

Secular changes in tonalite-trondhjemite-granodiorite composition as markers of the progressive cooling of Earth

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ABSTRACT

Archean tonalite-trondhjemite-granodiorite associations (TTG) are classically thought to generate through partial melting of hydrous metabasalts. However, the chemical composition of the least differentiated TTG parental magmas evolved from 4.0 to 2.5 Ga. During this interval, the Mg# as well as the Ni and Cr contents increased, which is interpreted as reflecting increased interactions between felsic melts generated by metabasalt melting and mantle peridotite. Similarly, (CaO + Na₂O) and Sr also increased over time, thus reflecting an increase in the abundance of plagioclase in the melt residue. The presence or absence of residual plagioclase is interpreted in terms of melting depth. The demonstrated interaction between TTG parental magmas and the mantle rules out their genesis by fusion of previously underplated metabasalt and favors the melting of subducted slab material. At 4.0 Ga, Earth's geothermal gradient was sufficiently high to allow slab melting at shallow depths where plagioclase was stable. Consequently, due to the small thickness of the overlying mantle wedge, felsic magmas interacted little with the mantle. At 2.5 Ga, however, owing to lower geothermal gradients, the melting depth was greater and plagioclase became no longer stable in the thick mantle wedge overlying the subducted slab. As a result, felsic magmas reacted strongly with the mantle peridotite. The changes of TTG composition during Archean time can be thus interpreted as reflecting the progressive cooling of Earth.

Keywords: Archean, early continental crust, Earth cooling, slab melting, TTG.

INTRODUCTION

It is now generally thought that Archean tonalite-trondhjemite-granodiorite (TTG) associations, which are the main components of the Archean continental crust, were generated by partial melting of a hydrous metabasaltic source, leaving a residue of garnet amphibolite or eclogite (see Martin, 1995, for review). However, there is little agreement on the geodynamic setting in which this melting could have taken place. Two main sources of melt are proposed: (1) basaltic material previously underplated beneath thickened crust (Rudnick, 1995; Albarède, 1998; Smithies, 2000), and (2) basaltic rocks corresponding to a subducted oceanic slab; because of the high geothermal gradient, this material melted instead of dehydrating (Martin, 1986, 1995; Condie, 1989; Rollinson, 1997; Albarède, 1998). As pointed out by Martin (1999) and Smithies (2000), the main difference between these two models is that melts derived from the subducted slab must ascend through (and probably interact with) the mantle. By contrast, this is clearly not the case in the melting of underplated material. Consequently, we might expect to find some evidence for interaction between TTG parental magmas and mantle. Present-day adakites, considered as analogues of Archean TTGs, show evidence of olivine assimilation by slab melts during their ascent

through the mantle wedge (Maury et al., 1996; Martin, 1999; Rapp et al., 1999).

Even if it was generally hotter during the Archean than today, the whole Earth was progressively cooling down. Thermal modeling (Brown, 1986) indicates that Earth's heat production decreased by as much as 50% from 4.0 to 2.5 Ga. Such a change would have significantly modified the conditions of melting of the basaltic source for the TTG. In the case of subducted slab melting, a temporal decrease in the geothermal gradient along the Benioff plane is expected to result in increasing depth of melting during the Archean. However, no important change in melting depth is expected in the case of underplated basalt.

This paper is based on a compilation of more than 1100 chemical analyses of Archean TTGs covering a range of different ages (129 emplaced before 3.5 Ga; 320 between 3.5 and 3.0 Ga; and 652 after 3.0 Ga). We excluded all the so-called sanukitoids in this database because of their at least partly mantle-derived origin (Rapp et al., 1999). The purpose of this study is to (1) discuss the compositional evolution of TTG magmas from 4.0 to 2.5 Ga, (2) address the problem of possible interaction between TTG magmas and the mantle, (3) compare Archean TTG associations with modern adakites as well as with liquids generated by experimental melting of hydrous basalts, and (4) propose a consistent model accounting for

the genesis of these magmas as well as their evolution over geologic time.

PRESENTATION OF DATA

Figure 1 shows Mg# [Mg/(Mg + Fe)], Ni, Cr, Sr, and (Na₂O + CaO) plotted against TTG emplacement age. For each period of time, TTG compositions scatter across a relatively wide range, either due to different degrees of partial melting of the basaltic source or subsequent fractional crystallization. Although the latter mechanism is not reported in all Archean TTGs, its role is locally well demonstrated (e.g., in zoned plagioclase crystals). Geochemical modeling (Martin, 1995) shows that the main cumulate assemblage consists of hornblende and plagioclase with possible subordinate amounts of accessory phases.

During fractional crystallization, Mg, Ni, and Cr display a compatible behavior because the hornblende/liquid partition coefficients (K_d) are high in felsic liquids [$(K_d)_{Mg} > 20$, $(K_d)_{Ni} \approx 12$, and $(K_d)_{Cr} > 20$]. Thus, their contents in the magmas decrease during differentiation. The same conclusion can be drawn for Na₂O and CaO, as well as for Sr, the low K_d values of which in hornblende are offset by their high partition coefficient in plagioclase [$(K_d)_{Sr} > 4$].

In summary, fractional crystallization of plagioclase + hornblende results in a decrease of Mg# as well as Ni, Cr, Sr, and (Na₂O + CaO). Within each age bracket, we may consider the highest values of Mg#, Ni, Cr, Sr, and (Na₂O + CaO) as being representative of the less differentiated and more primitive TTG parental magma. Thus, the upper envelope of the data set reflects the compositional variation of the primitive TTG parental magmas with time, which can be interpreted in terms of melting conditions in the magma source as well as possible interactions with the mantle.

INTERPRETATION OF DATA

Mg#, Ni, and Cr Variations: Interactions with the Mantle Wedge

The maximum Mg# evolves from 0.45 at 4.0 Ga to 0.65 at 2.5 Ga (Fig. 1, A–C). In the same time interval, Ni increases from 30 to 70 ppm and Cr from 50 to 200 ppm, respectively. Figure 2A presents a plot of MgO versus SiO₂ comparing TTG compositions with modern adakites as well as liquids produced by experimental melting of basalts. Both adakites

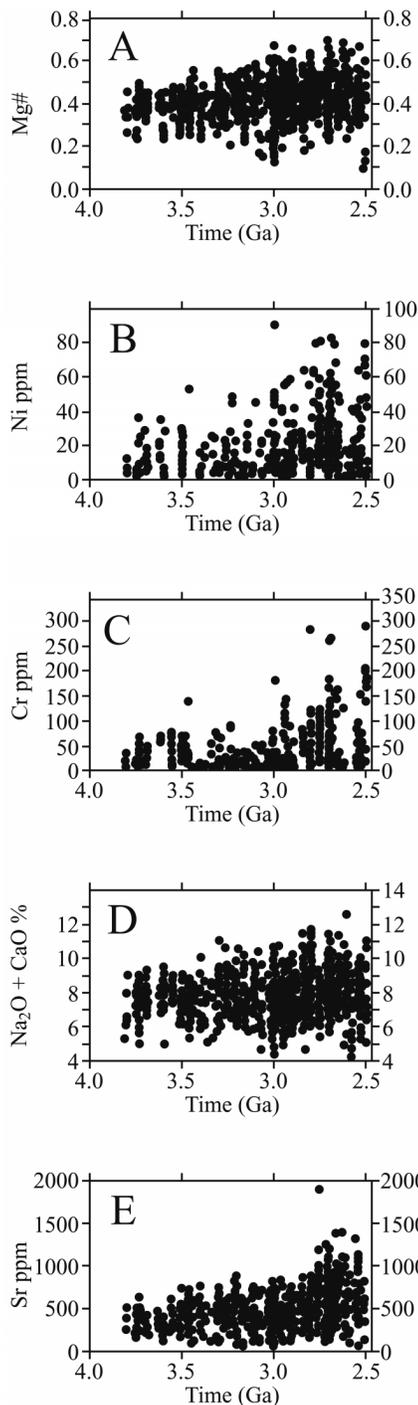


Figure 1. Diagrams showing time evolution of various compositional parameters of primitive parental tonalite-trondhjemite-granodiorite magmas during Archean.

and TTGs are richer in MgO than the experimental basalt melts. Such differences have already been reported for adakites (Maury et al., 1996; Smithies, 2000; Prouteau et al., 2001) and for TTG (Martin, 1999). In agreement with these studies, Rapp et al. (1999) considered that during ascent through the mantle, melts undergo assimilation of olivine and fractional crystallization involving orthopyroxene and garnet. This mechanism is able to modify

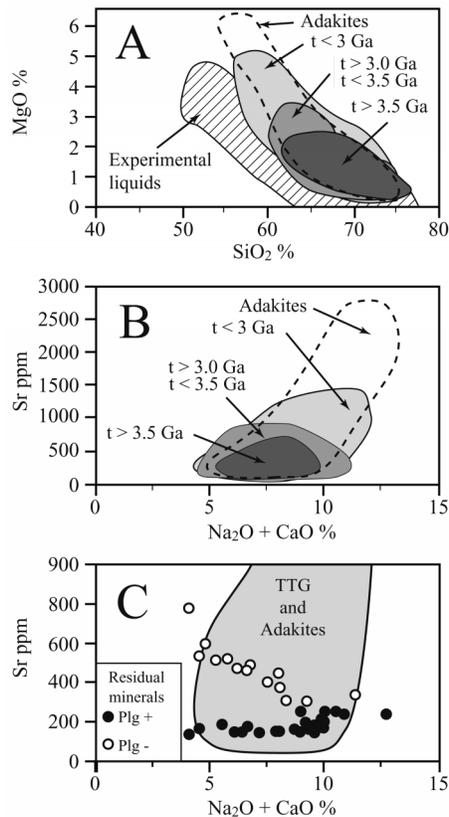


Figure 2. MgO vs. SiO₂ (A) and Sr vs. (Na₂O + CaO) (B) diagrams comparing composition of tonalite-trondhjemite-granodiorite (TTG) at different times (*t*, gray fields) with modern adakites (fields with white dotted lines) and melts produced by experimental basalt melting (hatched area). (C): Sr vs. (Na₂O + CaO) plot showing compositions of experimental melts obtained with (filled circles) or without (open circles) residual plagioclase (Plg), compared with TTG and adakite compositions (gray field).

significantly the contents of SiO₂, MgO, Ni, and Cr, without changing the slab-melt signature as recorded by incompatible elements.

Petrological evidence for reactions between magma and the mantle wedge was given by Kepezhinskas et al. (1995), who showed that Cenozoic mantle xenoliths from Kamchatka were metasomatized by slab melts. Furthermore, Schiano et al. (1995) reported adakitic glass inclusions in olivine crystals from xenoliths from Batan Island. Such processes can modify the adakitic magma (enriched in MgO, Ni, and Cr) as well as the mantle wedge composition.

Assuming that the high MgO, Ni, and Cr contents of adakites and TTGs reflect effective interactions between felsic melts and the mantle, we can draw the following conclusions.

1. Both Archean TTGs and modern adakites have chemical signatures typical of magmas generated by melting of metabasalts at high pressure in equilibrium with a garnet-bearing residue (Martin, 1995, 1999). However, the

MgO, Ni, and Cr contents are significantly higher in these magmas compared with pure experimental metabasalt melts. This is because the natural magmas interacted with mantle peridotite after their genesis. Because adakites are slightly richer in MgO than Archean TTGs for the same degree of differentiation, it may be concluded that there is a greater degree of interaction of adakites with the mantle at present.

2. The composition of the less differentiated TTGs progressively evolves through time. It changes from low Mg#, Ni, and Cr at 4.0 Ga toward higher values at 2.5 Ga. We interpret this progressive change as being due to increasing melt and mantle interactions: the efficiency of these interactions was greater at 2.5 Ga than at 4.0 Ga.

3. That mantle-melt interactions are shown to take place in both adakites and Archean TTGs implies that the source of the melts is located at great depth, under a mantle slice. In other words, they are formed by melting of metabasalts under an important mantle thickness, so that significant interactions can take place. In addition, the temporal increase in the degree of melt-mantle interaction could be related to an increased depth of melting of the basaltic source.

Variations in Sr and (Na₂O + CaO): Depth of Melting

In comparison with any other element, Sr shows the most spectacular change during the Archean (Fig. 1, D–E). Its content in the less differentiated TTGs increases from ~550 ppm at 4.0 Ga to 1200 ppm at 2.5 Ga. Over the same time interval, (Na₂O + CaO) increases from 9% to 11%. Figure 2B shows that adakite and TTG compositions remain similar with respect to Sr and (Na₂O + CaO). The representative points define a unique trend, even if some adakites are richer in Sr and (Na₂O + CaO). Zamora (2000) studied glasses produced by experimental melting of a single Sr-poor (Sr = 88 ppm) oceanic basalt from Taitao in Chile. He explored a wide pressure-temperature range (850–1150 °C and 7–35 kbar, respectively) and determined a total of 53 glass compositions. Figure 2C clearly shows that the presence or absence of residual plagioclase in the source controls the amount of Sr in the melt. This is not the case for (Na₂O + CaO), the behavior of which is strongly dependent on other residual phases such as garnet, hornblende, and clinopyroxene. Residual plagioclase appears to buffer the Sr content of the liquid. On the contrary, when plagioclase is not stable, the ratio Sr_{glass}/Sr_{source} can be as high as 10. This implies that the Sr content of the TTG parental magma may reflect the stability of plagioclase during melting.

The temporal increase of Sr content in

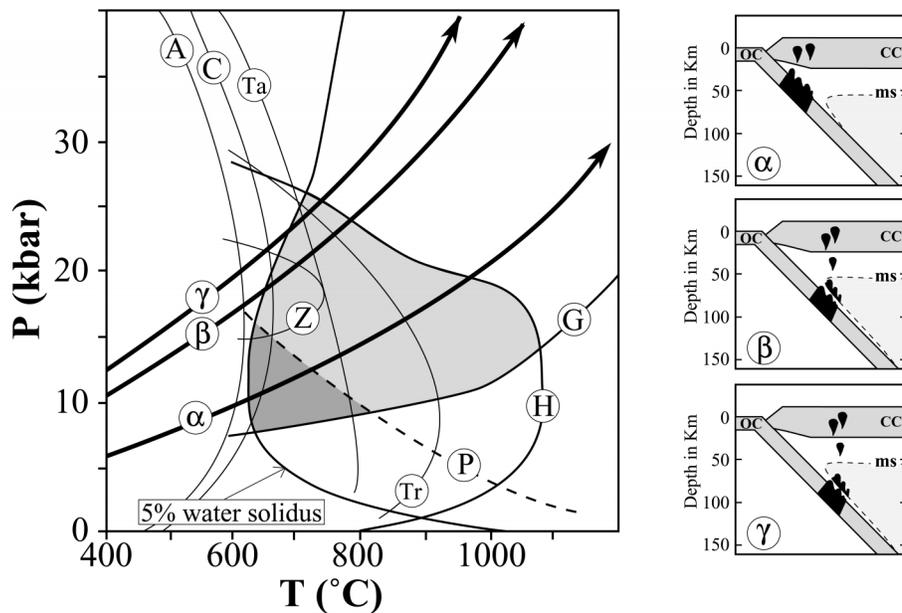


Figure 3. Pressure-temperature (P - T) diagram and schematic cross section of subduction zone. In Early Archean (4.0 Ga), geothermal gradient (α) along Benioff plane was very high; subducted slab melts at shallow depth with plagioclase as residual phase. Because of small thickness and low temperature of wedge, mantle-melt interactions are limited or absent. At 2.5 Ga, Earth was cooler and geothermal gradient (β) along Benioff plane was lower; slab melting occurs at greater depth without residual plagioclase. Overlying mantle wedge is thick and hot, and interactions may occur between slab melts and mantle. Geothermal gradient γ refers to modern adakites. P - T diagram shows solidus of tholeiite with 5% water as well as main dehydration reactions of oceanic lithosphere. H is hornblende out, A is anthophyllite out, C is chlorite out, Ta is talc out, Tr is tremolite out, Z is zoisite out. G and P outline stability fields of garnet and plagioclase, respectively. Gray field is P - T domain where slab melts can coexist with hornblende- and garnet-bearing residue. OC is oceanic crust; CC is continental crust; ms is solidus of hydrated mantle; areas in black indicate magma.

TTGs, together with the enrichment in ($\text{Na}_2\text{O} + \text{CaO}$), is thus interpreted as reflecting the declining role played by residual plagioclase in the genesis of TTG parental magmas from 4.0 to 2.5 Ga. We can draw the following conclusions.

1. The presence or absence of plagioclase in the melting residue of a TTG source governs the behavior of Sr, whereas it only partly controls ($\text{Na}_2\text{O} + \text{CaO}$).

2. The secular change in TTG composition is interpreted as reflecting plagioclase behavior. In the 4.0 Ga TTG rocks, the low Sr and ($\text{Na}_2\text{O} + \text{CaO}$) contents indicate plagioclase stability during melting. In contrast, the high Sr and ($\text{Na}_2\text{O} + \text{CaO}$) contents in the 2.5 Ga TTG rocks demonstrate a lack of residual plagioclase in the melt sources. Consequently, the role of residual plagioclase progressively decreased during Archean time.

3. Because plagioclase stability strongly depends on pressure and thus also on depth (Fig. 3), we infer that the depth of TTG magma genesis increased with time. At 4.0 Ga, the depth of partial melting was relatively shallow and plagioclase could have remained stable in the source region. On the contrary, the depth of partial melting was greater at 2.5 Ga, so the

source rocks were outside the plagioclase stability field.

DISCUSSION

Environment of TTG Genesis

Our study clearly points out that Archean TTGs and modern adakites have similar compositions (Fig. 2) and plot on the same variation trend. Consequently, we may assume that they are generated by similar mechanisms: both are produced by partial melting of hydrous basalt at mantle depth. However, both have MgO, Ni, and Cr contents that differ from liquids produced by the experimental melting of basalts. This difference reflects an interaction between felsic magmas and mantle material: the higher the MgO content, the higher the degree of interaction. The existence of such interactions for TTGs and adakites is a strong argument in favor of their origin by melting of the subducted oceanic slab rather than underplated basalts. Unlike slab melting, the fusion of underplated basalts prevents felsic magmas from coming into contact with mantle peridotite and consequently precludes any interaction. The existence of adakitic glass inclusions in olivine crystals from mantle peridotite (Schiano et al., 1995) further supports the slab-melting hypothesis.

Prouteau et al. (2001) performed basalt-melting experiments showing that TTG-like trondhjemitic melts are produced only when free water is available in the source, while dehydration melting generates granitic liquids. Free water is only available in the case of subducted slab melting, thus leading to the genesis of trondhjemites. However, less free water is available in the case of basalts underplated under continental crust. Thus, dehydration melting should be the dominant process here, leading to the genesis of granitic liquids. All these arguments, linked to the fact that the modern TTG-like magmas (adakites) are only known in subduction environments, strongly suggest that TTGs are generated in a subduction-related geodynamic setting through melting of the subducted slab.

It is noteworthy that TTGs older than 3.5 Ga show very little interaction with mantle peridotites, which would be consistent with melting of the roots of oceanic plateau. Nevertheless, even for the Early Archean, experimental melts are poorer in MgO than the parental magmas of TTGs (see Fig. 2, upper envelope of the data set).

TTG Evolution Through Time

In the preceding discussion we proposed that, from 4.0 to 2.5 Ga, (1) the Mg#, Ni, and Cr increase is related to an increasing degree of interaction between slab melt and mantle peridotite, and (2) the enrichment in ($\text{Na}_2\text{O} + \text{CaO}$) and Sr is linked to the declining importance of residual plagioclase during basalt melting and, consequently, an increase in melting depth. To summarize, melting at 4.0 Ga occurred at shallow depth (plagioclase stable) and the felsic magmas interacted weakly with the mantle. At 2.5 Ga, the melting depth was greater (plagioclase not stable) and felsic magmas reacted strongly with the mantle peridotite. These observations and interpretations can be accounted for as follows.

At 4.0 Ga, geothermal gradients were very high along subduction planes (Fig. 3), which may be explained by the higher heat production in the Early Archean (Brown, 1986), and by the fact that plates were smaller than today (Hargraves, 1986; Lagabrielle et al., 1997). Spreading rates were faster, so Archean oceanic slabs had a younger average age (10–20 m.y. compared to 60 m.y. for modern slabs) at the onset of subduction (Bickle, 1978; Martin, 1986; Drummond and Defant, 1990). Peacock et al. (1994) showed that the subduction-related thermal regime is strongly dependent on the age of the subducted crust: older crust has a lower geothermal gradient.

Figure 3 shows that, with a high geothermal gradient (α), the conditions of slab melting can be reached at shallow depth within the stability field of plagioclase. In the presence

of residual plagioclase, Sr and (Na₂O + CaO) will behave as compatible elements and thus will not enter the generated melts. Melting of the slab at shallow depth implies a very thin mantle wedge over the slab melting zone (α in Fig 3). Depending on crustal thickness and subduction dip, no overlying mantle wedge can even be envisaged. Therefore, the ascending slab melts would either cross no mantle at all or only a very thin slice, thus reducing the probability of interaction. Moreover, the temperature of the mantle crossed by the slab melts would be low, thus diminishing the efficiency of possible reactions. This absence or scarcity of mantle-melt interactions would result in low Mg#, Ni, and Cr in TTG magmas.

Between 4.0 and 2.5 Ga, Earth's temperature decreased and the size of tectonic plates increased, leading to lower geothermal gradients along Benioff planes. Figure 3 shows that, while a lower geothermal gradient (β) would still allow hydrous slab melting, this process must occur at greater depth and outside the plagioclase stability field. In this case, Sr and (Na₂O + CaO) will behave as incompatible elements and thus enter the resulting melts. Inset β of Figure 3 shows that the mantle overlying the melting zone is thicker and warmer than for a shallow-depth melting. Because of this, ascending slab melts must cross even thicker and hotter mantle peridotites, thus increasing the efficiency of interaction and yielding magmas rich in Mg#, Ni, and Cr.

Until now, it has been considered that the composition, and consequently the condition of genesis of TTG, remained roughly identical throughout the Archean. This paper demonstrated that conditions of melting significantly changed from 4.0 to 2.5 Ga and that these changes are recorded in TTG composition. As Earth cooled, the depth of slab melting increased and, as a result, slab-melt and mantle-peridotite interactions also increased.

Similar conclusions can be drawn for modern arc magmas. As pointed out by Smithies (2000), modern adakites resemble Late Archean TTGs more closely than Early Archean TTGs. Because of low geothermal gradients at present, it is likely that adakite genesis is only possible under exceptional circumstances, close to the threshold between slab melting and slab dehydration (geothermal gradient γ in Fig. 3). Under these conditions, the depth of melting can be even greater than that inferred for some 2.5 Ga TTGs. In this context, the chemical characteristics of adakites—high

Sr, (Na₂O + CaO), Mg#, Ni, and Cr—can only be explained by very deep slab melting.

Still lower geothermal gradients prevent slab melting and favor slab dehydration. Aqueous fluids released by dehydration reactions ascend into the mantle wedge, which is then metasomatized and starts melting, giving rise to the typical calc-alkaline magmas. A number of authors (Drummond and Defant, 1990; Schiano et al., 1995; Prouteau et al., 2001) have proposed that slab melts could be involved in the genesis of most island arc magmas. Present-day geothermal gradients lead to low degrees of partial melting in the slab. The melts are totally consumed by reactions with the overlying mantle wedge; in this way, the slab melts act as metasomatizing agents. Rapp et al. (1999) showed that (1) large volumes of adakitic magmas are generated when the degree of slab melting is high; and (2) slab melts are all consumed by reactions with the mantle when the degree of melting is low. Moyen et al. (2001) suggested that the low geothermal gradients at the end of the Archean allowed only low degrees of slab melting, so all the slab melts were initially consumed in reactions with the mantle. Subsequent melting of this material may have generated magnesian-potassic (sanukitoid-like) magmas.

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