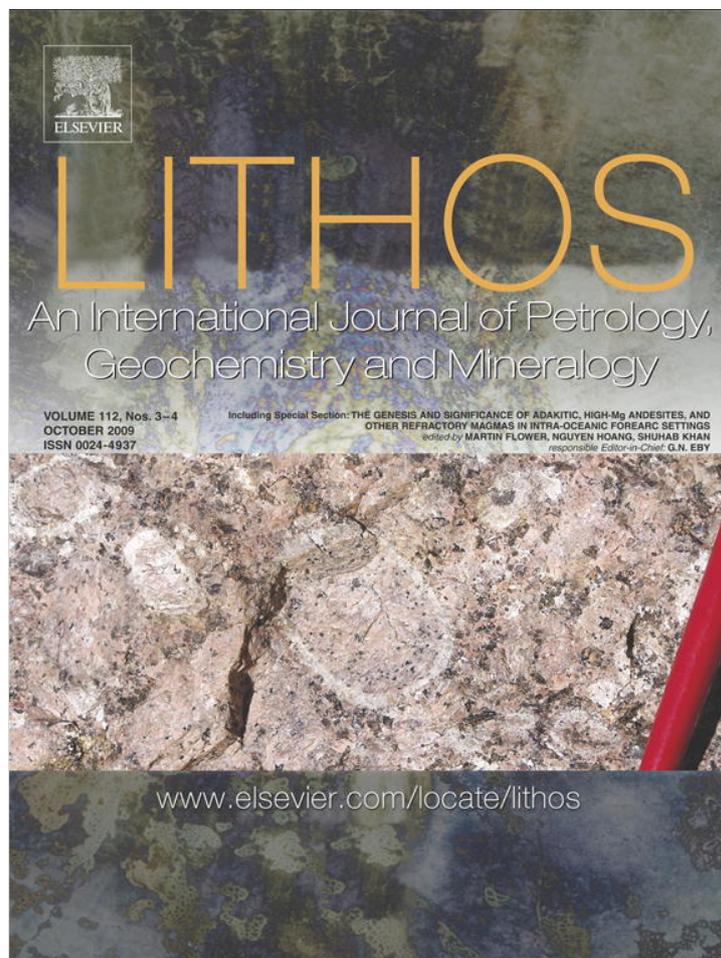


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High Sr/Y and La/Yb ratios: The meaning of the “adakitic signature”

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ABSTRACT

The name of “adakite” is used to describe a far too large group of rocks, whose sole common feature is high Sr/Y and La/Yb ratios. However, such a signature can be achieved via different processes: melting of a high Sr/Y (and La/Yb) source; deep melting, with abundant residual garnet; fractional crystallization or AFC; or interactions of felsic melts with the mantle, causing selective enrichment in LREE and Sr over HREE. A database of the compositions of “adakitic” rocks—including “high silica” and “low silica” adakites [Martin, H., Smithies, R.H., Rapp, R.P., Moyen, J.-F., Champion, D.C., 2005. An overview of adakite, tonalite–trondhjemite–granodiorite (TTG) and sanukitoid: relationships and some implications for crustal evolution. *Lithos*, 79(1–2), 1–24.], “continental” adakites and Archaean adakites—was assembled. Geochemical modeling of the potential processes is used to interpret it, and reveals that (1) the classical model of “slab melting” provides the best explanation for the genesis of high-silica adakites; (2) low-silica adakites are explained by garnet-present melting of an adakite-metasomatized mantle, i.e., at depths greater than 2.5 GPa; (3) “Continental” adakites is a term encompassing a huge range of rocks, with a corresponding diversity of petrogenetic processes, and most of them are different from both low- and high-silica adakites; (4) Archaean adakites show a bimodal composition range, with some very high Sr/Y examples (similar to part of the TTG suite) reflecting deep melting (>2.0 GPa) of a basaltic source with a relatively high Sr/Y, while lower Sr/Y rocks formed by shallower (1.0 GPa) melting of similar sources. Comparison with the Archaean TTG suite highlights the heterogeneity of the TTGs, whose composition spreads the whole combined range of HSA and Archaean adakites, pointing to a diversity of sources and processes contributing to the “TTG suite”.

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1. Introduction

In 1978, R.W. Kay described “magnesian andesites” from Adak Island in the Aleutians. Besides showing a high mg# (molecular ratio $Mg/Mg + Fe \times 100$), Kay’s rocks are rich in large-ion lithophile elements (LILE) and have high Sr/Y ratios; collectively, these features were explained by interaction of low-degree, felsic melts from the subducted oceanic crust with the peridotite mantle. The term of “adakite” was only proposed 12 years later—in reference to Kay’s work—by Defant and Drummond (1990), to describe a group of mostly acid rocks (dacites, rarely andesites or rhyolites) whose major (sodic and aluminous) and trace element chemistry (rich in LREE and LILE, strongly depleted in Y and HREE, and therefore easily identified by high Sr/Y and La/Yb ratios) suggested an origin by “derivation by melting of young subducted lithosphere” (Defant and Drummond, 1990). Ironically, the rocks described by Kay (1978) at Adak are not adakites by Defant and Drummond’s definition—they are much SiO₂-poorer, have higher mg# and higher Sr/Y and La/Yb ratios. Rocks resembling Kay’s andesites have been recognized and diversely described as

“magnesian andesites” or “bajaites” (Saunders et al., 1987; Rogers and Saunders, 1989; Calmus et al., 2003)—or sometimes as adakites (e.g. Stern and Killian, 1996), causing much confusion as the term “adakite” was now being used for at least two different types of rocks. This was pointed out by Martin et al. (2005), who identified “High-silica adakites” (HSA) and “low-silica adakites” (LSA), corresponding respectively to adakites in the sense of Defant and Drummond, and to the high-mg# andesite/bajaite group.

More confusion was brought in by the introduction, in the early 2000’s, of the term of “C-type” adakites, “continental” adakites, or even the paradoxical “potassic” adakites (adakites being initially defined as sodic dacites!) (Rapp et al., 2002; Wang et al., 2004; Xu et al., 2004; Guo et al., 2006; Zhou et al., 2006; Ding et al., 2007; Gao et al., 2007; Guo et al., 2007; Wang et al., 2007a,b; Xiao et al., 2007). Collectively, these terms refer to essentially any sort of intermediate or acid igneous rock, plutonic or volcanic, whose Sr/Y ratio is high enough—in the author’s opinion—to be regarded as “adakitic”. Adakites have also been identified in Archaean greenstone belts (Putchel et al., 1999; Polat and Kerrich, 2000, 2001, 2002; Polat and Munker, 2004; Naqvi et al., 2006; Polat and Kerrich, 2006; Ujike et al., 2007; Manikyamba et al., 2007, 2008).

On the basis of a wealth of experimental data (see review in Moyen and Stevens, 2006), there is little if any doubt on the fact that adakites—*sensu* Defant and Drummond (1990), i.e. Martin et al. (2005)’s HSA—

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can be formed by partial melting of mafic rocks, within the field of garnet stability—i.e., at depths greater than 10–12 kbar, at least. Whether the model holds for the other “adakitic” rocks is, however, a different issue; whether this is the only way to obtain an adakitic composition can also be discussed. The possibility to generate intermediate or felsic magmas by melting of mafic rocks at depth was known since the experimental work of [Arth and Hanson \(1972\)](#); in the late 70's and 80's, geochemical interpretation of the relatively similar Archaean TTG (Tonalite–Trondhjemite–Granodiorite) series lead to the same model ([Barker and Arth, 1976](#); [Maaløe, 1982](#); [Martin, 1987](#); [Drummond and Defant, 1990](#)). However, the identification of adakites—modern lavas potentially formed by melting of meta-mafic rocks ([Defant and Drummond, 1990](#); [Sen and Dunn, 1994](#))—renewed interest for this process, as adakites then appeared as a present-day, natural laboratory to study the Archaean crust-forming processes ([Drummond and Defant, 1990](#); [Drummond et al., 1996](#); [Martin, 1999](#); [Foley et al., 2002](#)) and established the comparison between adakites and TTGs as a classical model, to be either defended or challenged (e.g. [Smithies, 2000](#)).

Adakites (both LSA and HSA) are arc rocks and are restricted to subduction environments; more precisely, they are associated to “hot” subductions, where a young, hot lithosphere (possibly a ridge) is subducted ([Defant and Drummond, 1990](#); [Morris, 1995](#); [Maury et al., 1996](#); [Martin, 1999](#)). Along the South American Andean margin, the correlation between the age of the subducted lithosphere and the “adakitic” character of the lavas formed is striking ([Defant and Drummond, 1990](#); [Martin, 1999](#)). Other atypical subduction zones such as “flat” ([Gutscher et al., 2000](#)), “young” (recently initiated: [Peacock et al., 1994](#)) or “fast” ([Honda, 1985](#); [Molnar and England, 1990](#)) subductions seem to allow abnormally hot thermal regimes ([Peacock, 1990, 1993](#); [Martin, 1999](#)), resulting in slab melting and adakitic magmas. Likewise, slab breakoff and/or formation of “slab windows” can permit melting of the slab at the edge of the “window” (e.g. [Thorkelson, 1996](#); [Thorkelson and Breitsprecher, 2005](#)). It seems, therefore, likely that adakites form when a subduction zone is abnormally hot, therefore allowing the subducted slab to melt rather than dehydrate (as commonly occurs).

This argument has been used (notably by [Drummond and Defant, 1990](#); [Martin, 1999](#); [Martin et al., 2005](#)) to infer that the Archaean TTG suite formed in a similar way, therefore providing support to an “arc” origin for TTGs, and therefore for an early plate tectonic regime on Earth. This inference, however, critically relies on the similarity of adakites and TTGs—which can be disputed, although this is beyond the scope of this paper. Nevertheless, the relative similarity of adakites with the Archaean TTG suite, as well as the apparently restricted geodynamical settings in which they occur on the modern Earth (“hot” subductions) has prompted considerable interest and numerous studies on adakites, or adakitic rocks.

However, in the past 10 years, the situation evolved to the point where (1) the term adakite is used to describe an ever-growing group of rocks, with various characteristics (and, presumably, petrogenesis and origin); (2) adakites are, explicitly or implicitly, associated with hot (or flat) subductions causing melting of the subducting slab, and old adakites are regarded as geochemical markers of paleo-subductions. At the extreme, this leads to spurious discussions where naming a rock “adakite” becomes a sufficient demonstration of their (hot) subduction related origin, sometimes resulting in re-evaluation of established geodynamical models (by adding a new subduction event), or to inferences on e.g. the style of Archaean tectonics. Another equally spurious reasoning has been used, whereby a specific rock (clearly not matching Defant and Drummond's definition) is called “adakite”, and is, rightfully, demonstrated to be unrelated to slab melting; the inescapable conclusion then becomes that “adakites are not related to slab melting”. Both “logical” chains, of course, are spurious: only rocks actually matching the definition of adakites can be regarded as evidence (of a sort) for slab melting, and even in this

case, alternative scenarios are possible, as geochemistry bears no direct information on geodynamics.

In this paper, I will (1) review and discuss the geochemistry and probable origin of the different rocks that have been called “adakite” or “adakitic”, on the basis of a >750 analysis database of published rock compositions; (2) discuss the origin of the so-called “adakitic” signature (high Sr/Y and La/Yb ratios) in all these rocks, and its potential signification(s).

2. Different types of adakites

The original adakites were defined by [Defant and Drummond \(1990\)](#) as

“Andesites, dacites and sodic rhyolites (dacites seem to be the most common products), or their intrusive equivalents (tonalites and trondhjemites) (...) characterized by >56% SiO₂, >15% Al₂O₃ (rarely lower), usually <3% MgO (rarely above 6% MgO), low Y and HREE relative to island-arc andesites, dacites and rhyolites (for example, Y and Yb <18 and 1.9 ppm respectively), high Sr relative to island-arc ADR (= andesites, dacites and rhyolites) (rarely <400 ppm), low high-field strength elements (HFSEs) as in most island arc ADR.”

The combined Sr, Y and REE cutoff values correspond to Sr/Y >40, and La/Yb >20 (or (La/Yb)_N >10). Defant and Drummond gave no value for Na₂O or K/Na ratios, but it is implicit from their definition (“equivalents to tonalite and trondhjemites”) that adakites should be sodic. [Martin et al. \(2005\)](#), compiling >300 adakite analyses, refined this definition and proposed that adakites should have >3.5% Na₂O and K₂O/Na₂O ratios around 0.4. Martin et al. also concluded that adakites have mg# ~50 (somewhat higher than typical island-arc ADR that have mg# of ~40 at 60% SiO₂); FeO + MgO + MnO + TiO₂ ~7%; and relatively high Ni and Cr contents (24 and 36 ppm in average, respectively). Since the compatible elements (Fe, Mg, Ti, Mn, Ni and Cr) are tightly correlated to SiO₂, this requirement effectively corresponds to an andesitic to dacitic nature. [Richards and Kerrich \(2007\)](#) compared the definitions used by different authors for “adakites”; in details the definitions can differ somewhat, but generally share the same common features, outlined above.

Since the original definition of adakites, however, the name has been used to describe a wide range of rocks. Among all the criteria listed above, the requirement for low HREE and Y (and associated high La/Yb and Sr/Y) is commonly the only one used, overlooking the other information (sodic andesite to dacites with relatively high mg#). “Adakite”, “adakitic” or “adakite-like” has been used to describe rocks with SiO₂ ranging from 50% to >75%, with mg# between <10 and >70 and K₂O/Na₂O ratios up to >1.5 ([Fig. 1](#)). Even the Sr/Y ratio shows huge variations; most of the rocks referred to as adakites have 40 < Sr/Y < 100, but values as high as 400 and as low as 10 are reported! Interestingly, in the classical discriminant diagrams (Sr/Y vs. Y and La/Yb vs. Yb) proposed by [Defant and Drummond \(1990\)](#) and [Martin \(1999\)](#), there is a significant overlap between the fields of “adakites” and “normal arc lavas”, as the latter can reach La/Yb and Sr/Y values as high as 60 and 80, although they normally have higher Yb_N (>5) and Y (>12 ppm) values. This leaves, however, a significant overlapping area, and in any case emphasizes the danger of using a single parameter (Sr/Y, or La/Yb) as the sole or main identification criteria ([Fig. 2](#)).

The following discussion focuses mostly on Sr/Y ratios. It may be argued that, since Sr is potentially affected by mobility during low temperature alteration, La/Yb is a better indicator of the “adakitic” character of a magma. However, for several reasons, this paper uses Sr/Y as the main indicator: (1) this work relies on published data; especially for relatively old analyses, REE and particularly HREE (Yb) are not always analyzed or not always reliable, such that one has to rely on the more easily obtained Sr and Y that are present for all the

data set. This is an intrinsic limitation to the approach based on data compilation. (2) The differences discussed here are in the order of magnitude range (as evidenced by the use of log diagrams, see below). It is extremely unlikely that alteration would have effects of that magnitude, and if it had it would affect major elements and mineralogy to a large extent, such that altered samples would be easily filtered out of the database (and indeed, would most likely not have made their way into publication). Smaller effects on the other hand are well possible, but small differences are not interpreted in this work, that has a much more global perspective. (3) Whenever both Sr/Y and La/Yb ratios are available, there is a very good correlation between the two (at least at the scale of the whole dataset, i.e. ignoring a few outliers that may very well be altered samples indeed!). This suggests that both ratios do carry the same information, and it is therefore possible to use either. Here, I decided to use the most commonly available in order to extend the size of the database and draw global conclusions.

2.1. High-silica adakites (HSA)

A critical re-examination of the published literature led Martin et al. (2005) to coin the term of “high-silica adakites” (as opposed to the low-silica adakites, described below) to describe the adakites that do actually match the original definition (Defant and Drummond, 1990). In the rest of this paper, these rocks will be referred to as “HSA”. Geochemical as well as experimental and geodynamical arguments (reviewed by Martin et al., 2005) convincingly show that the most likely way to form HSA is by partial melting of metabasalts, in the field of garnet stability (see, however, the alternative model proposed by Macpherson et al. (2006), discussed below Section 4.2.2).

Recent debate focused on the nature of the residuum of HSA and TTG; high pressure melting would produce an eclogitic residuum (garnet + clinopyroxene + rutile), whereas at lower pressure, the residuum would be a garnet–amphibolite (garnet + amphibole). Differentiating both situations is a difficult proposition; it seems, however, that an eclogitic residuum will yield melts with higher Nb/Ta ratios than an amphibolitic one, largely owing to the effect of rutile (Foley et al., 2000, 2002; Schmidt et al., 2004). HSA, having relatively elevated Nb/Ta (14 ± 4), probably correspond to a rutile-bearing residuum.

2.2. Adakitic plutons

With growing interest in adakites, the term was expanded to encompass plutonic rocks with comparable characteristics. “Plutonic adakites” are, therefore, tonalites and trondhjemites; they do however match most or all of the chemical characteristics of HSA, and can very probably be regarded as plutonic equivalents of the extrusive adakites (Figs. 1 and 2).

2.3. Low-silica adakites (LSA)

The first extension of the definition of adakites is towards the low SiO₂ values, encompassing rocks with SiO₂ down to 50%. This group was described by Martin et al., 2005 as “low-silica adakites” (adakites from Adak island actually belong to this group). Low-silica adakites have 50% < SiO₂ < 60%, and correlatively high contents in compatible elements (Fig. 1). Their Sr/Y and La/Yb values are extreme (100–300 and 40–80 resp.), much higher than in the more classical adakites (40–100 and 20–40) (Fig. 2). Uncharacteristically however, they also have high K₂O (>2%) and K₂O/Na₂O ratios (0.6 ± 0.2). Apart from their Sr–Y and La–Yb characteristics, they do not match the definition of adakites.

Since the original work of Kay (1978), all interpretations of “HSA”, “bajaites” or “high-magnesium andesites” (or high-mg# andesites) (Saunders et al., 1987; Rogers and Saunders, 1989; Kelemen, 1995; Calmus et al., 2003; Kelemen, 2003, 2008) proposed similar models—interactions between slab melts and the peridotitic

mantle. More recently, this model received experimental support, as Rapp et al. (2000, 2007) and Martin et al. (in press) demonstrated that melting of an “adakite-metasomatized mantle” (i.e., a mixed composition, adakite + periodite) indeed yields magmas similar to the LSA, both in terms of major (Rapp et al., 2000) and trace elements (Rapp et al., 2007). It must be stressed that, from a thermodynamical/experimental perspective, there is no difference between (i) equilibration of a felsic melt with peridotites and assimilation of some mantle minerals during magma ascent; and (ii) metasomatism of the mantle, resulting in an enriched mantle composition, that subsequently melts. In both scenarios, bulk equilibrium is achieved at certain *P–T* conditions, for a system with a given bulk composition; if equilibrium is achieved (a bold proposition, but the basic hypothesis of experimental petrology!), only one single liquid composition can exist.

2.4. Fractionated andesites

Richards and Kerrich (2007) recently pointed out that a large portion of the “ordinary” calc-alkaline series do evolve into the adakitic field—at least for some elements. In such situations, the “adakitic” rocks typically occur in the same volcano (or unit) as “non-adakitic” rocks, and the evolution between the two types can be ascribed to processes like fractional crystallization or AFC. Distinctive characteristics of rocks from this group are (i) their association with non-adakitic rocks, in a complete differentiation series, only part of which occurs in the “adakitic” field; (ii) decoupling of the La/Yb and Sr/Y ratios compared to adakites (see Section 5.3 below), typically with low Sr/Y relative to the La/Yb values; (iii) a generally potassic chemistry ($0.5 < K_2O/Na_2O < 1$, compared to ~ 0.4 for adakites); (iv) somewhat lower MgO and mg#, more similar to “normal” arc magmas than to adakites (Fig. 1).

Decreasing the Y and HREE contents of arc magmas (and, consequently, increasing Sr/Y and La/Yb into the “adakitic” range) is easily achieved by fractionation of either amphibole (Davidson et al., 2007a,b, 2008) or garnet (Alonso-Perez et al., 2003; Macpherson et al., 2006; Ulmer, 2007; Muntener et al., 2008) from an ordinary, low or moderate Sr/Y & La/Yb andesite, and it is therefore not unexpected that most calc-alkaline magmas have the potential to reach adakite-like compositions, at least for this limited group of elements (Richards and Kerrich, 2007).

2.5. Continental adakites, K-adakites

In the past few years, a large group of rocks, mostly from China, have been described as adakites (Rapp et al., 2002; Wang et al., 2004; Xu et al., 2004; Guo et al., 2006; Zhou et al., 2006; Ding et al., 2007; Gao et al., 2007; Guo et al., 2007; Wang et al., 2007a,b; Xiao et al., 2007). This group is hugely diverse, encompassing both volcanic and plutonic rocks, with SiO₂ contents ranging from <60% to >75% (Fig. 1) (the highest silica content of all reported “adakites” from the literature). Their common characteristics are (1) low Y and Yb values (but not always high Sr/Y or La/Yb!) (Fig. 2); (2) a geodynamical setting not typically associated with active subduction (although paleo-subduction has sometimes been proposed), but rather with continental collision or intracontinental strike–slip movement.

The common feature of most “continental” adakites (except maybe some examples in Tibet, that more closely match the original definition of adakites—Gao et al., 2007; Wang et al., 2007a,b) is their high K₂O contents and high K/Na ratios (typically between 0.7 and 2); they effectively are granites or granodiorites, some actually are potassic I-type granites (KCG in Barbarin, 1999). Some of them have been referred to as “K-adakites”, emphasizing this situation (Clemens et al., 2007; Xiao et al., 2007). Continental adakites have Sr/Y ratios between 150 and 15 (more potassic examples having typically lower Sr/Y), such that a portion of this group is actually made of potassic,

low Sr/Y rocks... Nearly none of the “continental” adakites matches the original definition (Defant and Drummond, 1990), nor are they any similar to LSA in general.

Models for the generation of “continental” adakites generally involve deep (>10–15 kbar) melting of continental crust, either at the base of an orogenic wedge, or as delaminated eclogites sinking in the

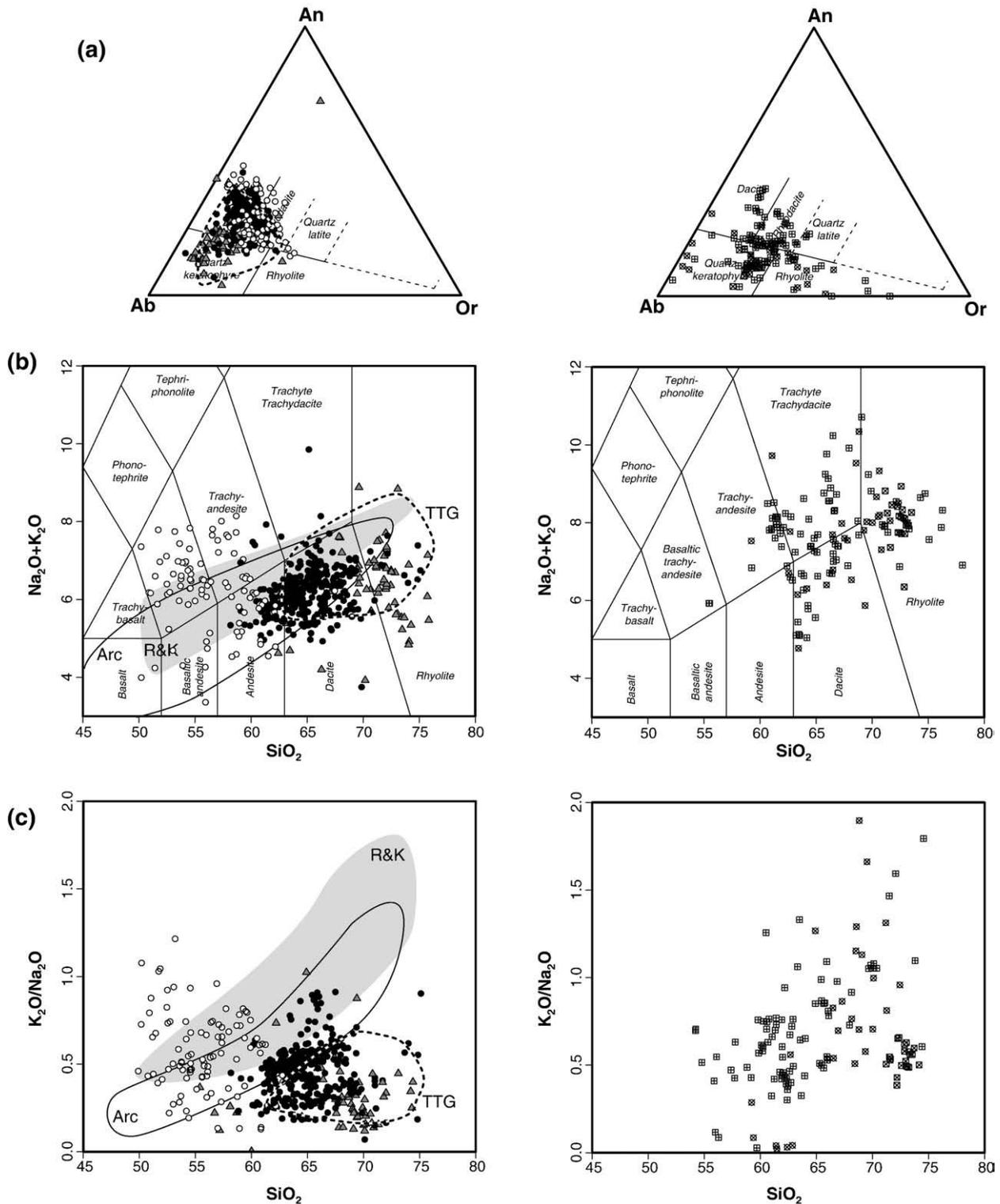


Fig. 1. Major elements characteristics of “adakitic” rocks. Left column: HSA (full circle) and LSA (open circle); Archaean adakites (grey triangles). For comparison, the diagrams also show the fields of (1) Archaean TTGs (from the compilation by Martin and Moyen, 2002); (2) “ordinary” arc magmas (GEOROC project, <http://georoc.mpch-mainz.gwdg.de/georoc>), thin solid line; (3) “fractionated andesites” of Richards and Kerrich (2007), light grey (R&K). Data from the literature, mostly from the compilation in Martin et al. (2005) completed by files from the GEOROC project. Right Column: “continental” adakites and sodic rhyolites from the literature (references in text). Squares with diagonal cross: Yungai ignimbrite (Coldwell et al., 2007; Coldwell, 2008); squares with vertical cross: continental adakites from Eastern and Northern China, mostly from the Sulu and related Cretaceous belts; circles with diagonal cross (Wang et al., 2004; Xu et al., 2004; Guo et al., 2006; Wang et al., 2007b; Xiao et al., 2007): Continental adakites from Tibet (Miocene) (Gao et al., 2007; Guo et al., 2007). (a) Normative An–Ab–Or diagram (O’Connor, 1965); (b) Total alkali–silica (TAS) diagram (Le Bas et al., 1986). (c)–(e): Harker-type diagrams for K_2O/Na_2O , Al_2O_3 and MgO.

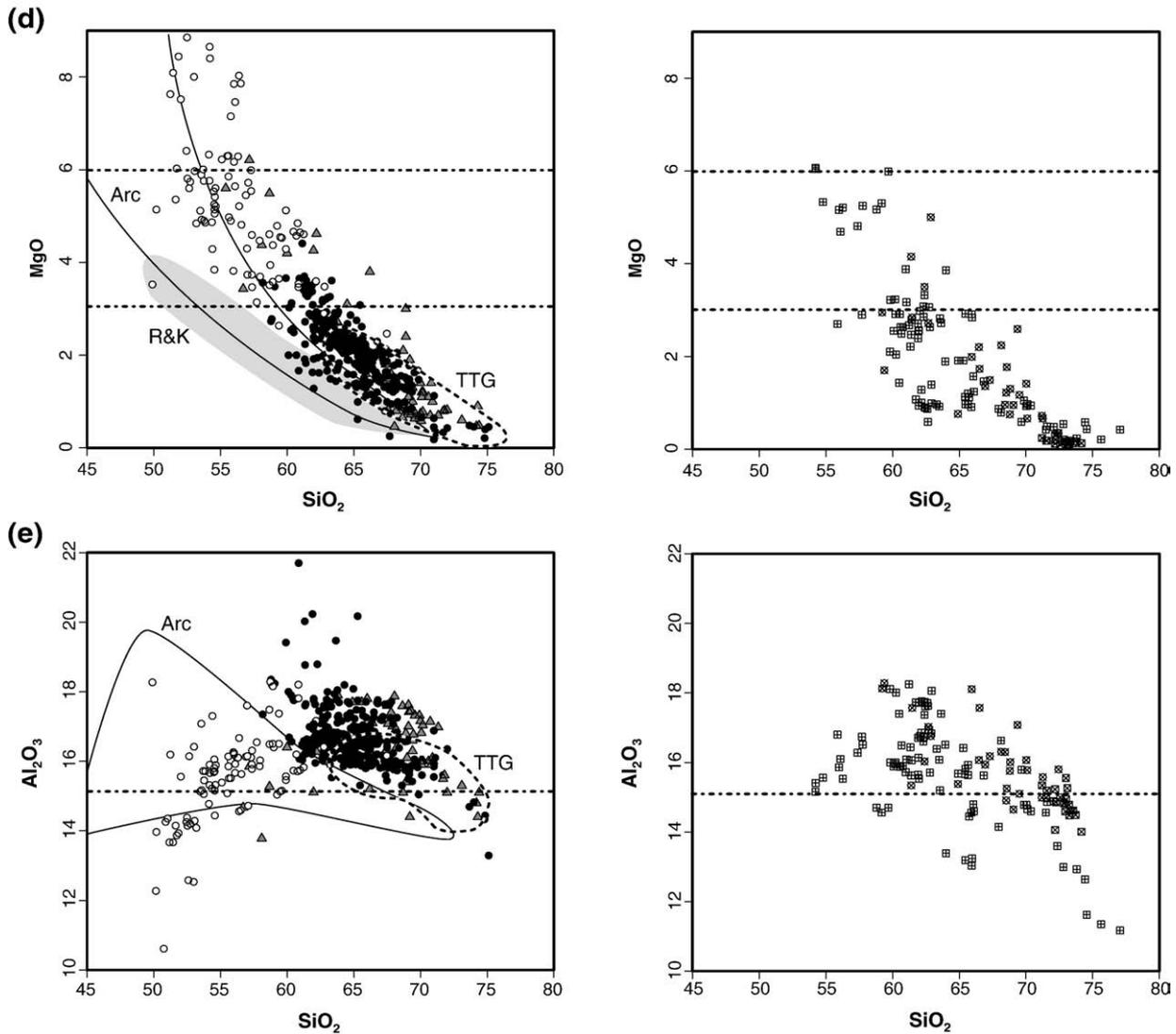


Fig. 1 (continued).

mantle. In the latter case, it is proposed that interactions with the mantle, similar in nature to the interactions described above for LSA, can result in melts with higher mg#.

2.6. Sodic rhyolites

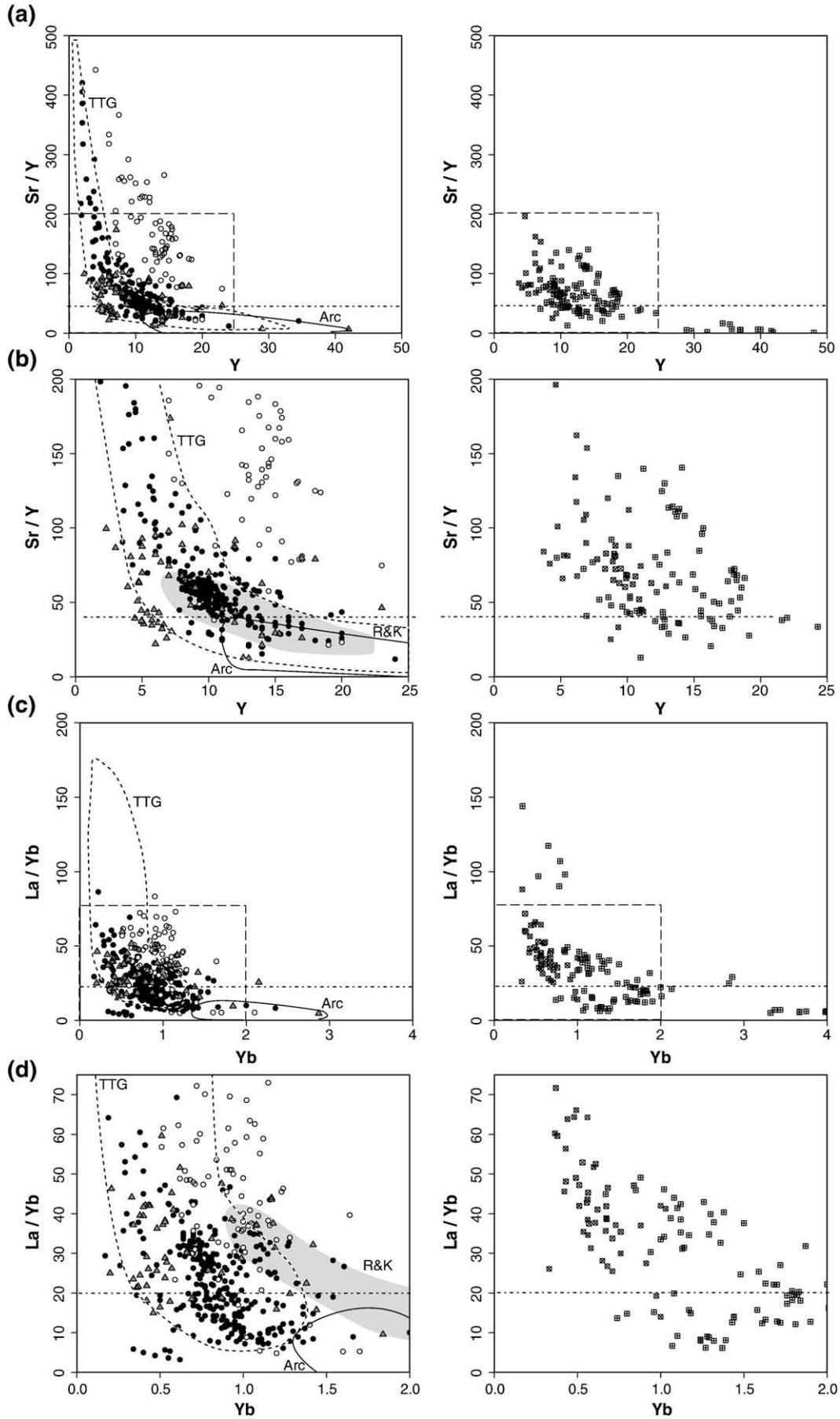
Recently, rhyolitic ignimbrites from Peru were described as “adakites” (Coldwell et al., 2007; Coldwell, 2008). The Yungay ignimbrites have indeed the relatively high (75–100) Sr/Y ratios expected from adakites; on the other hand, they are rhyolites (and not dacites), are somewhat more potassic ($K_2O/Na_2O > 0.5$) than high-silica adakites, with a much lower mg# (~10). Apart from the Sr/Y and La/Yb ratio, they meet none of the components of the definition of adakites. Yungay ignimbrites are proposed to be partial melts of the lower crust—presumably of already felsic rocks, as a more mafic source would be unable to produce low mg# melts.

2.7. Archaean adakites

Adakites on the modern Earth are mostly regarded as a marker for hot subduction, characterized by slab melting. Progressively however, this interpretation shifted to the somewhat more general conclusion that adakites are markers of subduction. In the context of the debate regarding the existence and modalities of Archaean plate tectonics, adakites progressively became interpreted as a marker of Archaean subduction (although careful studies do not use adakites alone, but in conjunction with other rock types, collectively pointing to the existence of subduction processes).

Some occurrences of Archaean adakites are now described, in Late-Archaean (<2.7 Ga) blocks from the Canadian Superior Province (Polat and Kerrich, 2000, 2001, 2002; Polat and Munker, 2004; Ujike et al., 2007), the Baltic Shield (Putchel et al., 1999) and the Indian Dharwar Craton (Naqvi et al., 2006; Manikyamba et al., 2007, 2008). However,

Fig. 2. Sr–Y and La–Yb systematics of “adakitic” rocks. Symbols, fields and data origin as in Fig. 1. (a) and (b): Sr/Y vs. Y diagram (Defant and Drummond, 1990; Martin, 1999). (c) and (d): La/Yb vs. Yb diagram (Martin, 1987, Martin, 1999). In all cases, the horizontal line indicates the cutoff value of Sr/Y = 40 and La/Yb = 20 for the original definition of (Defant and Drummond, 1990). The dashed box in (a) and (c) indicates the outline of the zoom in (b) and (d).



different examples actually turn out to be fairly different in nature. Examples from the Wawa greenstone belt (Polat and Kerrich, 2000, 2001) are generally felsic (straddling the boundary between dacites and rhyolites); they have high Na₂O and low K₂O, and consequently low K₂O/Na₂O ratios (0.3–0.4). The original work relies on REE and HFSE to characterize these adakites; examination of the published data reveals that their Sr/Y ratios are appropriately high, at 50–100. Although more felsic than modern adakites, the Wawa examples nevertheless meet most of the components of the definition.

Even more felsic examples are reported from the Sandur Belt of the Dharwar Craton (Manikyamba et al., 2008), where the “adakites” are actually very differentiated rhyolites (>75% SiO₂!). In contrast, “adakites” such as these from the Eastern Dharwar Craton (Naqvi et al., 2006; Manikyamba et al., 2007) are andesitic (60% < SiO₂ < 65%), relatively potassic (K₂O/Na₂O > 0.8) and have a low mg# (~30–40), owing to large Fe contents more than low Mg. Their Sr/Y values are not typical, as they have low (20–40) Sr/Y ratios, barely reaching the cut-off value defined above. The “adakitic” character of Dharwar samples is therefore very discrete (as they are neither really sodic, nor magnesian, and do not have typically high Sr/Y or La/Yb ratios).

3. How high is a high Sr/Y ?

Compared to other igneous rocks, adakites (and related rocks) have high Sr/Y and La/Yb ratios. Chondrites have Sr/Y of 6 and La/Yb slightly below 1.5 (Sun and McDonough, 1989), well under the typical HSA values (about 60 and 20, respectively). LSA have even higher ratios, around 200 and 50. On the other hand, the continental crust has higher Sr/Y and La/Yb than chondrites, each between 15 and 20 (Taylor and McLennan, 1985; Rollinson, 1993; Rudnick and Gao, 2004). Granites (that form the continental crust), either S or I types, have variable but moderate Sr/Y (2–20) and La/Yb (5–30) (Data compilation of published analyses by the author). The lower crust, according to some estimates (Weaver and Tarney, 1984), could have very high Sr/Y (>80) and La/Yb (18) ratios, although most estimates propose lower values (Sr/Y = 15–20, La/Yb = 5–15; GERM database <http://earthref.org>), similar to the bulk crust.

In the oceanic crust, MORBs have Sr/Y between 2 and 10 and La/Yb between 0.5 and 5, and OIBs can extend to both Sr/Y and La/Yb nearing 50. The threshold at Sr/Y = 40, as proposed by Defant and Drummond (1990) therefore appears to be robust, as it does indeed separate the high Sr/Y adakites from the normal, lower Sr/Y rocks from both the continental and the oceanic crust. On the other hand, many ordinary calc-alkaline suites do straddle the boundary, with Sr/Y ratios in the range of 20–50, once more demonstrating that care should be exercised in relying on a single indicator to define a rock.

Non-adakitic arc lavas (Fig. 3) are indeed clearly distinct from both HSA and LSA, as they do have somewhat lower (although overlapping) La/Yb and much lower Sr/Y; significantly they are also shifted “downwards” in the Sr/Y vs. La/Yb diagram: more than the value of any of the two indicators, the coupled systematic is more discriminant.

Interestingly, La/Yb turns out to be less reliable as an indicator, as indeed a large overlap exists between different rock groups (much larger so than for Sr/Y), or even within one group. La/Yb values between 10 and 50 are not really discriminant as they are found in all sorts of rocks (adakites and “normal” felsic igneous rocks alike).

4. Origin of the high Sr/Y and La/Yb “adakitic” signature

4.1. Source and pressure effects

High Sr/Y ratios are commonly interpreted as reflecting deep melting. Indeed, as the pressure increase, plagioclase becomes unstable (therefore releasing Sr), whereas garnet becomes stable and a more and more important phase, trapping Y. The result is a dramatic increase of the Sr/Y ratio with increasing pressure; La and Yb

have comparable behaviours, such that the La/Yb ratio shows the same pattern.

The reasoning above, however, implicitly assumes a source of constant composition; clearly, a source with higher Sr/Y will give melts with a Sr/Y higher than melts from a low Sr/Y source. Reasonable values for source rocks range from <5 (MORB-type basalts) to 10–15 (continental crust) and more (arc basalts), potentially producing melts with a large range of Sr/Y values, all things being equal.

Experimental data are used here to discuss the role of both the pressure and the source composition. A database of nearly 500 published experiments was used, encompassing melting both of amphibolitic, and of pelitic or greywacky, lithologies (partially published in Moyen and Stevens, 2006). For more than 400 of them (273 amphibolites, 136 “crustal” sources), mineral proportions are published. From the mineral proportions, and published Kd (partition coefficients) values, bulk repartition coefficients *D* were calculated. The *D* values, together with the published *F* (melt fractions) allow to use a batch melting equation (Shaw, 1970)

$$\frac{C_l}{C_0} = \frac{1}{F + D(1 - F)} \quad (1)$$

to calculate the ratio *C_l/C₀*, i.e. the degree of enrichment of the melt (*C_l*) relative to the source (*C₀*).

The enrichment in Sr/Y (i.e., (Sr/Y)_{melt}/(Sr/Y)_{source}) is plotted against pressure for both the amphibolitic and “crustal” sources (Fig. 4a and b). As could be expected, the pressure exerts a strong control, with very low enrichment factors at low pressure and high enrichments (up to ~30 times) at high pressure. However, the boundary between the “low” and the “high” pressures (corresponding to the garnet-in line) is very variable; it is around 15 kbar for amphibolitic sources, but as low as 5–6 kbar for the more aluminous crustal sources. Consequently, crustal sources are able to produce high Sr/Y melts, 10–20 times enriched over their source, at relatively low (5–10 kbar) pressures. Accessory phases are not taken into account when calculating the enrichments of the melts; this is probably problematic for the crustal sources, where phases like zircon can coexist with the melt. However, since zircon has high (>100) Kd's for the HREE including Y, its presence will lower the Y contents of the melts and raise their Sr/Y; therefore, the melts produced have Sr/Y even higher than predicted by the calculation above.

The role of the source Sr/Y was also investigated (Fig. 4c). The Sr/Y values of the melts produced for both type of sources were plotted against pressure (*P*), for two source Sr/Y values: a relatively low value of 3 (close to a typical N-MORB), and a higher value of 10, equivalent to the PAAS (Post-Archaean Average Shale) of Taylor and McLennan (1985) and comparable with the estimates for the bulk continental crust (Taylor and McLennan, 1985; Rollinson, 1993). Obviously, the high Sr/Y source yields melts with Sr/Y's three times higher than the low Sr/Y source.

Consequently, it appears that high Sr/Y do not directly correlate to deep melting. “Enriched” sources will also contribute to high Sr/Y values in the melt, because they have intrinsically higher Sr/Y ratios, but also because they are more aluminous and have more potential for forming garnet at moderate depths. As an illustration, a Sr/Y ratio of 80–100 (higher than most HSA) must be formed at >20 kbar if the source was a MORB-like amphibolite; but can also be formed at pressures as low as 5–10 kbar, if the source was a crustal lithology with normal, crustal Sr/Y values. A lower crustal source could be even worse—some estimates propose Sr/Y ratios of up to 80 (Weaver and Tarney, 1984), meaning that practically any melt in the lower continental crust will have “adakitic” Sr/Y greater than 40. Interpretations of high Sr/Y rocks as corresponding to deep melting (thickened orogenic crust, lower crustal delamination, etc.) are therefore far from being robust, especially in the case of rocks with a clear continental crust origin.

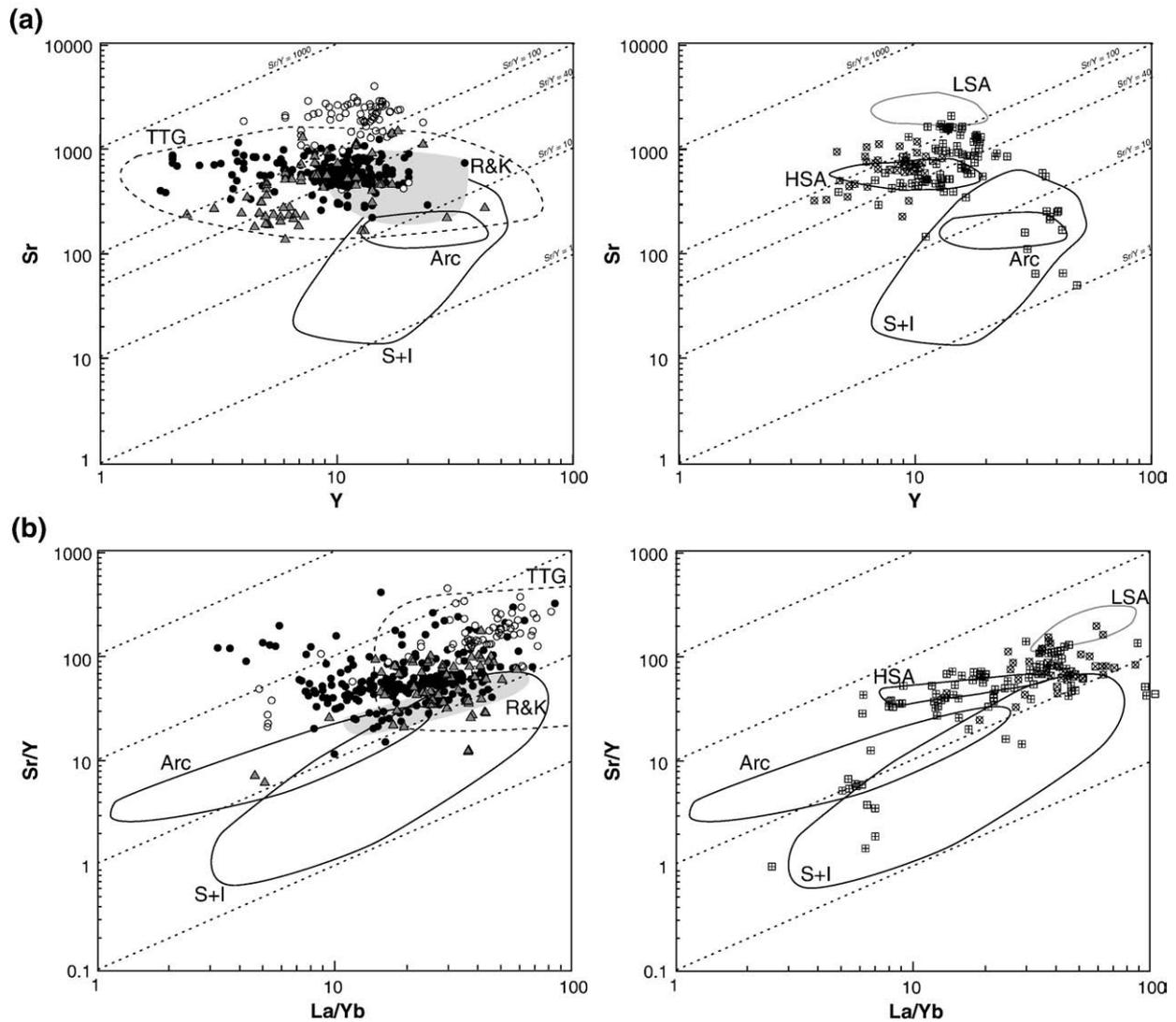


Fig. 3. Sr vs. Y (a) and Sr/Y vs. La/Yb (b) diagrams for the same samples and fields as Fig. 1. All diagrams use log–log scales.

Discussing the nature of the source is therefore critical to any interpretation that aims at constraining the depth of melting. Indicators like K/Na (Fig. 1), Rb/Sr or Nb/Th (a measure of the Nb–Ta anomaly, taken as a typical feature of the continental crust) do indeed point towards a range of possible origins for all the rocks studied here; the “continental” adakites consistently have a much more “crustal” signature than the HSA, consistent with the interpretations proposed in the original papers. Unsurprisingly, the “crustal” signature (low Nb/Th, high Rb/Sr) also anti-correlates with the mg#, more crustal rocks having lower mg#.

The crustal origin of some of the alleged “continental adakites” – proposed by the authors themselves, and evident from the geochemistry – does therefore, actually, argue against deep melting; in this case, the high Sr/Y ratios do probably reflect only a Sr/Y rich source, such as the normal continental crust, regardless of the melting depth. Assuming the source had a Sr/Y of ca. 15 (average continental crust, Taylor and McLennan, 1985), a conservative estimate given the potentially much higher Sr/Y of the lower crust, an enrichment factor around 20 at 15 kbar (Fig. 4) would yield melts with Sr/Y = 300, much higher than nearly all the “continental adakites”, such that melting at depths > 10 kbar is actually precluded by the moderate Sr/Y (50–100) of these rocks!

4.2. Fractionation

Fractionation of minerals with a high K_D for Y and HREE will lead to a low Y and HREE (and consequently, high Sr/Y and La/Yb) magma. The two most likely minerals are amphibole and garnet.

4.2.1. Amphibole fractionation: shallow evolution

Amphibole has a high K_D for HREE, but even higher for the medium and heavy REE (such as Dy); therefore, amphibole fractionation can be traced by decreasing Dy/Yb ratios with differentiation (Davidson et al., 2007a,b, 2008). In addition, in natural systems amphibole fractionation is seldom isolated and is typically accompanied by plagioclase removal. The net effect of amphibole and plagioclase fractionation is an increase in La/Yb, decrease in Dy/Yb, and moderate increase or even decrease in Sr/Y. This sort of correlation is observed in most arc lavas–adakites and otherwise – suggesting that at least the final stages of the recorded geochemical evolution reflect amphibole + plagioclase fractionation.

However, this late evolution only marginally alters the Sr/Y and La/Yb ratios; many of the suites reported by Richards and Kerrich (2007) cover only limited ranges for these parameters, typically from 10 to 20 or 30 for La/Yb, from 30 to 50 or 60 for Sr/Y. Evolutions of the

same magnitude also occur in high-silica adakite suites, but with Sr/Y ranging from 50–60 to 100; late-stage fractionation is apparently not enough to evolve a non adakitic suite into an adakitic one. This has been modeled, for the relatively similar Archaean TTGs, by [Moyen et al. \(2007b\)](#), with the same conclusion: amphibole + plagioclase fractionation can shape the geochemical trends observed, but has little or no potential to actually yield adakitic signatures in the first place. This is because (i) amphibole fractionation does typically not occur in isolation, but together with plagioclase, largely negating the

effects of amphibole; (ii) although amphibole is rather efficient in changing the trace elements budget, it is also a very mafic component; the amount of amphibole that can be formed is therefore limited by the Fe and Mg budget to a small mass fraction (in the region of 20%), strongly reducing its potential effect. Therefore, while shallow amphibole-dominated fractionation certainly plays a role in many calc-alkaline suites, including adakites, a specific parental magma, already adakitic, is required to reach truly high Sr/Y values (high La/Yb are easier to obtain in this way).

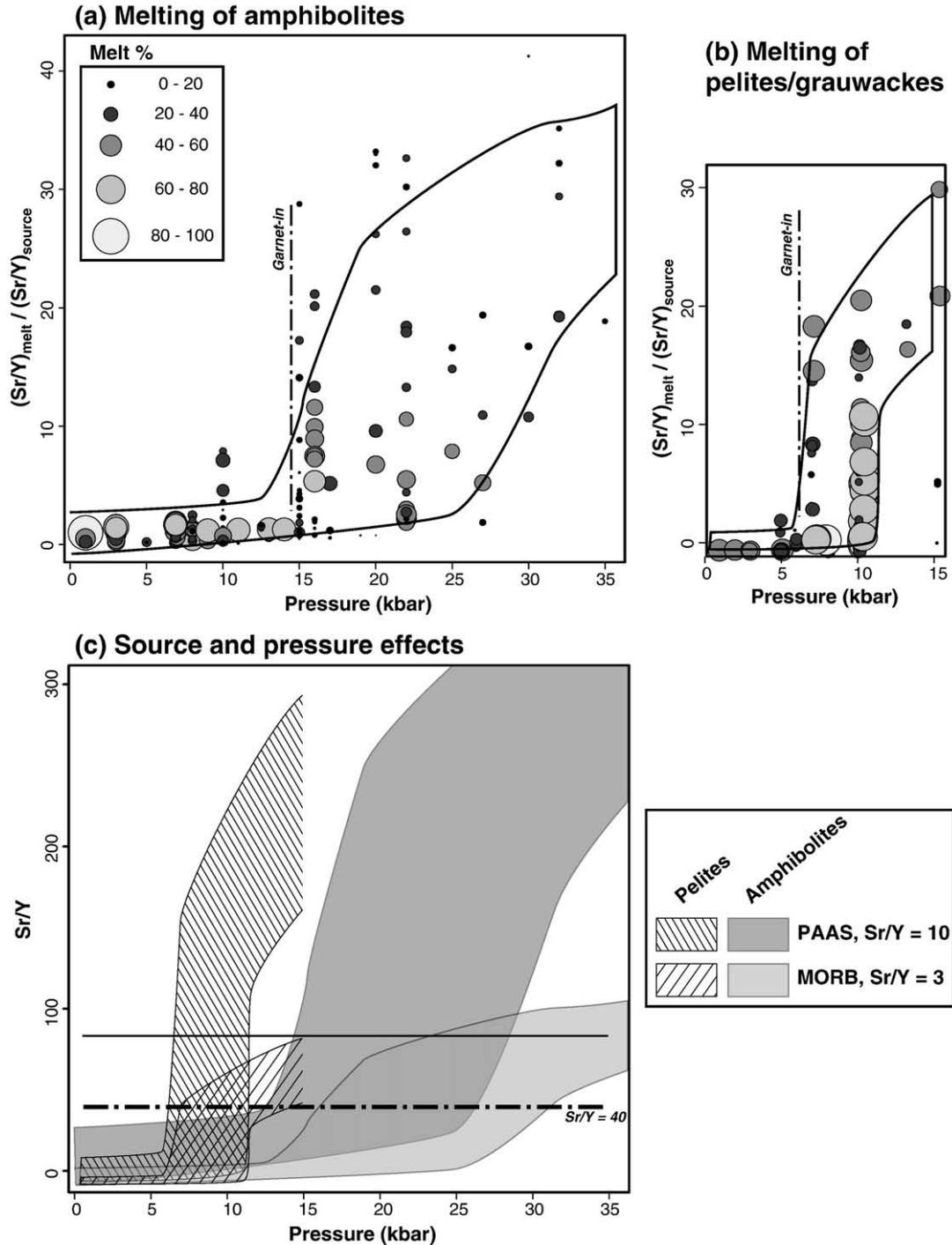


Fig. 4. Sr/Y enrichment as a function of the depth of melting and the composition of the source. (a) and (b) (Sr/Y) enrichment as a function of depth of melting for amphibolitic (a) and “crustal” (pelites and greywackes, b) sources. The size of circles are proportional to the melt amount (F). (c) Absolute Sr/Y values for the melting of amphibolitic (grey) and crustal (hatched) sources; the fields correspond to the range of data, as in panels (a) and (b). Two source composition are used, a MORB-like source ($Sr/Y = 3$) and a PAAS (Post-Archaean Average Shale, [Taylor and McLennan, 1985](#)) source ($Sr/Y = 10$). The horizontal lines correspond to $Sr/Y = 40$ (the cut-off value in [Defant and Drummond, 1990](#)) and ca. 90 (example in text).

4.2.2. Garnet fractionation: deep evolution

Another possibility that could lead to “adakitic” signatures (specifically to HSA) is deep fractionation of a garnet-dominated assemblage (Macpherson et al., 2006). The process has been demonstrated to be experimentally feasible (Muntener and Ulmer, 2006; Ulmer, 2007; Muntener et al., 2008; Ulmer et al., 2008), as garnet is indeed a liquidus phase of calc-alkaline magmas at relatively high pressures (>12 kbar). Obviously, garnet fractionation will very efficiently rise the Sr/Y and La/Yb ratios; unlike amphibole fractionation, garnet will also increase the Dy/Yb ratio (Macpherson et al., 2006; Davidson et al., 2007a).

Since melting and fractionation are essentially symmetrical processes, there are very little way to distinguish between high pressure melting, and high pressure fractionation; in both case, the melt is in equilibrium with a garnet-rich solid that controls its chemistry, such that the resulting melt is a high silica adakite in either case. So far, no simple criterion based on major or trace elements allows to separate both processes. Perhaps the most convincing evidence so far is the mismatch between the isotopic composition of the subducted slab, and the nearby adakitic (HSA) magmas, described in Mindanao by Macpherson et al. (2006). However, whether this process is generally applicable, or not, remains unknown.

4.3. Interactions with the mantle

In all the rocks considered here, there is generally a rough correlation between mg# (and related parameters, such as Cr, Ni, etc.) and the Sr/Y ratio (as well as La/Yb) (Fig. 5). This strongly suggests a genetic link between the two parameters. As mg# values as high as these observed in the LSA (≈ 60) are difficult to reach without a mantle source, or at least a mantle component, there are indeed strong suggestions that mantle interactions increase the La/Yb and Sr/Y ratios of the melts. This hypothesis is explored here using geochemical modeling of such interactions.

Modeling mantle-melt interactions is a difficult proposition, as we still lack a clear understanding of the petrogenetical processes occurring in the mantle during adakite–peridotite interactions (see, however, Rapp et al., 2000, 2007; Martin et al., in press). With the limited goal of understanding the geochemical relations between different rock types studies here, and of unraveling the meaning of the adakite (and related) geochemical signatures, I used a simple approach, based on batch melting (fractional melting has been used in some studies (Hoffer et al., 2008) for essentially similar results) of a modified mantle composition. A mass fraction a of adakite melt (composition C_a) in mixed in the mantle (C_m), such that the composition of the metasomatized mantle is

$$C_{mm} = a.C_a + (1 - a)C_m \quad (2)$$

a (or rather, $a/1-a$) corresponds to the melt:rock ratio in the sense of Rapp et al. (2000, 2007), i.e. the relative melt and rock proportions actually involved in the interactions. The melt:rock ratio can be high; this does not mean that the mantle as a whole was soaked with melts, rather than the scale of the interactions was such that only limited portions of the mantle were allowed to react with the melt. Low melt:rock ratios correspond to interactions involving large amounts of the mantle—maybe corresponding to narrow magma pathways, or magma percolating the mantle on a grain scale, with a correspondingly high interface surface between melt and mantle. In contrast, high melt:rock ratios can be obtained where large magma conduits restrict the contact surface between the melt and the peridotite, and/or high magma flow in large conduits reduces the interaction time, and/or armouring of the edges of the conduit makes further reactions difficult to impossible. Consequently, in geological situations, the melt:rock ratio can vary between zero and infinity, as a function of the magma flow rate and of the size of the magma pathways!

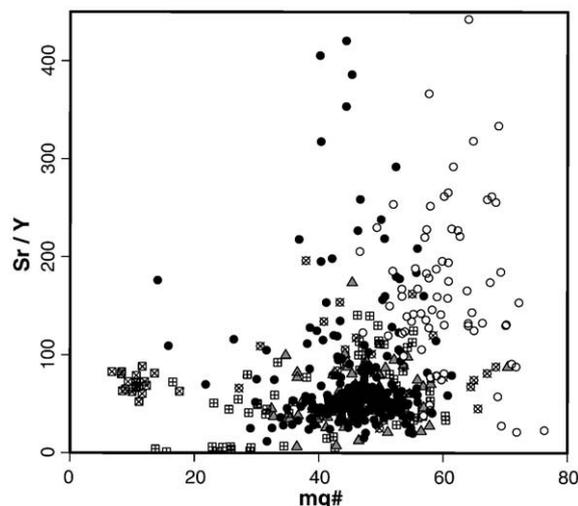


Fig. 5. mg# vs. Sr/Y diagram showing the importance of mantle interactions in generating high Sr/Y ratios. Symbols as in Fig. 1.

The composition of the melt, using Shaw's batch melting equation (Shaw, 1970), is therefore

$$C_l = \frac{C_{mm}}{F + D(1 - F)} \quad (3)$$

From a petrological point of view, this is probably a realistic approach, as it effectively mimics the global reequilibration that occurs as a function of the bulk composition. Furthermore, this model allows for melt consumption ($a > F$) or, conversely, additions to the melt ($F > a$) during the interactions; the parameter F/a indicates the amount of melt gained or lost during the interactions. However, it is difficult to decide on reasonable values for a and F , and the model is difficult to constrain.

Partition coefficients are from published values (Rollinson, 1993); more recent and precise estimates could be used, but in the light of the conclusions presented below, the only effect that really matters is the contrast between garnet, to a lesser degree amphibole, and the “normal” minerals of the lherzolitic mantle, such that the additional accuracy would not translate in a better understanding of the petrogenetic processes. In order to obtain at least an approximation of the evolution of the mg# during such interactions, “pseudo” partition coefficients were used for Fe and Mg, an oversimplification with the purpose of simplifying the calculations. Since the mantle and LSA have very similar Fe contents, a D of ≈ 1 was used for Fe; for Mg, based on the fact that studies of mantle melting show that $\left(\frac{Mg}{Fe}\right)_{melt} \approx \alpha \left(\frac{Mg}{Fe}\right)_{mantle}$, with $\alpha = 0.2-0.3$, (Stakes et al., 1984; Winter, 2002), I used a D of 5.

Despite the apparent lack of control on the key parameters a and F , it turns out that the problem can be largely simplified. Indeed, the only relevant parameter controlling the composition of the melts after the interactions is the ratio F/a , i.e. the net gain or loss of melt during the process (Fig. 6). With increasing F/a values (i.e., towards a net melt gain—the interactions result in more addition to the melt than formation of new minerals by reactions between the melt and the peridotite), the resulting melt evolves to higher mg#, but also lower incompatible elements contents (REE, Sr, Y), and lower La/Yb and Sr/Y ratios. In contrast, low F/a (i.e., the interactions result mostly in the formation of new minerals out of the melt, reducing its net volume) concentrate the incompatible elements, increase the La/Yb and Sr/Y ratios, and generate lower mg# melts—although still with values higher than in the non-reacted adakites.

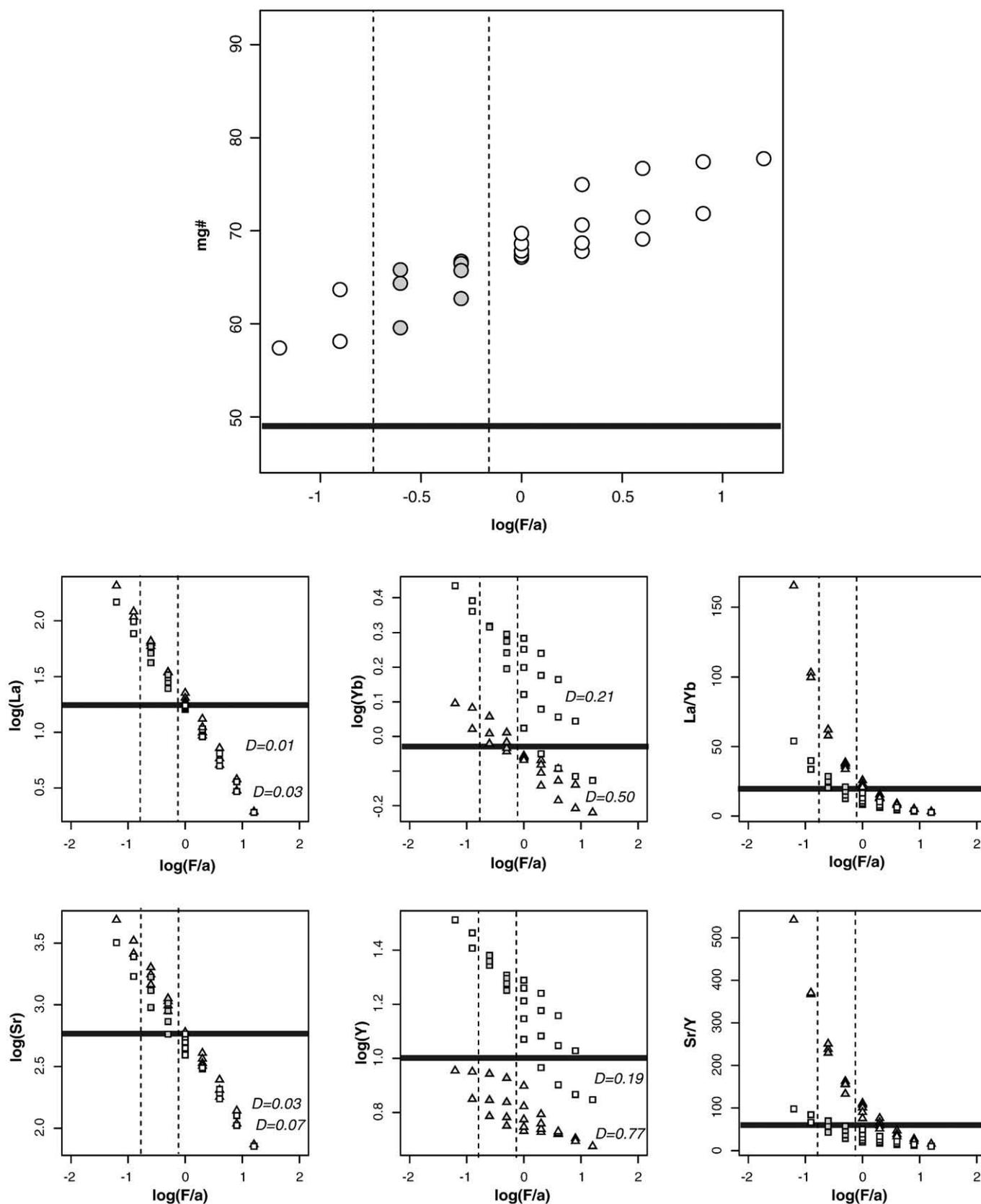


Fig. 6. Effects of the mantle interactions on compatible (mg#) and incompatible elements (La, Yb, Sr, Y) and ratios (La/Yb, Sr/Y). The elements and ratios are plotted against F/a , the ratio between the melt escaping the system and the melt entering it, i.e. an indication of the net gain or loss of melt during the interactions. The scale is logarithmic for F/a , and for the element abundances (La, Yb, Sr, Y), linear otherwise. The thick black line corresponds to the HSA composition used in the model. The dashed line show the F/a value that yields values closer to these observed for LSA. In the bottom diagrams, triangles indicate garnet-present interactions, squares indicate garnet-free melting of the mantle; the corresponding D values are indicated on the diagrams.

Quantitatively, there is a linear relation between the log of the F/a ratio, and the log of the concentration in the melt (Fig. 6). For incompatible elements ($0.01 < D < 1$), empirically the slope of the data array in the F/a vs. C_1 depends mostly on the bulk distribution coefficient D , and is close to $-(1 + 0.5 \log D)$; the lower the D , the better the correlation. For D values < 0.01 , the previous relation does not hold and the slope tends to -1 ; for higher D values, it tends to 0 but the points become more dispersed and D is not anymore the only controlling parameter.

Even though it is very simplified, the model proposed here is nevertheless able to reproduce in some details the geochemical features of the LSA, and to explain how mantle-HSA interactions can generate LSA melts.

5. Discussion

5.1. The need for garnet to achieve high Sr/Y LSA

LSA have very fractionated REE patterns with corresponding very high La/Yb and Sr/Y ratios, even when compared to HSA (Fig. 7); this is largely a factor of high LREE (and Sr) more than low HREE, as the Y and Yb values are comparable for both LSA and HSA (around 10 and 0.9 ppm in both cases). Compared to HSA, LSA have a REE pattern typified by the absence of a concave HREE profile, with the HREE normalized abundance decreasing with increasing atomic number; the HSA on the other hand have concave patterns (with normalized concentrations not decreasing, or even increasing, after Er). This can be summarized by Yb/Lu ratios—around 10 for the LSA, about 5 for HSA.

Since LSA are mostly basalts or basaltic andesites, fractionation played a minor role in their petrogenesis and they are close to primary magmas; their REE and Sr/Y systematic must be explained by source-related processes (HSA-mantle interactions). Generating an LSA pattern from an HSA-type melt, through interactions with the mantle, therefore requires a differential enrichment in incompatible elements, with LREE and Sr being more enriched than HREE and Y. During this process, the models presented above show that all the incompatible elements are concentrated in the melt; however, the degree to which they are concentrated depends on their incompatibility, the most

incompatible elements being more enriched. An LSA signature therefore requires a significant difference in the behavior of LREE and HREE during the mantle-melts interactions.

The modeling done here reveals that garnet is the only mineral able to fractionate strongly the REE pattern. Apart from amphibole, all potential minerals (olivine, pyroxenes, phlogopite) have low K_D (well below 1) for the HREE; worse, the difference between K_D^{HREE} and K_D^{LREE} is not large enough to strongly fractionate the REEs. Amphibole has relatively high K_D 's for HREE (between 1 and 2). However, amphibole does not strongly fractionate the LREE from HREE ($K_D^{\text{Yb}}/K_D^{\text{La}} \approx 8$). Furthermore, amphibole is not able to generate the expected lack of concavity for the HREE, nor the high Yb/Lu ratios ($K_D^{\text{Yb}}/K_D^{\text{Lu}} = 1.1$). Garnet on the other hand has high K_D for HREE (2–7), can strongly fractionate LREE from HREE ($K_D^{\text{Yb}}/K_D^{\text{La}} \approx 250$), does not generate a concave HREE pattern and raises the Yb/Lu ratio ($K_D^{\text{Yb}}/K_D^{\text{Lu}} = 0.6$). Obviously, the details of the discussion above (and the exact values) depend on accurate estimates of K_D . However, the only significant point is the contrast between garnet and the other minerals—a first order feature, regardless of the actual values used.

Quantitatively, two models were calculated (Fig. 7), one with 10% garnet and the other with 10% amphibole; clearly, only the garnet-present situation is able to reproduce adequately the LSA signature.

Experiments on partial melting of adakite-metasomatized mantle (Rapp et al., 2000, 2007) has shown that garnet is stable above 2.5 GPa in metasomatized peridotites; this therefore places a minimum depth on the site of the interactions—they have to be at > 2.5 GPa, 70–80 km or so, and therefore the primary melting (forming the adakitic melt that will subsequently interact with the mantle) must occur below this depth.

5.2. The mg# vs. Sr/Y system—complex meaning of “adakitic” signatures

As discussed in the previous sections, high Sr/Y and La/Yb ratios can be created by a large range of processes, and it is not necessarily straightforward to assess the relative role of each. The diversity of the processes involved can be nicely illustrated (and discussed) using a mg# vs. Sr/Y diagram (obviously, replacing mg# by Cr or Ni for the X axis, and Sr/Y by La/Yb on the Y-axis, would produce fairly similar diagrams) (Fig. 8). Of course, the diagram alone is not sufficient to

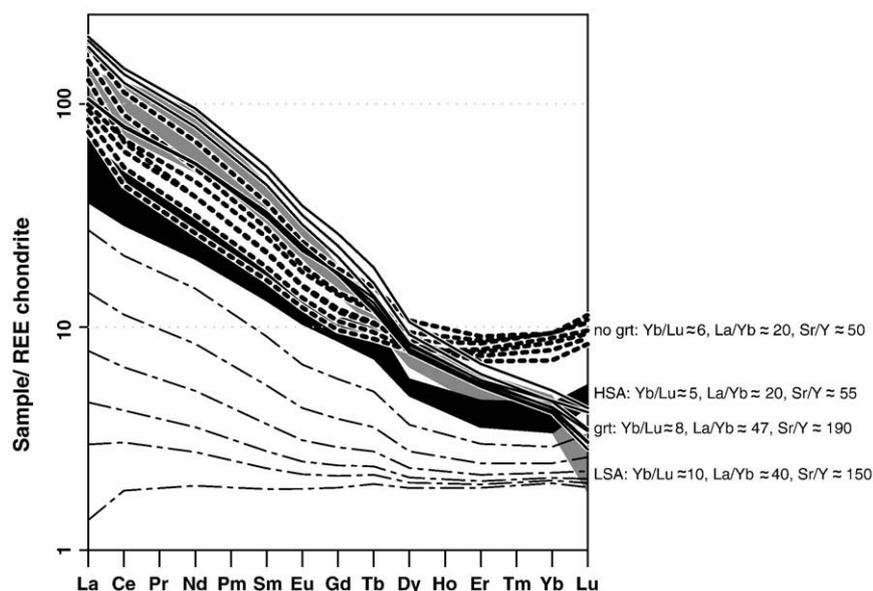


Fig. 7. Chondrite-normalized (Nakamura, 1974) REE diagrams showing the results of the mantle interactions models. Black field: HSA; grey field: LSA; the fields are bounded by the 25th and the 75th percentile of the data. Thin, dash-dot lines at the bottom: compositions of the source, i.e. the metasomatized mantle, for respectively (from the bottom) $a = 0, 1/32, 1/16, 1/8, 1/4, 1/2$. Solid lines: model with 10% garnet; Thick dotted lines: model with no garnet, but 10% amphibole. Only curves with $F/a = 1/2$ and $1/4$ (giving a better fit with the LSA) are plotted, for clarity; they correspond to the vertical “bands” highlighted in Fig. 6. Values on the right-hand side of the diagram correspond to key ratios for adakites and the models.

discuss petrogenesis of different rock types, but it nicely summarizes most observations made in this work.

HSA are adequately modeled by melting of a mafic source ($mg\# = 70$), at depths exceeding 15 or 20 kbar (depending on the Sr/Y ratio of the source—the higher the Sr/Y, the lower the required pressure). 20 kbar is needed if the source is MORB-like with $Sr/Y = 3$, but a richer source with $Sr/Y = 10$ needs only 15 kbar. The LSA are well modeled by the melting of an HSA-metasomatized mantle, with garnet as a residual phase as discussed above. In the diagram Fig. 8, the LSA actually plot between the composition of HSA, and the modeled melts, probably reflecting the fact that more or less “intense” interactions can produce a range of compositions between pure HSA and “pure” hybridized melts.

The “continental” rocks (C-type adakites, etc.) are very scattered in this diagram, reflecting the heterogeneous nature of this “type”. The Yungai ignimbrites (Coldwell et al., 2007; Coldwell, 2008), with their extremely low $mg\#$ (around 10) are best modeled by melting of a low- $mg\#$ source (about 40) at moderate depths (below 15 kbar and even

less if the source already had a high Sr/Y), in agreement with the original interpretation. The “C-type adakites” plot along various trends, either melting of continental (low $mg\#$) source material, or interactions of such melts with the mantle; this is again in agreement with the different models proposed for their origin (e.g. Wang et al., 2004; Guo et al., 2006; Xiao et al., 2007); again, the “continental” or “C-type” adakites can be anything, with a range of possible origins.

Interesting features appear for Archaean magmas. Archaean adakites plot along two trends, one above (Manitouwadge, Dayohessarah and part of Hemlo adakites: Polat and Kerrich, 2000, 2001) and the other below (Ramagiri, Baltic shield, part of Hemlo: Puchel et al., 1999; Naqvi et al., 2006) the HSA “cluster”. The high Sr/Y group plots along the trends generated by deep melting (15–20 kbar) of relatively rich mafic sources ($Sr/Y = 10$), and their composition would be difficult to generate from a source with a lower Sr/Y, suggesting that the source of Archaean adakites was a high Sr/Y basalt. Even with a high Sr/Y source, high pressures are required, higher than for the HSA even (they plot on or above the 20 kbar melting curve),

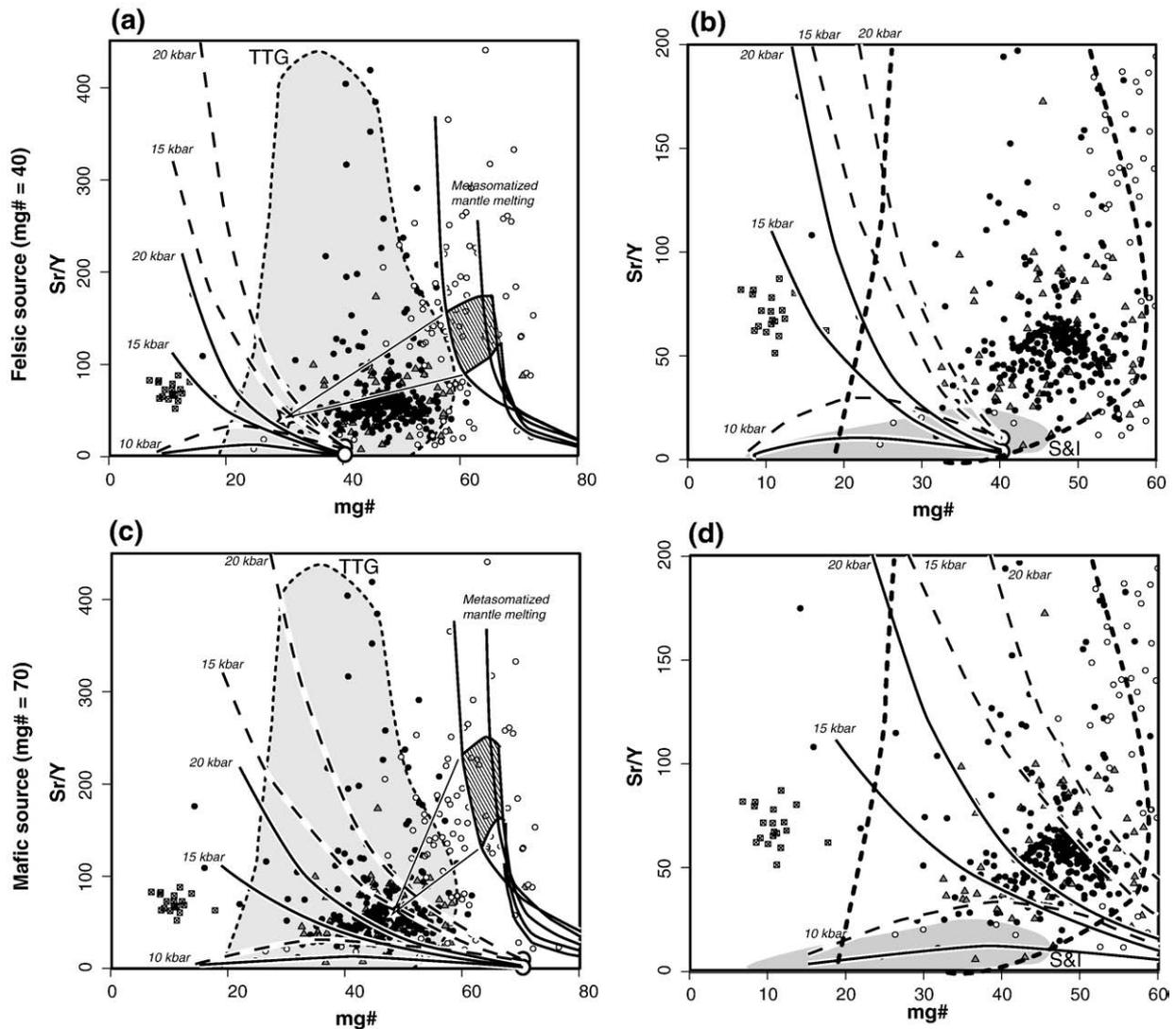


Fig. 8. $mg\#$ vs Sr/Y diagrams, showing models for melting of different sources and for mantle-melt interactions; fractionation curves would have a similar shape. (b) and (d) are zoomed-in versions of (a) and (c) resp. The top two diagrams (a) and (b) investigate the melting (and subsequent interactions with the mantle) of a crustal source, $mg\# = 40$; (c) and (d) investigate melting of a MORB-type source ($mg\# = 70$). Melting curves are calculated by fitting the experimental data for different pressure bands (as presented Fig. 4) by curves giving the enrichment in Sr/Y (and in $mg\#$) as a function of F , and by calculating the resulting evolution for different source compositions. Two sources (white dots) were used for each diagram, a low Sr/Y source ($Sr/Y = 3$), corresponding to the solid curves and a higher Sr/Y (10) source, dashed. Mantle interaction curves are modeled as explained in Figs. 6 and 7 and explanations in the text; the different curves correspond to different a values, the hatched zone indicates F/a ratios of 1/4 to 1/2. The stars indicates the initial liquid composition used for the mantle model, and the thin line graphically depict the effect of more or less intense interactions. Symbols as in Fig. 1.

suggesting a very deep origin for these melts; an indirect confirmation of that is given by their high SiO_2 (they are rhyolites, compared to the dacitic “normal” HSA), that can reflect low melt fractions, as would be expected for high pressure melting (Moyen and Stevens, 2006). In addition, the high Sr/Y Archaean adakites also have relatively elevated Nb/Ta (around 15, as for the HSA; Fig. 9), consistent with a deep, rutile-present melting (Foley et al., 2000, 2002; Schmidt et al., 2004).

The low Sr/Y group, on the other hand, plots along shallower melting trends—10 kbar melting if the source was the same high Sr/Y basalt as previously. They also have lower Nb/Ta (close to 5), suggesting a rutile-free source (Fig. 9). Whereas the high Sr/Y adakites can indeed correspond to slab melting (at 15–20 kbar), the demonstration is far less convincing for the other examples, as the relatively shallow depth required (10 kbar) allows for lower crustal melting as well. More convincing approaches use whole rock packages, with different but consistent rock types associated in a given unit, rather than a unique rock type (Polat and Kerrich, 2006; Smithies et al., 2006).

The composition of Archaean TTGs has been added, for comparison. It spreads most of the diagram. The extreme compositions plot along a low pressure melting trend, in some case of the low Sr/Y source but more commonly of the high Sr/Y basalts. At the other extreme, very high Sr/Y rocks are observed, more or less along the trends of deep melting (>20 kbar) of, again, high Sr/Y sources; once more, they correspond to high SiO_2 plutons (Moyen et al., 2007b). All other intermediate compositions are observed; collectively, these observations suggest that the TTG group is widely heterogeneous, and contains rocks all (or most) formed by partial melting of basalts (probably high Sr/Y), but under a range of P – T conditions (Moyen and Stevens, 2006; Moyen et al., 2007a,b, in press).

Even though the model is fairly crude and certainly not designated to adequately model S-type granites, it can still be observed that they nevertheless plot along the trends generated by low pressure (10 kbar or even less) melting of low mg# sources—although some examples do plot towards higher Sr/Y values, suggesting possible deeper melting in some cases.

5.3. Sr/Y and La/Yb systematics: coupling and decoupling

Sr/Y and La/Yb ratios are largely—but not completely—correlated. In details, the two ratios show systematic differences, with La/Yb

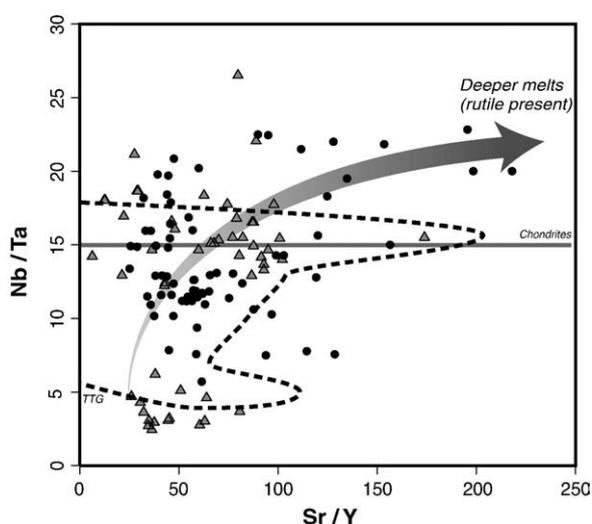


Fig. 9. Sr/Y vs Nb/Ta for modern HSA and Archaean adakites. Modern HSA have chondritic Nb/Ta ratios (thick line); Archaean adakites, together with the TTGs (dashed field), show a bimodal distribution with both low Nb/Ta (typically with relatively low Sr/Y values) and high Nb/Ta (with higher Sr/Y) values. High Nb/Ta probably reflect a rutile-present residuum, and therefore correspond to higher depth of melting (see discussion in text).

ratios showing much smaller “inter-rock type” differences compared to the “within-group” spread. A plot of Sr/Y vs. La/Yb further reveals that, while both the HSA and the LSA plot as short, tightly correlated arrays with a gentle slope, the “crustal” granites (S- and I-types) plot along a more loosely correlated region with a steeper slope. Non-adakitic arc magmas plot on a tight array with La/Yb comparable to adakites, but lower Sr/Y (although there is some limited overlap). Archaean TTGs plot as a very loose cluster more or less encompassing both HSA and LSA (although the TTGs have much higher SiO_2 and lower mg# than the LSA, and their high Sr/Y and La/Yb therefore requires another explanation, as discussed in section 5.2). Comparing different rock types (HSA, LSA and crustal granites) reveals that the two ratios are closely related within each group, especially the HSA and LSA (thereby providing indirect evidence that, despite the supposed mobility of Sr, the Sr/Y ratios have been moderately modified by alteration and are reliable, at least in a population big enough to be statistically valid). On the other hand, Sr/Y and La/Yb are actually decoupled between the three rock types, with “normal” granites having the lower Sr/Y compared to La/Yb, HSA slightly higher and LSA even higher.

Modeling of mineral fractionation vectors and melting trends, as above, shows that decoupling the two ratios is extremely difficult. Olivine, pyroxenes or phlogopite have no potential to decouple the two ratios. Garnet will very efficiently increase both ratios when coexisting with a melt (either as a residual phase during melting, or as a fractionating phase during cooling), and La/Yb will be increased in greater amounts. Amphibole has the opposite effect—it will increase both ratios, Sr/Y slightly more than La/Yb. Plagioclase, in contrast, will reduce both ratios—Sr/Y will decrease more than La/Yb, due to the high Kd of Sr in plagioclase. These three minerals are the only examples in which Sr and La have different behaviours, resulting in potential decoupling of Sr/Y from La/Yb.

The position of HSA above the mantle array in the Sr/Y vs. La/Yb diagram is therefore consistent with a garnet-rich and plagioclase-poor residuum, as any plagioclase would decrease the Sr/Y relative to La/Yb and bring the melt’s composition below the mantle array. Furthermore, it can be concluded from this diagram that garnet had to be present in significant amounts, at least 30% and probably more, during melting. Taken together, the two requirements effectively require melting at high pressures, above the plagioclase-out line.

LSA show both higher Sr/Y and La/Yb, with Sr/Y being shifted towards higher values compared to HSA. Although they do not define as nice an array as the HSA, they nevertheless plot along a positively-sloped region, much steeper than the LSA array. This is consistent with melting (1) of a source with high Sr/Y (compared to La/Yb), or in other words, whose Sr/Y was already “shifted” upwards from the mantle array, which is the case for the HSA; (2) in presence of 5–10% garnet. This is consistent with melting of an adakite-metasomatized mantle, with Sr/Y and La/Yb ratios largely inherited from the adakitic melt—itsself shifted above the mantle array by the first melting.

Again, modeling “normal” granites is beyond the scope of this work. However, it can be observed that the “sub-mantle”, steeper array of S-type and I-type granites is well in agreement with a plagioclase-rich and garnet-poor residuum, that will yield melts with lower Sr/Y and La/Yb ratios compared to the source (a relation reverse to what is observed for both HSA and LSA). Plagioclase can decouple the Sr/Y and La/Yb, this time by “lowering” the Sr/Y relative to La/Yb. Owing to the heterogeneous nature of the continental crust, a large range of source compositions can exist (from basalts, to an Archaean TTG-like component), and garnet-free or garnet-poor melting of these sources can easily generate the range of compositions observed in S- and I-type granites. Of course, garnet-present melting does occur in the crust (see above), and even at relatively low depths. Melting vectors similar to the one discussed for HSA would then occur, still generally keeping the compositions below the basalt array—and,

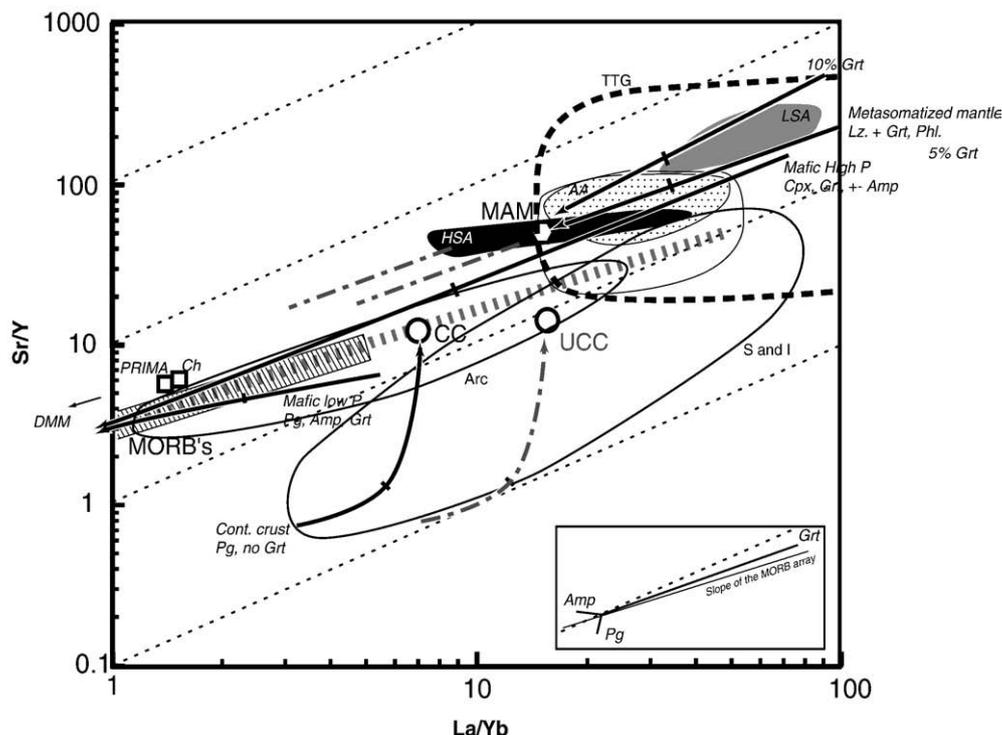


Fig. 10. Sr/Y vs. La/Yb diagram: models of melting and mantle interactions. For clarity, only the fields for the rock type discussed are represented: HSA (black), LSA (grey), Archaean adakites (dots, label AA), TTG (empty field, thick dashed contour) and normal granites ("S and I", fine solid line). The field of MORBs (from the GEOROC database) is hatched; it actually extends much further to the left. MORBs represent the extremity of a "mantle array" (thick, grey dotted line) expanding to higher La/Yb and Sr/Y to the OIB. The squares indicate the composition of the primitive mantle (PRIMA) and the chondrites (Ch); the depleted mantle is out of the diagram, to the left (Sr/Y = 3.5, La/Yb = 0.2). CC and UCC are the compositions of the bulk, and upper continental crust respectively (Taylor and McLennan, 1985). MAM is the mantle-adakite mix used in the mantle interaction models ($\alpha = 1/2$ here). Melting curves: "Mafic low P" = low pressure (10 kbar) melting with a garnet-plagioclase amphibolite residuum; this generates melts below the source array. "Mafic high P" = 20 kbar melting of a similar source, generating HSA-like melts. The two grey, dash-dot curves above it indicate the approximative emplacement of melting curves for a slightly more depleted source (further to the left on the mantle array); as the slope of the melting curve is greater than the slope of the mantle array, they would indeed generate higher Sr/Y (relative to La/Yb), for lower F values of course; which could provide an explanation for the extension of the HSA array, that is not parallel to the melting curve. "Metasomatized mantle": melting of a garnet-lherzolite, with 5 or 10% garnet, and a source corresponding to "MMA". The two curves bracket the field of LSA. "Cont crust": melting of a continental type lithology, with a plagioclase-rich residuum. The dash-dot grey curve on the right is the same, for an UCC source. Inset: vectors showing the relative effects of different minerals.

within the limitations of this diagram, adding more scatter and confusion to the already complex "crustal" domain.

5.4. High Sr/Y, or low Y?

The high Sr/Y (or La/Yb) is regarded as a typical characteristics of adakites; it is, however, a composite indicator, reflecting simultaneously high Sr and low Y (the same holds, of course, for La and Yb). It is therefore worth investigating the relative contribution of each parameter. Using straight concentrations in broad studies like this one is not necessarily easy, because concentrations vary greatly as a function of differentiation; in that case, Sr is compatible during low-pressure, plagioclase present differentiation; in Harker-type diagrams, Y also displays a compatible behavior (decreases when SiO₂ increases). Both can therefore vary significantly during differentiation, and this is why interpretations generally rely on using ratios such as Sr/Y (ratios between two elements with similar behavior, compatible in that case).

Indeed, plotting Sr vs. Y (Fig. 11), together with melting trends modeled as in the previous sections, shows, unsurprisingly, that melting trends are not able to explain the data scatter within one group; the trends observed probably relate to late fractionation. Despite the fact that Sr, a fluid-mobile element, is potentially disturbed by low temperature alteration, the lack of random scattering of Sr concentrations within one rock group suggests that it remains a statistically valid petrogenetic indicator (at least in a database that big, where outliers are easily identified). On the other hand, different rock type occupy different portions of the diagram, and it is clear that the high Sr/Y ratio can result from different situations, either high Sr as in

the case of LSA; or very low Y, as in the case of Archaean adakites (and parts of the TTGs). High Sr in LSA can be modeled by melting of a metasomatized mantle with some garnet in the residuum (as required by the Sr/Y vs. La/Yb models), although garnet cannot be too abundant (as it would otherwise lower the Y contents below the source, contrarily to what is observed). In this case, the most important effect is not so much the Y depletion (Y is actually slightly enriched relative to the hybrid source), but the strong Sr enrichment.

With comparable Sr/Y ratio, the very low Y in Archaean adakites is difficult to explain only with mineral effects, and does require a source that is both Y poor and moderately Sr-rich, effectively a source that already has relatively high Sr/Y's due to low Y contents. A similar conclusion regarding the source composition was attained by Moyen et al. (2007b) for the high Sr (and high Sr/Y) TTGs of the meso-Archaean Barberton granite-greenstone terrain, for which the source had to be Y poor with high Sr/Y, such that I suspect this is a common feature of at least some Archaean basalts, as sometimes suggested (Jahn et al., 1980; Condie, 1981; Jahn, 1994; Hollings and Kerrich, 2006; Moyen et al., 2007b). This would confer the Archaean basalts a more "primitive" composition, closer to the PRIMA.

6. Conclusions

The term "adakite" has been used for a variety of rocks with very diverse geochemical characters—and diverse origins—, the only common point being high Sr/Y (and associated high La/Yb). The problem with such a loose definition is that there are several ways to arrive to high Sr/Y ratios (high Sr/Y source, deep melting, interactions with the mantle), such that using only Sr/Y (and La/Yb) as a criterion

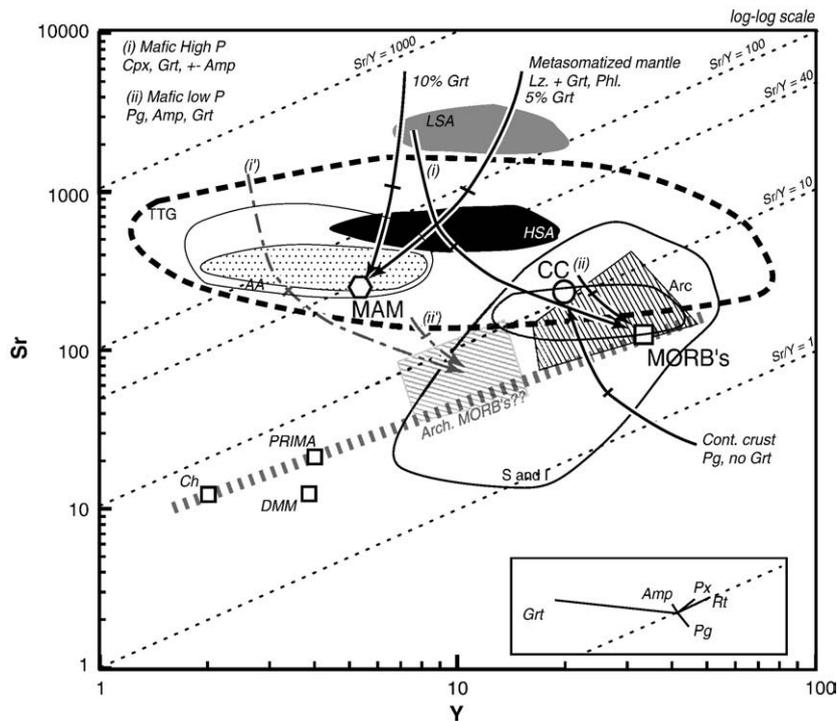


Fig. 11. Sr vs. Y diagram: models of melting and mantle interactions. Same symbols and abbreviations as Fig. 10. The dashed, grey melting curves (i') and (ii') indicate how Archean basalts with lower Y and Sr, and higher Sr/Y (grey, hatched field "Arch. MORB's??") could generate melts similar to the high Sr/Y portion of Archean adakites—whose high Sr/Y is an effect of a low Y more than a high Sr.

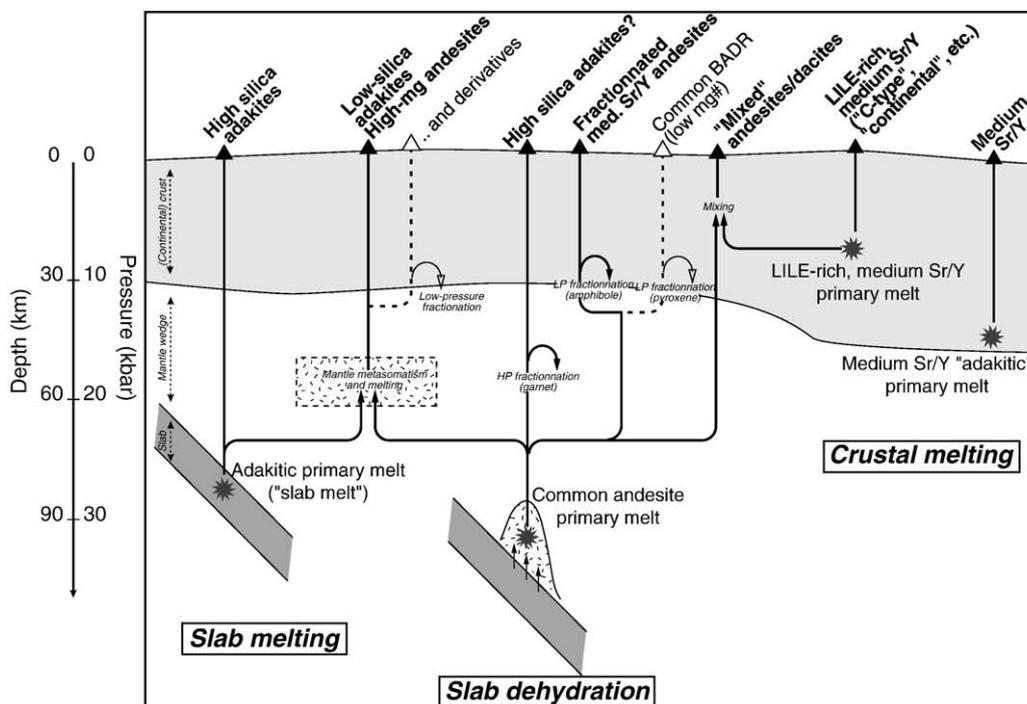


Fig. 12. Multiple pathways to high Sr/Y values. This summary sketch presents the different ways to obtain high Sr/Y, as discussed in this paper, and to form all the diverse rocks sometimes referred to as "adakites" or "adakitic". Slab melting (left) give rise to high-silica adakites, that can either directly erupt, or interact with the mantle to form some member of the low silica adakite/high mg# andesite group. Slab dehydration (middle) forms "common" andesites or andesitic basalts, that can have a range of different fates: interact with crustal melts to form "mixed" dacites; fractionate at shallow depth to evolve "fractionated andesites", either relatively high mg#, high La/Yb and medium Sr/Y if fractionation is controlled by amphibole or ordinary BADR (basalt–andesite–dacite–rhyolites) if fractionation is controlled by pyroxene (Kelemen, 2008); fractionate at high depth (with garnet being an important component) to form rocks that appear to be very similar to high silica adakites (Macpherson et al., 2006; Muntener et al., 2008; Ulmer et al., 2008); or, finally, interact with the mantle in the same way as slab melts, to form again members of the LSA/HMA group. Finally, melting within the crust can relatively easily form felsic, high Sr/Y rocks.

leads to using the same name for rocks with contrasting characteristics and, maybe even more critically, contrasting petrogenesis and geodynamical environments. It is the author's view that the term "adakite" should only be used for one single type of rocks: the "high silica adakites" (Martin et al., 2005), corresponding to the rocks originally described by Defant and Drummond (1990). Ironically, the rocks observed in Adak Island by Kay (1978) do not match this definition, and are not "adakites"—they correspond to what is now called "low-silica adakite", more closely related to "high-mg# andesites"—themselves a composite group.

On the other hand, the extension of the name "adakite" to any individual rock (from basalt, to rhyolite; with mg# from 20 to 70, and K/Na from 0.5 to 2) that has even moderately high Sr/Y (20–40, compared to the threshold of 40 proposed by Defant and Drummond), brings nothing but confusion to the debate, as it can be applied to a very large portion of all the intermediate or acid igneous rocks! I contend that, even with the use of qualifiers ("C-type" adakites, "K-adakites, adakit"-ic" or adakite"-like"), the term should not be used in this case, and replaced by the more precise (albeit more generic) "high-Sr/Y" (or, when appropriate, "medium Sr/Y", as a rock with Sr/Y between 20 and 40 does not have a high Sr/Y ratio).

The so-called "adakitic" signature is a composite one. It can reflect a range of situations and processes (Fig. 12) such as high Sr/Y sources, garnet-present melting or interactions with the mantle (also in the garnet stability field), or even garnet fractionation. However, in many cases the difference between these processes can be made with a careful petrogenetical study, one that is not restricted to pointing to "high Sr/Y". Cleared of the semantic/definition issues that clutter it, the debate on the origin (and geodynamical meaning) of adakites becomes much simpler. The restricted composition range of adakites ("true" adakites, sensu Defant and Drummond, 1990, or HSA) does not allow for a huge diversity of mechanism; a high pressure evolution (15–20 kbar) is required, in which garnet plays a dominant role. Both garnet fractionation, or melting leaving a garnet-rich residuum, are possible options; a wealth of experimental and geochemical data show that melting a meta-basalt at pressures of 15–20 kbar does form adakitic (HSA) melts, with appropriate compositions both for major and trace elements. This, in association with the restricted situation in which adakites are found ("hot" subduction), strongly supports the slab melting model. Much of the studies proposing alternative petrogenetic/geodynamic models for adakites were actually based on rocks that were not adakites—by the definition proposed here, matching these of Drummond and Defant (1990) or Martin (1999) or Martin et al. (2005). The other high (or medium) Sr/Y rocks are, certainly, high pressure melts (i.e., more than 10 kbar), of different sources; this can occur in a range of situations, encompassing underplated mafic rocks (in a continental arc), delaminated crust (in a collision) or lower collisional crust, etc; this does not make them "adakites".

The Archaean TTG series has often been compared to modern adakites, and much controversy surrounded the issue of their similarity—or difference (Martin, 1999; Smithies, 2000; Condie, 2005; Martin et al., 2005). It is increasingly clear, however, that the term "TTG" is a misnomer, in that it artificially groups rocks with different origins—with diversely enriched sources melting at diverse depths (Moyen, 2008). All comparisons involving "the TTGs" as a whole, regarded as a uniform group, are therefore intrinsically flawed (unless TTG is used in a very generic term, exclusively as a way to oppose the Archaean plagioclase-rich granitoids, to the modern granitoids dominated by K-feldspar). In the mg# vs. Sr/Y diagram used here, at least two end-member compositions of "TTG" are evident: a low-mg# and (comparatively) low Sr/Y group of mostly tonalites (SiO₂ ~ 65%), that can be produced by relatively shallow (10 kbar) melting of basaltic precursors, and probably corresponds to intracrustal melting at the base of a thick crust (either an intra-plateau or similar, or a tectonically thickened crust); and very high Sr/

Y group (SiO₂ ~ 70%), that does not have very high mg# as the LSA do, and is therefore not related to mantle-melt interactions, but rather to deep (>20 kbar) melting of a basaltic source (possibly in a slab melting scenario). The second group is relatively rare, therefore suggesting that slab melting did occur in the Archaean, but might not be much more widespread than it is now. In both cases, a relatively high Sr/Y source is required, suggesting that this may be a feature of at least some widespread Archaean basalts. Archaean adakites show the same dual nature (high Sr/Y and low Sr/Y series), and therefore probably reflect the same range of processes: even within a reasonably restrictive definition of "adakite", geochemical differences still have to be interpreted, and can provide valuable constraints on geodynamical scenarios.

Acknowledgments

This work is based on a compilation of analytical data on adakites and related rocks; I'm therefore grateful to all the colleagues who contributed published or unpublished analyses. The bulk of the database comes from Hervé Martin (Martin et al., 2005); contributions by Ali Polat (Polat and Kerrich, 2000, 2001, 2002) and Beverly Coldwell (Coldwell et al., 2007; Coldwell, 2008) are gratefully acknowledged. Jeremy Richards and Robert Kerrich agreed to supply their database of arc magmas, for comparison purposes (Richards and Kerrich, 2007). Diagrams were drafted using V. Janousek's program GCDkit (Janousek et al., 2006), one of the few programs able to gracefully deal with such large geochemical databases.

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