic continental crust is a feasible process. According to the A/CKN, K/Na and Mg$^+$ relations, experimental melts, obtained by interaction between basic magma and tonalitic rocks, are plotted on the Bt-granite field of the diagram by Moyen et al., or on the Closepet granite field with lower Mg$^+$ (Figure 5). Therefore, some late Archaean granitoids, like those observed in the Dharwar Craton or in the Lewisian Complex, can be the result of an interaction process between hydrous basic magma and older tonalitic crust, in which the basic magma transfers H$_2$O and K$_2$O to the tonalitic crust. Newton suggested a similar process to explain the additional heating needed to melt the continental crust, although he did not explicitly consider a mafic igneous component in his work. According to this author, and based on the study of Closepet granite, the mantle-derived fluid phase favoured potassium mobility and its deposition in the middle crust, lowering the solidus temperature of the source rocks of granites.

**Model of growth of early continental crust**

Experimental studies place important constraints on the origin of the main types of Archaean igneous rocks. Therefore, a schematic, conceptual model is proposed here to put these rocks in the framework of the evolving Archaean tectonics (Figure 10). This model is based on the experimental studies carried out to determine the origin of TTG rocks and K-granites, and on the hypotheses proposed by different authors about the origin of Archaean granitoids, and reviewed in this work, besides the activity of some type of Archaean plate tectonics is assumed. Taking into account that heat production was 2 to 4 times greater than that at present, the Archaean plate tectonics must have been characterized by many small and thin lithosphere plates. Accordingly, processes like ridge–trench interactions and subduction of young lithosphere were more frequent than at present. The model also considers the decrease of geothermal gradients with time and the petrological consequences of this progressive cooling since early Archaean. The last considered assumption is that the earth’s cooling could have favoured an increase in the dip angle of subduction zones with time.

A large number of small plates of basic composition (basalt–komatiite) formed from a primitive magmatic ocean, are characteristic of the early Archaean (Figure 10a). This process favoured the formation of a global, thin oceanic lithosphere. TTG magmas represent new continental crust generated between 4.0 and 2.5 Ga by partial melting of hydrated basaltic crust (Martin et al. and references therein; Figure 10b and c). This process could have taken place in two different tectonic settings: partial melting of subducting slabs (Figure 10b) or partial melting of a thickened hydrous mafic crust (Figure 10c). These different settings have also been explained as two stages during Archaean, as it was previously discussed. In fact, the tectonic setting in which the first continental crust was formed is still a matter of debate. Some authors have proposed that the TTG magmas were not formed in subduction-like settings. In our model, we have considered that the TTG magmas were formed mainly by partial melting of subducting slabs with low subduction angles (protosubduction zones), where the interaction with the mantle wedge is not possible (Figure 10a–c). This is in agreement with the studies of Martin and Smithies, and with the chemical composition of Archaean TTG rocks. However, the partial melting at the base of a basaltic crust thickened by underplating could be a possible punctual process (Figure 10c).

Progressive cooling of the earth produced subduction zones with steeper dip angles and increase in plate thickness (Figure 10a–d). This geometrical change favoured the interaction between TTG magmas and the mantle wedge overlying the subducting plate. The increase in Cr, Ni and Mg$^+$ of TTG rocks with time can be a result of this change (Figure 10d). According to our experimental results, TTG complexes should have become more trondhjemitic with deeper sources, showing more depleted HREE. Interestingly, Sr contents of TTG rocks increase with time relative to CaO + Na$_2$O, which is explained as due to larger melting depths. These observations suggest future research lines, e.g. to explore a possible relation between the age of TTG rocks and specific geochemical features as decreasing Ca/Na ratio (trondhjemitic composition) and higher HREE depletion with time.

In summary, TTG magmas were generated during Archaean times by partial melting of subducting slabs. Melting depths increased with time, which allowed a higher interaction between the slab melt and the mantle wedge at the end of Archaean. This can explain the compositional variation of TTG rocks with time.
The main contribution of the upper-plate mantle wedge to the igneous processes is in the genesis of sanukitoids. The generation of these magmas predominantly at the end of Archaean has been considered as a part of the cratoni-
ization processes\textsuperscript{49}. According to the published studies, sanukitoid magmas could have been originated by partial melting of the mantle wedge with the participation of melt from the subducting tholeiites and also, perhaps, from sediments (Figure 10\textit{e}). Therefore, it can be considered that the generation of sanukitoids is related to subduction and collision-suturing tectonic settings. However, the origin of the necessary heat to trigger the entire process is prob-

**Figure 10.** Petrogenic model for TTG rocks, sanukitoids and K-granites. See text for details.
lematic. According to Stevenson et al.\textsuperscript{13}, based on the study of sanukitoids from the Superior Province, high temperature at shallow depths is achieved in a model of delamination of the subducted lithosphere and upwelling of the asthenosphere. However, in subduction tectonic settings, sanukitoids can be generated at shallow depths in the mantle wedge as a consequence of several processes such as subduction of young lithosphere, ridge–trench interaction, detachment of subducted slabs, or interaction of slab-derived melts with a refractory mantle wedge (Figure 10 d).

The crustal evolution continued with the stabilization of cratons. Most of this process took place at the Archaean–Proterozoic boundary, after the generation of voluminous K-granite batholiths. Some K-granite batholiths dominated by biotite (Bt-granites) were originated by partial melting of pre-existing TTG. However, some of the K-granite batholiths were generated with the participation of basic magma (sanukitic affinity) along with older TTG (i.e. Closepet granite\textsuperscript{13}). It has been proposed that the intrusion of sanukitoids into a tonalitic magma could have favored the magmatization of the core of orogenic belts\textsuperscript{61}. The fluids released from the crystallizing hydrous sanukitic magma could have pervaded the continental crust and modified its composition from tonalitic to granodioritic\textsuperscript{61}. This metasomatic process triggered by the intrusion and crystallization of a sanukitoid magma rich in volatiles can produce granodioritic gneisses or modified tonalites similar to those observed in the Lewisian Complex\textsuperscript{59}, NW Scotland, and those of Madras granulites\textsuperscript{54}, India (Figure 10 f). Alternatively, or at later stages, partial melting of the host rocks (tonalites and trondhjemites) allowed mixing between the anatectic melt and the crystallizing sanukitic magma, giving rise to large volumes of granodiorites that may form batholiths (Figure 10 g). The interaction, ascent and emplacement of granodioritic batholiths could have been favored by the activity of late orogenic extensional regimes, which is in agreement with the geological characteristics of K-granites. These rocks appear mainly associated with late extensional faults and are considered as syn- and post-tectonic\textsuperscript{90}.

Conclusion

The progressive cooling of the earth from the early Archaean conditioned the chemical composition of rocks formed in convergent plate boundaries. TTGs were mainly generated by partial melting of subducting slabs, although they show some geochemical differences that could be indicative of different source depths. At pressures of >10 kbar, trondhjemitic composition (low Ca/Na ratio), with steep REE pattern and slightly positive Eu-anomaly originated with garnet as the peritectic phase, whereas tonalitic composition (higher Ca/Na ratio) originated at pressures of <10 kbar, without garnet as peritectic phase. Cooling of the earth favored the increase of dip in down-going plates, with the consequent interaction of TTG magmas with the upper-

plate mantle wedge. Therefore, the main contribution of the mantle in the petrogenesis of Archaean continental igneous rocks took place at the end of this time. During the late Archaean, other lithologies like K-granites appeared in some terranes associated with sanukitoids. These K-granites were probably generated by the interaction between sanukitoid magmas and migmatized tonalitic crust. Therefore, this contribution offers new insights into how the plate tectonic evolution conditioned the growth and chemical evolution of the continental crust. Since the Archaean–Proterozoic boundary, plate tectonics shows modern characteristics. In addition, the whole composition of the continental crust turned out to become granodioritic, which has been more or less constant from the early Proterozoic up to the present.


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