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Genesis of Archean tonalite–trondhjemite suites: Plume or subduction related?

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Abstract. Discussed are two probable models for lateral growth of continental crust in the Early Precambrian: accretion of island arcs and accretion of oceanic plateaus. Important constraints on geodynamic settings in which Archean crust was generated can be obtained from the study of magmatic products found in granite–greenstone provinces—tholeiitic basalts and rocks of the tonalite–trondhjemite–granodiorite series (TTG). The komatiite–tholeiite and tholeiitic-basalt series are differentiated into island-arc and plume (oceanic plateau) assemblages based on their geochemical signatures and the character of associated lithologies. Because of the geochemical similarity between Archean TTG suites and adakites (which are generated through oceanic slab melting in subduction zone), the tonalite–trondhjemite–granodiorite series is widely considered to be subduction related. Our case study in the Early Archean TTG suite of the Onot block (SW margin of the Siberian craton) shows that tonalite–trondhjemite suites, unlike adakites, bear no major element evidence that their initial melts interacted with mantle wedge peridotites. The TTG-associated amphibolites, just like model metabasite sources of tonalite melts, have trace element signatures identical to modern and Archean basalts of plume related oceanic plateaus, and not to MORB-like abyssal tholeiites. Archean TTG suites were not restricted solely to subduction related settings, but could also have formed through melting at the bottom a of thick crust generated by accretion of oceanic plateaus. The most promising criteria to reconstruct geodynamic settings can be provided by (i) compositional characteristics of metabasite enclaves in TTG suites and the model source for tonalite–trondhjemite melts, (ii) Mg#'s of TTG rocks and their similarity to experimental melts, and (iii) isotope parameters of TTG rocks and their associated amphibolites.

Introduction

Continental crust growth is believed to occur mainly through subduction-related magmatism at convergent plate margins and within-plate magmatism initiated by rising mantle plumes [*Rudnick,* 1995]. The latter results in volcanism in the form of continental flood basalts and oceanic plateaus, as well as underplating of mafic melts near the crust/mantle boundary [*Condie,* 1997a, 1999; *Rudnick,* 1995]. The established fact that the average composition of continental crust matches island arc and continental margin andesites [*Taylor and McLennan,* 1985] supplies the main argument for the leading role of subduction magmatism in crust formation with a minor role of other processes.

Two probable models for lateral growth of continental crust (through accretion of island arcs and oceanic plateaus) are discussed for the Early Precambrian [*Condie,* 1994]. However, it is not quite clear how much the subduction and plume mechanisms contributed to crustal growth. From theoretical considerations, at the early evolutionary stage the earth's thermal regime was such that mantle plumes were more frequent [*Campbell and Griffiths,* 1992], and seafloor spreading rate was higher [*Abbott and Hoffman,* 1984], which implies a greater rate for oceanic lithosphere subduction in the Archean. Hence, both mechanisms played an equally important role, and neither is seen as being predominant. Critical constraints can be obtained by studying Archean

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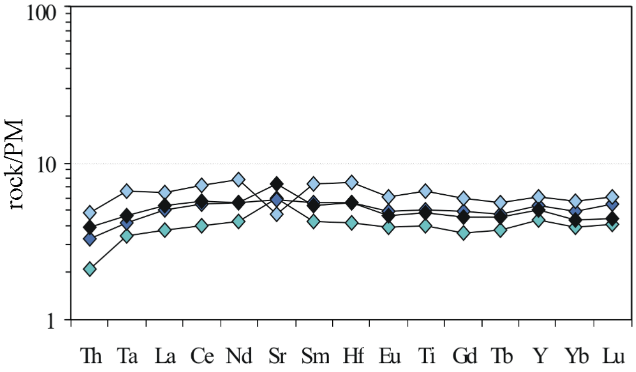

Figure 1. Multi-element patterns (hereinafter, normalized to primitive mantle, as per [*Sun and McDonough,* 1989]) of Late Archean basalts from the Lumby Lake greenstone belt, southwestern Superior Province, after [*Tomlinson et al.,* 1999].

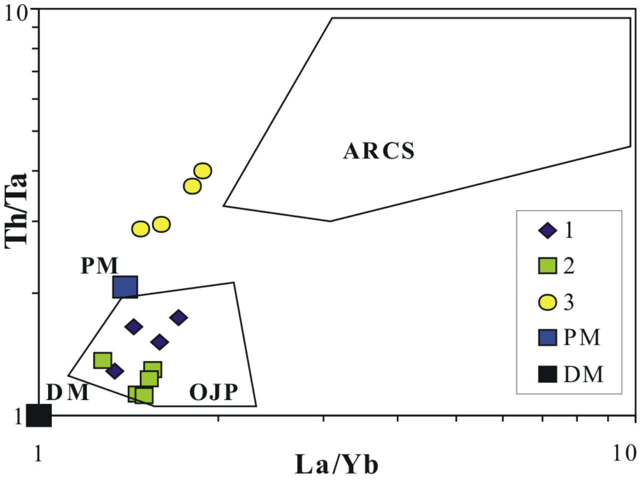

Figure 3. Th/Ta vs. La/Yb diagram for basalts of oceanic plateaus, island arcs, and Archean greenstone belts.
1 – Late Archean basalt of the Lumby Lake greenstone belt, southwestern Superior Province, Canadian shield, after [*Tomlinson et al.,* 1999], 2 – basalts of the Aruba Plateau, 3 – Late Archean basalts of the Schreiber–Hemlo greenstone belt, southern Superior Province, Canadian shield [*Kerrich et al.,* 1999]. Outlined are fields for basalts of the Ontong Java Plateau (OJP) and island arc volcanics (ARCS) [*Condie,* 1994, 1997b]. PM = primitive mantle, DM = depleted mantle.

magmatic rocks in granite–greenstone provinces. These are mainly mafic volcanics: tholeiitic basalts and tonalite–trondhjemite–granodiorite series (TTG) rocks.

Detailed studies over the last decade enable identification of both oceanic plateau and island arc fragments among Archean greenstone belts [*Condie,* 1994; *Kusky,* 1989; *Kusky and Kidd,* 1992; *Puchtel et al.,* 1998; etc.]. This identification draws mainly on the character of lithologic associations in which the volcanics occur and on their geochemical signatures. Plume related associations are marked by the predominance of the komatiite/tholeiite and tholeiite-series volcanics with thin intercalations of pelagic and hemipelagic sediments [*Kent et al.,* 1996], whereas subduction related ones are distinguished by the presence of calc-alkaline volcanics and thicker turbidite sequences. Because ancient oceanic plateaus were tectonically dismembered in the course of accretion and transformed by subsequent processes, their identification presents a challenge. One of the most important identification criteria is provided by geochemical data. Judging from basalt chemistry, both submarine plateaus and island arc assemblages were present in the Archean. Studies on greenstone volcanics of the Superior Province (Canadian shield), Baltic shield, and Pilbara craton have shown that Archean plume derived komatiite–basalt and basalt suites (Figure 1), just like their modern analogues (Figure 2), have nearly flat REE and multi-element patterns and immobile trace element ratios that are close to the primitive mantle (PM) values (Figure 3) [*Polat and Kerrich,* 2000; *Puchtel et al.,* 1998; *Tomlinson et al.,* 1999]. Subduction related volcanics are marked by fractionated multi-element patterns with negative Nb (Ta) and Ti anomalies and elevated Th/Ta (La/Nb) and La/Yb ratios (Figures 3, 4).

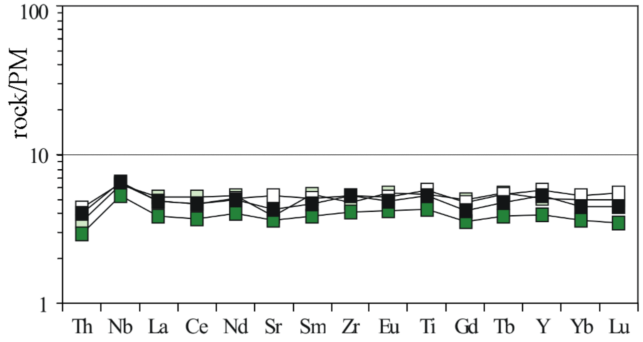

Figure 2. Multi-element patterns of basalts from the Aruba oceanic plateau, Caribbean Basin, after [*White et al.,* 1999].

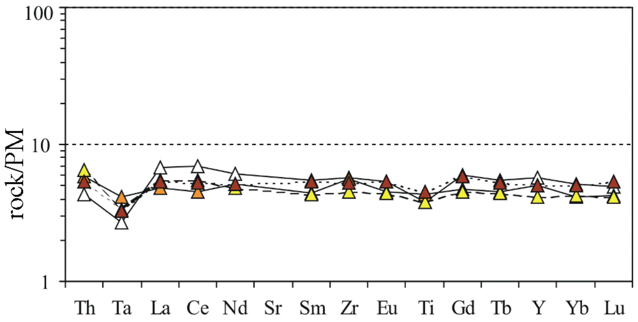

Figure 4. Multi-element patterns of Late Archean basalts of the Schreiber–Hemlo greenstone belt, southern Superior Province, after [*Kerrich et al.,* 1999].

A Review of Models for the Formation of Archean Tonalite–Trondhjemite Suites and Adakites

Unlike komatiite–basalt suites, their spatially associated and nearly coeval felsic volcanics are inferred to have formed in subduction settings through melting of the downgoing oceanic slab [*Hollings et al.,* 1999]. The subduction model is also believed to be of prime importance to the genesis of the tonalite–trondhjemite–granodiorite series [*Martin,* 1994]. Therefore, the second most important component in the Archean crust is in fact assumed to be linked to a single postulated genetic mechanism, which is in sharp contrast to the broad variety of settings for mafic magmatism. The subduction model is supported by the geochemical similarity between Archean TTG suites and adakites (Cenozoic low-K volcanics of intermediate to felsic composition) (Figures 5, 6), widespread at the Pacific margin of America and in a number of regions elsewhere. Adakites have been firmly demonstrated to form through melting of the downgoing oceanic slab in subduction zones, whose thermal regime is similar to Archean [*Drummond and Defant,* 1990; *Martin,* 1994, 1999].

It is noteworthy that, along with the subduction model, a number of models were proposed that involve TTG genesis through melting of a metabasalt source at within the crust, caused by magmatic underplating and/or rising mantle plumes [*Atherton and Petford,* 1993; *Barnes et al.,* 1996; *Condie,* 1994; *de Wit,* 1998; *Shchipansky and Podladchikov,* 1991]. On the other hand, the well documented modern occurrences of plume magmatism, such as Iceland, produce an extremely small volume of felsic melts, and their composition differs from TTG suites and adakites [*Martin,* 1994, 1999].

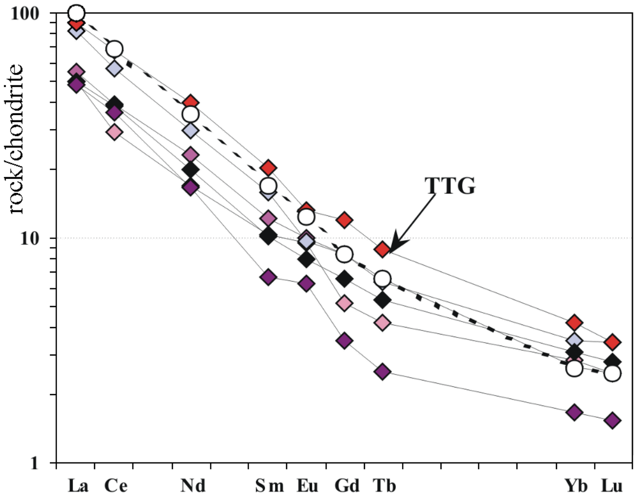

Figure 5. REE patterns (hereinafter, normalized to chondrite, as per [*Boynton,* 1984]) for the Early Archean tonalite–trondhjemite suite of the Onot block, Sharyzhalgai basement uplift, Siberian craton. For comparison shown is the average composition of Archean tonalite–trondhjemite–granodiorite (TTG) suites, after [*Martin,* 1994].

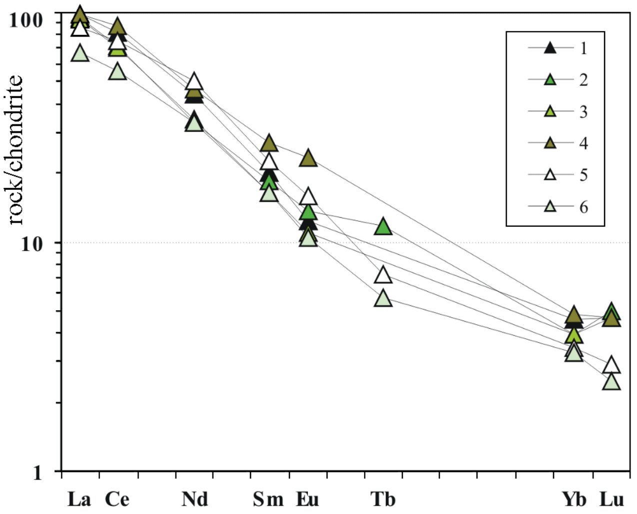

Figure 6. REE patterns for adakites of the Pacific margin of South America, after [*Kay et al.,* 1993; *Stern and Kilian,* 1996].

Indeed, no present day cases of TTG rocks being formed in plume systems had been reported until recently. Tonalites in association with plume derived basalts were first found by [*White et al.,* 1999] while studying the Aruba oceanic plateau in the Caribbean Basin. The Aruba tonalites are clearly similar to Archean TTG suites in terms of their major and trace element compositions. They are featured by elevated Al_2O_3 (14–16%) and Sr (200–400 ppm) contents and increased Sr/Y (10–40) and La/Yb (3–7) ratios (Figure 7), although the last two ratios are not as high as in Archean TTG rocks (Sr/Y = 60, $(La/Yb)_n = 40$, after [*Martin,* 1999]). Therefore, the Aruba tonalites exemplify TTG generation through melting at the bottom of a thick oceanic plateau crust.

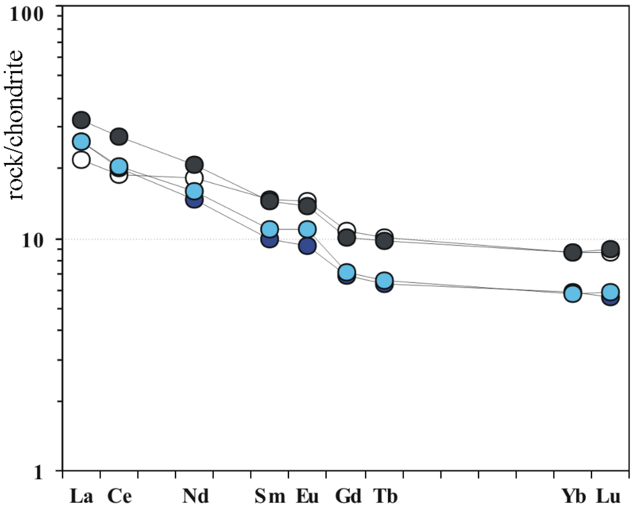

Figure 7. REE patterns for adakites of the Aruba Plateau, Caribbean Basin, after [*White et al.,* 1999].

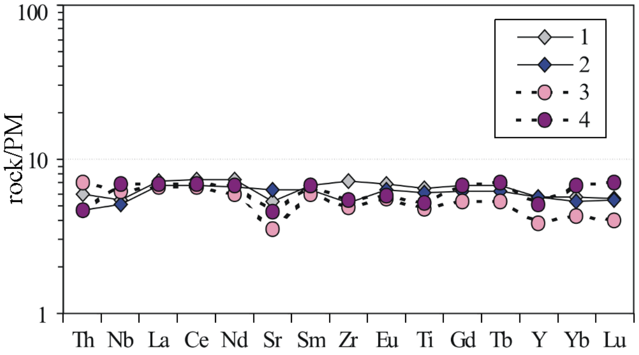

Figure 8. Multi-element patterns for metabasites of the Onot block. 1–2 – amphibolites from enclaves in plagiogneisses (tonalite–trondhjemite suite) of the Onot greenstone belt, 3–4 – lower crustal granulites of the Onot block.

Analyzing Potential Criteria for Reconstructing Original Geodynamic Settings for Archean TTG Suites

The use of geologic criteria for reconstructing original geodynamic settings of Archean and, particularly, Early Archean TTG suites (that make plagiogneiss, or gray gneiss assemblages) is strongly obstructed by the fact that these are often the oldest, repeatedly reworked rocks, far away in time from the formation of those geologic assemblages they are tectonically juxtaposed with. Under these circumstances, of prime importance may become petrologic and geochemical evidence, including TTG compositional features, P-T conditions of formation of the initial melt, and metabasite source composition. Additional information is provided by the composition of associated metabasites, everywhere represented by amphibolite enclaves among plagiogneisses. Let us see how advantageous the use of these criteria can be.

According to experimental data, Archean high-alumina TTG rocks, variably depleted in the heavy REE and Y, must have been produced in equilibrium with residual garnet and/or amphibole at P>10–15 kbars [*Rapp and Watson,* 1995; *Sen and Dunn,* 1994]. This implies melting at the bottom of an over-thickened crust or at a subcrustal depth and is consistent with TTG origin in subduction-related and mantle plume settings. The available data show that crustal thickness in oceanic plateaus may range from over 35 km (as in the Ontong Java Plateau) to ca. 20 km (as in the Kerguelen Plateau) through to 10–15 km (as in the Caribbean Basin) [*Saunders et al.,* 1996]. Crustal thickness estimated for Archean oceanic plateaus by [*Kent et al.,* 1996] using the adiabatic partial melting model of *McKenzie and Bickle* [1988] assuming a potential mantle temperature of 1600°C is ca. 43 km. Hence, the lower crustal sections of oceanic plateaus can be transformed to garnet-bearing granulite or eclogite, which means that conditions prerequisite for tonalite–trondhjemite melt genesis can be implemented. Therefore, the likely P-T conditions of melt generation are such that there is virtually no choice between the two options for TTG genesis here discussed.

Another criterion can be provided by the composition of the metabasite source of tonalite–trondhjemite melts and associated amphibolites. With plume derived TTG rocks, either of the two metabasites must be similar to oceanic plateau basalts. In order to test this criterion, let us address our study in the Archean TTG suite of the Onot block at the southwestern margin of the Siberian craton.

In the Onot block (part of the Sharyzhalgai basement uplift), Early Archean (3250±100 and 3287±8 Ma) [*Bibikova et al.,* 1983, 2002] plagiogneisses and gneissic plagiogranites of tonalite–trondhjemite composition compose elongated tectonic blocks and sheets among stratified sequences of the Onot greenstone belt [*Nozhkin et al.,* 2001]. In terms of major and trace element patterns, these plagiogneisses and gneissic plagiogranites are typical representatives of Archean TTG suites with their distinctive strongly fractionated REE patterns (Figure 5). The plagiogneisses contain enclaves in the form of sub-conformable sheets and lenses of amphibolites, matching tholeiitic basalt in composition. The amphibolites have non-fractionated nearly flat PM-normalized multi-element patterns. Similar characteristics are shown by the lower crustal mafic granulites, which represent, judging by the available data [*Turkina,* 2001], the bottom of the crust of the Onot block (Figure 8). Based on the features in point, both the metabasites at the level of tonalitic melt crystallization and the mafic lower crust at the level of melt generation are similar to modern oceanic plateau basalts and their analogues from Late Archean greenstone belts (Figures 8, 9). The fact that mafic enclaves in Archean TTG suites are rather similar to plume-derived basalts than MORB was noted earlier as well [*Tarney and Jones,* 1994].

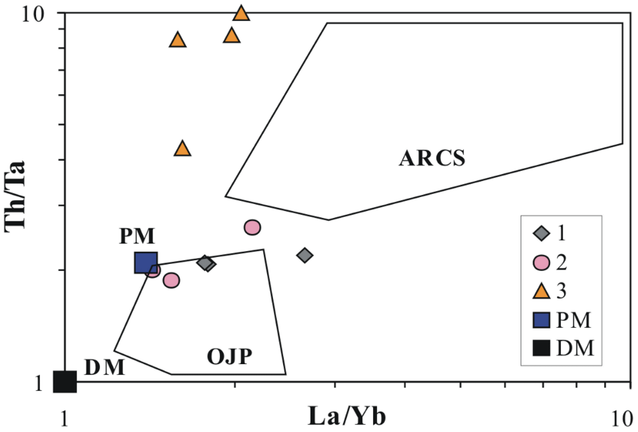

Figure 9. Th/Ta vs. La/Yb diagram for metabasites of the Onot block.
1 – amphibolites from enclaves in plagiogneisses (tonalite–trondhjemite suite), 2 – lower crustal mafic granulites of the Onot block, 3 – Late Archean basalts of the Onot greenstone belt. Outlined are fields for basalts of the Ontong Java Plateau (OJP) and island arc volcanics (ARCS) [*Condie,* 1994, 1997b]. PM = primitive mantle, DM = depleted mantle.

According to the estimates performed, the melts matching the Onot plagiogneisses and plagiogranitoids may have originated in equilibrium with a garnet-amphibolite residue containing 15–20% garnet [*Nozhkin et al.,* 2001]. The calculated composition for the metabasite source for tonalite–trondhjemite melts (Figure 10) is comparable to the amphibolites from enclaves and to those modern and Archean basalts whose origin is attributed to plume volcanism. Similar chemical signatures are shown by the model source for the Aruba tonalites, which in turn matches basalts of this oceanic plateau (Figure 11). The only difference between the Aruba and Archean tonalites is that the former are higher in the heavy REE, which implies a small proportion of residual garnet (2–3%), and, hence, a lower pressure and shallower depth for magma generation, which is consistent with the thinner crust of the young oceanic plateaus as compared to Archean ones. The established similarity between the Early Archean tonalites of the Onot block and the Aruba Plateau tonalites (in terms of their magma source compositions and associated mafic rock chemistries) corroborates the formation of the Onot TTG suite and other comparable assemblages through melting of metabasites at the bottom of a thick oceanic plateau crust.

Assuming a subduction related origin for tonalite–trondhjemite melts, their source must be ocean floor basalts produced in spreading systems. Unfortunately, no reliable evidence on composition of the Archean oceanic crust is available, which is thought to be due to its rapid recycling into the mantle [*Condie,* 1994]. To date, two examples of mafic volcanics that are interpreted as being products of Archean oceanic crust have been reported. These are Late Archean mafic volcanics of the Irinogorsky structure, Baltic shield, considered as fragments of a suprasubduction assemblage [*Shchipansky et al.,* 2001], and Early Archean basalts from the Cleaverville area, Pilbara craton, classed as mid-oceanic ridge derivatives [*Ohta et al.,* 1996]. It is readily apparent that in both cases the mafic volcanics are MORB-like rocks, depleted markedly in the most incompatible elements (Th, Nb), and that they differ sharply in composition from the source inferred for the Onot TTG suite (Figure 10).

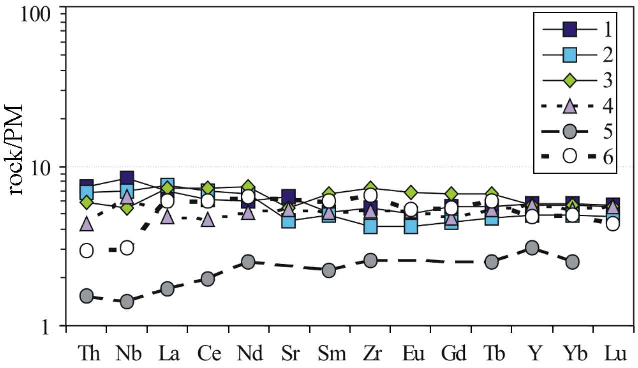

Figure 10. Multi-element patterns of model metabasite sources for the tonalite–trondhjemite suite (plagiogneisses and gneissic plagiogranites) of the Onot block.
1–2 – calculated patterns for model metabasite sources for the plagiogneisses and gneissic plagiogranites. For comparison shown are (3) amphibolites from enclaves in plagiogneisses, (4) basalts of the Aruba oceanic plateau, (5) basalts of the Irinogorsky structure, Baltic shield [*Shchipansky et al.,* 2001], (6) basalts of the Pilbara craton [*Ohta et al.,* 1996].

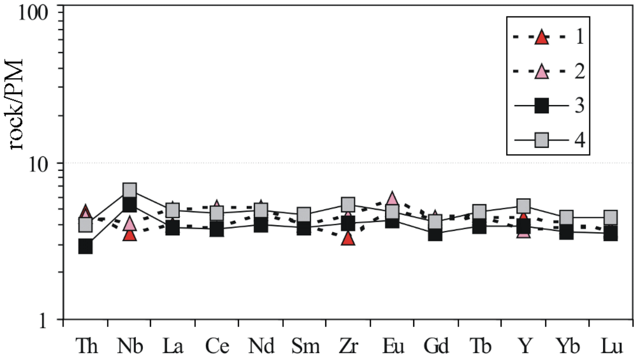

Figure 11. Multi-element patterns of model metabasite sources for tonalites (1–2) and basalts (3–4) of the Aruba oceanic plateau.

Earlier, a number of workers, including [*Sen and Dunn,* 1994] and [*Tarney and Jones,* 1994], pointed out that estimated compositions for felsic melts derived from the MORB source are depleted in Ba and Sr relative to Archean TTG suites, and, hence, the source of tonalite–trondhjemite suites must have higher contents of these components. Evidently, oceanic plateau basalts, enriched in Ba and Sr relative to MORBs, may be the most suitable candidate for the source for Archean TTG suites.

An additional criterion to estimate the character of the source of tonalite–trondhjemite melts can be provided by isotope compositions of TTG rocks. Adakites of the Cook Island and the Cerro Pampo volcanic center (Pacific margin of South America) have high positive $\varepsilon_{\mathrm{Nd}}(\mathrm{T})$ values, between 5 and 9.8, the highest of them approximating DM values, which is consistent with their genesis through melting of a MORB-like mafic source and which supports a subduction-related origin for these rocks [*Kay et al.,* 1993; *Stern and Kilian,* 1996]; the entire range of measured $\varepsilon_{\mathrm{Nd}}(\mathrm{T})$ values from +9.8 to −1.9 for adakites of the Andean volcanic zone must be due to a varying contribution of crustal material in the form of subducted sediments. The Aruba tonalites and basalts are virtually identical in terms of their $\varepsilon_{\mathrm{Nd}}(\mathrm{T})$ (6.6–6.8 and 6.7–7.8, respectively) [*White et al.,* 1999]; however, it is important that either of the two has a less radiogenic Nd isotope composition than MORB ($\varepsilon_{\mathrm{Nd}}(\mathrm{T}) = 9.8$). Basalts from other oceanic plateaus also have $\varepsilon_{\mathrm{Nd}}(\mathrm{T})$ values that are significantly lower than MORB; e.g., for the Ontong Java Plateau these values are between +4 and +7 [*Kerr et al.,* 1997], which implies contribution from an undepleted lower mantle plume source.

Archean TTG rocks, judging by published data, are marked by a rather broad range of $\varepsilon_{\mathrm{Nd}}(\mathrm{T})$ values, from close to DM to negative. These variations must be due mainly to crustal contamination of initial melts produced

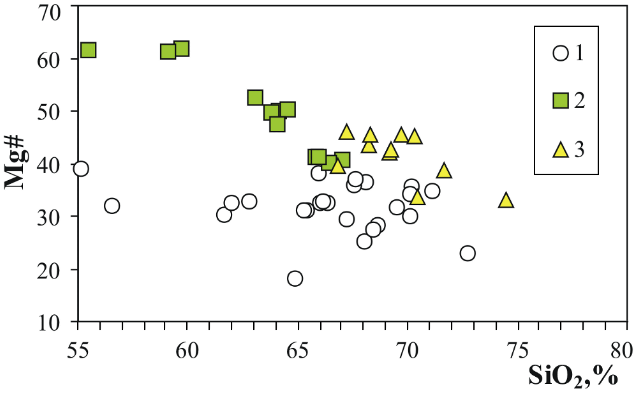

Figure 12. Mg# vs. SiO_2 diagram for the tonalite–trondhjemite suite of the Onot block and for adakites.
1 – experimental tonalite–trondhjemite melts [*Rapp and Watson,* 1995; *Sen and Dunn,* 1994], 2 – adakites of the Andean volcanic zone [*Kay et al.,* 1993; *Stern and Kilian,* 1996], 3 – TTG rocks of the Onot block.

from metabasites derivative from a depleted mantle source. On the other hand, one cannot preclude that the mafic sources of Archean TTG rocks could have originated, by analogy with modern oceanic plateau basalts, from a less depleted mantle. This is supported by isotope compositions of basalts and komatiites ($\varepsilon_{\rm Nd}$(T) = 2.8–4.4) of the Kostomuksha greenstone belt (Baltic shield), thought to be an obducted fragment of an oceanic plateau [*Puchtel et al.,* 1998]. Adequate interpretation of Nd isotope composition data for Archean assemblages is a painstaking exercise (see [*Moorbath et al.,* 1997]). Detailed discussion of this issue is beyond the scope of this study. It should be stressed, however, that the use of isotopic criteria to reconstruct source compositions for tonalite–trondhjemite melts in the Archean may prove highly rewarding, as evidenced by the case studies in Cenozoic rock assemblages.

Lastly, let us address compositional peculiarities of Archean TTG suites and adakites. It was noted earlier [*Turkina,* 2000] that, despite the indisputable similarity between adakites and Archean TTG suites, they are not entirely identical geochemically, adakites being essentially more melanocratic, higher in the heavy REE and Y, and, not infrequently, abnormally high in Sr. A detailed analysis of major element data shows [*Smithies,* 2000] that, unlike adakites, Early Archean assemblages and most Late Archean TTG suites plot on the Mg# vs. SiO_2 diagram in the low-Mg region with elevated SiO_2, overlapping the field of experimental melts derived from metabasite sources [*Rapp and Watson,* 1995; *Sen and Dunn,* 1994]. Low Mg# is also characteristic of the Onot block TTG suite (Figure 12). Contrariwise, adakites differ dramatically in terms of their Mg# (40–60) from experimental melts with Mg# = 25–40. It has been firmly demonstrated that the elevated Mg# of adakites results from the fact that initial melts derived from the subducting slab interacted with mantle wedge peridotites on their way of migration [*Kelemen et al.,* 1993; *Stern and Kilian,* 1996; *Yogodzinski and Kelemen,* 1998]. Therefore, unlike adakites, the Early Archean TTG suites of the Onot block and of many other Archean assemblages provide no major element evidence that the melt migrated through or interacted with mantle wedge peridotites, which is clearly at odds with a subduction-related origin.

Conclusions

Our analysis, based on a case study in Early Archean plagiogneisses and gneissic plagigoranites of the Onot block, shows that a number of characteristics of tonalite–trondhjemite suites (including their low Mg# and the fact that the inferred metabasite sources of initial TTG melts and plagiogneiss-associated amphibolites are similar to mafic volcanics from modern oceanic plateaus and their counterparts in Archean greenstone belts) are not explicable in the context of the subduction model. This model, which invokes adakite genesis through melting of the oceanic slab plunging steeply into subduction zone [*Drummond and Defant,* 1990; *Martin,* 1994, 1999], suggests a melting source that matches MORB-like basalts in terms of trace element and isotope compositions and assumes that the initial melt's Mg# increased through interaction with mantle wedge peridotites. In order to account for the lower Mg# and elevated SiO_2 content of Archean TTG rocks as compared to adakites, invoked is flat subduction of the oceanic plate or tectonic underplating, which makes it possible to do virtually without tonalite melt transport through mantle peridotite [*Abbott and Hoffman,* 1984; *Martin and Moyen,* 2002; *Smithies and Champion,* 2000].

Alternative to flat subduction are models for TTG production through melting at the bottom of thickened (35–40 km or more) crust, formed by accretion of oceanic plateaus [*Smithies and Champion,* 2000] or by stacking and obduction of oceanic crust [*de Wit,* 1998]. As was shown above using our case study in the Onot TTG rocks, the former option is corroborated by the similarity between trace element compositions of the tonalite melt source and metabasites at the level of melt crystallization on the one hand and plume derived basalts on the other. Underplating of mafic melts at the bottom of the crust above a rising mantle plume may provide a heat source to initiate tonalite melt generation.

Needless to say, generation of Archean TTG suites is not restricted to subduction related environments, and further studies are required to elucidate geodynamic settings in which they were generated. The analysis here presented shows that TTG suites may well have been formed at the bottom of a thick crust produced by accretion of oceanic plateaus. The most promising criteria to reconstruct geodynamic settings may primarily be provided by (i) compositional characteristics of metabasite enclaves in TTG suites and the model source for tonalite–trondhjemite melts, (ii) Mg#'s of TTG rocks and their consistency with experimental melts, and (iii) isotope parameters of TTG suites and their related amphibolites.

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