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Editor's Note

P. R. Castillo is a Professor of Geology at Scripps Institution of Oceanography (SIO), University of California at San Diego. He received a BSc from University of the Philippines in 1977, an MSc from University of Akron (USA) in 1983, and a PhD from Washington University (USA) in 1987. He held positions at Carnegie Institution of Washington and University of Miami before he joined SIO in 1990. Pat is a field geologist on land and at sea, a petrologist, and an isotope geochemist. He participated in 15 seafloor mapping and sampling expeditions, including 3 ODP legs. He emphasizes chemical geodynamics in research and uses petrology and geochemistry to understand physical processes associated with subduction zones and ocean ridges. He publishes significant papers in leading journals such as Nature, Science, Geology, Earth and Planetary Science Letters, Journal of Geophysical Research, Journal of Petrology, etc. Soon after the recognition of the now famous "Dupal Anomaly" in 1980's, Pat pointed out with insight that the two maxima of the isotopic "Dupal Anomaly" in the southern hemisphere are in fact closely associated with the two large-scale regions of low seismic velocity in the lower mantle that also correspond to surface loci of active hotspots. He proposed that these hotspots are manifestations of the chemical structure of the mantle and the nature of mantle convection (Nature, 336: 667—670, 1988). Indeed, Pat stands high, thinks big, and is ahead of time, and ahead of many of us. His research on seafloor basalts has revealed many surprises about the scale and amplitude of mantle chemical and isotopic heterogeneities. He studies the geochemistry of present-day mid-ocean ridge basalts (MORB), but he also emphasizes the birth of ocean basins and MORB mantle compositional evolution over the past ~ 200 Ma. His studies of the Jurassic ocean crust in the Nauru Basin and the Cretaceous igneous complexes in this and other basins in the western Pacific have incited further international efforts towards understanding the intra-plate volcanism, including two ODP legs drilling into the Ontong Java Plateau. Pat's contributions to the study of subduction zone magmatism are provocative. His recognition of high-field element (HFSE) enrichments in some arc lavas (Geology, 30: 707 — 710, 2002) opens our mind that slab-dehydration may not be the only trigger for subduction-zone magmatism. Importantly, Pat is among the very first who cautioned us with evidence, insight and strong arguments that the so-called "adakites" are not necessarily derived from partial melting of subducting slabs (Contrib. Mineral. Petrol., 134: 33—51, 1999).

Thanks to the alert by P. J. Wyllie of California Institute of Technology, I studied the "Science Citation Index from Web of Knowledge" (SCI-WoK) that the term "adakite" first appeared in Chinese SCI journals in 2000, about 10 years after the "adakite" proposal by Defant and Drummond [1], but Chinese SCI papers on adakites have flooded rapidly in the past 5 years. As of December 1st, 2005, 53 adakite papers have been published in Chinese SCI journals, which takes ~ 24% of the total published adakite papers recorded in SCI-WoK. Such high productivity reflects the great efforts and achievements by our Chinese scientists, but in the mean time it is also difficult to avoid some misperceptions about adakites, adakitic rocks and their significance. For this reason, and because of the probable/potential significance of adakites and adakitic rocks in the context of continental crust growth and Cu-Au mineralization, it is timely to have an overview on adakite genesis. I am delighted that Pat Castillo, a leading researcher on adakites, accepted the invitation for such an overview. I agree with the referees that Pat's overview is excellent, objective and comprehensive. Slab melting may indeed occur to produce adakites, but adakites or adakitic rocks do not necessarily form through slab melting. Thus, caution is needed before reaching the conclusion that volcanic rocks with adakitic geochemistry must be produced by partial melting of subducting oceanic crusts.

(Yaoling Niu, Executive Editor, Department of Earth Sciences, Durham University, UK)

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An overview of adakite petrogenesis

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Abstract The term adakite was originally proposed to define silica-rich, high Sr/Y and La/Yb volcanic and plutonic rocks derived from melting of the basaltic portion of oceanic crust subducted beneath volcanic arcs. It was also initially believed that adakite only occurs in convergent margins where young and thus still hot oceanic slabs are being subducted, but later studies have proposed that it also occurs in other arc settings where unusual tectonic conditions can lower the solidus of older slabs. Currently, adakite covers a range of arc rocks ranging from pristine slab melt, to adakite-peridotite hybrid melt, to melt derived from peridotite metasomatized by slab melt. Adakite studies have generated some confusions because (1) the definition of adakite combines compositional criteria with a genetic interpretation (melting of subducted basalt), (2) the definition is fairly broad and relies on chemistry as its distinguishing characteristic, (3) the use of high pressure melting experiment results on wet basalts as unequivocal proofs of slab melting and (4) the existence of adakitic rocks with chemical characteristics similar to adakites but are clearly unrelated to slab melting. Other studies have shown that adakitic rocks and a number of the previously reported adakites are produced through melting of the mafic lower crust or ponded basaltic magma, high-pressure crystal fractionation of basaltic magma and low-pressure crystal fractionation of basaltic magma plus magma mixing processes in both arc or non-arc tectonic environments. Despite the confusing interpretations on the petrogenesis of adakite and adakitic rocks, their investigations have enriched our understanding of material recycling at subduction zones, crustal evolutionary processes and economic mineralization.

Keywords: adakite, slab melting, metasomatism, eclogite, amphibolite, Archean TTG, magnesian andesite, high-Nb basalt, subduction zone, arc magmatism.

Adakite is a petrologic term that Defant and Drummond[1] first introduced ~ 15 years ago to refer to "volcanic or intrusive rocks in Cenozoic arcs associated with subduction of young (⩽25 Ma) oceanic lithosphere"; these rocks are "characterized by ⩾56 wt% SiO_2, ⩾15% Al_2O_3 (rarely lower), usually < 3% MgO (rarely above 6% MgO), low Y and HREE relative to ADRs (for example, Y and Yb ⩽ 18 and 1.9 ppm, respectively), high Sr relative to island arc ADR (rarely < 400 ppm), low high-field strength elements (HFSEs), as in most island arc ADRs, and $^{87}Sr/^{87}Sr$ usually < 0.7040)", Partial melting of subducted basalt, which would have been metamorphosed at the zone of arc magma generation to eclogite or amphibolite, gives adakite such a distinct set of compositional characteristics (Table 1). The identification of adakite represents a significant progress in the study of arc magmatism because it has enhanced our understanding on the fate of the oceanic slab after it has been subducted into the mantle, and hence the issue of crustal recycling at convergent margins. Moreover, it suggests a formation mechanism for the Archaean trondhjemite-tonalite-granodiorite (TTG) rock association that makes up a large portion of the continental crust and thus provides an indication to crustal evolutionary processes[2−7]. Finally, the occurrence of adakite is of great economic importance because it has been genetically linked to the majority of known Cu-Au mineralization worldwide[8−12]. Consequently, adakite has spawned a plethora of investigations. However, the current literature on adakite becomes confusing because the definition of adakite has evolved considerably and more problematically, many igneous rocks with chemical characteristics similar to those of adakite but unconnected to slab melting (henceforth called adakitic rocks) casts serious doubts to the petrogenetic significance of the term.

The main objective of this brief overview is to trace the history of the term adakite, discuss the use or abuse of the term and present some of the fundamental reasons for the current diverging views on the subject. For the purposes of this overview, the discussion is limited to Phanerozoic adakite and adakitic rocks. Note that space consideration prohibits critical evaluations of compting model for the petrogenesis of adakite and adakite rock and may have resulted in oversimplification of ideas as well as prohibit exhaustive discussion and acknowledgement of all the related work—for these the author sincerely apologizes. The connection

Table 1 Main geochemical features of adakite

Characteristics	Possible links to subducted slab melting[1,7,27,56]
high SiO_2 (⩾56 wt%)	high-P melting of eclogite/garnet amphibolite
high Al_2O_3 (⩾15 wt%)	at ~ 70 wt% SiO_2; high P partial melting of eclogite or amphibolite
low MgO (< 3 wt%)	and low Ni and Cr; if primary melt, not derived from a mantle peridotite
high Sr (> 300 ppm)	melting of plagioclase or absence of plagioclase in the residue
no Eu anomaly	either minor plagioclase residue or source basalt depleted in Eu
low Y (< 15 ppm)	indicative of garnet (to a lesser extent, of hornblende or clinopyroxene) as a residual or liquidus phase
high Sr/Y (> 20)	higher than that produced by normal crystal fractionation; indicative of garnet and amphibole as a residual phase or liquidus phase
low Yb (< 1.9 ppm)	meaning low HREE; indicative of garnet as a residual or liquidus phase
high La/Yb (> 20)	LREE enriched relative to HREE; indicative of garnet as a residual or liquidus phase
low HFSE's (Nb, Ta)	as in most arc lavas; Ti-phase or hornblende in the source
low $^{87}Sr/^{86}Sr$(< 0.704)	plus low $^{206}Pb/^{204}Pb$, K/La, Rb/La, Ba/La and high $^{143}Nd/^{144}Nd$; normal-MORB signature

or lack thereof between slab melting and TTG formation also abound in the literature and readers are referred to Rollinson and Martin[6] for recent discussions on this topic.

1 Background

The concept that some of the crustal materials subducted into the mantle at convergent margins get melted and recycled back into the crust is not new. Armstrong[13] proposed that continental sediments being subducted at the margins of continents are the source of arc volcanics and intrusives right after the birth of the plate tectonics paradigm has been entrenched firmly as a theory. That the subducted oceanic crust itself gets melted was extensively discussed in the early 1970's[14] and deemed acceptable as a primary cause of arc magma generation in the early 1980's[15]. For example, Marsh and co-workers[16,17] specifically proposed that slab melting produces high-Al basalts, which may represent primary arc magmas. The notion of wholesale melting of the subducted slab, however, was basically superceded by results of many petrologic investigations that indicate that slab dehydration can reasonably explain the main geochemical characteristics of arc lavas[18−21]. A new concept was conceived from these results, and this concept reduces the contribution of the subducted slab to arc magma generation to a less grandiose scale of a generic "subduction component" that metasomatizes as well as lowers the melting temperature of the mantle wedge peridotite, the main source of arc magmas. The subduction component provides the majority of convergent magmas their hallmark signature, notably their general enrichment in the abundances of volatiles and fluid-mobile incompatible trace elements such as large ion lithophile elements (LILE; e.g. Rb, K, Ba, Sr), but strong depletion in high field strength elements (HFSEs; e.g. Nb, Ta, Zr, Ti, Hf), which make it unique from magmas emplaced in other tectonic settings[19−23]. Moreover, the new concept implies that the majority of primary convergent margin magmas generated through partial melting of such metasomatized mantle wedge undergo fractional crystallization and magma mixing processes and invariably assimilate crustal materials to produce the spectrum of arc lavas. Consequently, the majority of petrologic studies on arc magmatism focus on the subduction component——its source (whether the basaltic portion of the crust, the overlying sediments or both), relative contribution to the mantle wedge (%) and transfer mechanism from the slab to the mantle (whether in the form of hydrous fluids squeezed from the slab, or hydrous melt formed by partial melting of the slab or both).

A generally accepted outcome of many arc petrologic studies is that the subduction component comes mainly from dehydration of the basaltic portion of the subducting slab and from a modest extent (< 10%) of melting of the overlying sediment[24−26]. Back in the late 1970's, the uncommon trace element characteristics of some magnesian andesites (56－59 wt% SiO_2) from Adak Island in the western section of the Aleutian arc volcanic chain, however, led Kay [27] to believe that these lavas must have had a petrogenetic history different from that of typical convergent margin lavas. The andesites are relatively primitive, having relatively high MgO (5 wt%) and Ni (150 ppm) contents and have distinctively low FeO*/MgO ratios (<1.2), yet much higher Sr contents and higher Sr/Y and La/Yb ratios than typical convergent margin lavas. Kay [27] proposed that these andesites must have been small amounts of hydrous melts generated through partial melting of the basaltic portion of the subducted Pacific plate that equilibrated with mantle peridotite. The relatively low Sr and Pb, but high Nd isotopic compositions of these lavas lend support to the slab-derived origin of the melt that equilibrated with peridotite. Such a notion of slab melting had been proposed earlier to account for lavas with similarly uncommon compositional signature in e.g., the Cascades[28], southern Andes[29] and Baja California[30]. Defant and Drummond [1] used the term adakite for slab derived melt in reference to the work done by Kay[27] on magnesian andesites from Adak Island in the Aleutians.

2 Adakite from slab melting

Published reports on adakite can be grouped simply into those perpetuating its slab melting origin[3,31−36] and those asserting that slab melting is not the only way to generate the composition of adakitic rocks[37−42]. The production of adakite magma through melting of subducted basaltic crust is anchored on strong experimental and observational grounds. Experimental work on water- saturated or dehydration melting of amphibolites has produced adakite melt[43−49]. Adakitic glass inclusions in arc lavas, mineralogy of xenoliths within subduction related lavas[36,50] and migmatitic veins with intermediate to felsic compositions in ophiolites[51−54] have also been observed. Finally, ion probe analyses of clinopyroxene phenocrysts in primitive Aleutian magnesian andesites show atypical correlation between $Mg^{\#}$ and Sr and Nd/Yb, suggesting a slab melt that equilibrated with mantle olivine is necessary to generate the archetypal adakite[55].

Defant and Drummond[1] originally suggested that adakite only occurs in modern convergent margins where young (< 25 Ma) and thus still hot oceanic crusts are being subducted, consistent with results of combined partial melting models for subducted basaltic crust and two-dimensional thermal models of subduction zones[56]. Follow-up studies endorsed the presence of adakites or the involvement of slab-derived melts in many of these localities (Table 2) although alternative petrogenetic models of the rocks in a number of these localities have previously been proposed. For example, the "Setouchi" magnesian andesites in southwest Japan are primary melts generated in the upper mantle[57,58]; the "bajaites" in Baja California are generated in the mantle that has been thermally relaxed and P_{H_2O} lowered due to breakdown of amphibole[59]; the dacites in Mt. St. Helens are produced by melting of the lower crust[60]. Follow-up studies also added other adakite localities where moderately old (>25 Ma) oceanic crusts are being subducted during subduction initiation[33], subduction collision[34,61], tearing of the slab leading to the opening of an asthenospheric window[62,63], and shallowing of subduction angle[64−66]. For example, adakite is formed from melting of relatively old oceanic crust during arc initiation and arc collision in the tectonically complex southern Philippines[33,34,61] and in the flat subduction zones in the northern Andes[64−66]. A few modifications to the criteria for identifying adakite were also introduced. For example, the La/Yb ratio (and hence the degree of light REE enrichment), one of the two key trace element ratios for distinguishing adakite from normal arc andesites-dacites-rhyolites (ADRs), has been relaxed to slightly lower values in order to accommodate the characteristics of adakites produced in some of these localities[33,34,67].

Table 2 Partial list of arc localities where adakites have been identified

Locations	References
Aleutians	[27, 68, 96]
Austral Chile	[35, 97−104]
Baja California, Mexico	[30, 72, 63]
Cascade	[1, 28, 105]
Ecuador	[66, 106, 107]
Southwest Japan	[58, 108]
Kamchatka	[36, 109−111]
Los Chocoyos, Guatemala	[1]
Northern Andes	[64, 66]
Northern Philippines	[1, 50]
Panama and Costa Rica	[1, 31, 32]
Papua New Guinea	[1]
Skagway Batholith, Alaska	[1]
Southern Philippines	[33, 34, 61, 112]
Woodlark Basin	[1]
Mian-Lueyang, C. China	[67]
Jungar, N.W. China	[88]
Gangdese, S. Tibet	[89]

A more significant shift in the definition of adakite is about the proportion of pristine adakite[1] relative to adakite generated with direct or indirect participation of mantle peridotite. Similar to Kay[27], Yogodzinski *et al.*[68] emphasized that although some of the magnesian andesites in western Aleutians, the location for archetypal adakite, indeed have the high Sr content and La/Yb ratio signature of slab melt, they are also fairly primitive, having moderate MgO and relatively high Ni and Cr contents. These are believed to be generated by the equilibration of slab melt with mantle peridotite[27,55,68]. Other adakite studies have recognized similar fairly primitive characteristics. Moreover, a recent study proposed that there is a primitive magnesian andesite or "low silica" variety of adakite, which is a product of melting of mantle peridotite that has been previously metasomatized by primary slab melt[69,70]. This low silica adakite is chemically different from the "high silica" variety, which consists of both the pristine slab melt and slab melt that has equilibrated with mantle peridotite, in that e.g., it has lower light REE, Sr and Rb concentrations and lower Sr/Y for given Y content than the latter (Fig. 1). Thus it is important to note that whichever classification is used, there is growing evidence that mantle peridotite is either directly or indirectly involved in the generation of the majority of adakites.

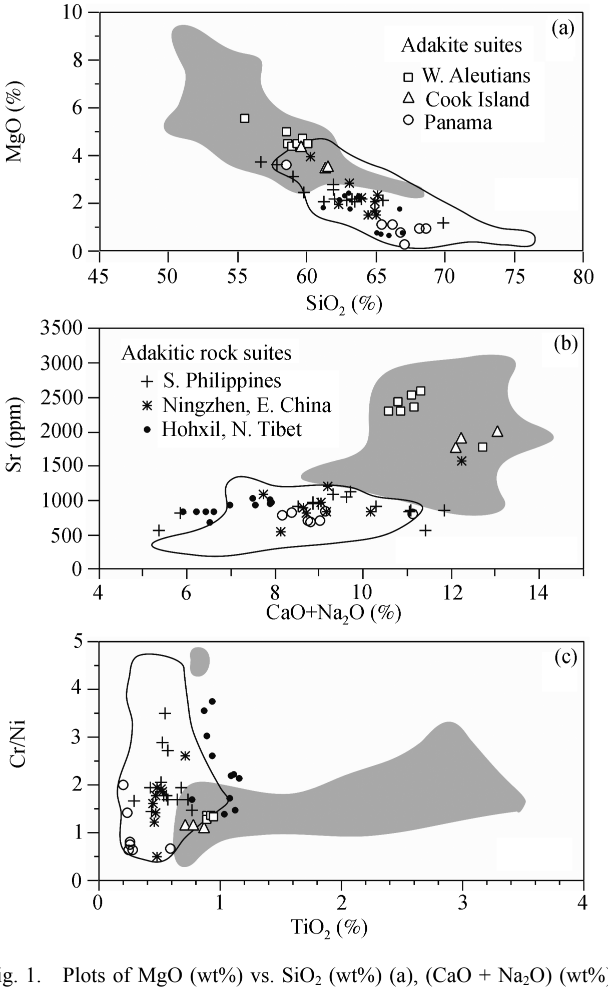

Fig. 1. Plots of MgO (wt%) vs. SiO_2 (wt%) (a), (CaO + Na_2O) (wt%) vs. Sr (ppm) (b) and TiO_2 (wt%) vs. Cr/Ni (c) showing some of the chemical differences between low silica adakite (gray field) and high silica adakite (white field) varieties (modified after ref. [70]). Representative adakite[27,32,55,103] and adakitic rock[42,67,84] suites are also shown.

The low silica adakite variety is not to be confused with the alkalic, HFSE-enriched, high-Nb basalt (HNB) that was also proposed to be produced by a similar concept of metasomatism of the mantle with slab melt[10,32,34,71]. Adakite is usually associated with HNB and such association has been used as circumstantial evidence of slab melting. Basically, it is proposed that adakite derived from melting of subducted basaltic crust stabilizes in the mantle wedge amphibole, which later breaks down and releases HFSE into the mantle wedge peridotite. Such a metasomatized peridotite later becomes the source of HNB[10,32,34,72]. However, this model is controversial because combined major-trace element and Sr-Nd isotope data for some of the primitive, high-K calc-alkalic HNB show that the source of HFSE is a geochemically enriched component in the mantle wedge[73,74].

3 Adakitic rocks produced by other petrogenetic processes

As mentioned earlier, there are many adakitic rocks with chemical characteristics that are identical to those of adakite (Table 1). One possible origin of these rocks is through partial melting of thickened lower crust[38−40,75−80]. Adakitic rocks also belong to either pristine crustal melt group or crustal melt that has equilibrated or interacted with mantle peridotite group (Fig. 1). That is, in addition to the low MgO variety, there are some lower crust derived adakitic rocks that have high MgO, low FeO/MgO for given MgO (or high $Mg^{\#}$) and high compatible trace elements (e.g., Ni, Cr) indicative of mantle peridotite signature. The latter group is proposed to be generated by the interaction between peridotite and melts derived from lower crustal materials that have been delaminated into the mantle[41,81−84]. Interestingly, many of the recently reported adakitic rocks are in China[41,67,77−80,83−87] in addition to the few proposed adakites[67,86,88,89] there.

Similar to adakite generation from subducted oceanic crust, the generation of adakitic rocks from mafic lower crust is consistent with the results of basalt melting at high pressure where garnet is a stable and residual phase. However, an effective and hence commonly used argument for a lower crust origin and at the same time argues against an oceanic slab origin for the adakitic rocks in China is based on their radiogenic isotopic signature, particularly their Sr and Nd isotopic ratios

(Fig. 2), which reflect the composition of their source or sources. Their isotopic ratios are very similar if not identical to those of the continental crust and are different from those of adakites. Adakite derives its abundant Sr and Nd elemental contents from the subducted oceanic basalt and is thus expected to have oceanic crust-like isotopic signature, as shown by some of the reported adakites elsewhere (Fig. 2). Another important argument against a subducted slab origin for the majority of adakitic rocks in China is based on tectonic and other geophysical evidence for possible absence of subducted slab protoliths or outright non-arc environments during the generation of these adakitic rocks[41,80,83−85].

Another possible source of adakitic rocks is through differentiation of parental basaltic magma. Slab derived adakites in the tectonically complex southern Philippines, mentioned earlier as one of the adakite type localities (Table 2), outcrop in several areas[33,34,61]. Detailed investigations show that the purported adakites in one of these areas (Camiguin Island) are mainly andesite and dacite lava flows interbedded with basalt, basaltic andesite and occasional rhyolite flows in a fairly small cluster of young (<2 Ma) volcanoes[33,34,37,61]. Note that this invalidates one of the criteria for designating adakite as a slab derived melt-that it is rarely associated with basalt or basaltic andesite. As mentioned earlier, adakite is purported to be only associated with HNB or basalts belonging to the alkalic rock series and hence extremely enriched in large-ion lithophile elements[1,10,32]. Whereas the andesites and dacites in southern Philippines may be designated as slab derived rocks based primarily on their chemical characteristics, as is the norm for identifying adakite in the field (Fig. 3 and see discussion below), the intrinsic spatial and temporal association of the different flows and overall chemical and isotopic integrity of the Camiguin Island lava series strongly suggest they belong to a single, genetically related basalt to rhyolite arc lava series[37]. Modeling results show that these andesites and dacites can be related to the more primitive Camiguin basalts derived from the metasomatized mantle wedge through combined crystal fractionation of primarily hornblende and clinopyroxene (± apatite) and mixing of differentiated magmas with primitive magmas periodically refluxed into the magma chamber.

Macpherson *et al.*[42] studied another area (Surigao Peninsula) in the southern Philippines adakite locality and also concluded that the adakitic rocks previously reported there by Sajona et al.[33,34,61] could not have been derived by slab melting. The liquid line of descent of these adakitic rocks mimics the high-pres- sure crystal fractionation trend of primitive arc magmas under uppermost mantle conditions[90]. Combined with tectonic arguments, Macpherson *et al.*[42] thus concluded that the Surigao adakitic rocks are most probably products of high pressure crystal fractionation of the original arc basalts derived from the metasomatized mantle

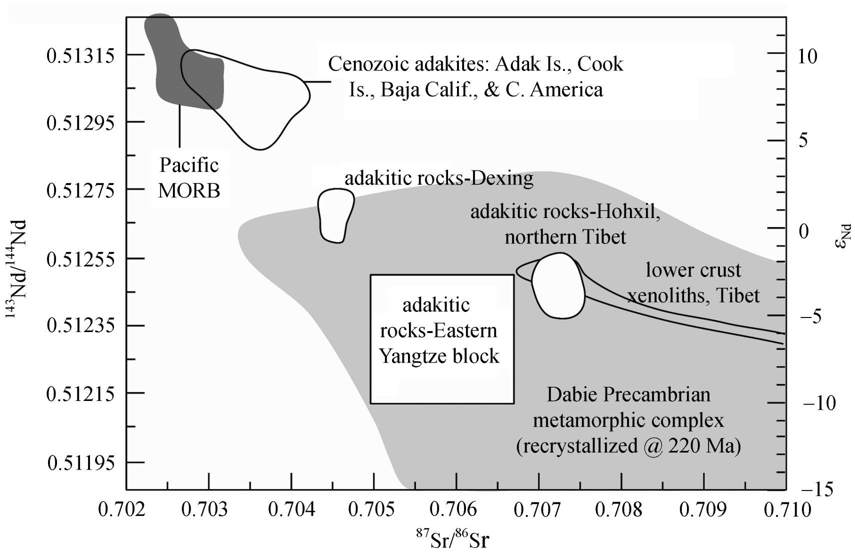

Fig. 2. $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ ratios for some of the reported adakitic rocks in China[41,80,84]. Fields for Cenozoic adakites[27,32,72,100,103] and Dabie metamorphic complex[113] are shown for reference. Note the more heterogeneous and distinctively higher $^{87}Sr/^{86}Sr$ but lower $^{143}Nd/^{144}Nd$ ratios of the adakitic rocks compared to those of the adakites.

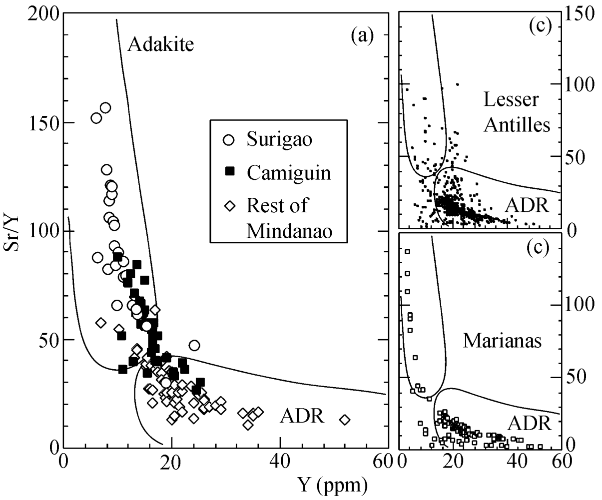

Fig. 3. Sr/Y vs. Y diagram commonly used to show "distinct" adakite and arc andesite, dacite and rhyolite (ADR) compositional fields. Although many normal arc lavas plot within the ADR field and adakites plot within the adakite field, there are a few arc rocks series that define continuous trends running through both fields, e.g., A. southern Philippines arc lavas[37], B. Lesser Antilles arc lavas[114] and C. Marianas arc lavas[114].

wedge that were ponded in the lower crust. It is also possible that these adakitic rocks could have been derived through partial melting of the ponded basalts at high pressure[42].

Similar to the adakitic rocks in China, the non-slab origin of adakitic rocks from both Camiguin and Surigao areas in southern Philippines is supported by detailed field observations and analysis of geochemical and Sr-Nd-Pb isotope data[37,42]. Additionally, results of a recent Os isotopic investigation of Cu-Au mineralization associated with the reported adakites in different areas in Mindanao, including those from Surigao, also argue against the slab melting model[91]. Almost all the samples analyzed have $^{187}Os/^{188}Os$ ratios that are similar to those of young mid-ocean ridge basalts and "normal" arc rocks, suggesting that the ultimate origin of siderophile metals associated with adakitic rocks is the mantle, not the crust. This is in direct conflict with the proposal that slab derived adakites are the source of siderophile element enrichment not only in southern Philippines but also globally[8−12]. Consequently, the validity of slab melting origin of some of the reported adakites in southern Philippines and perhaps elsewhere on the globe (Table 2) is dubious[37,42,91−93].

4 Discussion and comments

Defant and Drummond's[1] original intention of defining a rock type produced specifically through slab melting has generated a wide spectrum of interesting but confusing results. On the one end, the presence of adakites irrespective of age and rock association becomes a routine tool for some investigators because not only it provides a priori petrogenetic history for these rocks but also an avenue to propose novel geodynamic models to heat the slab in regions where they occur. On the other end, the presence of igneous rocks having identical compositional characteristics of adakite and even some of the previously reported adakites in e.g., southern Philippines and northern Andes stimulates other investigators to expose the inadequacies of the slab melting mechanism for the generation of all igneous rocks with adakite chemical characteristics (Table 1) and to present alternative petrogenetic models for these rocks. In any case, the current diverging interpretations on the origin of adakites and adakitic rocks are to be welcomed because they lead to more discoveries than the slab melting model alone. However, these diverging interpretations also pose the obvious question——what is the rightful petrogenesis of adakites or adakitic rocks? To this, the author is in the opinion that majority of the chemical characteristics presented in Table 1 is not unique to slab melts and thus it is possible that adakites and adakitic rocks can be generated at different tectonic settings. Moreover, it appears that the common link among igneous rocks with high Sr/Y and La/Yb ratios is the involvement of garnet and/or amphibole in their generation either during partial melting or magmatic differentiation. However, the research topic is still relatively young and more data and observations are still being generated. Thus, instead of answering the question directly, this overview focuses on presenting the fundamental reasons as to why the confusion has arisen in order to put the various interpretations into proper perspectives.

Under proper physicochemical conditions, there is no denying that subducted basalt can melt. The fact that there are adakite-like glass inclusions in arc peridotites, adakite-like veins in obducted oceanic slab and xenolith and mineralogical evidence for slab melt equilibration with mantle peridotite makes a very strong case for slab melting to occur naturally. Thus adakite is most probably being generated in at least some subduction zones.

One source of confusion is that despite its proposed, highly-specific slab melt origin, adakite covers a broad range of rock types. As mentioned earlier, adakite does not refer to a single rock type, but to a series of arc volcanic and plutonic rocks ranging from silica-rich and MgO-poor, pristine slab melt[1] to MgO-richer magnesian andesite produced by the equilibration of slab melt with mantle peridotite[27,68] and then lately, to magnesian andesite produced by melting of the peridotite mantle metasomatized by slab melt[69,70].

Another source of confusion is the mineralogical and lithological characteristics of adakite. In common with the majority of arc rocks, adakite is petrographically highly variable and generally contains plagioclase as a ubiquitous phase. Thus, adakite is identified almost exclusively by its chemistry, primarily using its high Sr/Y and La/Yb ratios and low Y and Yb contents. Hence the two almost universally used diagnostic tools to define adakite are the Sr/Y ratio vs. Y concentration and La/Yb ratio vs. La concentration diagrams. These are usually employed, particularly the Sr/Y vs. Y diagram (Fig. 3), to depict distinct fields for low Sr/Y and La/Yb - high Y and Yb normal ADR's and high Sr/Y and La/Yb and low Y and Yb adakites. Although the majority of arc rocks indeed plot in the ADR field, there are a number of arc lavas that define a continuum from ADR to adakite field. For example, in addition to those from Camiguin and Surigao in southern Philippines, there are other arc lavas belonging to the same rock series that range continuously from low Sr/Y ADR field to high Sr/Y adakite field.

The broad chemical and lithologic spectra of adakite can be traced back to the quantity of pristine slab melt that can physically make its way to volcanic arcs without at least being contaminated by the peridotite mantle. Experimental results show that silica-rich melt coming from the slab would quickly freeze in the peridotite mantle[94]. Rapp *et al.*[69] showed a similar scenario, although only when the "effective" adakite melt: peridotite ratio is <1∶1. Thus pristine slab melt most likely comprises a small proportion of adakite, and later adakite studies seem to be coming into such a consensus [95]. In other words, the majority of adakites is produced through equilibration with or direct melting of mantle peridotite. This apparent preponderance of peridotite- influenced variety of adakite leads to another question on the difference between a mantle-derived adakite and a parental arc magma derived from melting of mantle peridotite metasomatized by a subduction component consisting mainly of slab-derived melt. It is important to note that to begin with, it is widely accepted that adakite is volumetrically minor compared to typical arc magma derived from the metasomatized mantle wedge[1,27,30], even in localities where adakites occur (Table 2). This is due to the notion that adakite is exclusively generated in subduction zones where unusual tectonic phenomena, such as subduction of young oceanic crust, initiation of subduction, subduction collision, slab tearing, and shallowing of subduction angle occur.

Many adakite studies have also explicitly used the results of high pressure melting experiments on wet basalts (metamorphosed to garnet bearing lithologies, e.g., garnet amphibolite or eclogite) as proofs of slab melting. Together with high Sr/Y and La/Yb ratios, these experimental results may have given some investigators a false sense of confidence for a slab melting origin of these rocks. However, although the results indeed show that the product of such melting experiments is adakitic in composition, such a geochemical characteristic does not affirm a particular tectonic setting[92]. Thus, as noted earlier, without additional critical supporting data including radiogenic isotopes and detailed field and geophysical evidence, the adakitic rocks in many areas in China and even a number of those that were designated as adakites in e.g., southern Philippines and northern Andes[92] could have been easily considered as products of slab melting.

Finally, although the slab melting mechanism cannot produce the adakitic rocks and even some of those that have been designated as adakites, there is no single alternative model for their production. Nevertheless, these alternative models cannot be ignored because they are specifically designed to challenge the slab melting mechanism, and hence are usually based on more detailed field observations including tectonic considerations, integrated chemical and isotopic analyses and rigorous geochemical modeling. Moreover, relative to adakite, adakitic rocks come from a larger array of possible sources. Although adakitic rocks produced by crystal fractionation and magma mixing mechanism can possibly occur only in amphibole bearing lavas in periodically replenished magma chambers, those generated by melting of the lower crust potentially can occur in a variety of tectonic settings (e.g., subduction zones, continental collision zones, extensional environment); those produced by high pressure crystal fractionation of ponded mafic magmas possibly can occur in many more tectonic environments. This variety of tectonic settings is in marked contrast to the slab melting origin of adakite, which is theoretically restricted to current and paleo-subduction zones. In short, the possible volume of adakite produced by slab melting is lesser compared to the adakitic rocks produced by other processes, and this implies that without the proposed steeper geothermal gradient in the Archean, slab melting is not the most effective mechanism to produce a large volume of TTG[2,70].

5 Summary

Adakite is a relatively new petrologic term that was originally designed to refer to a group of silicic arc igneous rocks primarily produced by direct melting of the basaltic portion of subducted/subducting oceanic crust. It is characterized mainly by a distinct set of chemistry, particularly its high Sr/Y and La/Yb ratios and low Y and Yb contents. It was also originally proposed to be mainly a direct product of melting of subducted young oceanic crust. Results of high-pressure melting experiments on wet basalts as well as some field and mineralogical data lend strong support to the possibility of slab melting. Experimental results, however, also suggest that pristine slab melt most likely will not survive during transit through the peridotitic mantle wedge and hence, majority of adakites in modern arcs most likely consists of hybrid magmas or magmas produced by melting of the mantle wedge metasomatized by slab melt. In any case, slab melting most probably occurs in subduction zones and hence is an important source of the generic subduction component at the very least.

Some confusion about adakite petrogenesis arises because the definition of adakite has evolved quite considerably to include a number of arc rock types that traditionally have been considered to be largely coming from the mantle. Moreover, the chemical characteristics of slab melt, currently the only criterion for distinguishing adakite, are shared with many other arc or non-arc rock types that involve garnet and/or amphibole as residual phases during their generation. Detailed studies show that these adakitic rocks and even previously identified slab melts in at least a few adakite localities could not have been generated by slab melting. Instead, these were produced by low pressure fractional crystallization of amphibole-bearing basalts inside periodically replenished magma chambers, high pressure fractional crystallization or melting of metamorphosed basalts ponded in the lower crust and melting of the lower mafic crust. These alternative models are also consistent with the results of laboratory experiments and are constrained by more detailed field observations, trace element modeling and are supported by radiogenic isotope data. Moreover, because some of these adakitic rocks are not necessarily restricted to subduction zone environments, these are potentially more volumetrically important than adakite. Thus, igneous rocks with high Sr/Y and La/Yb ratios and low Y and Yb contents cannot be used as definitive indicators for slab melting. Caution is necessary.

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References

1. Defant, M. J., Drummond, M.S., Derivation of some modern arc magmas by melting of young subducted lithosphere, Nature, 1990, 347: 662—665.
2. Drummond, M. S., Defant, M. J., A model for trondhjemite- tonalite-dacite genesis and crustal growth via slab melting: Archaean to modern comparisons, J. Geophys. Res., 1990, 95: 21503—21521.
3. Martin, H., Adakitic magmas: modern analogues of Archaean granitoids, Lithos, 1999, 46: 411—429.
4. Smithies, R. H., The Archean tonalite-trondhjemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite, Earth Planet. Sci. Lett., 2000, 182: 115—125.
5. Kamber, B. S., Ewart, A., Collerson, K. D., Bruce, M. C. *et al.*, Fluid-mobile trace element constraints on the role of slab melting and implications for Archean crustal growth models, Cont. Mineral. Petrol., 2002, 144: 38—56.
6. Condie, K. C., TTGs and adakites: are they both slab melts? Lithos, 2005, 80: 33—44.
7. Rollinson, H., Martin, H., Geodynamic controls on adakite, TTG and sanukitoid genesis: implications for models of crust formation, Introduction to the Special Issue, Lithos, 2005, 79: ix—xii.
8. Thiéblemont, D., Stein, G., Lescuyer, J. L., Epithermal and porphyry deposits: The adakite connection, Comptes Rendus de l'Académie des Sciences, Paris, 1997, 325: 103—109.
9. Sajona, F. G., Maury, R. C., Association of adakites with gold and copper mineralization in the Philippines, Comptes Rendus de l'Académie des Sciences, Paris, 1998, 326: 27—34.
10. Defant, M. J., Kepezhinskas, P., Evidence suggests slab melting in arc magmas, EOS, 2001, 82: 62—70.
11. Oyarzún, R., Márquez, A., Lillo, J. *et al.*, Giant vs small porphyry copper deposits of Cenozoic age in northern Chile: Adakitic vs normal calc-alkaline magmatism, Mineral, Deposita, 2001, 36: 794—798.
12. Mungall, J. E., Roasting the mantle: Slab melting and the genesis of major Au and Au-rich Cu deposits, Geology, 2002, 30: 915—918.
13. Armstrong, R. L., A model for the evolution of strontium and lead isotopes in a Dynamic Earth, Rev. Geophys., 1968, 6: 175—199.
14. Nicholls, A., Ringwood, A. E., Effect of water on olivince stability in tholeiites and the production of silica-saturate magmas in the island arc environment, J. Geol., 1973, 81: 285—300.

15. Sekine, T., Wyllie, P. J., Phase relationships in the system $KAlSiO_4$-SiO_2-H_2O as a model for hybridization between hydrous siliceous melts and peridotite, Contrib. Mineral. Petrol., 1982, 79: 368－374.
16. Marsh, B. D., Some Aleutian andesites: their nature and source, J. Geol, 1976, 84: 27－45.
17. Brophy, J.G., Marsh, B. D., On the origin of high-alumina arc basalt and the mechanics of melt extraction, J. Petrol., 1986, 27: 763－789.
18. Davidson, J. P., Deciphering mantle and crustal signatures in subduction zone magmatism, in, Subduction: Top to Bottom (eds. Bebout, G. E. *et al*.), Am. Geophys. U. Geophys. Mono., 1996, 96: 251－262.
19. Tatsumi, Y., Hamilton, D. L., Nesbitt, R. W., Chemical characteristics of fluid phase from the subducted lithosphere: evidence from high-pressure experiments and natural rocks, J. Volcanol. Geotherm. Res., 1986, 29: 293－309.
20. Gill, J. B., Orogenic Andesites and Plate Tectonics, Berlin, Springer-Verlag, 1981, 358.
21. Hawkesworth, C. J., Gallagher, K., Hergt, J. M. *et al.*, Mantle and slab contributions in arc magmas, Ann. Rev. Earth Planet. Sci., 1993, 21: 175－204.
22. Perfit, M. R., Gust, D. A., Bence, A. E. *et al*., Chemical characteristics of island arc basalts: implications for mantle sources, Chem. Geol., 1980, 30: 227－256.
23. Woodhead, J., Eggins, S., Gamble, J., High field strength and transition element systematics in island and back-arc basin basalts: evidence for multi-phase extraction and a depleted mantle wedge, Earth Planet. Sci. Lett., 1993, 114: 491－504.
24. Othman, D. B., White, W. M., Patchett, J., Geochemistry of marine sediments, island arc magma genesis and crust-mantle recycling, Earth Planet. Sci. Lett., 1989, 94: 1－21.
25. Elliot, T., Plank, T., Zindler, A. *et al.*, Element transport from slab to volcanic front at the Mariana arc, J. Geophys. Res., 1997, 102: 14991－15019.
26. Plank, T., Langmuir, C., The chemical composition of subducting sediment and its consequences fro the crust and mantle, Chem. Geol., 1998, 145: 325－394.
27. Kay, R. W., Aleutian magnesian andesites : melts from subducted Pacific Ocean crust, J. Volcanol. Geotherm. Res., 1978, 4: 117－132.
28. Condie, K.C., Swenson, D. H., Compositional variations in three Cascade stratovolcanoes: Jefferson, Rainier and Shasta, Bull. Volcanol., 1973, 37: 205－320.
29. Lopez-Escobar, L., Petrology and chemistry of volcanic rocks of the Southern Andes, in Andean Magmatism, Chemical and Isotopic Constraints (eds. Harmon R. S., Barreiro, B. A.), Shiva Geology Series, 1984, 47－71.
30. Saunders, A. D., Rogers, G., Marriner, G. F. *et al*., Geochemistry of Cenozoic volcanic rocks, Baja California, Mexico: Implications for the petrogenesis of post-subduction magmas, J. Vol. Geotherm. Res., 1987, 32: 223-245.
31. Defant, M. J., Richerson, M., De Boer, J. Z. *et al*., Dacite genesis via both slab melting and differentiation: petrogenesis of La Yeguada volcanic complex, Panama. J. Petrol., 1991, 32: 1101－1142.
32. Defant, M. J., Jackson, T. E., Drummond, M. S. *et al*., The geochemistry of young volcanism throughout western Panama and southeastern Costa Rica: an overview, J. Geol. Soc., 1992, 149: 569－579.
33. Sajona, F. G., Maury, R. C., Bellon, H. *et al*., Initiation of subduction and the generation of slab melts in western and eastern Mindanao, Philippines, Geology, 1993, 21: 1007－1010.
34. Sajona, F. G., Bellon, H., Maury, R. C. *et al*., Magmatic response to abrupt changes in geodynamic settings: Pliocene-Quaternary calc-alkaline lavas and Nb enriched basalts of Leyte and Mindanao (Philippines), Tectonophys., 1994, 237: 47－72.
35. Drummond, M. S., Defant, M. J., Kepezhinskas, P. K., The petrogenesis of slab derived trondhjemite–tonalite–dacite adakite magmas, Trans. R. Soc. Edinburgh: Earth Sci., 1996, 87: 205－216.
36. Kepezhinskas, P. K., Defant, M. J., Drummond, M. S., Na-metasomatism in the island arc mantle by slab melt-peridotite interaction: evidence from mantle xenoliths in the north Kamchatka arc, J. Petrol., 1995, 36: 1505－1527.
37. Castillo, P. R., Janney, P. E., Solidum, R., Petrology and geochemistry of Camiguin Island, southern Philippines: insights into the source of adakite and other lavas in a complex arc tectonic setting, Contrib. Mineral. Petrol., 1999, 134: 33－51.
38. Atherton, M. P., Petford, N., Generation of sodium-rich magmas from newly underplated basaltic crust, Nature, 1993, 362: 144－146.
39. Arculus, R. J., Lapierrre, H., Jaillard, E., Geochemical window into subduction and accretion processes: Raspas metamorphic complex, Ecuador, Geology, 1999, 27: 547－550.
40. Yumul, G. P. Jr., Dimalanta, C. B., Faustino, D. V. *et al*., Silicic arc volcanism and lower crust melting: an example from the central Luzon, Philippines, J. Geol., 1999, 154: 13－14.
41. Xu, J., Shinjio, R., Defant, M. J. *et al*., Origin of Mesozoic adakitic intrusive rocks in the Ningzhen area of east China: Partial melting of delaminated lower continental crust? Geology, 2002, 12: 1111－1114.
42. Macpherson, C. G., Dreher, S. T., Thirwall, M. F., Adakites without slab melting: high pressure processing of basaltic island arc magma, Mindanao, the Philippines, Earth Planet. Sci. Lett., in press.
43. Beard, J. S., Lofgren, G. E., Effect of water on the composition of partial melts of greenstones and amphibolites, Science, 1989, 144: 195－197.
44. Beard, J. S., Lofgren, G. E., Dehydration melting and water-saturated melting of basaltic and andesitic greenstones and amphibolites at 1, 3 and 6.9 kb., J. Petrol., 1991, 32: 465－501.
45. Rapp, R. P., Watson, E. B., Miller, C. F., Partial melting of amphibolite, eclogite and the origin of Archaean trondhjemites and tonalites, Precambrian Res., 1991, 51: 1－25.
46. Rushmer, T., Partial melting of two amphibolites: contrasting experimental results under fluid-absent conditions, Contrib. Mineral. Petrol., 1991, 107: 41－59.
47. Winther, T. K., Newton, R.C., Experimental melting of anhydrous low-K tholeiite: evidence on the origin of Archaean cratons, Bull. Geol. Soc. Den., 1991, 39.
48. Wolf, M. B., Wyllie, P. J., Dehydration-melting of solid amphibolite at 10 kbar: textural development, liquid interconnectivity and applications to the segregation of magmas, Contrib. Mineral. Petrol., 1991, 44: 151－179.
49. Sen, C., Dunn, T., Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: implications for the origin of ada-

kites, Contrib. Mineral. Petrol., 1994, 117: 394—409.
50. Schiano, P., Clochiatti, R., Shimizu, N. *et al*., Hydrous, silica-rich melts in the sub-arc mantle and their relationships with erupted arc lavas, Nature, 1995, 377: 595—600.
51. Sorensen, S. S., Petrology of amphibolite–facies mafic and ultramafic rocks from Catalina schist, southern California: metamorphism and migmatisation in a subduction zone metamorphic setting, J. Met. Geol., 1988, 6: 405—435.
52. Sorensen, S. S., Barton, M. D., Metasomatism and partial melting in a subduction complex: Catalina schist, southern California, Geology, 1987, 15: 115—118.
53. Sorensen, S. S., Grossman, J. N., Enrichment in trace elements in garnet amphibolites from a paleo-subduction zone: Catalina schist, southern California, Geochim. Cosmochim. Acta, 1989, 53: 3155—3177.
54. Bebout, G. E., Barton, M. D., Metasomatism during subduction: products and possible paths in the Catalina schist, California, Chem. Geol., 1993, 108: 61—92.
55. Yogodzinski, G. M., Kelemen, P. B., Slab melting in the Aleutians: Implication of an ion probe study of clinopyroxene in primitive adakite and basalt, Earth Planet. Sci. Lett., 1998, 158: 53—65.
56. Peacock, S. M., Rushmer, T., Thompson, A. B., Partial melting of subducting oceanic crust, Earth Planet. Sci. Lett., 1994, 121: 227—244.
57. Tatsumi, Y., Ishizaka, K., Origin of high-magnesian andesites in the Setouchi volcanic belt, southwest Japan, I. Petrographical and chemical characteristics, Earth Planet. Sci. Lett., 1982, 60: 293—304.
58. Tatsumi, Y., Geochemical modeling of partial melting of subducting sediments and subsequent melt– mantle interaction: generation of high-Mg andesites in the Setouchi volcanic belt, Southern Japan, Geology, 2001, 29: 323—326.
59. Rogers, G., Saunders, A., Magnesian andesites from Mexico, Chile and the Aleutian Islands: implications for magmatism associated with ridge-trench collision, in Boninites (ed. Crawford, A.J.), Unwin Hyman, London, 1989, 416—445.
60. Smith, D. R., Leeman, W. P., Petrogenesis of Mount St. Helens dacitic magmas, J. Geophys. Res., 1987, 92: 10313—10334.
61. Sajona, F. G., Maury, R. C., Pubellier, M. *et al*., Magmatic source enrichment by slab-derived melts in a young post-collision setting, central Mindanao (Philippines), Lithos, 2000, 54: 173—206.
62. Yogodzinski, G. M., Lees, J. M., Churikova, T. G. *et al*., Geochemical evidence for the melting of subducting oceanic lithosphere at plates edges, Nature, 2001, 409: 500—504.
63. Calmus, T., Aguillon-Robles, A., Maury, R.C. *et al*., Spatial and temporal evolution of basalts and magnesian andesites (bajaites) from Baja California, Mexico: the role of slab melts, Lithos, 2003, 66: 77—105.
64. Gutscher, M. -A., Maury, F., Eissen, J.-P. *et al*., Can slab melting be caused by flat subduction? Geology, 2000, 28: 535—538.
65. Beate, B., Monzier, M., Spikings, R. *et al*., Mio-Pliocene adakite generation related to flat subduction in southern Ecuador: the Quimsacocha volcanic center, Earth Planet. Sci. Lett., 2001, 192: 561—570.
66. Bourdon, E., Eissen, J. -P., Monzier, M. *et al*., Adakite-like lavas from Antisana volcano (Ecuador): Evidence from slab melt metasomatism beneath the Andean Northern volcanic zone, J. Petrol., 2002, 43: 99—217.
67. Xu , J., Wang, Q., Yu, X.Y., Geochemistry of high-magnesian andesites and adakitic andesite from the Sanchazi block of the Mian-Lue ophiolitic melange in the Qinling Mountains, central China: Evidence of partial melting of the subducted Plaeo-Tethyan crust, Geochem. J., 2000, 34: 359—377.
68. Yogodzinski, G. M., Kay, R. W., Volynets, O. N. *et al*., Magnesian andesite in the western Aleutian Komandorsky region: implications for slab melting and processes in the mantle wedge, Geol. Soc. Am. Bull. 1995, 107: 505—519.
69. Rapp, R. P., Shimizu, N., Norman, M. D. *et al*., Reaction between slab-derived melts and peridotite in the mantle wedge: Experimental constraints at 3.8 GPa, Chem. Geol., 1999, 160: 335—356.
70. Martin, H., Smithies, R. H., Rapp, R. *et al*., An overview of adakite, tonalite-trondhjemite-granodiorite (TTG), and sanukitoid: Relationships and some implications for crustal evolution, Lithos, 2005, 79: 1—24.
71. Wang, Q., Zhao, Z., Bai, Z. *et al*., Carboniferous adakites and Nb-enriched arc basaltic rocks association in the Alataw Mountains, north Xinjiang: Interactions between slab melt and mantle peridotite and implications for crustal growth, Chinese Sci. Bull., 2003, 48: 2108—2115.
72. Aguillón-Robles, A., Caimus, T., Bellon, H. *et al*., Late Miocene adakite and Nb-enriched basalts from Vizcaino Peninsula, Mexico: Indicators of East Pacific Rise subduction below southern Baja California, Geology, 2001, 29: 531—534.
73. Wallace, P. J., Carmichael, I. S. E., Quaternary volcanism near the Valley of Mexico: implications for subduction zone magmatism and the effects of crustal thickness variations on primitive magma compositions, Contrib. Mineral. Petrol., 1999, 135: 291—314.
74. Castillo, P. R., Solidum, R.U., Punongbayan, R. S., Origin of high field strength element enrichment in the Sulu Arc, southern Philippines, revisited, Geology, 2002, 30: 707—710.
75. Rudnick, R. L., Making continental continental crust, Nature, 1995, 378: 571—578.
76. Petford, N., Atherton, M., Na-rich partial melts from newly underplated basaltic crust: the Cordillera Blanca Batholith, Peru, J. Petrol., 1996, 37: 1491—1521.
77. Xiong, X. L., Li, X. H., Xu, J. F. *et al*., Extremely high-Na adakite-like magmas derived from alkali-rich basaltic underplate: The Late Cretaceous Zhantang andesites in the Huichang Basin, SE China, Geochem. J., 2001, 37: 233—252.
78. Chung, S. L., Liu, D.Y., Ji, J. Q. *et al*., Adakites from continental collision zones: Melting of thickened lower crust beneath southern Tibet, Geology, 2003, 31: 1021—1024.
79. Hou, Z. Q., Gao, Y. F., Qu, X. M. *et al*., Origin of adakitic intrusives generated during mid-Miocene east-west extension in southern Tibet, Earth Planet. Sci. Lett., 2004, 220: 139—155.
80. Wang, Q., McDermott, F., Xu, J. F. *et al*., Cenozoic K-rich adakitic volcanic rocks in the Hohxil area, northern Tibet: Lower-crustal melting in an intracontinental setting, Geology, 2005, 33: 465—468.
81. Kay, R. W., Kay, S. M. Delamination and delamination magmatism, Tectonophys., 1993, 219: 177—189.
82. Kay, R. W., Kay, S. M., Andean adakites: Three ways to make them, Acta Petrologica Sinica, 2002, 18: 303—311.
83. Gao, S., Rudnick, R. L., Yuan, H. L. *et al*., Recycling lower conti-

nental crust in the North China craton, Nature, 2004, 432: 892—897.
84. Wang, Q., Xu, J. F., Zhao, Z. H. *et al*., Cretaceous high-potassium intrusive rocks in the Yueshan-Hongzhen area of east China: Adakites in an extensional tectonic regime within a continent, Geochem. J., 2004, 38: 417—434.
85. Zhang, Q., Qian, Q., Wang, E. *et al*., An east China plateau in mid-Late Yanshanian period: Implications for adakites, Chinese J. Geol. (in Chinese with English abstract), 2001, 36: 248—255.
86. Zhang, Q., Wang, Y., Qian, Q. *et al*., The characteristics and tectonic-metallogenic significance of the adakites in Yanshan period from eastern China, Acta Petrol. Sinica (in Chinese with English abstract), 2001, 17: 236—244.
87. Defant, M. J., Xu, J. F., Kepezhinskas, P. *et al*., Adakites: Some variations on a theme, Acta Petrol. Sinica, 2002, 18: 129—142.
88. Xu, J., Mei, H., Yu, X. *et al*., Adakites related to subduction in the northern margin of Jungar arc for the Late Paleozoic: Products of slab melting, Chinese Sci. Bull., 2001, 46: 1312—1316.
89. Qu, X. -M., Hou, Z. -Q., Li, Y. -G., Melt components derived from a subducted slab in late orogenic ore-bearing porphyries in the Gangdese copper belt, southern Tibetan plateau, Lithos, 2004, 74: 131—148.
90. Müntener, O., Kelemen, P. B., Grove, T. L., The role of H_2O during crystallization of primitive arc magmas under uppermost mantle conditions and genesis of igneous pyroxenites: an experimental study, Contrib. Mineral. Petrol., 2001, 141: 643—658.
91. Dreher, S. T., Macpherson, C. G., Pearson, D. G. *et al*., Re-Os isotope studies of Mindanao adakites: Implications for sources of metals and melts, Geology, 2005, 33: 957—960.
92. Garrison, J. M., Davidson, J. P., Dubious case for slab melting in the northern volcanic zone of the Andes, Geology, 2003, 31: 565—568.
93. Solidum, R. U., Castillo, P. R., Hawkins, J. W., Geochemistry of lavas from Negros Arc, west central Philippines: insights into the contribution from the subducting slab, Geochem. Geophys. Geos., 2003, 4: 1—26.
94. Yaxley, G. M., Green, D. H., Reactions between eclogite and peridotite; mantle refertilisation by subduction of oceanic crust, Bull. Suisse Mineral. Petrogr., 1998, 78: 243—255.
95. Prouteau, G., Scaillet, B., Pichavant, M. *et al*., Evidence for mantle metasomatism by hydrous silicic melts derived from subducted oceanic crust, Nature, 2001, 410: 197—200.
96. Myers, J. D., Frost, C. D., A petrologic investigation of the Adak volcanic center, central Aleutian arc, Alaska, J. Volcanol. Geotherm. Res., 1994, 60: 109—146.
97. Lopez-Escobar, L., Frey, F. A., Vergara, M., Andesites and high-alumina basalts from Central South Chile high Andes: geochemical evidences bearing to their petrogenesis, Contrib. Mineral. Petrol., 1977, 63: 199—228.
98. Martin, H., Archaean and modern granitoids as indicators of changes in geodynamic processes, Rev. Bras. Geocienc., 1987, 17: 360—365.
99. Futa, K., Stern, C. R., Sr and Nd isotopic and trace element compositions of quaternary volcanic centres of the southern Andes, Earth Planet. Sci. Lett., 1988, 88: 253—262.
100. Kay, S. M., Ramos, V.A., Marquez, M., Evidence in Cerro Pampa volcanic rocks of slab melting prior to ridge trench collision in southern South America, J. Geol., 1993, 101: 703—714.
101. Bourgois, J., Lagabrielle, Y., Le Moigne, J. *et al*., Preliminary results on a field study of the Taitao ophiolite Southern Chile : implications for the evolution of the Chile Triple Junction, Ophioliti, 1994, 18: 113—129
102. Guivel, C., Lagabrielle, Y., Bourgois, J. *et al*., Cotten, J., Magmatic reponses to active spreading ridge subduction: multiple magma sources in the Taitao Peninsula region 468—478 S, Chile triple junction, Third International Symposium on Andean geodynamics ISAG 96 Saint-Malo, France, ORSTOM editeur, 1996, 575–578.
103. Stern, C. R., Kilian, R., Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Austral Volcanic Zone, Contrib. Mineral. Petrol., 1996, 123: 263—281.
104. Sigmarsson, O., Martin, H., Knowles, J., Melting of a subducting oceanic crust in Austral Andean lavas from U-series disequilibria, Nature, 1998, 394: 566—569.
105. Defant, M. J., Drummond, M. S., Mount St. Helens: potential example of the partial melting of the subducted lithosphere in a volcanic arc, Geology, 1993, 21: 541—550.
106. Monzier, M., Robin, C., Samaniego, P. *et al*., Arnaud, N., Sangay volcano, Ecuador: Structural development, present activity and petrology, J. Volc. Geotherm. Res., 1999, 90: 49—79.
107. Samaniego, P., Martin, H., Robin, C. *et al*., Transition from calc–alkalic to adakitic magmatism at Cayambe volcano, Ecuador: insights into slab melts and mantle wedge interactions, Geology, 2002, 30: 967—970.
108. Morris, P.A., Slab melting as an explanation of Quaternary volcanism and aseismcity in Southwest Japan, Geology, 1995, 23: 395-398.
109. Kepezhinskas, P. K., Origin of the hornblende andesites of northern Kamchatka, Int. Geol. Rev., 1989, 31: 246–252.
110. Honthaas, C., Bellon, H., Kepezhinskas, P. K. *et al*., Nouvelles datations $^{40}Kr/^{40}Ar$ du magmatisme cretace quaternaire du Kamchatka du Nord Russie, C. R. Acad. Sci. Paris, 1990, 320: 197—204.
111. Kepezhinskas, P. K., Defant, M. J., Drummond, M. S., Progressive enhancement of island arc mantle by melt-peridotite interaction inferred from Kamchatka adakites, Geochim. Cosmochim. Acta, 1996, 60: 1217—1229.
112. Maury, R. C., Sajona, F. G., Pubellier, M. *et al*., Fusion de la croute oceanique dans les zones de subduction r collision recentes: l’exemple de Mindanao, Philippines, Bull. Soc. Geol. France, 1996, 167: 579—595.
113. Ma, C., Li, Z., Ehlers, C. *et al*., A post-collisional magmatic plumbing system: Mesozoic granitiod plutons from the Dabie high-pressure and ultrahigh-pressure metamorphic zone, east-central China, Lithos., 1998, 45: 431—457.
114. GEOROC electronic database, Max Planck Institut fur Chemie, Mainz, Germany, http://georoc.mpch-mainz.gwdg.de/georoc/Entry.html.

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