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THE ARCHAEAN-PROTEROZOIC TRANSITION: SANUKITOID AND CLOSEPET TYPE MAGMATISM

Abstract: Two specific types of granitoids, sanukitoids and Closepet-type, emplaced mainly at the Archaean-Proterozoic transition. Their major and trace element compositions are also intermediate between typical Archaean TTG and modern arc granitoids. Petrogenetic models show that they formed by melting of mantle peridotite previously transformed (metasomatised) by felsic melts adakitic in composition. They are assumed to formed in subduction zone geodynamic environment and to reflect the progressive cooling of our planet : 1) during Archaean times Earth heat production was high enough to allow production of huge amounts of subducted slab melts, leading in TTG genesis. 2) at the end of Archaean, due to Earth cooling, the degree of slab melting was low and all slab melts were consumed with reaction with mantle peridotite whose subsequent melting gave rise to sanukitoids and Closepet-type granites; 3) after 2.5 Ga, Earth heat production was too low to allow slab melting and modern arc magmas are produced by melting of the mantle wedge peridotite metasomatised by fluids coming from subducted slab dehydration. Of course, such changes do not take place exactly at the same time all over the world, and as adakite are still generated today, archaic mechanisms coexisted together with new ones during a relatively large period of time, even if subordinated.

Keywords: Archaean-Proterozoic transition, TTG, sanukitoid, Closepet-type granite, change in petrogenetic mechanisms, slab melting, Earth heat production.

INTRODUCTION

The genesis of Earth continental crust started very early in the history of our planet: as soon as 4.40 Ga ago zircons recorded the existence of granitic (*s.l.*) crust (Wilde *et al.* 2001). The first half of our planet history mainly corresponded to the extraction of juvenile crust from the mantle. Even before 4.0 Ga, recycling mechanisms existed (Cavosie *et al.* 2004; 2005), but they were highly subordinated processes. Due to the greater Earth heat production (Brown 1985), the petrogenetic processes that operated were different from modern ones (see: Martin, Moyen 2002; Martin *et al.* 2005, for review). Schematically, prior to 2.5 Ga continental crust was mostly generated by hydrous basalt melting, which depending on the authors could be fluid-absent (dehydration melting), fluid-present or fluid-saturated (see : Moyen, Stevens 2005, for review); whereas, after it has been produced by fluid metasomatised mantle peridotite melting. In both cases melting is supposed to occur in subduction-like geodynamic environment (Martin 1986). The transition between archaic and modern petrogenetic mechanisms roughly took place at the Archaean–Proterozoic transition, about 2.5 Ga ago. However, if the rate of typical Archaean TTG (Tonalitic, Trondhjemitic and Granodioritic) juvenile crust production

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remained high until 2.5 Ga, simultaneously, high-Mg dioritic, tonalitic and granodioritic magmatic rocks were generated and emplaced into all Archaean cratons between 2.8 and 2.5 Ga. These plutons generally referred as late granodioritic or granitic plutons are significantly rarer than TTG; they were first identified by Shirey, Hanson (1984) and called Archaean sanukitoids. Now described from most Late Archaean terranes (Shirey, Hanson 1984; Stern 1989; Stern, Hanson 1991; Smithies, Champion 1999a), these rocks as well as the closely related high-Mg and high-K granites called "Closepet type" granites (Moyen *et al.* 2001a; Moyen *et al.* 2003a; Martin *et al.* 2005). These rocks possess both modern (classical calc-alkaline differentiation similar to Basalt Andesite Dacite Rhyolite (BADR) association, transition element contents) and archaic (low HREE contents, strongly fractionated REE patterns, etc.) characteristics. Consequently, because of their « transitional » composition and their emplacement at a hinge period, they appear to be very important for our understanding of the Archaean - Proterozoic transition.

The study of this late Archaean magmatism is complicated by the fact that these mainly mantle derived magmas strongly interacted with the crust in which they intruded. Their mantle characters were obliterated and altered by a superimposed crustal signature, such that they were often considered as having a mixed origin. Consequently, the changes in magma production at the Archaean - Proterozoic transition could be discussed only after an accurate determination of both the source and the conditions of melting and differentiation of their juvenile component. This is the reason why this paper will only refer to the mantle component of both sanukitoids and Closepet-type granites, thus excluding all samples with $SiO_2 > 62\%$.

SANUKITOIDS AND CLOSEPET TYPE GRANITOIDS

Definition

Shirey, Hanson (1984) first recognized a suite of Late Archaean felsic intrusive and volcanic rocks in the Superior Province that has both mineralogical and chemical compositions clearly different of typical TTG. Because the major element geochemistry of these rocks resembles that of Miocene high-Mg andesite (sanukite) from the Setouchi volcanic belt of Japan (*e.g.* Tatsumi, Ishizaka 1982), Shirey, Hanson (1984) referred to them as 'Archaean sanukitoids'. Sanukitoids are now generally regarded as a minor, though widespread, component of most Late Archaean terranes, having been documented from the Superior Province (Shirey, Hanson 1984; Shirey, Hanson 1986; Stern, Hanson 1991; Stevenson *et al.* 1999), Baltic shield (Querré 1985; Lobach-Zhuchenko *et al.* 2000; Lobach-Zhuchenko *et al.* 2005; Samsonov *et al.* 2005), South India (Balakrishnan, Rajamani 1987; Krogstad *et al.* 1995; Sarvothaman 2001; Moyen *et al.* 2003a) and the central Pilbara craton (Smithies, Champion 1999a).

Recently, the Late Archaean Closepet-type Granite has been described in South India (Jayananda *et al.* 1995; Moyen *et al.* 2001a; Moyen *et al.* 2003b), which shows several characteristics of sanukitoids. Similarly, some plutons from Wyoming (Frost *et al.* 1998), Shandong, China (Jahn *et al.* 1988), Limpopo (Barton *et al.* 1992) also show Closepet-type composition.

Composition

Based on the South Indian craton study, Moyen *et al.* (2003a) proposed a typology for Archaean granites. The following definitions are from these authors.

Table 1. Average composition and standard deviation for TTG, Sanukitoids and Closepet type granites (Martin *et al.* 2005).Average modern arc granitoid composition is from Martin (1994).

	TTG (n= 1094)		Sanukitoid <62% SiO_2 (n=31)		Closepet-type <62% SiO_2 (n= 43)		Modern Arc Granitoid (n= 250)	
	Average	*Std. dev.*	Average	*Std. dev.*	Average	*Std. dev.*	Average	*Std. dev*
wt %								
SiO_2	69.51	*3.64*	59.76	*2.9*	57.83	*3.5*	68.10	*6.20*
Al_2O_3	15.59	*1.14*	16.07	*0.9*	16.19	*1.4*	15.07	*1.60*
Fe_2O_3*	3.24	*1.56*	5.97	*1.5*	7.53	*1.7*	4.36	*2.00*
MnO	0.05	*0.05*	0.09	*0.02*	0.13	*0.08*	0.09	*0.10*
MgO	1.25	*0.77*	3.97	*1.3*	3.47	*1.9*	1.55	*1.00*
CaO	3.16	*1.11*	5.67	*1.5*	5.59	*1.4*	3.06	*0.64*
Na_2O	4.72	*0.77*	4.50	*0.7*	4.04	*0.8*	3.68	*0.49*
K_2O	1.95	*0.77*	2.83	*0.8*	3.25	*0.8*	3.40	*1.10*
TiO_2	0.38	*0.21*	0.75	*0.3*	1.23	*0.5*	0.54	*0.32*
P_2O_5	0.15	*0.10*	0.40	*0.1*	0.74	*0.3*	0.15	*0.08*
ppm								
Rb	66	*43*	65	*22*	93	*37*	110	*50*
Ba	713	*465*	1543	*563*	1441	*653*	715	*205*
Nb	7	*5*	10	*8*	18	*7*	12.1	*5*
Sr	490	*217*	1170	*638*	978	*350*	316	*150*
Zr	155	*108*	184	*129*	323	*109*	171	*53*
Y	12	*16*	18	*11*	37	*13*	26	*5*
Ni	18	*17*	72	*35*	38	*43*	10.5	*8.0*
Cr	40	*75*	128	*85*	100	*58*	23	*15*
V	48	*29*	95	*19*	129	*44*	76	*45*
La	31.4	*23.8*	59.9	*28*	90.9	*46*	31	*9*
Ce	57.8	*257.0*	126	*47*	188	*80*	67	*17*
Nd	22.4	*17.0*	54.8	*16*	84.9	*34*	27	*7*
Sm	3.5	*2.3*	9.8	*3*	14.5	*6*	5.3	*14*
Eu	0.9	*0.4*	2.3	*0.62*	3.2	*1.09*	1.0	*0.5*
Gd	2.4	*1.4*	6	*1.4*	9.2	*2.1*	5.5	*1*
Dy	1.7	*0.9*	3.2	*0.8*	5.6	*1.1*	5.2	*0.1*
Er	0.76	*0.49*	1.41	*0.5*	2.68	*0.7*	3.0	*1*
Yb	0.64	*0.40*	1.32	*0.7*	2.05	*0.8*	3.2	*0.5*
Lu	0.13	*0.10*	0.26	*0.1*	0.34	*0.1*	0.5	*0.1*
K_2O/Na_2O	0.41		0.63		0.80		0.92	
Mg#	0.43		0.57		0.48		0.41	
A/CNK	1.00		0.77		0.80		0.98	
$(La/Yb)_N$	32.2		30.0		29.3		6.4	

Sanukitoids

The sanukitoids are typically medium-grained, equigranular monzodiorites to granodiorites, containing small (5–10 mm) clusters of biotite, hornblende and rare relict hornblende-rimmed clinopyroxene; in rare occasions orthopyroxene can be present.

Microgranular, mafic dioritic to monzodioritic enclaves are common. The paragenesis consists of quartz, plagioclase ($An_{20–30}$), perthitic microcline, hornblende and biotite. Accessory phases are magnetite, ilmenite, epidote, sphene, apatite, zircon and allanite.

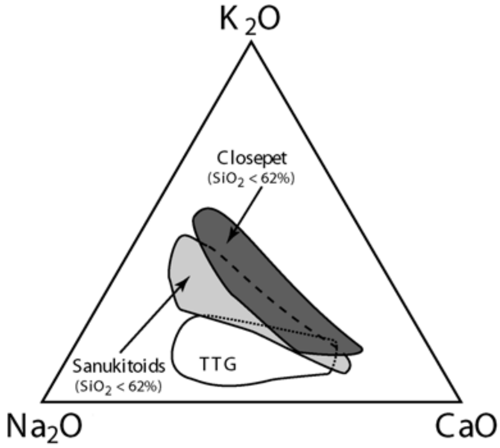

Fig. 1. K_2O−Na_2O−CaO triangle comparing the compositions of Archaean TTG, Sanukitoids and Closepet type granites (adapted from Moyen *et al.* 2003a).

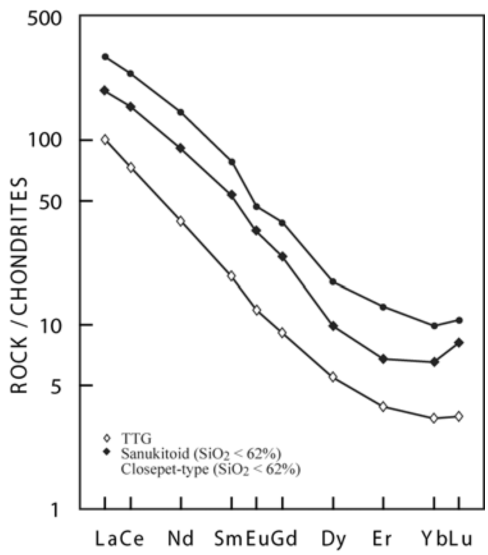

Fig. 2. Chondrite normalized REE patterns for Archaean TTG, Sanukitoids and Closepet type granites.

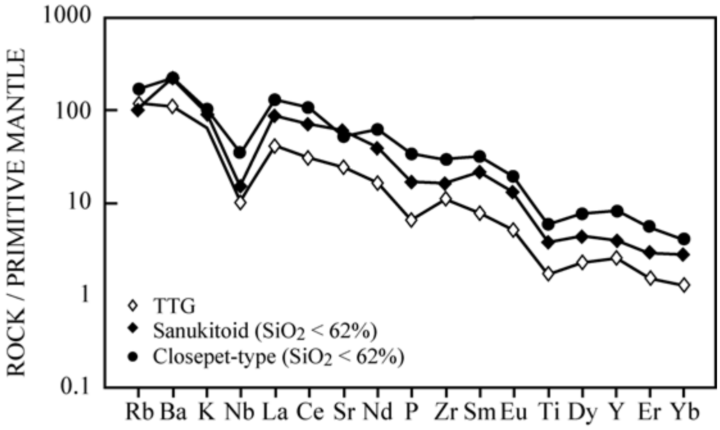

Fig. 3. Primitive mantle (McDonough *et al.* 1992) normalized multi element diagram for Archaean TTG, Sanukitoids and Closepet type granites.

The sanukitoids with SiO_2 < 62% are meta-aluminous (A/CNK = 0.77; Tab. 1) and moderately potassic (K_2O/Na_2O = 0.63; Fig. 1). Mg# is quite high (0.57), Ni and Cr contents (72 and 128 ppm, respectively) are high too. Sr and Ba are typically greater than 1000 ppm and Na_2O (4.50%) and K_2O (2.83%), (as well as most LILE) contents are high as well. Similarly, LREE (e.g. La_N = 190) contents are high and HREE (e.g. $Yb_N \approx 6.3$) low resulting in strongly fractionated patterns ($(La/Yb)_N \approx 30$; Fig.2).

Closepet-type granites

In South India, the Closepet batholith is made up of several cogenetic facies. The dominant facies is a porphyritic monzogranite, with large (2-5 cm) to very large (~10 cm) phenocrysts of K-feldspar in a coarse grained matrix made up of quartz, perthitic microcline, plagioclase (An_{20-30}), biotite and amphibole. Accessory minerals are magnetite, ilmenite, zircon, sphene, allanite and apatite; they are always very abundant.

On the field, this porphyritic monzogranite is associated with migmatites and anatectic granites derived from melting of the surrounding TTG basement (Jayananda *et al.* 1995; Moyen *et al.* 1997; Moyen *et al.* 2001b). Large (several tens to few metres), dioritic to monzonitic comagmatic enclaves are found within the porphyritic granite. This monzonite is fine grained (0.1 - 1 mm), with occasional K-feldspar phenocrysts with rapakivi texture. Major mineral phases are plagioclase (An_{20-35}, 30 to 45 %), perthitic microcline (15-20 %), amphibole (5-30 %), biotite (5-10 %) and quartz. In some places, diopside has been observed as relict within amphibole grains, leading Jayananda *et al.* (1995) to propose the name of "clinopyroxene-bearing monzonite" to describe this facies. Accessory phases are identical to porphyritic monzogranite ones.

The clinopyroxene-bearing monzonites are silica-poor (50-55% SiO_2); they are meta-aluminous (A/CNK = 0.80; Tab. 1). Their Mg# (0.48), Ni (38 ppm) and Cr (100 ppm) are moderately high. Closepet-type granites are K_2O–richer (K_2O = 3.25%) than sanukitoids, thus resulting in greater K_2O/Na_2O (0.8; Fig. 1). They also have high Sr and Ba contents (1441 and 978 ppm respectively). They are generally very rich in LREE (La_N = 290) but due to their higher Yb content ($Yb_N \approx 7$) they display similar $(La/Yb)_N$ ratios (~30; Fig. 2). No negative anomaly in Zr, Ti or Y is observed, giving to this rocks the same trace element signature than the "NEB" (Niobium-enriched basalt; Sajona *et al.* 1996; Fig. 3). While the

Closepet-type granite bears several similarities with sanukitoids, at comparable Si contents it is more potassic and less aluminous and its most discriminating feature is its high HFSE contents ("NEB-signature").

The same characteristics (to a less pronounced extent), are found in the dominant porphyritic monzogranite. However, it has been demonstrated (Jayananda *et al.* 1995; Moyen *et al.* 2001) that this monzogranite results from mixing or mingling between the clinopyroxene-bearing monzonite and anatectic granites. Hence, the geochemical characteristics of the porphyritic monzogranites are intermediate between "true" Closepet-type signature, and biotite-bearing granite characteristics.

PETROGENESIS

As it has been discussed in the previous section, sanukitoids and Closepet type granites show many petrological, mineralogical and chemical similarities, such that their petrogenesis will be discussed together.

The high Mg# (>> 0.62) and the high Cr and Ni concentrations in the primitive members of the sanukitoid and Closepet-type granite suites preclude a crustal source, including basaltic crust. On the other hand, the same rocks are extremely LILE-rich; which, because of the high Mg#, Cr and Ni, cannot be interpreted in terms of enrichment through fractional crystallization. Contamination of a LILE-rich felsic continental crust by komatiitic or basaltic magmas could reliably generate sanukitoid magmas. However, Stern *et al.* (1989) using a quantitative modelling ,demonstrated that interaction between mafic or ultramafic melts and felsic crust cannot reproduce both characteristics of primitive sanukitoids (high Mg#, Ni and Cr together high SiO_2 and LILE contents). More recently, Smithies, Champion (1999a) reached exactly the same conclusion. As they demonstrated that interaction between mantle derived magma and felsic crust cannot account for sanukitoid characteristics, the only reliable possibility is that they could derive from melting of a metasomatised peridotitic source. In this case metasomatism must account for the LILE-rich, HFSE-depleted nature of the rocks (*e.g.* Shirey, Hanson 1984; Stern 1989; Smithies, Champion 1999b).

If sanukitoids and Closepet-type granite differ from typical Archaean TTG (Martin *et al.* 2005), they also share some similarities. For instance, both sanukitoids and TTG have high LILE and strongly fractionated REE patterns, with typically low Yb and Y concentrations. In TTG these features are interpreted as typical of liquids generated by melting of a basaltic source leaving a garnet bearing residue, in other words it is interpreted in terms of subducted slab-melt signature (Martin 1986; Martin 1987). Consequently, re-melting of peridotite previously metasomatised via addition of slab-melt is regarded as the most likely petrogenetic model for Archaean sanukitoid (Shirey, Hanson 1984; Stern *et al.* 1989; Stern, Hanson 1991; Rapp *et al.* 1999; Smithies, Champion, 1999a; Martin *et al.* 2005).

GEODYNAMIC IMPLICATIONS AND ARCHAEAN-PROTEROZOIC BOUNDARY

The sanukitoids and Closepet-type granites mainly emplaced at the Archaean-Proterozoic boundary, during a period where the mechanisms of genesis of the juvenile continental crust changed from melting of the hydrous slab melt (Archaean) to fusion of the fluid metasomatised mantle wedge (post-Archaean).

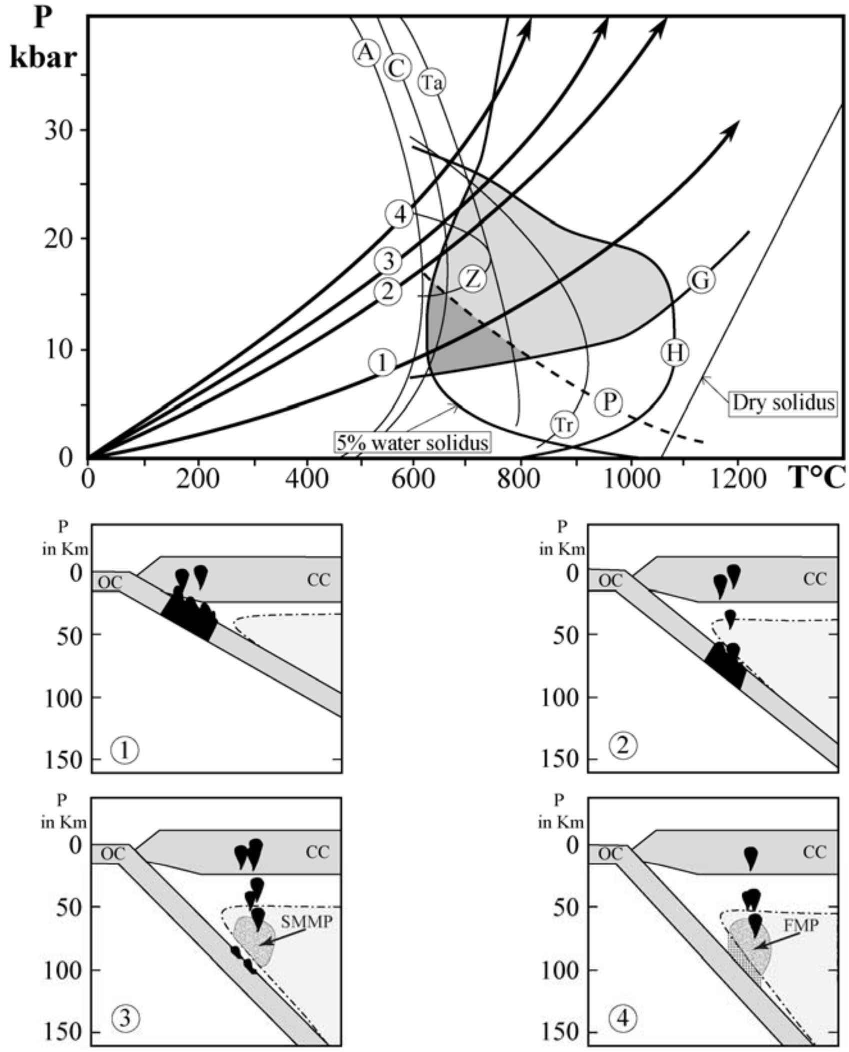

Fig. 4. P-T diagram and synthetic cross-section of subduction zones (after Martin, Moyen 2002). (1) In Early Archaean (4.0 Ga) geothermal gradient along the Benioff plane was very high; thus subducted slab melts at shallow depth; due to wedge small thickness and low temperature, mantle and melt interactions are limited or absent; (2) At 2.7 Ga, Earth was cooler; geothermal gradient was lower and slab melting occurred at greater depth. Overlying mantle wedge is thick and hot, and interactions can occur between mantle and slab melts; (3) At the Archaean-Proterozoic transition, geothermal gradients are too low to allow high degree of subducted slab melting. Slab melts are totally consumed in reaction with the mantle, whose subsequent melting generates both sanukitoids and Closepet-type granites. (4) After 2.5 Ga, geothermal gradients are so low that slab melting is precludes. Oceanic crust dehydrates and liberated fluids metasomatize the mantle wedge whose melting produces modern arc magmatism. Dehydration reactions are :(H = hornblende out, A = antigorite out, C = chlorite out, Ta = talc out, Tr = tremolite out, Z = zoisite out. G and P lines stability fields of garnet and plagioclase respectively. Grey field is P-T TTG window. OC = oceanic crust, CC = continental crust, dotted line = solidus of hydrous mantle, black areas = magma, dotted area = fluids; SMMP = slab melt metasomatized peridotite; FMP = fluid metasomatized peridotite.

It is now widely admitted that as today, the Archaean juvenile continental crust has been generated in a subduction zone environment. The model, presented here will follow this line of thinking. Today, in a subduction zone, geothermal gradient along the Benioff plane is low (Fig. 4) and dehydration reactions in subducted basalt occur before hydrous solidus temperature is reached.

Consequently, oceanic slab becomes dry and is unable to melt at low temperature. Fluids liberated by dehydration reactions rise up towards the surface through the mantle wedge that they re-hydrate thus inducing its partial melting. In addition, fluids metasomatize the mantle wedge. In other words, modern juvenile continental crust is generated in subduction geodynamic environments, by melting of mantle wedge, whose composition has been modified by fluids liberated by subducted slab dehydration. During Archaean times Earth heat production was greater, resulting in greater geothermal gradients in subduction zones. Following such high geothermal gradients, the relative positions of dehydration reaction curves and hydrous basalt solidus are inverted: subducted oceanic slab reaches its hydrous solidus temperature before dehydration began and can melt at low temperature, giving rise to TTG magmas. Consequently, TTGs result of relatively shallow depth melting of subducted oceanic crust transformed into garnet amphibolite or eclogite.

Martin, Moyen (2002) showed that from 4.0 to 2.5 Ga the depth of melting of the subducted slab progressively increased. They also demonstrated that as melting depth increased, the thickness of the mantle wedge cross cut by ascending TTG also increased. In other words mantle peridotite/slab melt interactions increased through Archaean times.

Recently, the interaction of felsic magma with mantle peridotite has been experimentally investigated; which led Rapp *et al.* (1999) to established the concept of "effective melt/rock ratio". Indeed, slab-melt reacts with mantle peridotite, leading to the crystallization of metasomatic minerals such as phlogopite and amphibole; part or whole slab-melt is consumed by these reactions. When the melt/rock (*i.e.* slab-melt/peridotite) ratio is high, not all slab-melt is consumed during peridotite metasomatism and so, contaminated melt (TTG) reaches the surface. When the melt/rock ratio is low, all the slab-melt is consumed in metasomatic reaction with the peridotite. Subsequent melting of this metasomatised peridotite, however, produces magmas that retain a strong slab-melt signature (sanukitoid and Closepet-type granite). Thus, depending on the effective melt/rock ratio, two kinds of magmas can be produced: 1) slab-melt contaminated by peridotite and 2) magma derived from peridotite contaminated by slab-melt.

We propose that during the whole Archaean the Earth heat production was high enough to allow high degree of melting of subducted slab, consequently all slab melt was consumed by mantle interaction and TTG were generated. However in course of time geothermal gradient decreased and interaction with mantle wedge increased. At about 2.5 Ga, decrease in geothermal gradients led to the low degree of melting of the subducted slab, such that the whole amount of slab melt was consumed by mantle metasomatism. Subsequent melting of this metasomatised mantle generated sanukitoid and Closepet-type granites. After Archaean times geothermal gradients were too low to allow slab melting and modern continental crust was generated by fluid metasomatised mantle wedge melting.

SUMMARY – CONCLUSION

The temporal evolution of magmas at the Archaean- Proterozoic boundary can be synthesized as follows (Fig.4):

1) In the Early Archaean (T > 3.5 Ga), terrestrial heat production was important such that melting of subducted basalts occurred at shallow depth. TTG magmas were generated but they poorly or did not interacted with mantle wedge peridotite.

2) In the Middle to Late Archaean, the heat production was lower and melting of the subducted slab took place at greater depth. The efficiency of slab-melting lead to high slab-melt/mantle peridotite ratios. Thus, the slab-melt were not totally consumed in reaction with peridotite (Rapp *et al.* 1999), and so TTG magma were emplaced into the crust.
3) During the Late Archaean, and particularly at the Archaean-Proterozoic boundary, Earth heat production and the efficiency of slab-melting had both declined. Slab-melt/mantle peridotite ratios had correspondingly declined such that some slab-melts were totally consumed in reaction with mantle peridotite (Rapp *et al.* 1999). Subsequent melting of this metasomatised mantle peridotite produced Archaean sanukitoids and Closepet-type granites.
4) Since the Lower Proterozoic, Earth's heat production was too low to allow subducted slab-melting under 'normal' conditions. Consequently, a slab dehydrates and classic BADR cal-alkaline magmatism results from melting of a peridotite that has been metasomatised by dehydration fluids.

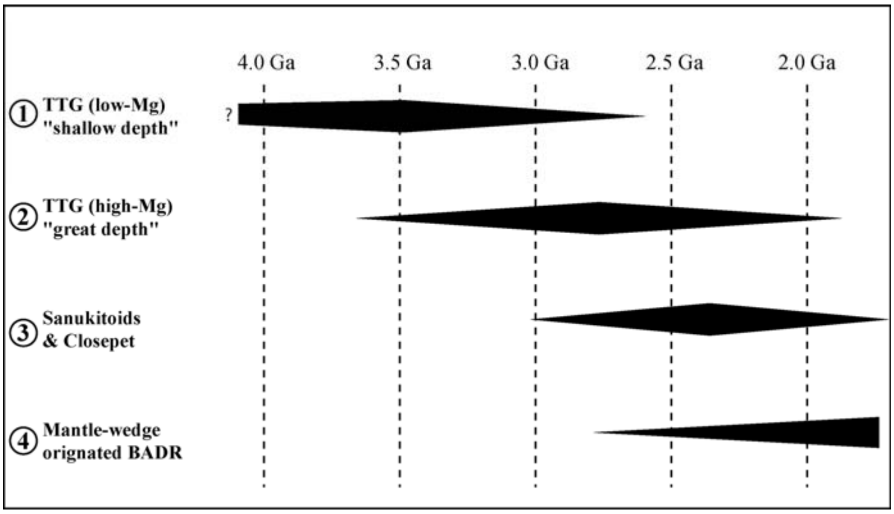

Fig. 5. Schematic diagram illustrating the evolution juvenile crustal magmatism in course of Earth history. The thickness of the dark domain is indicative of the volumetric importance of the magmatism. It clearly points to large domain of overlapping at the Archaean-Proterozoic transition (2.5 Ga).

Of course, this presentation of magma genesis timing in course of Earth history is very simplistic and schematic. If today, in subduction environments, BADR magmatism is the more widespread; slab melt can also take place, leading to adakite genesis. In other words, when today, in subduction environment, Archaean like thermal regimes are established, TTG-like (adakite) magmas can be produce, but this mechanism remains widely subordinated. In course of Earth cooling, new thermodynamic conditions appeared, but not everywhere at the same time, because local conditions play an important role in controlling these thermodynamic regimes. It certainly resulted some kind of overlapping of mechanisms (Fig. 5), leading for instance to simultaneity of TTG and sanukitoid magmatism, etc. In other words the progressive character of changes is statistic: in the Early Archaean the main process was shallow slab melting that generated low-Mg TTG, during Late Archaean times the prominent mechanism was great depth slab melting with high interaction with mantle peridotite that produced high-Mg TTG, but in the same time, in some places low-Mg were still generated. However, low-Mg TTG genesis that was the prominent process during Early Archaean, became subordinated in the Late Archaean. The same is observed for the change from TTG to sanukitoid and Closepet-type and after to typical BADR associations (Fig. 5).

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