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Adakites without slab melting: High pressure differentiation of island arc magma, Mindanao, the Philippines

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Abstract

New geochemical data for Pleistocene magmatic rocks from the Surigao peninsula, eastern Mindanao, the Philippines, demonstrate typical adakitic traits, including elevation of Sr/Y and depletion of the heavy rare earth elements. $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios of the adakites do not support melting of the subducted Philippine Sea Plate but resemble Pliocene arc lavas generated in the same subduction zone. Excepting the heavy rare earth elements, the adakites and arc lavas also possess similar ratios of incompatible elements suggesting that the adakites were ultimately derived from melting of the mantle wedge. The wide range of SiO_2 in the adakites and its strong correlation with trace element concentrations and ratios indicate two possible mechanisms for generating the adakitic signature. (1) Adakitic melt was produced from basaltic arc magma by fractional crystallisation of a garnet-bearing assemblage. (2) Solidified basaltic rock containing garnet melted to yield adakitic magma. In either case the basaltic precursor was generated from fluid-modified mantle then differentiated within the garnet stability field. In Surigao this requires differentiation within mantle. The Surigao example suggests that any subduction zone has the potential to produce adakitic magma if basalt crystallises at sufficient depth. This has important implications for the geodynamics of modern and ancient subduction zones that have generated similar rocks.

Keywords: subduction; magmatism; differentiation; adakite; slab

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1. Introduction

Thermal models predict that hydrated basalt in subducted ocean crust is too cold to melt when it lies beneath the volcanic arc of most modern subduction zones [1,2]. While some models incorporate melting of subducted crust [3], the geochemistry of arc lavas indicates (i) that devolatilisation is the main mechanism transferring material out of the slab, and (ii) that the overlying mantle wedge is, volumetrically, the major source of arc lavas [4–7]. Partial melting of subducted crust should leave a garnet-bearing residue [8,9], producing magmas with intermediate SiO_2, elevated Al_2O_3, Sr/Y and La/Y, and low Y. Rocks of this type, which have become known as adakites, have been generated in active subduction zones where young ocean crust is subducted (<25 Ma). This

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observation has been interpreted as evidence that young ocean crust is more prone to melting than older crust because it retains a greater proportion of its initial heat [10].

Constraining the origin of modern adakites is important for several reasons. First, the presence of adakitic rocks implies an unusual thermal regime compared to most modern subduction zones. Second, many major and trace element characteristics of adakites resemble tonalite–trondhjemite–granodiorite gneisses, which are important components in Archean terranes. Therefore, modern adakitic magmatism may provide an analogue for continental growth processes in the early Earth [11–14]. Finally, several suites of adakitic rocks are associated with porphyry and epithermal style Cu-, Au-mineralization [15–17]. While the metallogenic significance of this link is contested [18–20] the association offers to shed light on the thermal and dynamic state of subduction zones that host such deposits.

Since their first description as products of melting young slab [10], increasing numbers of adakitic suites have been recognized that were emplaced where the subducted crust was old, and thus inferred to be cold. This observation has two possible implications for the slab-melting hypothesis. The first possibility is that certain exceptional subduction zone geometries permit melting of subducted basaltic rocks which are greater than 25 million yr of age. Several such mechanisms have been advanced including melting the leading edges of newly subducted slabs [21], shear heating of slab interiors that are exposed along fracture zones [22], or prolonged slab residence in the shallow mantle as a result of decreasing angle of subduction [23]. Each of these "cool slab" models appeals to a unique thermal structure and slab melting mechanism for the subduction zone in question.

The alternative implication is that melting of subducted crust does not generate all, or even any, adakitic magma. For example, arc crust that is sufficiently thick for garnet to be stable in basaltic rock is proposed as a source for adakitic magmatism in the Andes, western US and Tibet [24–28]. However, this mechanism is not feasible where arc crust is less than ~30 km thick; the minimum depth of garnet amphibolite or eclogite *P*–*T* conditions. For arcs with thin crust this has led to the default interpretation that subducted crust is the only part of the subduction zone where basaltic rocks can attain a suitable mineralogy to act as adakite sources.

The Surigao peninsula in Mindanao, the Philippines, hosts adakitic rocks generated during subduction of the Philippine Sea Plate at the Philippine Trench (Fig. 1). This plate margin initiated at ~7 Ma, to the east of Luzon, since when it has propagated southwards. Subduction of the Philippine Sea Plate beneath Mindanao began in the late Miocene or early Pliocene [29]. The Philippine Sea Plate crust that was subducted beneath Mindanao at that time was more than 50 million yr old [30] and so was too cold to melt under normal subduction zone conditions [1].

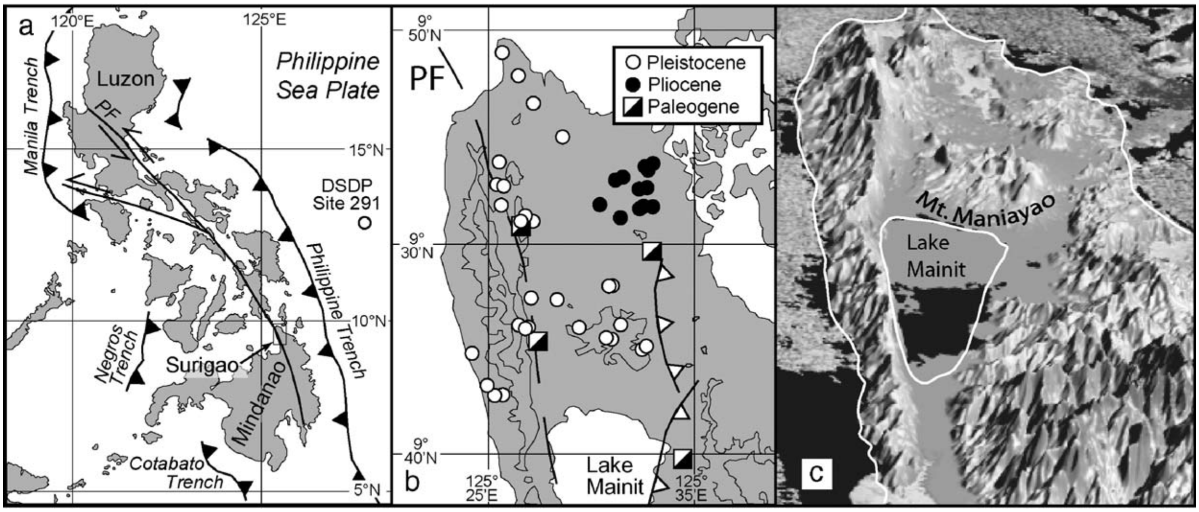

Fig. 1. (a) Philippine archipelago showing location of the Surigao peninsula on Mindanao. Plate boundaries after Hall [58]. PF is the Philippine Fault. (b) Sampling locations of Pleistocene, late Miocene to Pliocene and Paleogene volcanic rocks. Dashed line is the Philippine Fault (PF) and solid, barbed lines are Miocene reverse faults that have been reactivated in the opposite sense. The low-lying region between these faults and the PF is an extensional or transtensional basin [32]. (c) Radar image of Surigao topography viewed from SSW, with the coast and shore of Lake Mainit outlined in white.

Furthermore, the Surigao crust is relatively thin and unlikely to host garnet-bearing basaltic rocks [21]. To account for the presence of adakites by slab melting, Sajona et al. [21] required a mechanism to melt the cool slab. In any incipient subduction zone a large thermal contrast will exist between the leading edge of the new slab and the mantle it penetrates. Numerical simulations indicate that the leading edge of a new slab may be heated to melting point, even if it is more than 25 million yr old [1]. Therefore, Sajona et al. [21] proposed that the presence of Pleistocene adakites in Surigao indicates an old slab melting in a very young subduction zone, rather than melting of a young slab.

We present new geochemical data to test the slab-melt hypothesis in Surigao. Our data indicate that the

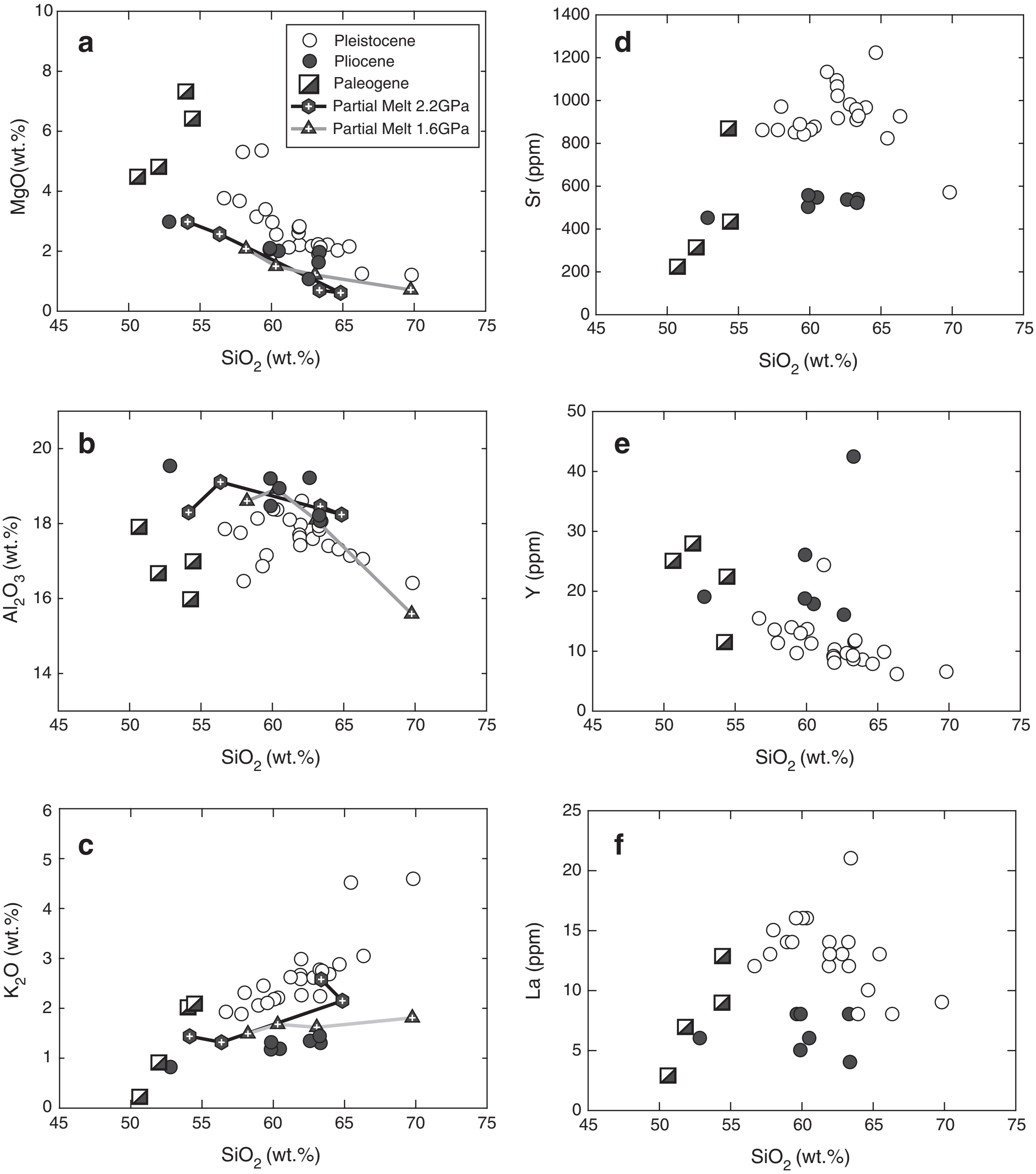

Fig. 2. Variation of selected major and trace element concentrations of Surigao magmatic rocks. Plots of (a) MgO, (b) Al_2O_3, (c) K_2O, (d) Sr, (e) Y and (f) La versus SiO_2. In (a–c) compositions of high pressure, synthetic partial melts of hydrous metabasalt [9] are shown for comparison.

geochemical distinction between these adakites and more normal island arc lavas (generated by the same subduction zone) result from differentiation of the adakites in the garnet stability field. Our model removes the need to postulate several different mechanisms to melt old subducted crust. Instead, adakites can be regarded as part of the spectrum of magmas that may be produced by any subduction zone.

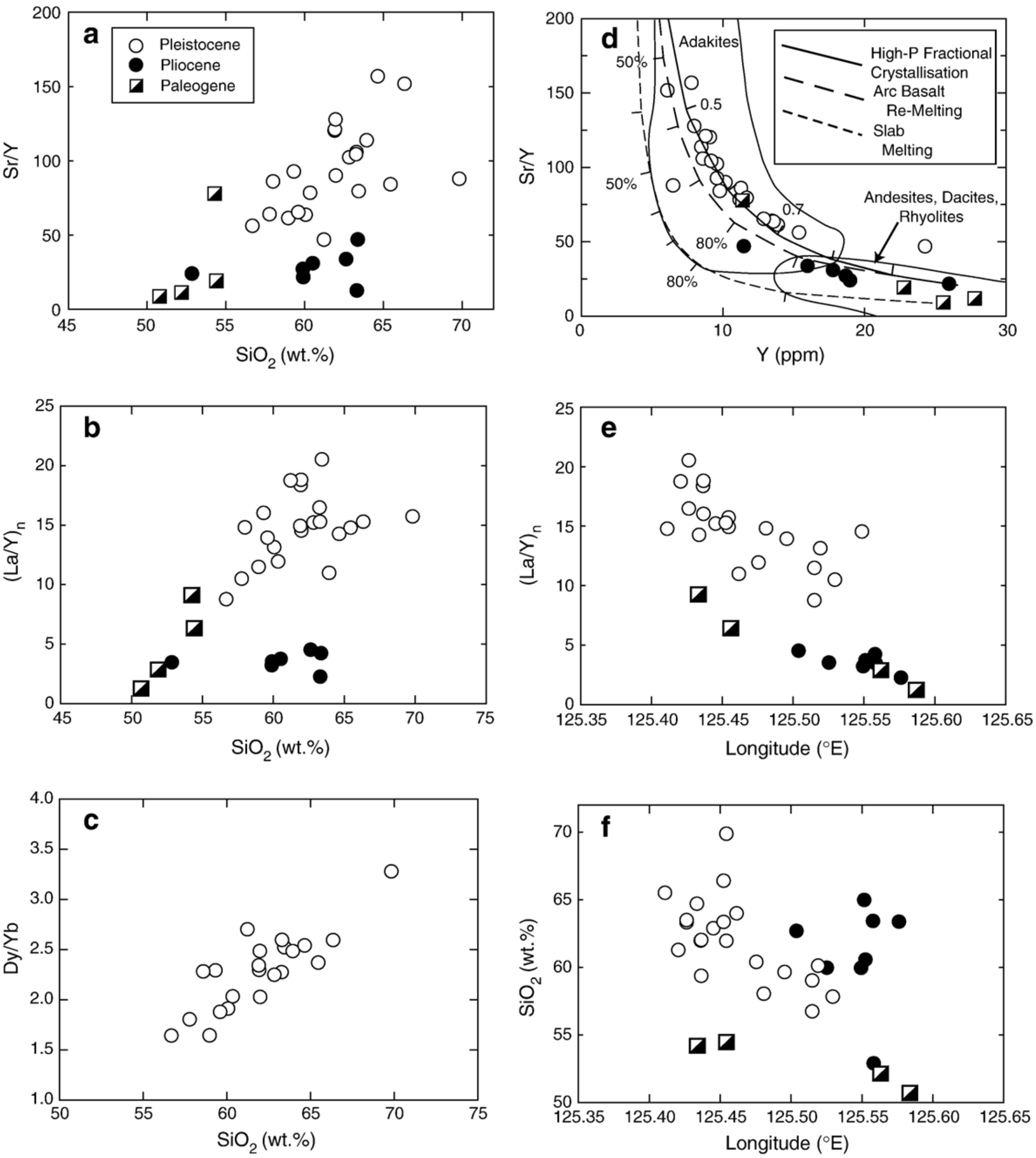

Fig. 3. (a) Sr/Y, (b) La/Y (normalised to N-MORB), and (c) Dy/Yb versus SiO_2 in Surigao magmatic rocks. (d) Sr/Y versus Y showing fields of adakites and island arc andesites, dacites and rhyolites [10]. The solid line illustrates fractional crystallisation of a high pressure mineral assemblage (see caption to Fig. 4) from basaltic melt initially containing 555 ppm Sr and 26.5 ppm Y (357460). Tick marks indicate the fraction of melt remaining. Long dashed line shows partial melting of a rock with the same initial Sr and Y as 357460. Short dashed line is partial melting of basalt from DSDP site 291 on the Philippine Sea Plate [65] with 24.7 ppm Y and its Sr content doubled to 218 ppm to simulate seafloor alteration. Tick marks indicate the extent of partial melting, which were calculated using partition coefficients from [8] and a residual mineralogy of 50% garnet, 50% clinopyroxene [9]. (e) $(La/Y)_n$, and (f) SiO_2 versus longitude, which is a measure of depth to the subducted slab beneath Surigao.

2. Surigao del Norte

Surigao del Norte lies at the northern extremity of eastern Mindanao (Fig. 1a). The basement consists of ophiolitic rocks overlain by volcanic and sedimentary rocks derived from a Paleogene arc [31,32]. In the east, the mountains of the Pacific Cordillera rise towards the south while the western peninsula is dominated by the elongate Malimono Ridge (Fig. 1b and c). Between these is a low-lying central plain occupied in the south by Lake Mainit. The plain is separated from the Malimono Ridge by the Philippine Fault, a sinistral strike-slip fault extending the length of the Philippine archipelago (Fig. 1a and b). To the east, the central plain meets the Pacific Cordillera along Oligo-Miocene reverse faults that show evidence of recent reactivation as normal faults (Fig. 1b). Since initiation of the Philippine Fault during the early Pleistocene the central plain has evolved as a down-faulted basin [32]. Extension, and implied lithospheric thinning, to produce the basin could result from transtension across an eastward step in the Philippine Fault south of Surigao del Norte [32], from trench-normal extension due to rollback of the new slab [33], or from trench-parallel extension due to oblique subduction of the Philippine Sea Plate [34].

Magmatic rocks associated with the Philippine Trench are preserved as hybabyssal stocks and lava flows throughout the central and western part of Surigao del Norte (Fig. 1b). Intrusive relationships with sedimentary units and radiometric dating [31] indicate that magmatism in the eastern part of the peninsula occurred from the very latest Miocene into the Pliocene. Magmatism from the Quaternary cone of Mt. Maniayao and further to the west (Fig. 1b) is Pleistocene or younger [31]. Major and trace element concentrations and Sr and Nd isotopic ratios were determined for a new suite of rocks that includes both Pliocene and Pleistocene suites (Fig. 1b; see supplementary data).

3. Results

Late Miocene to Pliocene rocks, hereafter called the Pliocene arc, are island arc basaltic andesite and andesite (Figs. 2, 3 and 4a). The Pleistocene igneous rocks display characteristics typical of adakites, such as intermediate SiO_2 contents, elevated Al_2O_3, high Sr/Y, and low Y and heavy rare earth element (HREE) concentrations (Supplementary Table 1; Figs. 2–4). However, Sr is not the only incompatible trace

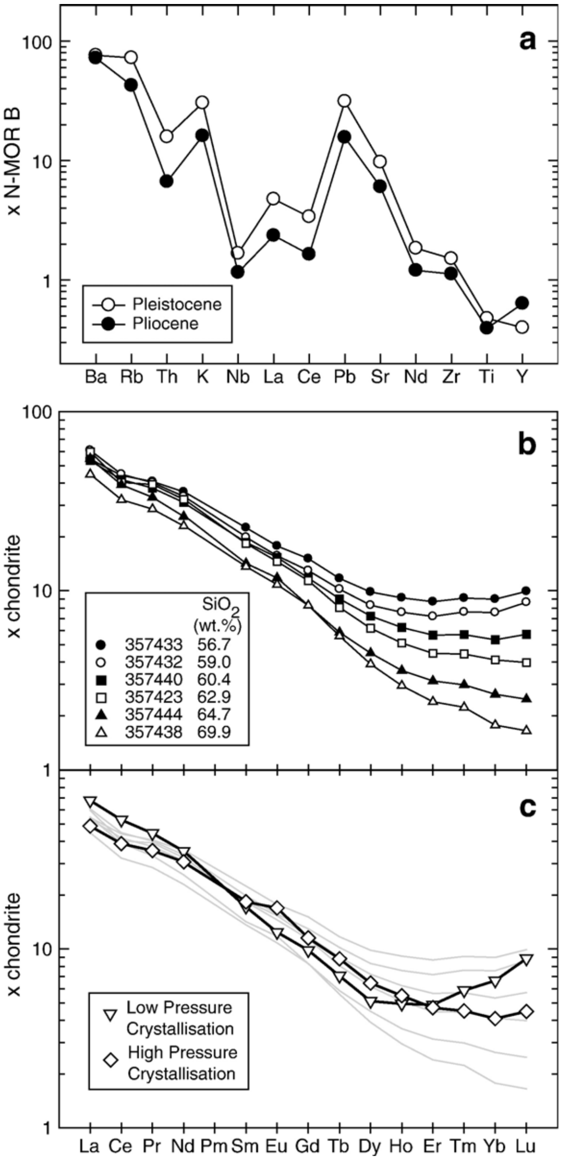

Fig. 4. (a) Incompatible trace element concentrations of Pliocene and Pleistocene andesites from Surigao with similar SiO_2 contents (60.5 wt.%), normalised to N-MORB [66]. (b) Chondrite-normalised rare earth element concentrations for Pleistocene adakitic rocks from Surigao showing progressive depletion in the heavy rare earth elements with increasing SiO_2. (c) Chondrite-normalised rare earth element concentrations of liquid evolved from the lowest-SiO_2 (56.7 wt.%) adakite by fractional crystallisation at low and high pressures. Low pressure assemblage is plagioclase, amphibole and FeTi-oxide in the proportions 74.3 : 21.5 : 4.2 based on phenocrysts in the Pleistocene rocks. High pressure assemblage is clinopyroxene, orthopyroxene, garnet, amphibole and allanite in the proportions 52.8 : 17.2 : 12.3 : 17.4 : 0.2, based on the equilibrium assemblage in experimental basaltic melt containing 56.5 wt.% SiO_2 at 1.2 GPa [44], but with the garnet fraction reduced by 20%. Partition coefficients from [8,67].

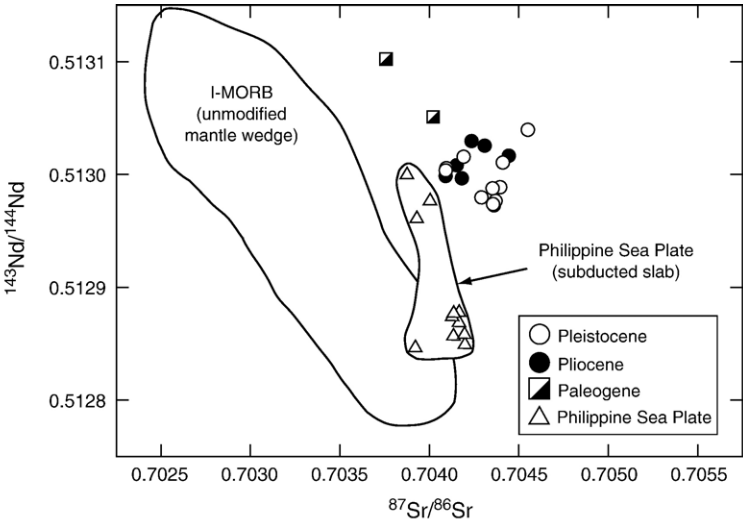

Fig. 5. $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ of Pliocene and Paleogene magmatic rocks from Surigao. Altered basalt from the subducting Philippine Sea Plate [68] and the Indian Ocean MORB [35] to represent the mantle wedge are shown for comparison. Surigao data from this work and [69].

element that is enriched relative to Pliocene rocks with similar SiO_2; all elements except Y and the HREEs are enriched by similar amounts (Fig. 4a,b). Within the Pliestocene suite it is the depletion in Y that is the major control on the development of the adakitic signature (Figs. 2d,e, and 4a). The strength of the adakite signature is highly variable within the suite and correlates with silica (Figs. 3a–c and 4b). There is also a geographic control on composition; the adakitic signal is strongest in the west and decreases towards Mt. Maniayao (Fig. 3e and f).

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ display similar, limited ranges in the Pleistocene and Pliocene rocks. Both are distinct from the upper mantle beneath Mindanao, which is believed to resemble I-MORB [35], and from the composition of unleached, altered basalt drilled from the Philippine Sea Plate immediately outboard of the Philippine Trench (Fig. 5).

4. Discussion

The strength of the adakite signature in Pleistocene rocks shows significant variation. Large ranges in Sr/Y are common to several adakitic suites (e.g. [10,21,24,36]), however, the correlation with, and wide range of, SiO_2 suggests that the adakite signal at Surigao (i) was diluted by a more mafic component, (ii) varied in response to changing degrees of slab melting, or (iii) developed from a more mafic, arc-like magma or basaltic protolith. If the last possibility is true then adakitic magmas can be developed without the need to invoke slab melting.

4.1. Modification of adakitic slab melts

Two mechanisms could modify the composition of true slab melts towards those of arc lavas. Slab melts could mix with contemporaneous arc lavas or they could interact with mafic or ultramafic rocks during transport from their source to the surface.

Mixing between a strongly adakitic magma and a more mafic island arc magma (low SiO_2, Sr/Y and La/Y, and high MgO) is precluded on three counts. First, magma mixing should produce straight arrays in binary plots. However, Al_2O_3, the light rare earth elements and Sr display inflections at around 60 wt.% SiO_2 (Fig. 2b,d, f). Second, adakitic rocks are more common in the west of the peninsula while arc lavas occur in the east (Fig. 3e and f). This observation conflicts with models based on theory or experimental data, which predict that partial melting of subducted crust should occur closer to the trench than the fluid-fluxed melting of the mantle wedge which produces typical arc magmas [8–10,36]. Finally, if the adakitic melts had interacted with arc magma then they should possess isotopic characteristics intermediate between those of the slab and arc lavas. Fig. 5 demonstrates that the adakites are entirely distinct from Philippine Sea Plate crust and that their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios are very similar to Pliocene arc rocks. In making this comparison we have deliberately chosen data for basaltic rocks from the shallow crust of the Philippine Sea Plate that were not acid-leached prior to analysis, as these will most accurately represent the subducted crust. Using analyses of acid-leached basalt from the slab would only increase the discrepancy between the slab and adakitic compositions. Furthermore, $^{87}Sr/^{86}Sr$ tends to decrease with depth in altered oceanic crust [37,38]. If slab melts are produced as average of melt fractions from the upper and lower crust [39] then they should have even lower $^{87}Sr/^{86}Sr$ than the shallowest lavas. The isotopic differences between adakites and slab suggest that the former are not derived directly from the latter. Instead, both Pliocene and Pleistocene rocks are displaced to high $^{87}Sr/^{86}Sr$ relative to the $^{143}Nd/^{144}Nd$ of the upper mantle (Fig. 5). In conjunction with the similarities of all trace element ratios, except those involving Y and the HREEs (Fig. 4a), this suggests both the adakitic and arc suites are ultimately derived from similar sources.

The second means of changing slab melt composition is assimilation of rocks from the mantle or crust. With respect to SiO_2 the Surigao adakites possess high Mg-numbers (Supplementry Table 1) and are relatively rich in elements that are abundant in peridotite, such as MgO (Fig. 2a) and Ni. Similar characteristics have been interpreted as evidence of melt-mantle interaction in other adakitic suites [14,40]. Laboratory experiments demonstrate that variable interaction between slab-derived adakite and peridotite should produce suites of silicic magma in which SiO_2 correlates positively with Al_2O_3 and negatively with Na_2O or K_2O. This is because assimilation involves precipitation of orthopyroxene, depleting the melt in silica but enriching it in incompatible elements [41]. Neither of these relationships is observed in the Surigao adakites. Indeed there is a strong positive correlation between silica and K_2O (Fig. 2c). Furthermore, reaction between silicic melt and peridotite can modify trace element concentrations in the hybridized melts but has a negligible effect on ratios of incompatible trace elements [41]. Therefore, even if such reaction had modified SiO_2 and MgO in some Surigao adakites it would not have a significant effect on key ratios such as Sr/Y and La/Y. The correlations in Fig. 3a–c suggest that the major and trace element systematics of the adakites result from a common process, and not one that can leave little imprint on incompatible trace element ratios.

Sr and Nd isotopic data are also inconsistent with a major role for interaction between slab melt and mantle wedge. Mantle peridotite beneath the Philippines has lower $^{87}Sr/^{86}Sr$ than the subducted Philippine Sea Plate at similar $^{143}Nd/^{144}Nd$. Slab melts interacting with this wedge would have their compositions driven towards lower $^{87}Sr/^{86}Sr$, i.e. away from those of Surigao adakites (Fig. 5). The mantle wedge may have been modified by slab-derived fluids during earlier phases of subduction, but it is unlikely that any peridotitic lithology would contain sufficient Sr to buffer $^{87}Sr/^{86}Sr$ in the adakites, which are particularly rich in Sr (Fig. 2d). Any contaminant would require even higher Sr contents (>1200 ppm) to influence $^{87}Sr/^{86}Sr$ whilst having a negligible effect on other aspects of melt chemistry (Fig. 4a).

There is insufficient control on the isotopic composition of the Surigao basement to unequivocally dismiss the possibility that these isotope ratios have been modified by assimilation of crustal rocks. However, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ do not correlate with SiO_2 or MgO as would be predicted if crustal rocks were assimilated during differentiation. Furthermore, a contaminant with exceptionally high Sr, and Sr/Nd, would again be required to displace the isotope ratios of true slab melts away from those of the Philippine Sea Plate (Fig. 5).

4.2. Variable melting of the Philippine Sea Plate

Low degree partial melts of hydrous basalt are rich in SiO_2 and alkalis but poor in MgO and FeO [8,9]. As melting progresses silica and alkalis in the melt are diluted and the concentrations of ferromagnesian components increase. The Surigao suite displays these characteristics (Fig. 2a–c) so may result from variable degrees of partial melting of subducted basalt crust. However, the trace element and isotopic characteristics are not consistent with this origin. Basaltic rocks from the Philippine Sea Plate contain too little Sr to replicate the trace element variation observed in the Surigao suite. Even doubling the Sr content of the subducted basalt, to simulate seafloor alteration [8,38], results in Sr–Y variation unlike that observed at Surigao, or in any putative slab melts (short dashed line, Fig. 3d).

$^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ data also suggest that Surigao adakites were not generated by melting of Philippine Sea Plate crust. Variations in partial melting would have a negligible impact on the Sr and Nd isotopic ratios of the magmas produced. Instead of resembling the subducted slab, the Surigao adakites are most similar to Pliocene arc lavas (Section 4.1). Slab melting is also inconsistent with osmium isotope data [42]. The high Re/Os ratios of ocean floor basalt mean that, at more than 50 million yr old, the Philippine Sea Plate crust should have developed extremely high $^{187}Os/^{188}Os$, which would also be passed on to slab melts. In fact, the majority of Surigao adakitic rocks possess $^{187}Os/^{188}Os$ within the range of most island arc lavas [42].

4.3. Adakite production from arc basalt

Incompatible trace element ratios and isotopic characteristics of the Pleistocene rocks are similar to those of Pliocene arc lavas except for extreme depletion of Y and the HREEs (Fig. 4b). Y and the HREE are strongly correlated with SiO_2 (Figs. 2e and 4b). Since, (i) magma mixing, assimilation of mantle or crust, and variable slab melting cannot satisfactorily explain the geochemistry of the adakites, and (ii) the isotopic data suggest that the Pliocene and Pleistocene rocks ultimately share a source in mantle wedge, we conclude that the adakitic signature of the Pliocene rocks was produced either by solid fractionation from arc magma, or by partial melting of arc magma that had completely solidified.

Plagioclase is by far the most abundant phenocryst in the adakitic rocks (25–50%), followed by hornblende (10–15%), with trace quantities of biotite, Fe–Ti oxide and clinopyroxene. Differentiation of an amphibole-dominated assemblage has been proposed as a mechanism to produce adakitic rocks on Camiguin Island, north of Mindanao [43], but a plagioclase–amphibole assemblage is unable to reproduce the trace element signature of the Surigao suite. In particular, removal of these phases would produce concave–upwards patterns between the middle and heavy rare earth elements (Fig. 4c) and result in decreasing Dy/Yb with increasing SiO_2. The increase of Dy/Yb with differentiation (Fig. 3c) requires that a phase with $D_{Yb} > D_{Dy}$, such as garnet, was involved in the development of the adakitic signature. The rare earth element patterns are consistent with fractionation of an assemblage containing clinopyroxene, orthopyroxene, garnet and amphibole in proportions similar to those crystallised in basaltic melt at 1.2 GPa (Fig. 4c; [44]). Crystallisation of a small quantity of a light rare earth element-bearing phase, such as allanite, is also required to account for the depletion of La and Ce in the most silica-rich compositions (Figs. 2f and 4). Employing Pliocene arc lava as a starting composition suggests that 30% to 50% crystallisation of the high pressure assemblage is sufficient to produce the Surigao suite (solid line, Fig. 3d).

Alternatively, adakitic rocks may be produced by remelting arc magma that solidified at depths where garnet was stable. Garnet and amphibole may crystallise from basaltic melt at high pressure (see above; [44]) or may develop during isobaric cooling of rocks emplaced slightly shallower than the depth where garnet becomes a liquidus phase [45]. As already noted, major element variations in the Surigao suite closely resemble andesite and dacite compositions generated in the laboratory by isobaric melting of hydrous metabasalt over a range of temperatures (Fig. 2a–c). Remelting arc lava, which contains more Sr (and other trace elements) than ocean floor basalt, produces a better fit to adakitic Sr–Y systematics than melting subducted ocean crust (long dash line, Fig. 3d) but requires extremely high degrees (>50%) of batch melting with residual garnet, amphibole and pyroxene (Fig. 3d). Such high degrees of melting may not generate adakite if garnet is a minor component of the source, c.f. [44], although there is experimental evidence that garnet is precipitated during low degrees of partial melting of hydrous basalt [8,9].

Castillo et al. [43] suggested that shallow, amphibole-dominated differentiation of arc lavas may generate some Philippine adakites. Remelting basaltic rock in thick, garnet-bearing crust has been proposed as a mechanism for generating adakitic magma from arc lithosphere [24–28]. Furthermore, garnet-, amphibole-bearing rocks have been documented from basal sections of exhumed arc crust in the Aleutian arc and Kohistan, where Moho depths are estimated to have been ≥30 km [45–47]. The Surigao example is distinct from these models in revealing a strong garnet fractionation signature in magmatism associated with relatively thin arc crust. Therefore, our data require that adakitic compositions were generated as a result of basaltic melt crystallising within the mantle.

A case can be made, based on simple buoyancy arguments, that basaltic melt should not pond until it reaches the Moho, which in arcs with crust less than ~35 km thick is too shallow for garnet crystallisation. However, Stratford and Stern [48] have imaged a strong seismic reflection and large drop in shear wave velocities at 35 km depth beneath the Taupo Volcanic Zone, New Zealand, where the crust is less than 20 km thick. They interpret this anomaly as a rising diapir of melt or a melt body trapped at a thermal boundary layer within the mantle. Basic arc magma provides the most likely candidate for a liquid body at this depth. A stalled diapir or melt body implies a mechanical and/or rheological barrier impeding further upward migration. Whether such a barrier lies within the arc lithosphere or marks a boundary between arc lithosphere and the underlying, convecting mantle is beyond the scope of this paper. However, the presence of substantial melt volumes within the shallow mantle wedge is consistent with the inferences from the Surigao geochemical data. At 35 km basaltic arc magma will crystallise a garnet-bearing assemblage. As discussed above this, in turn, will produce either silicic differentiated liquid with adakitic chemistry, or garnet-bearing mafic rock that could remelt to yield adakitic magma. In either case, during transport from the locus of crystallisation to the Moho the adakitic magma produced will have the opportunity to interact with mantle peridotite and acquire the elevated MgO, Ni and Cr concentrations and Mg-numbers observed at Surigao and in other adakite suites [14].

4.4. Adakite production in the East Philippine Arc

Surigao's low-lying central plain (Fig. 1c) is a young rift or transtensional feature [32], so the temperature at any depth beneath the plain will be higher than at the same depth further west, on the rift margin (Fig. 6). The strong spatial control on the composition of Surigao adakites infers that the temperature of solid–melt equilibrium increases from the west coast to the central plain (Fig. 3e and f). Lower geothermal gradients at the rift margin may allow more extensive crystallisation of magma here than is the case in the central part of the rift. Similarly, if remelting is responsible for adakite generation, then melting temperatures will be higher beneath the central plain than at a similar depth beneath the rift margins (Fig. 6). Therefore, Pleistocene thinning of the overriding plate provides a single mechanism to produce both the rifted morphology of the peninsula and the geographic control on melt chemistry.

4.5. Implications for other adakite suites

Fig. 6 summarises the mechanisms by which adakitic magma may be generated from arc basalt via crystallisation in the mantle wedge. This model has several important implications for petrogenesis of other adakitic magmatic suites.

First, adakitic magma can be derived from primitive arc magma, which is consistent with δ^{18}O values of adakites. Oceanic lithosphere and sediment are very heterogeneous in δ^{18}O [38,49–51], therefore, similar diversity would be predicted for melts derived from subducted slabs. However, adakitic rocks display a narrow range of δ^{18}O values [39] extending only slightly higher than other subduction zone magmatic rocks [51–55]. Pyroxene, garnet and amphibole all have lower δ^{18}O values than silicate melt with which they are in equilibrium [39,56]. Fractionation of these phases from magma, either by fractional crystallisation or partial melting, will produce a small increase in δ^{18}O

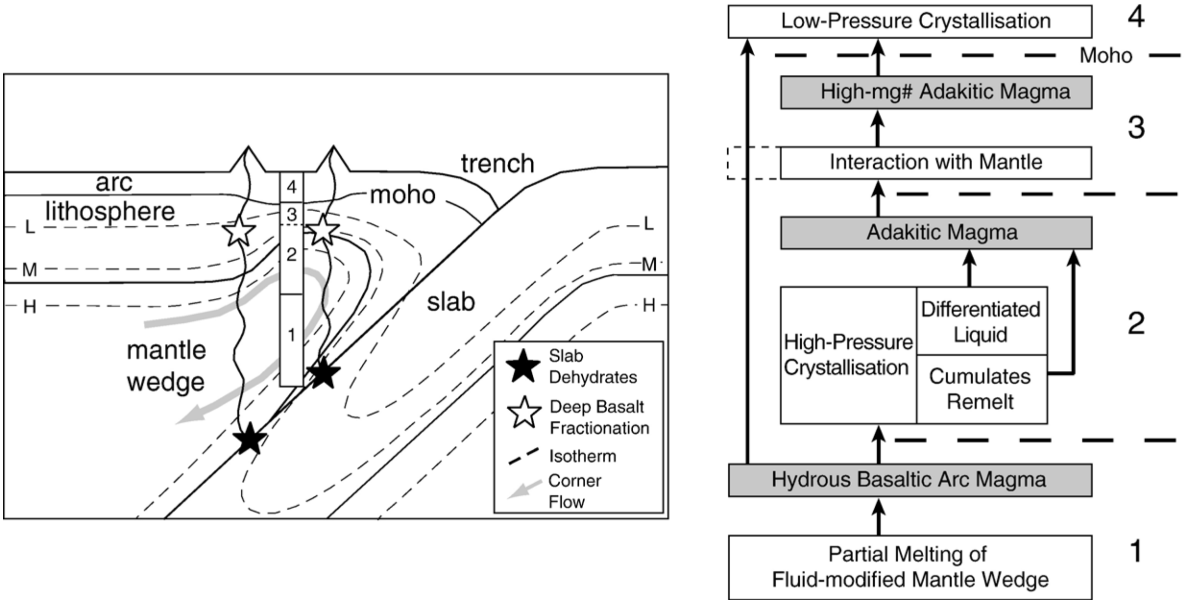

Fig. 6. Schematic illustration of adakite production by deep differentiation in an arc with thin crust. The slab is subducted beneath overriding arc lithosphere and induces corner flow (convection) in the mantle wedge. Dashed lines are schematic isotherms (for relatively low (L), medium (M) and high (H) temperature) illustrating that at any depth the shallow mantle is hottest where the arc lithosphere is thinnest (after [2,70–72]). Numbers in the vertical column refer to the flow diagram on the right, which summarises the possible mechanisms identified for generating adakitic melt without slab melting. Stage 1; genesis of primitive arc basalt. Stage 2; high pressure processing of basalt yields adakitic magma either directly, by fractional crystallisation, or indirectly, by remelting crystallised basaltic rock. Stage 3; interaction between adakitic magma and mantle peridotite. Stage 4; low-pressure crystallisation. Where the crust is thick Stage 2 can occur above the Moho and Stage 3 would be bypassed [24–26]. In mature arcs with a high magma flux to the crust Stage 4 will obscure or obliterate adakitic chemistry.

values of the differentiated melts. This is more consistent with the limited oxygen isotopic variation in adakitic rocks than the fortuitous balance of sources required during melting of different slabs, each displaying its own diverse δ^{18}O distribution.

If adakitic magma can be produced from any primitive arc melt, why are adakites not more common in more arcs? The architecture, rheology and thermal structure of a subduction zone will control the extent to which deep crystallisation may occur and be overprinted by later differentiation. In Surigao, deep differentiation is recorded while shallow crystallisation appears to have had a negligible impact on geochemistry of the adakites. In contrast, the Pliocene rocks are typical arc lavas and do not record deep processing. This difference could reflect changes in magma plumbing across the arc with deeper ponding favoured at greater distance from the arc. Alternatively, variations in the magma flux through the arc could be responsible. An extensive magma plumbing system in mature arc crust will decrease the probability that the signature of deep crystallisation will survive shallow crystallisation, magma mixing or interaction with the crust itself (Fig. 6). In eastern Mindanao (or, indeed much of the eastern Philippines) there is currently no active volcanism associated with subduction of the Philippine Sea Plate, suggesting low melt productivity from the mantle wedge. The Pleistocene adakites were the last magmatic event to affect Surigao and so represent a waning melt flux to the crust. Ephemeral magmatism during the earliest stages of arc magmatism may, therefore, be conducive to creating conditions under which adakitic magmas can avoid further differentiation, and loss of their distinctive character, at shallower levels. A component with “slab fusion” characteristics has also been invoked in rocks generated in the nascent Izu–Bonin arc [57] but may, in fact, represent remobilisation of basaltic rock emplaced during earlier phases of subduction [30,58]. If differentiation in the mantle is responsible for adakite generation, then the link between young subducted lithosphere and those adakites identified by Drummond and Defant [10] could reflect the thermal and dynamic effect of young slabs on the shallow mantle wedge and overriding lithosphere, rather than melting of the slab itself.

Second, our conclusions indicate that unusually hot subducted slabs are not a pre-requisite of adakitic magmatism. The elegance of the original adakite model [10] was that each adakitic suite was linked by the common denominator of a young slab, which was inferred to be hot. Subsequent recognition of adakites associated with old slabs has broken this simple link but thrown up several exceptions to the rule. Each new case requires its own mechanism for heating old, cold slab to melting point. Two extreme examples of the absence of a hot slab are (i) genesis of adakitic magma where the slab is at very great depth [59], or (ii) genesis of adakites without any slab at the time of magmatism [60–62]. The alternative to having several exceptions to the rule is to have a new rule. Basalt that crystallises in the lithospheric mantle (Stage 2, Fig. 6) will remain part of the lithosphere until later perturbations of the geothermal gradient. Partial remelting of arc basalt stored in the lithospheric mantle would still result in adakitic magma regardless of the geodynamic process causing the basalt to melt. Non-arc basalts have different bulk compositions, lower water contents and less distinctive trace element ratios than those produced in subduction zones. Therefore, their remobilisation from sites of deep crystallisation may not happen so readily or will not produce such distinctive partial melts as those with a subduction zone provenance.

Third, the shallow mantle may act as a staging-post for at least some primitive magmas in subduction zones [11,62–64]. Evidence for interaction between adakitic melt and peridotite has previously been used as evidence that adakites must originate beneath the Moho [13,14,22,40] and thus, by inference, in the subducted slab. However, Surigao demonstrates that adakitic magma produced from deeply crystallised basalt must still traverse the uppermost mantle wedge (Stage 3; Fig. 6). Our model infers that mafic to ultramafic cumulates can develop within the mantle. In turn, this provides a location where a primary basaltic magma flux into the base of arc lithosphere can generate a magmatic flux into the crust that has a more evolved bulk composition [11,44,46,62].

5. Summary

Pleistocene igneous rocks from Surigao record the development of adakitic melts from typical arc magma by fractionation of a garnet-bearing assemblage. Basaltic arc magma stalled within the mantle, either at the base of the arc lithosphere or at some rheological boundary in the shallow mantle wedge. Fractional crystallisation or remelting of the stalled material produced the adakites. Our data imply that (i) adakitic magmatism can occur in any subduction zone where “normal” arc magmatism occurs, (ii) adakitic magmatism does not require an unusually hot subducted slab, (iii) adakitic magmatism can be generated outwith active subduction zones, and (iv) that the mantle beneath subduction zones can play an important role in determining the nature of volcanic outputs and of crust produced by subduction zones. These conclusions have important implications for interpreting geodynamics of modern adakites and adakite-related rocks found in Archean terranes.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2005.12.034.

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