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 sanukitoids 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[1], or simply to the fact that continents were very rare at that time[2]. 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[3,4], 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[5] of basaltic or komatiitic composition[6]. Therefore, the formation of a basaltic oceanic crust (4.5 Ga) preceded the formation of a felsic continental crust (4.0 Ga)[7]. Alternatively, other authors have proposed tectonic regimes for the Archaean, which differ qualitatively from those of post-Archaean times[8]. On the other hand, different models of continental growth have been proposed, which were summarized by Taylor and McLennan[9]. 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[9]. 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[10–13], and it has been possible to sort out different types of granites that also imply different sources and origin processes[13]. The principal hypothesis proposes an origin of K-granites, referred to as Bt-granites by Moyen *et al.*[13], by partial melting of older tonalitic gneisses[14], perhaps together with mixing with mantle-derived magmas[15]. On the other hand, the Archaean continental crust is also characterized by the presence of mantle-derived igneous lithologies referred to as sanukitoids[16].

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[17]. These lithologies are charac-

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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[18] than 150. Besides, TTG complexes show variable content in ferromagnesian components ($Fe_2O_3^T$ + MgO + MnO + TiO_2 = 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[18]. 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[19–25] and different studies have presented the main results of the experimental approach to this problem[26–32].

The different proposed processes for the origin of TTGs include fractional crystallization of basaltic magmas[33], mantle melting[34], re-melting of older tonalitic materials[35], partial melting of basaltic rocks or their metamorphic equivalents[36], and Na-metasomatism of pre-existing granites[37]. 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 a crystallization or partial melting process, with garnet as the most significant phase[21,35,36]. On the other hand, $^{87}Sr/^{86}Sr$ initial ratio suggests a mantle melting process or it may be indicative of a short residence time. The most accepted process for the origin of TTGs is the partial melting of basic lithologies in which garnet and/or amphibole are residual phases. This process could take place in subduction settings by partial melting of the subduction slab[17,23], or alternatively, TTG rocks may result from partial melting of a thickened hydrous mafic lower crust[38]. The partial melting process has been simulated with amphibolites and eclogites as starting material to yield melts with a composition similar to that of TTG magmas, which could also explain their REE patterns. Experimental conditions (water content, pressure and temperature) influence composition of melts and phase relationships. Tonalites and trondhjemites can be formed from partial melting of tholeiite with Archaean average composition over a wide range of conditions and without crystal fractionation after magma was extracted from the source. However, tonalites are generated at high temperatures, low pressures and high water contents in a tholeiitic source region[32]. On the contrary, trondhjemitic compositions could be obtained at low temperatures, high pressures and low water contents in the source region[32].

In contrast to the early appearance of TTG complexes, and as a first-order approximation, K-granites appeared at the end of the Archaean[8] or previously to the cratonization process. In some Archaean terranes, K-granites appear spatially and temporally associated with mantle-derived lithologies known as sanukitoids. The sanukitoids (Mg-diorites) generally crop out in low volume proportions (5%) and have been studied in the Canadian Shield[16,39,40], Wyoming[41], China[42], India[43,44], Pilbara[24], Greenland[45] and Baltic Shield[46]. The sanukitoids form intrusive complexes with structures revealing syn- and post-kinematic emplacement processes. They are defined as a series constituted by K-enriched (compared to TTG) diorites, monzodiorites, monzonites and granodiorites, characterized by an SiO_2 content between 55 and 60 wt%, K/Na ratio between 0.4 and 0.6, A/CNK ≈ 1 and high Mg# (0.43–0.62). With regard to trace elements, sanukitoids show high Ni (≈ 100 ppm), Cr (≈ 200 ppm), Sr (> 500 ppm), Ba (> 500 ppm), P_2O_5, K_2O and LREE contents (Ce_N > 100), with strongly fractionated REE pattern (Ce_N/Yb_N = 10–50)[13,17,47]. Similar to the TTG magmas, there are many hypotheses concerning the origin of sanukitoid magmas. Most authors acknowledge participation of the mantle in the process, based on their high Mg#, Cr and Ni contents[24,47]. To explain the enrichment in LREE and K_2O, the activity of a metasomatic process in the mantle before partial melting has been suggested. According to geochemical modelling and isotopic studies, the participation of fluids or melts released from a hypothetical subducting slab can explain the signatures of sanukitoids[16,39–41]. In this sense, experimental studies have indicated that Mg-andesites or sanukitoids can be obtained by assimilation of the overlying mantle wedge by ascending melts generated from the partial melting of subducting basalts[48].

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[49]. The origin of these K-granites constitutes one of the most important topics with regard to the evolution of the continental crust, as a compositional change took place in the continental crust at the Archaean–Proterozoic boundary[9,50]. K-granites belong to the calc-alkaline series and show high K/Na ratio (commonly >1), high Rb (150–250 ppm) and Sr (150–600 ppm). With regard to REE patterns, these lithologies show variable REE patterns and $(La/Yb)_N$ ratios [(La_N/Yb_N = 38(±6) or 80(±24))[51]; (La_N/Yb_N = 10–60)[11]; (La_N/Yb_N = 6–64)[52]]. 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 $Eu_N/[\sqrt{(Sm*Gd)_N}]$). There are many hypotheses concerning the origin of late-Archaean K-granites. These include partial melting of pre-existing tonalites[6,53], alkaline metasomatism[54,55], fractional crystallization of granitic or TTG magmas[56], derivation from the mantle[52], and mixing between sanukitoid magmas and anatectic melt derived from migmatization of TTG complexes[12,44]. The partial melting of older tonalitic gneisses has been widely proposed to account for the origin of K-granites. The high $^{87}Sr/^{86}Sr$ initial ratio has been cited as evidence for the participation of older crustal rocks in their origin[53–57]. According to Condie *et al.*[6], 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[58], the Dharwar Craton in India[12,44] and the North Marginal Zone of the Limpopo Belt in Zimbabwe[59].

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[60,61].

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[62]. Hornblende (49 vol.%), plagioclase (46 vol.%; An_{44}) 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[60]. 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[60]. The experiments indicate a decrease in the FeO, MgO, CaO and TiO_2 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[27]. TTG magmas are typically depleted in HREE, which require the presence of amphibole and/or garnet as solid phases during their genesis[63], the presence of which has been confirmed experimentally[60]. 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:

$$C_L/C_O = 1/[D_{RS} + F(1 - D_{RS})],$$

where C_L 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:

$$D_{RS}{}^{i} = x_1Kd_1 + x_2Kd_2 + x_3Kd_3 + \ldots,$$

where $D_{RS}{}^{i}$ is the bulk partition coefficient for the element i, x is the weight proportion of mineral and Kd 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[13] and they are considered as a product of partial melting of older TTG gneisses[11,64]. In this sense, different experimental studies were carried out to determine the partial melting process of Bt-Hbl-bearing tonalite, similar to TTG gneisses[61,65–68]. 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[61]. The melt composition is tonalitic/trondhjemitic or granodioritic depending on melting degree[61] (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

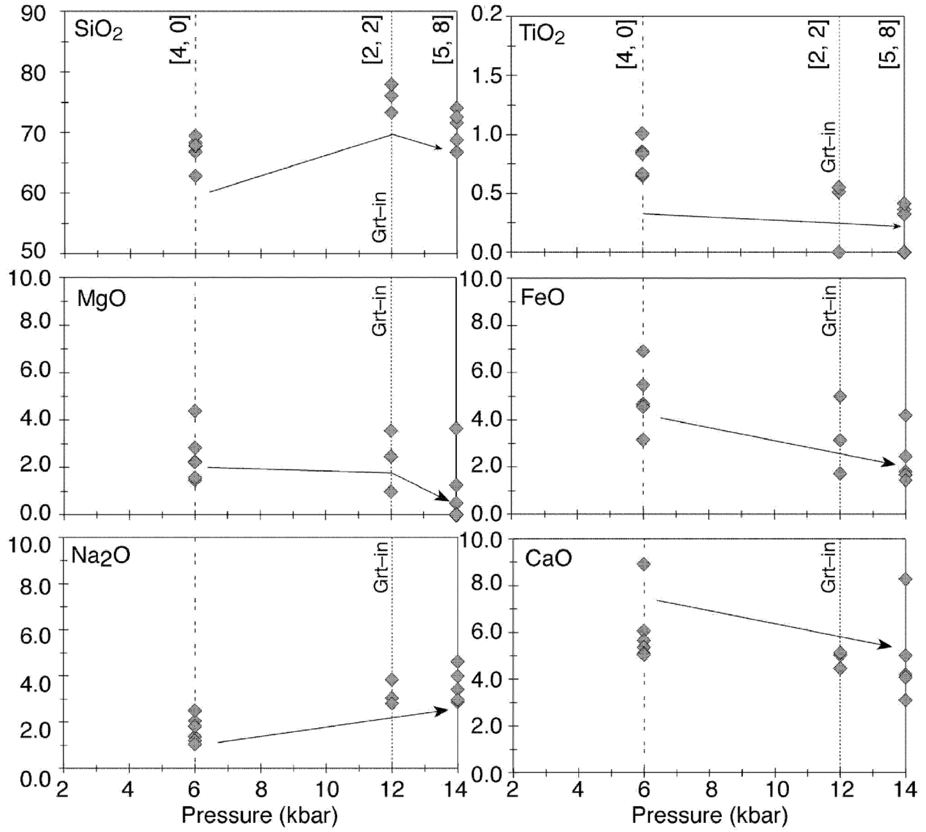

Figure 1. Compositional variation (wt%) as a function of pressure of melts obtained by fluid-absent melting of amphibolite at 900°C. Compositions are normalized to sum 100 (wt%). Numbers in brackets are melt and garnet modal proportions as vol.% respectively.

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

Run	SL-30	SL-1	SL-18	SL-31	SL-13	SL-28	SL-54	SL-19	SL-20	SL-134a	SL-134b	SL-133
S.M.	A	A	A	A	A	A	A	A	A	T	T	T
P (kbar)	4	6	6	6	10	10	12	12	14	6	6	6
T (°C)	950	850	900	950	900	950	850	900	900	950	950	950
H_2O %	0	0	0	0	0	0	0	0	0	0	3	10
La	39.32	41.09	39.68	35.86	37.99	42.84	41.79	43.02	46.71	249.13	105.88	86.27
Ce	27.07	24.99	26.84	28.34	25.57	30.38	23.82	24.02	26.55	172.77	82.24	66.92
Pr												
Nd	10.73	9.17	10.58	12.49	10.17	12.28	8.54	8.62	10.18	91.09	59.44	48.15
Sm	8.44	7.18	8.31	9.98	7.79	9.67	6.49	6.36	6.40	46.73	35.00	28.41
Eu	6.86	5.78	6.49	7.71	6.45	7.39	5.59	5.81	6.48	9.37	15.68	14.18
Gd	5.31	4.47	5.33	6.37	4.84	6.10	3.92	3.75	3.26	26.24	22.55	17.93
Tb												
Dy	4.62	3.89	4.57	5.57	3.93	5.31	3.25	2.98	2.17	14.44	13.66	11.03
Ho										10.76	12.94	11.49
Er	4.52	3.79	4.54	5.45	3.63	5.19	2.99	2.62	1.62	12.68	11.19	8.87
Tm												
Yb	5.07	4.29	5.05	6.06	4.26	5.81	3.53	3.20	2.21	11.75	9.39	7.53
Lu	5.16	4.38	5.16	6.14	4.36	5.90	3.62	3.28	2.29	13.21	9.93	7.97
Eu/Eu*	1.03	1.02	0.98	0.97	1.05	0.96	1.11	1.19	1.42	0.26	0.55	0.61

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 riolitic composition were for plagioclase and amphibole according to Arth[92] and La values from Dudas *et al.*[93] and Sisson[94], respectively. Kd considered for clinopyroxene is according to Fujimaki *et al.*[95], ilmenite, ortopyroxene from Nash and Crecraft[96], and garnet from Irving and Frey[97]. S.M., Starting material, A, Amphibolite; T, Tonalite; H_2O%, Water added (wt %). Eu/Eu* calculated as $Eu/Eu^* = Eu_N/(\sqrt{(Sm*Gd)_N})$.

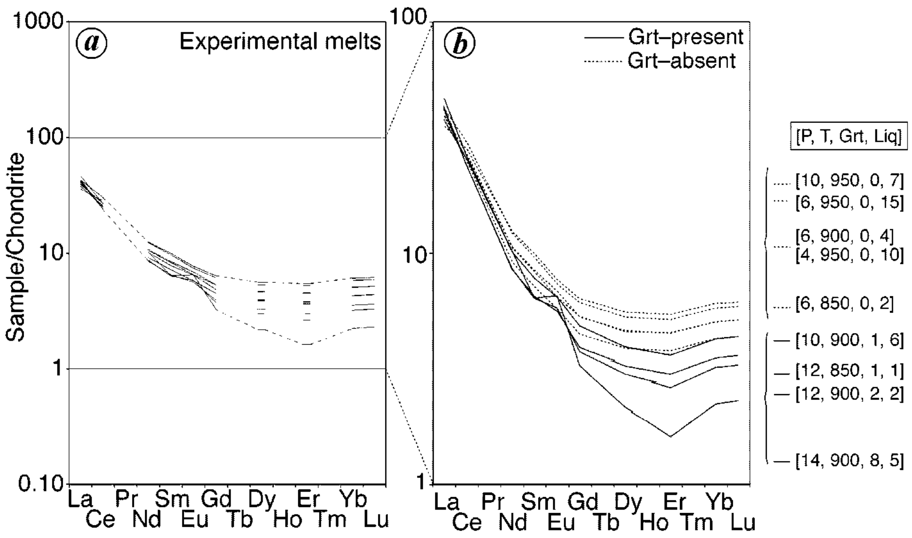

Figure 2. *a*, Experimental melt REE pattern obtained according to a batch melting process of amphibolite as starting material. Data normalized to Nakamura[91]. *P*, Pressure (kbar), T, Temperature (°C), Grt. Garnet proportion (vol.%); Liq, Melt proportion (vol.%). Grt-present, Garnet is a peritectic 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 melt.

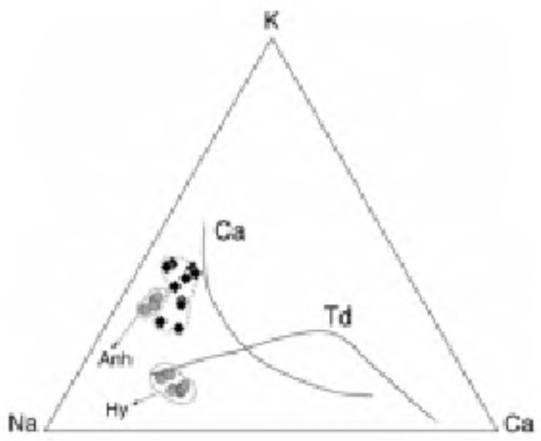

Figure 3. Ca–Na–K plot with average melt compositions, obtained in the interaction process of hydrous basic magma and tonalitic material (black diamonds). Grey circles represent experimental melts obtained in hydrous (Hy) and dehydration (Anh) melting of tonalite[61,65–67]. Ca, Calc-alkaline trend; Td, Trondhjemitic trend.

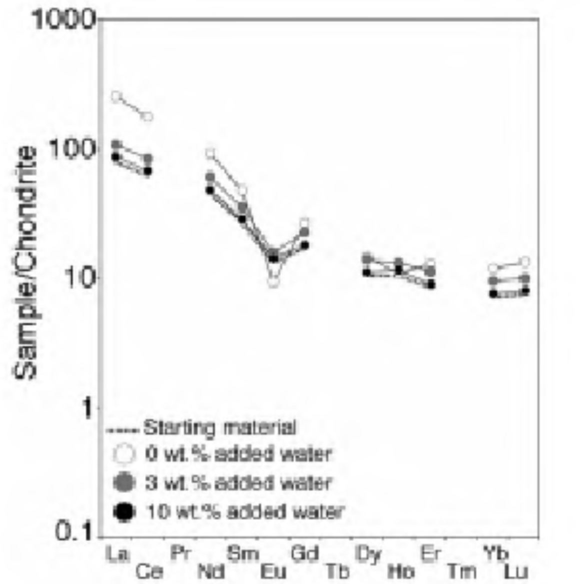

Figure 4. REE pattern of experimental melts obtained according to batch melting process of tonalite as starting material at 6 kbar and 950°C as a function of different added water contents.

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 melt[61], 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 melt[61] 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 Craton[44], or the granodiorite in the northern region of the Lewisian Complex[61,69], 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 melt[61]. The starting materials were a hydrous (6 wt% of H_2O) 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[61]. The phase assemblage is characterized by the presence of pyroxene, biotite or/and amphibole as peritectic phases depending on experimental conditions[61].

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[61]. Experimental melts obtained by an interaction process show a K-enriched trend with regard to trondhjemitic trend (Figure 3). This is the main difference with Archaean TTG rocks, which are plotted along the trondhjemitic trend[23]. 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[60,70] are plotted on the TTG field (Figure 5) defined by Moyen *et al.*[13]. 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[71], or with higher K_2O contents than that of the starting materials in other experimental studies (K_2O = 0.80 wt%)[72]. 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[70].

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 content[73]. 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[60] 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_N. 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[32]. 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 TiO_2 content with pressure; Figure 1), with correspondingly higher depletion in HREE (Figures 2, 6 and 7), higher $(La/Yb)_N$ ratio

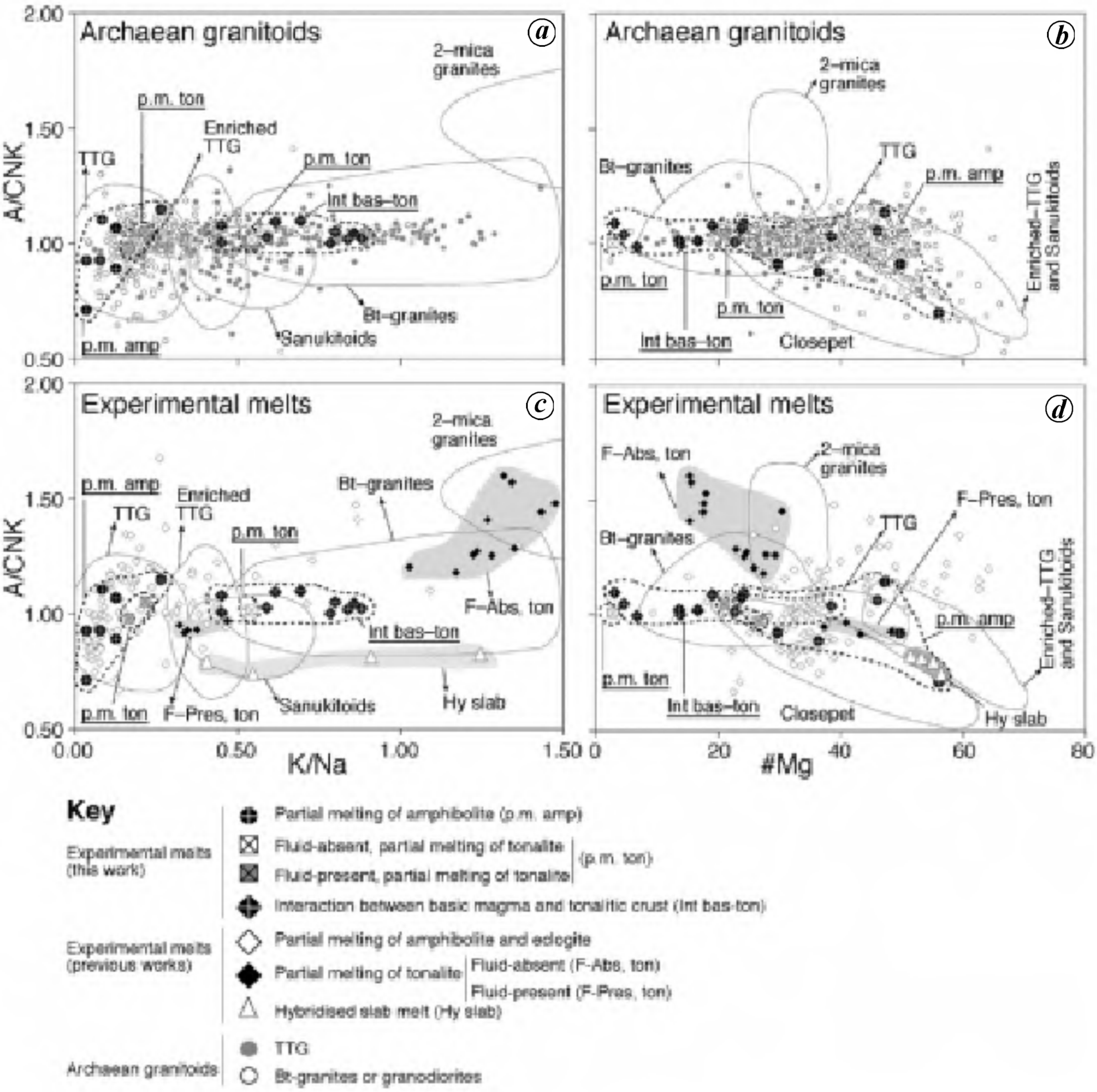

Figure 5. Experimental melts synthesized in this work, expressed as average compositions, obtained by partial melting of amphibolite[60,70], partial melting of tonalite under fluid-present and fluid-absent conditions[60,70], and interaction between a basic magma and tonalitic crust (op. cit.), compared 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[20], Lewisian Complex[100–102], SWPS[10,39], Slave Province[103], Wyoming[11], Finland[49,104], South Africa[52], Aldan Shield[105], Kaapvaal Province[106], Kraaipan terrane[107], India[55], Zimbabwe[59] and Australia[108]; Bt-granites or granodiorites (228 data) from Brazil[98,99], Dharwar Craton[12,43,44], SWPS[39], Greenland[57], Slave Province[10], Wyoming[11], South Africa[52], Aldan Shield[105], Kaapvaal Province[106], Kraaipan terrane[107], Madras Province[54], India[55]. 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[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[23] or melting at the base of a thickened crust[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[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[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 *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[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.

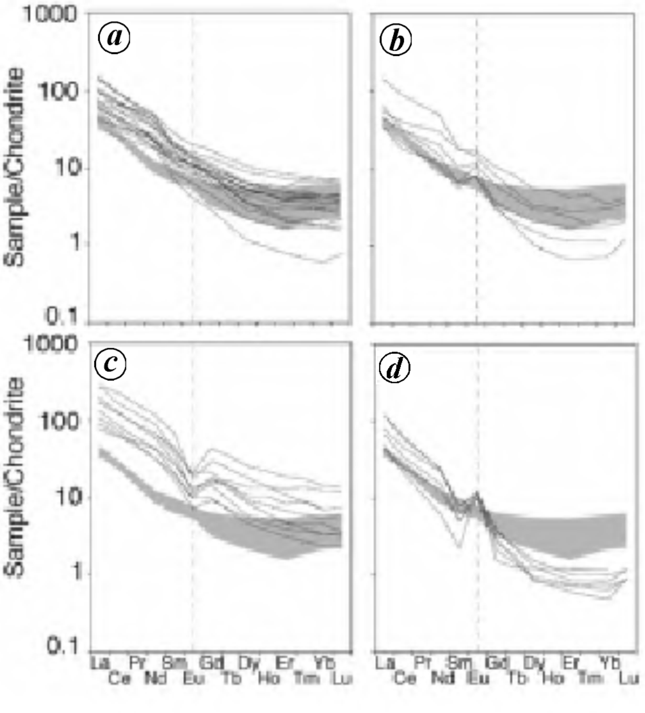

Figure 6. REE patterns of tonalitic gneisses (grey gneisses) without Eu-anomaly (***a***), positive Eu-anomaly (***b***), negative Eu-anomaly (***c***) and REE pattern of trondhjemitic gneisses from the Lewisian Complex and Aldan Shield (***d***). Grey field, REE pattern calculated for experimental melt. Data normalized to Nakamura[91]. Tonalite data from refs 10, 39, 40, 53, 55, 99–105, 107. Trondhjemite (s.s.) data from refs 100–101, 107.

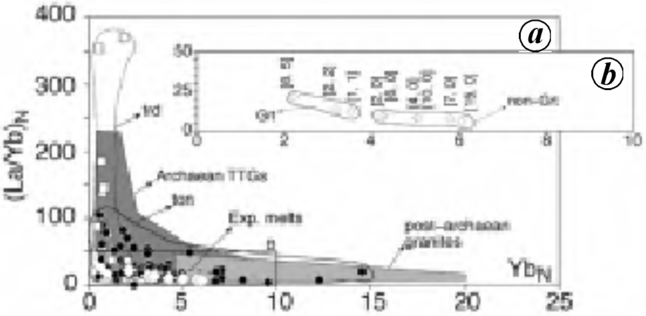

Figure 7. $(La/Yb)_N$ against Yb_N of tonalites (black circles) and trondhjemites (white squares), and experimental melts (white diamonds) in this study. Numbers in brackets are melt and garnet proportion as vol.% respectively. Grt and non-Grt, Experiments with and without garnet as peritectic phase, respectively. Archaean TTGs and post-Archaean granite fields according to Martin[23]. Data normalized according to Nakamura[91]. Tonalite and trondhjemite compositions are taken from the literature. For references, see Figure 6.

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[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[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[79]. Results of thermal models of modern subduction zones vary according to the considered starting and boundary conditions[80–84]. Models considering uniform viscosity in the mantle wedge[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 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 Archaean[25] (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 gneisses[11,42,64]. 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 associated[6,53,57]. Partial melting of TTG gneisses gave rise to Bt-granites, according to the typology established by Moyen *et al.*[13]. To test this process, different experimental studies about the partial melting of tonalite as starting material have been published[65–68]. The partial melting process produces melt compositions depending on the water present[61]. 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 heating[85] (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 granite[12,43,44] in India, or late Archaean granites in the Superior Province, which show a genetic relation between sanukitoids and older tonalites[39]. 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

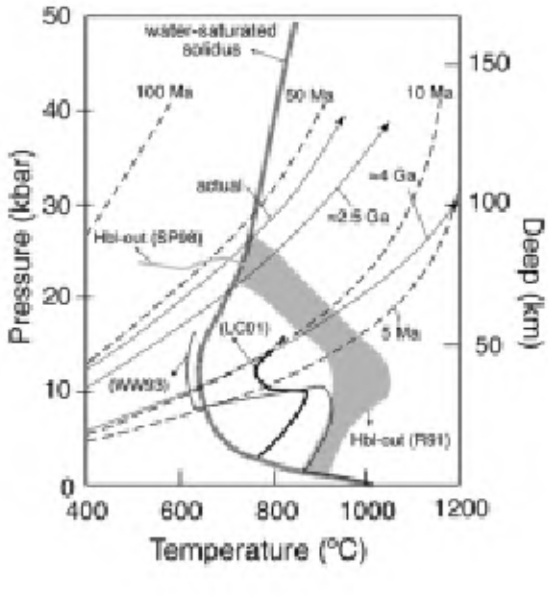

Figure 8. *P–T* diagram showing water-saturated basaltic solidus[109] and anhydrous solidii of amphibolites (LC01 (ref. 60) and WW93 (ref. 110)). Dashed lines indicate geothermal gradient along subducting slabs as a function of their ages[82,111]. Arrows indicate geothermal gradients along the Benioff plane for early Archaean (≈4 Ga), late Archaean (≈2.5 Ga) and actual[25,111]. Hbl-out (SP98) and (R91) according to Schmidt and Poli[112] and Rushmer[28], respectively.

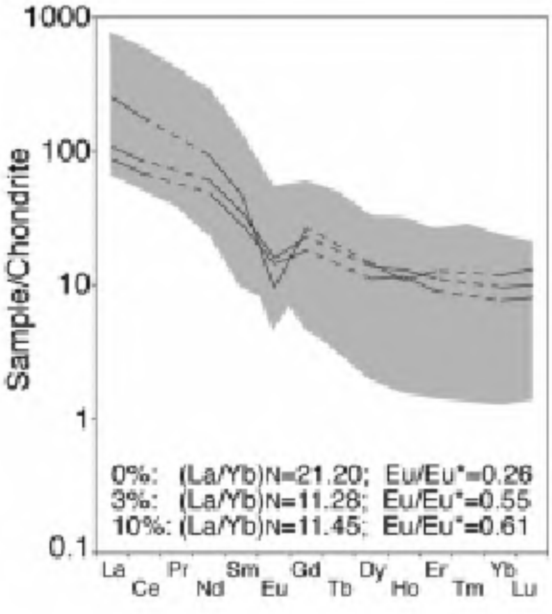

Figure 9. Comparison between REE content of experimental melt, calculated according to batch melting process of a tonalite as starting material, and REE profile of natural K-granites (grey field). For references of natural K-granites see Figure 5.

to generate K-granites[69]. K-rich veins and massive granodiorites appear with agmatitic structures evidencing partial melting and melt segregation by *in situ* transformation of the pre-existing continental crust[69]. A similar origin for K-rich granites has been proposed by Winther and Newton[27], which indicated that metasomatic redistribution of K_2O 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/CNK, 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.*[13], 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_2O and K_2O to the tonalitic crust[61]. Newton[86] 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[3] is assumed. Taking into account that heat production was 2 to 4 times greater than that at present[87], the Archaean plate tectonics must have been characterized by many small and thin lithosphere plates[7]. Accordingly, processes like ridge–trench interactions and subduction of young lithosphere were more frequent than at present[79]. The model also considers the decrease of geothermal gradients with time and the petrological consequences of this progressive cooling since early Archaean[25]. The last considered assumption is that the earth's cooling could have favoured an increase in the dip angle of subduction zones with time[8].

A large number of small plates of basic composition (basalt–komatiite) formed from a primitive magmatic ocean, are characteristic of the early Archaean[7] (Figure 10 *a*). 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.*[17] and references therein; Figure 10 *b* and *c*). This process could have taken place in two different tectonic settings: partial melting of subducting slabs[23] (Figure 10 *b*) or partial melting of a thickened hydrous mafic crust[88] (Figure 10 *c*). These different settings have also been explained as two stages during Archaean[24,76], 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[76]. 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 10 *a–c*). This is in agreement with the studies of Martin[23] and Smithies *et al.*[8], 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 10 *c*).

Progressive cooling of the earth produced subduction zones with steeper dip angles and increase in plate thickness (Figure 10 *a–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[8,17,25] can be a result of this change (Figure 10 *d*). 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_2O, which is explained as due to larger melting depths[25]. 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 (Figure 10 *a–d*).

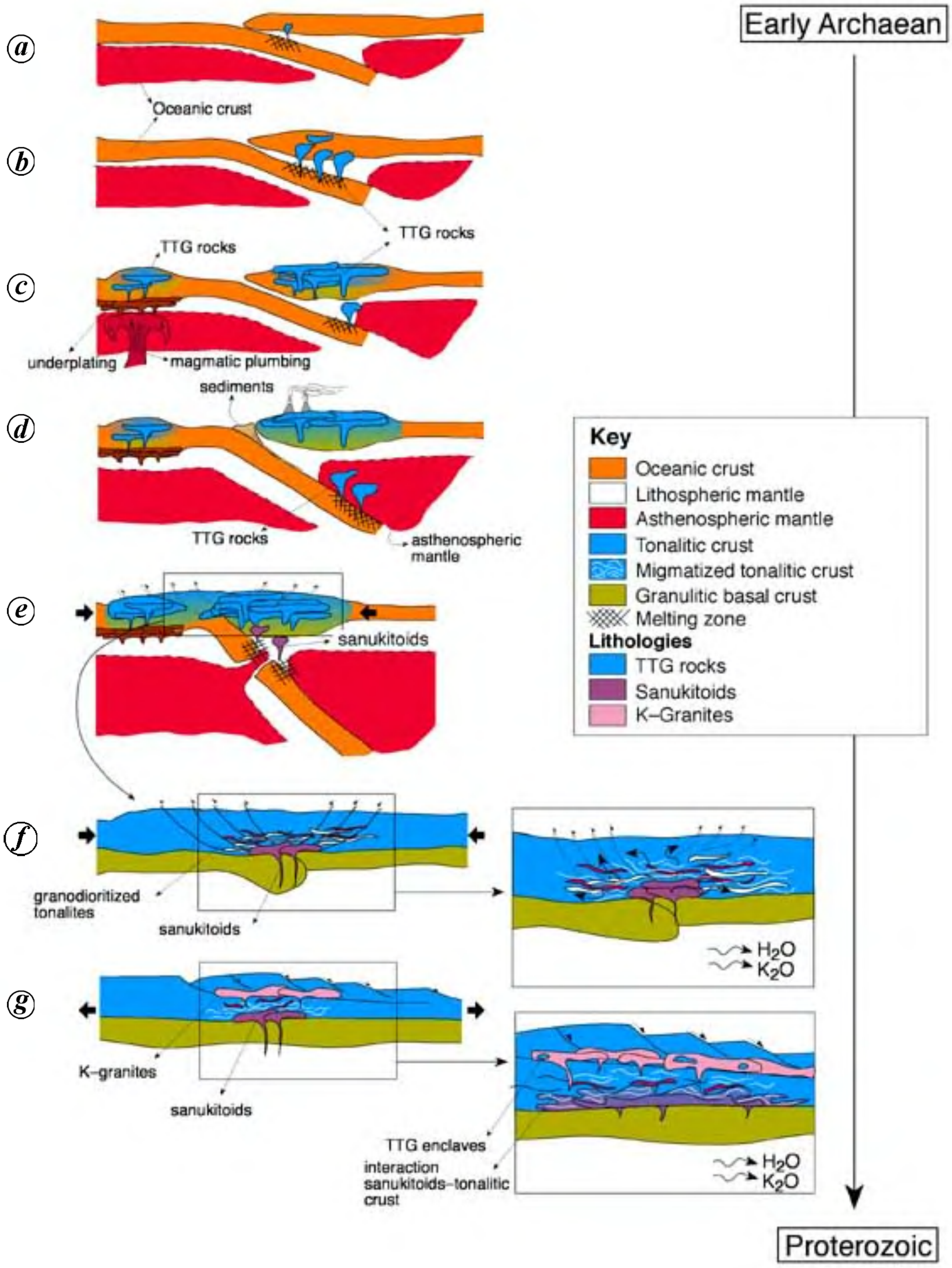

Figure 10. Petrogenetic model for TTG rocks, sanukitoids and K-granites. See text for details.

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 cratonization processes[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*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 problematic. According to Stevenson *et al.*[89], 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 like 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[13]). It has been proposed that the intrusion of sanukitoids into a tonalite crust favoured the migmatization of the core of orogenic belts[61]. The fluids released from the crystallizing hydrous sanukitic magma could have pervaded the continental crust and modified its composition from tonalitic to granodioritic[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[69], NW Scotland, and those of Madras granulites[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 sanukitoid 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 favoured 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[90].

Conclusion

The progressive cooling of the earth from the early Archaean conditioned the chemical composition of rocks formed in convergent plates 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 favoured 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.

1. Taylor, S. R., Growth of planetary crusts. *Tectonophysics*, 1989, **161**, 147–156.
2. de Wit, M. J., Roering, C., Hart, R. J., Armstrong, R. A., de Ronde, C. E. J., Green, R. W. E. and Tredoux, M., Formation of an Archaean continent. *Nature*, 1992, **357**, 553–562.
3. de Wit, M. J., On Archean granites, greenstone, cratons and tectonics: does the evidence demand a verdict?. *Precambrian Res.*, 1998, **91**, 181–226.
4. Van Kranendonk, Archaean tectonics. *Precambrian Res.*, 2004, **131**, 143–151.
5. Hargraves, R. B., Faster spreading or greater ridge length in the Archaean?. *Geology*, 1986, **14**, 750–752.
6. Condie, K. C., Bowling, G. P. and Allen, P., Origin of granites in an Archean high-grade terrane, southern India. *Contrib. Mineral. Petrol.*, 1986, **92**, 93–103.
7. Condie, K. C., *Plate Tectonics and Crustal Evolution*, Pergamon Press, 1989, 3rd edn, p. 492.
8. Smithies, R. H., Champion, D. C. and Cassidy, K. F., Formation of Earth's early Archaean continental crust. *Precambrian Res.*, 2003, **127**, 89–101.
9. Taylor, S. R. and McLennan, S. M., *The Continental Crust: Its Composition and Evolution*, Blackwell, 1985, p. 312.
10. Sutcliffe, R. H., Smith, A. R., Doherty, W. and Bernett, R. L., Mantle derivation of Archean amphibole-bearing granitoids and associated mafic rocks: evidence from the southern Superior Province, Canada. *Contrib. Mineral. Petrol.*, 1990, **105**, 255–274.
11. Frost, C. D., Frost, B. R., Chamberlain, K. R. and Hulsebosch, T. P., The late Archaean history of the Wyoming province as recorded by granitic magmatism in the Wind River Range, Wyoming. *Precambrian Res.*, 1998, **89**, 145–173.
12. Jayananda, M., Moyen, J. F., Martin, H., Peucat, J. J., Auvray, B. and Mahabaleswar, B., Late Archaean (2550–2520 Ma) juvenile magmatism in the eastern Dharwar craton, southern India: constraints from geochronology, Nd–Sr isotopes and whole rock geochemistry. *Precambrian Res.*, 2000, **99**, 225–254.
13. Moyen, J. F., Martin, H., Jayananda, M. and Auvray, B., Late Archaean granites: a typology based on the Dharwar Craton (India). *Precambrian Res.*, 2003, **127**, 103–123.
14. Champion, D. C. and Sheraton, J. W., Geochemistry and Nd isotope systematic of Archaean of the Eastern Goldfields, Yilgard Craton, Australia: implications for crustal growth processes. *Precambrian Res.*, 1997, **83**, 109–132.
15. Feng, R. and Kerrich, R., Cheochemical evolution of granitoids from the Archean Abitibi Southern volcanic zone and the Pontiac subprovince, Superior Province, Canada: implications for tectonic history and source regions. *Chem. Geol.*, 1992, **98**, 23–70.

16. Shirey, S. B. and Hanson, G. N., Mantle-derived Archaean monzodiorites and trachyandesites. *Nature*, 1984, **310**, 222–224.
17. Martin, H., Smithies, R. H., Rapp, R., Moyen, J. F. and Champion, D., An overview of adakite, tonalite–trondhjemite–granodiorite (TTG), and sanukitoids: relationships and some implications for crustal evolution. *Lithos*, 2005, **79**, 1–24.
18. Martin, H., The Archaean grey gneisses and the genesis of the continental crust. In *The Archaean Crustal Evolution* (ed. Condie, K. C.), Elsevier, Amsterdam, 1994, pp. 205–259.
19. Arth, J. G. and Barker, F., Rare-earth partitioning between hornblende and dacitic liquid and implications for the genesis of trondhjemitic–tonalitic magmas. *Geology*, 1976, **4**, 534–536.
20. McGregor, V. R., Archaean grey gneisses and the origin of the continental crust: evidence the Gothåb region, West Greenland. In *Trondhjemites, Dacites and Related Rocks* (ed. Barker, F.), Elsevier, Amsterdam, 1979, pp. 169–204.
21. Tarney, J., Weaver, B. L. and Drury, S. A., Geochemistry of Archaean trondhjemitic and tonalitic gneisses from Scotland and East Greenland. In *Trondhjemites, Dacites and Related Rocks* (ed. Barker, F.), Elsevier, Amsterdam, 1979, pp. 275–299.
22. Rollinson, H., Tonalite–Trondhjemite–Granodiorite magmatism and the genesis of Lewisian crust during the Archaean. In *Precambrian Crustal Evolution in the North Atlantic Region* (ed. Brewer, T. S.), Geological Society Special Publication, 1996, vol. 112, pp. 25–42.
23. Martin, H., Adakitic magmas: modern analogues of Archaean granitoids. *Lithos*, 1999, **26**, 411–429.
24. Smithies, R. H. and Champion, D. C., The Archaean high-Mg diorite suite: links to tonalite–trondhjemite–granodiorite magmatism and implications for Early Archaean crustal growth. *J. Petrol.*, 2000, **41**, 1653–1671.
25. Martin, H. and Moyen, J. F., Secular changes in tonalite–trondhjemite–granodiorite composition as markers of the progressive cooling of Earth. *Geology*, 2002, **30**, 319–322.
26. Beard, J. S. and Lofgren, G. E., Dehydration melting and water-saturated melting of basaltic and andesitic greenstone and amphibolites. *J. Petrol.*, 1991, **32**, 365–401.
27. Winther, K. T. and Newton, R. C., Experimental melting of hydrous low-K tholeiite: evidence on the origin of Archaean cratons. *Bull. Geol. Soc. Denmark*, 1991, **39**, 213–228.
28. Rushmer, T., Partial melting of two amphibolites: constraints experimental results under fluid-absent conditions. *Contrib. Mineral. Petrol.*, 1991, **107**, 41–59.
29. Wolf, M. B. and Wyllie, P. J., Dehydration-melting of solid amphibolite at 10 kbar: textural development, liquid interconnectivity and applications to the segregation of magmas. *Mineral. Petrol.*, 1991, **44**, 151–179.
30. Rapp, R. P., Watson, E. B. and Miller, C. F., Partial melting of amphibolite/eclogite and the origin of Archaean trondhjemites and tonalites. *Precambrian Res.*, 1991, **51**, 1–25.
31. Rapp, R. P. and Watson, E. B., Dehydration melting of metabasalt at 8–32 kbar: Implications for continental growth and crust–mantle recycling. *J. Petrol.*, 1995, **36**, 891–931.
32. Winther, K. T., An experimental based model for the origin of tonalitic and trondhjemitic melts. *Chem. Geol.*, 1996, **127**, 43–59.
33. Arth, J. G., Barker, F., Peterman, Z. E. and Friedman, I., Geochemistry of the gabbro–diorite–tonalite–trondhjemite suite of southwest Finland and its implications for the origin of tonalitic and trondhjemitic magma. *J. Petrol.*, 1978, **19**, 289–316.
34. Wyllie, P. J., Huang, W. L., Stern, C. R. and Maaløe, S., Granitic magmas: possible and impossible sources, water contents, and crystallization sequences. *Can. J. Earth Sci.*, 1976, **13**, 1007–1019.
35. Johnston, A. D. and Wyllie, P. J., Constraints on the origin of Archaean trondhjemites based on phase relationships of Nûk gneiss with H_2O at 15 kbar. *Contrib. Mineral. Petrol.*, 1988, **100**, 35–46.
36. Barker, F. and Arth, J. G., Generation of trondhjemitic–tonalitic liquids and Archaean bimodal trondhjemite–basal suites. *Geology*, 1976, **4**, 596–600.
37. Drummond, M. S., Ragland, P. C. and Wesolowski, D., An example of trondhjemite genesis by means of alkali metasomatism: Rockford Granite, Alabama Appalachians. *Contrib. Mineral. Petrol.*, 1986, **93**, 98–113.
38. Smithies, R. H., The Archaean tonalite–trondhjemite–granodiorite (TTG) series is not an analogue of Cenozoic adakites. *Earth Planet Sci. Lett.*, 2000, **182**, 115–125.
39. Sutcliffe, R. H., Magma mixing in late Archaean tonalitic and mafic rocks of the Lac des Iles area, Western Superior Province. *Precambrian Res.*, 1989, **44**, 81–101.
40. Stern, R. A. and Hanson, G. N., Archaean high-Mg granodiorite: a derivative of light rare earth elements-enriched monzodiorite of mantle origin. *J. Petrol.*, 1991, **32**, 201–238.
41. Mueller, P. A., Wooden, J. L., Schulz, K. and Bowes, D. R., Incompatible element rich andesitic amphibolites from the Archaean of Montana and Wyoming: evidence for mantle metasomatism. *Geology*, 1983, **11**, 203–206.
42. Jahn, B. M. *et al.*, Archaean crustal evolution in China: the Taishan complex, and evidence for juvenile crustal addition from long-term depleted mantle. *Precambrian Res.*, 1988, **38**, 381–403.
43. Jayananda, M., Martin, H., Peucat, J. J. and Mahabaleswar, B., Late Archaean crust–mantle interactions: geochemistry of LREE-enriched mantle derived magmas. Example of the Closepet batholith, southern India. *Contrib. Mineral. Petrol.*, 1995, **199**, 314–329.
44. Moyen, J. F., Martin, H. and Jayananda, M., Multi-element geochemical modelling of crust–mantle interaction during late-Archaean crustal growth: the Closepet granite (South India). *Precambrian Res.*, 2001, **112**, 87–105.
45. Steenfelt, A., Garde, A. A. and Moyen, J. F., Mantle wedge involvement in the petrogenesis of Archaean grey gneisses in West Greenland. *Lithos*, 2005, **79**, 207–228.
46. Bibikova, E. V., Petrova, A. and Claesson, S., The temporal evolution of sanukitoids in the Karelian Craton, Baltic Shield: an ion microprobe U–Th–Pb isotopic study of zircons. *Lithos*, 2005, **79**, 129–145.
47. Stern, R. A., Hanson, G. N. and Shirey, S. B., Petrogenesis of mantle-derived, LILE-enriched Archean monzodiorites and trachyandesites (sanukitoids) in southwestern Superior Province. *Can. J. Earth Sci.*, 1989, **26**, 1688–1712.
48. Rapp, R. P., Shimizu, N., Norman, M. D. and Applegate, G. S., Reaction between slab-derived melts and peridotite in the mantle wedge: experimental constraints at 3.8 GPa. *Chem. Geol.*, 1999, **160**, 335–356.
49. Kusky, T. M. and Polat, A., Growth of granite–greenstone terranes at convergent margins, and stabilization of Archaean cratons. *Tectonophysics*, 1999, **305**, 45–73.
50. Rudnick, R. L., Making continental crust. *Nature*, 1995, **378**, 571–578.
51. Sylvester, P. J., Archean granite plutons. In *Archean Crustal Evolution* (ed. Condie, K. C.), *Developments in Precambrian Geology*, Elsevier, 1994, vol. 11, pp. 261–314.
52. Kleinhanns, I. C., Kramers, J. D. and Kamber, B. S., Importance of water for Archaean granitoids petrology: a comparative study of TTG and potassic granitoids from Barberton Mountain Land, South Africa. *Contrib. Mineral. Pet.*, 2003, **145**, 377–389.
53. Martin, H. and Querré, G., A 2.5 Ga reworked sialic crust: Rb–Sr ages and isotopic geochemistry of late Archaean volcanic and plutonic rocks from E. Finland. *Contrib. Mineral. Petrol.*, 1984, **85**, 292–299.

54. Weaver, B. L., Rare–earth element geochemistry of Madras granulites. *Contrib. Mineral. Petrol.*, 1980, **71**, 271–279.
55. Condie, K. C., Allen, P. and Narayana, B. L., Geochemistry of the Archean low- to high-grade transition zone, Southern India. *Contrib. Mineral. Petrol.*, 1982, **81**, 157–167.
56. Ridley, J. R., Vearncombe, J. R. and Jelsma, H. A., Relations between greenstone belts and associated granitoids. In *Greenstone Belts* (eds de Wit, M. and Ashwal, L.), Oxford University Press, 1997, pp. 376–398.
57. Brown, M., Friend, C. R. L., McGregor, V. R. and Perkins, W. T., The late Archaean Qôrqut granite complex of southern West Greenland. *J. Geophys. Res.*, 1981, **86**, 10617–10632.
58. Evans, O. C. and Hanson, G. N., Late- to post-kinematic Archaean granitoids of the S.W. Superior Province: derivation through direct mantle melting. In *Greenstone Belts* (eds de Wit, M. and Ashwal, L.), Oxford University Press, 1997, pp. 280–295.
59. Berger, M. and Rollinson, H., Isotopic and geochemical evidence for crust–mantle interaction during late Archaean crustal growth. *Geochim. Cosmochim. Acta*, 1997, **61**, 4809–4829.
60. López, S. and Castro, A., Determination of the fluid–absent solidus and supersolidus phase relationships of MORB-derived amphibolites in the range 4–14 kbar. *Am. Mineral.*, 2001, **86**, 1396–1403.
61. López, S., Castro, A. and García-Casco, A., Production of granodiorite melt by interaction between hydrous mafic magma and tonalitic crust. Experimental constraints and implications for the generation of Archaean TTG complexes. *Lithos*, 2005, **79**, 229–250.
62. Castro, A., Fernández, C., de la Rosa, J. D., Moreno-Ventas, I. and Rogers, G., Significance of MORB-derived amphibolites from the Aracena Metamorphic Belt, Southwest Spain. *J. Petrol.*, 1996, **37**, 235–360.
63. Barker, F., Trondhjemites: definition, environment and hypotheses of origin. In *Trondhjemites, Dacites and Related Rocks* (eds Barker, F.), Elsevier, Amsterdam, 1979, pp. 1–12.
64. Collins, W. J., Melting of Archaean silialic crust under high H_2O conditions: genesis of 3300 Ma Na-rich granitoids in the Mount Edgar Batholith, Pilbara Block, Western Australia. *Precambrian Res.*, 1993, **60**, 151–174.
65. Carroll, M. R. and Wyllie, P. J., The system tonalite–H_2O at 15 kbar and the genesis of calc–alkaline magmas. *Am. Mineral.*, 1990, **75**, 345–357.
66. Skjerlie, K. P. and Johnston, A. D., Vapor–absent melting at 10 kbar of a biotite – and amphibole-bearing tonalitic gneiss: Implications for the generation of A-type granites. *Geology*, 1992, **20**, 263–266.
67. Skjerlie, K. P. and Johnston, A. D., Fluid-absent melting behaviour of an F-rich tonalitic gneiss at mid-crustal pressures: implications for the generation of anorogenic granites. *J. Petrol.*, 1993, **34**, 785–815.
68. Gardien, V., Thompson, A. B. and Ulmer, P., Melting of biotite + plagioclase + quartz gneisses: the role of H_2O in the stability of amphibole. *J. Petrol.*, 2000, **41**, 651–666.
69. Castro, A., The source of granites: inferences from the Lewisian complex. *Scottish J. Geol.*, 2004, **40**, 49–65.
70. López, S., Procesos de generación de magmas graníticos en la corteza arcaica. Aproximación mediante el estudio experimental de las relaciones de fases y composición de los fundidos, Ph D Thesys, University of Huelva, 2004, p. 288.
71. Skjerlie, K. P. and Patiño Douce, A. E., The fluid-absent partial melting of a zoisite-bearing quartz eclogite from 1.0 to 3.2 GPa; Implications from melting in thickened continental crust and for subduction-zone processes. *J. Petrol.*, 2002, **43**, 291–314.
72. Sen, C. and Dunn, T., Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: Implications for the origin of adakites. *Contrib. Mineral. Petrol.*, 1994, **117**, 394–409.
73. Xiong, X. L., Adam, J. and Green, T. H., Rutile stability and rutile/melt HFSE partitioning during partial melting of hydrous basalt: implications for TTG genesis. *Chem. Geol.*, 2005, **218**, 339–359.
74. Patiño Douce, A. and Beard, J. S., Dehydration melting of biotite gneiss and quartz amphibolite from 3 to 15 kbar. *J. Petrol.*, 1995, **36**, 707–738.
75. Foley, S., Tiepolo, M. and Vannucci, R., Growth of early continental crust controlled by melting of amphibolite in subduction zones. *Nature*, 2002, **417**, 837–840.
76. Foley, S. F., Buhre, S. and Jacob, D. E., Evolution of the Archaean crust by delamination and shallow subduction. *Nature*, 2003, **421**, 249–252.
77. Smithies, R. H., Champion, D. C., Van Kranendonk, M. J., Howard, H. M. and Hickman, A. H., Modern-style subduction process in the Mesoarchaean: geochemical evidence from the 3.12 Ga Whundo intra-oceanic arc. *Earth Planet. Sci. Lett.*, 2005, **231**, 221–237.
78. Bjørnerud, M. G. and Austrheim, H., Inhibited eclogite formation: the key to rapid growth of strong and buoyant Archean continental crust. *Geology*, 2004, **32**, 765–768.
79. Karsten, J. L., Klein, E. M. and Sherman, S. B., Subduction zones geochemical characteristics in ocean ridge basalts from the southern Chile ridge: implications of modern ridge subduction system for the Archaean. *Lithos*, 1996, **37**, 143–161.
80. Toksöv, M. N., Minear, J. W. and Julian, B. R., Temperature field and geophysical effects of a downgoing slab. *J. Geophys. Res.*, 1971, **76**, 1113–1138.
81. Turcotte, D. L. and Schubert, G., Frictional heating of the descending lithosphere. *J. Geophys. Res.*, 1973, **78**, 5876–5886.
82. Peacock, S. M., Fluid processes in subduction zones. *Science*, 1990, **248**, 329–337.
83. Peacock, S. M., Blueschist-facies metamorphism, shear heating, and P–T–t paths in subduction shear zones. *J. Geophys. Res.*, 1992, **97**, 17693–17707.
84. Gerya, T. V., Yuen, D. A. and Sevre, E. O. D., Dynamical causes for incipient magma chambers above slabs. *Geology*, 2004, **32**, 89–92.
85. Zegers, T. E., Granite formation and emplacement as indicators of Archaean tectonic process. In *The Precambrian Earth: Tempos and Events* (eds Eriksson, P. G. *et al.*), Elsevier, Amsterdam, 2004, vol. 12, pp. 103–118.
86. Newton, R. C., Fluids and melting in the Archean deep crust of southern India. In *High temperature metamorphism and crustal anatexis* (eds Ashworth, J. and Brown, M.), Mineralogical Society Series, 1990, vol. 2, pp. 149–179.
87. Bickle, M. J., Implications of melting for stabilization of lithosphere and heat loss in the Archaean. *Earth Planet. Sci. Lett.*, 1986, **80**, 314–324.
88. Atherton, M. P. and Petford, N., Generation of sodium-rich magmas from newly underplated basaltic crust. *Nature*, 1993, **362**, 144–146.
89. Stevenson, R., Henry, P. and Garièpy, C., Assimilation–fractional crystallization origin of Archean Sanukitoid Suites: Western Superior Province, Canada. *Precambrian Res.*, 1999, **96**, 83–99.
90. Kusky, T. M., Collapse of Archean orogens and the generation of late- to postkinematic granitoids. *Geology*, 1993, **21**, 925–928.
91. Nakamura, N., Determination of REE, Ba, Fe, Mg, Na and K in carbonaceous and ordinary chondrites. *Geochim. Cosmochim. Acta*, 1974, **38**, 757–775.
92. Arth, J. G., Behaviour of trace elements during magmatic processes – a summary of theoretical models and their applications. *J. Res. US Geol. Surv.*, 1976, **4**, 41–47.
93. Dudas, M. J., Schmitt, R. A. and Harward, M. E., Trace element partitioning between Volcanic Plagioclase and Dacitic Pyroclastic Matrix. *Earth Planet. Sci. Lett.*, 1971, **11**, 440–446.

94. Sisson, T. W., Hornblende-melt trace-element partitioning measured by ion microprobe. *Chem. Geol.*, 1994, **117**, 331–344.
95. Fujimaki, H., Tatsumoto, M. and Aoki, K., Partition coefficients of Hf, Zr and REE between phenocrysts and groundmasses. Proceedings of the fourteenth lunar and planetary science conference, Part 2. *J. Geophys. Res.*, 1984, **89**, Suppl. B662–B672.
96. Nash, W. P. and Crecraft, H. R., Partition coefficients for trace elements in silicic magmas. *Geochim. Cosmochim. Acta*, 1985, **49**, 2309–2322.
97. Irving, A. J. and Frey, F. A., Effect of compostition of the partitioning of rare earth elements, Hf, Sc and Co betweeen garnet and liquid. *EOS Trans., Am. Geophys. Union*, 1976, **57**, 339.
98. Martin, H., Peucat, J. J., Sabaté, P. and Cunha, J. C., Crustal evolution in the early Archaean of South America: example of Sete Voltas Massif, Bahia State, Brazil. *Precambrian Res.*, 1997, **82**, 35–62.
99. de Souza, Z. S., Potrel, A. L., Lafon, J. M., Althoff, F. J., Pimentel, M. M., Dall'Agnol, R. and de Oliveira, C. G., Nd, Pb and Sr isotopes in the Identidade Belt, and Archaean greenstone belt of the Rio Maria region (Carajás Province, Brazil): implications for the Archaean geodynamic evolution of the Amazonian Craton. *Precambrian Res.*, 2001, **109**, 293–315.
100. Weaver, B. L. and Tarney, J., Rare earth geochemistry of the Lewisian granulite gneisses, northwest Scotland: Implications for the petrogenesis of the Archaean Lower Continental Crust. *Earth Planet. Sci. Lett.*, 1980, **51**, 279–296.
101. Rollinson, H. and Fowler, M. B., The magmatic evolution of the Scourian complex at Gruinard Bay. In *Evolution of the Lewisian and Comparable Precambrian High Grade Terrains* (eds Park, R. G. and Tarney, J.), Geological Society Special Publications. Blackwell, 1987, vol. 27, pp. 57–71.
102. Burton, K. B., Capmas, F., Birck, J. L., Allègre, C. J. and Cohen, A., Resolving crystallization ages of Archaean mafic–ultramafic rocks using the Re–Os isotope system. *Earth Planet. Sci. Lett.*, 2000, **179**, 453–467.
103. Yamashita, K., Creaser, R. A., Jensen, J. E. and Heaman, L. M., Origin and evolution of mid- to late-Archean crust in the Hanikahimajuk lake area, Slave Province, Canada; evidence from U–Pb geochronological, geochemical and Nd–Pb isotopic data. *Precambrian Res.*, 2000, **99**, 197–224.
104. Martin, H., Petrogenesis of Archaean trondhjemites, tonalites and granodiorites from eastern Finland: major and trace element geochemistry. *J. Petrol.*, 1987, **28**, 921–953.
105. Jahn, B. M., Gruau, G., Capdevila, R., Cornichet, J., Nemchin, A., Pidgeon, R. and Rudnik, V. A., Archaean crustal evolution of the Aldan Shield, Siberia: geochemical and isotopic constraints. *Precambrian Res.*, 1998, **91**, 333–363.
106. Hunter, D. R., Smith, R. G. and Sleigh, D. W. W., Geochemical studies of Archaean granitoids rocks in the Southeastern Kaapvaal Province: implications for crustal development. *J. Afr. Earth Sci.*, 1992, **15**, 127–151.
107. Anhaeusser, C. R. and Walraven, F., Episodic granitoid emplacement in the western Kaapvaal Craton: evidence from the Archaean Kraaipan granite–greenstone terrane, South Africa. *J. Afr. Earth Sci.*, 1999, **28**, 289–309.
108. Foden, J. D., Nesbitt, R. W. and Rutland, R. W. R., The geochemistry and crustal origin of the Archaean acid intrusive rocks of the Agnew Dome, Lawlers, Western Australia. *Precambrian Res.*, 1984, **23**, 247–271.
109. Green, D. H., Anatexis of mafic crust and high pressure crystallization of andesite. In *Andesites: Orogenic Andesites and Related Rocks* (ed. Thorpe, R. S.), John Wiley, 1982, pp. 464–489.
110. Wyllie, P. J. and Wolf, M., Amphibolite dehydration melting: sorting out the solidus. In *Magmatic Processes and Plate Tectonics* (eds Prichard, H. M. *et al.*), Geological Society Special Publication, 1993, vol. 76, pp. 405–416.
111. Peacock, S. M., Rushmer, T. and Thompson, A. B., Partial melting of subducting oceanic crust. *Earth Planet. Sci. Lett.*, 1994, **121**, 227–244.
112. Schmidt, M. W. and Poli, S., Experimentally based water budgets for dehydrating slabs and consequences for arc magma generation. *Earth Planet. Sci. Lett.*, 1998, **163**, 361–379.

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