ANDEAN ADAKITES FROM SLAB MELTING, FOREARC SUBDUCTION EROSION AND CRUSTAL THICKENING

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INTRODUCTION

Neogene magmas with chemical characteristics of adakites as defined by Defant and Drummond (1990) are common along the Andean margin. For a magmatic rock to be an adakite it must have major and trace element features consistent with equilibration of the parental magma with a high-pressure garnet-bearing, plagioclase-poor basaltic composition residual mineral assemblage before erupting. Among critical chemical criteria are a steep heavy REE pattern, low heavy REE concentrations, and a high Sr concentration. Magmas of this type can be produced by at least three processes: a) melting of subducted oceanic crust, b) melting of crust removed by forearc subduction-erosion in the mantle wedge, and c) melting of tectonically thickened crust. Of these, melting of subducting oceanic crust appears to be by far the least common. More common is equilibration of mantle wedge derived magmas with crustal melts in thickened garnet-bearing crust. Evidence for adakite formation in association with subduction erosion is also being widely recognized. Melting of old and cold subducting oceanic crust in shallow subduction zones (Gutcher et al., 2000) is very unlikely to occur. The origin of adakitic magmas is best deciphered by matching the chemical chrematistics of the adakite with the tectonic setting of the magma (Fig. 1).

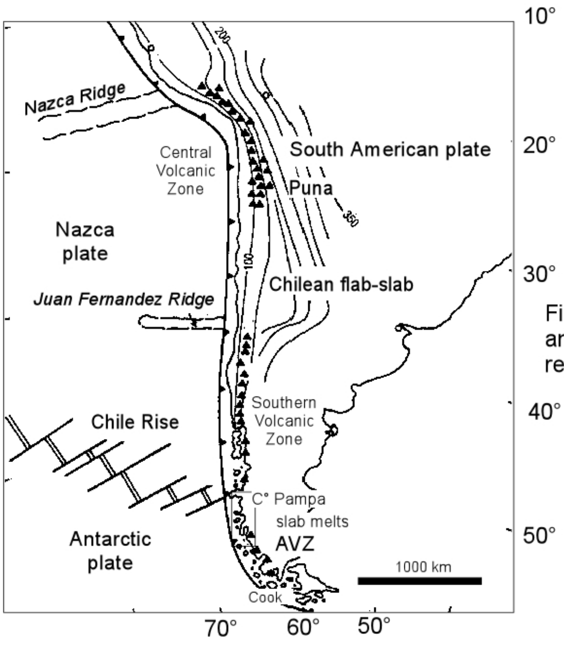

Figure 1. Map of southern and central Andes showing regions referred to in text.

SLAB MELT ADAKITES

The formation of many adakitic magmas formerly ascribed to slab melting has recently been questioned. The best remaining candidates are the Patagonian Miocene Cerro Pampa type adakites described by Kay et al. (1994), and possibly the Pleistocene to Holocene Austral Volcanic Zone (AVZ) adakites described by Stern and Killian (1996). Support for a role for slab melting in the origin of the Cerro Pampa adakites comes from a tectonic association with the collision of the Chile Ridge with the Chile Trench (Fig. 1) and their chemical characteristics. Importantly, the Cerro Pampa adakites erupted near the time that the young trailing edge of the Nazca plate subducted beneath them fulfilling the thermal requirement for melting of a hot young oceanic slab (e.g., Peacock et al., 1994).

Chemically, the REE and trace element characteristics of these adakites (63-68% SiO_2) can be modeled by ~ 3% partial melt of MORB basalt in the eclogite facies as required for melting of a subducting oceanic slab. Key trace element characteristics include extremely high Sr (1330-2300 ppm) concentrations, and steep heavy depleted REE pattern (La/Yb = 30-37) with no Eu anomalies. A slab-melt origin from a subducting slab also provides an explanation for a garnet-bearing, feldspar-poor residual mineralogy in a region where crustal thicknesses do not support a thick root. Even more persuasive evidence comes from MORB-like $^{87}Sr/^{86}Sr$ (0.7028-0.7031) ratio that are unknown elsewhere in the region. Contamination of the Cerro Pampa magmas during accent through the mantle wedge can explain their high Mg number and Cr and Ni contents, whereas contamination in the crust can explain their regionally low, but crustally influenced $^{143}Nd/^{144}Nd$ (> 0.5129) and Pb isotopic ratios. Evidence for crustal interaction also comes from crustal zircons with ages of U-Pb ages 123 to 1766 Ma in the Cerro Pampa adakites (see Ramos et al., 2005).

More recently, two other Cerro Pampa type adakite localities have been described in Patagonia at Puesto Nuevo near 49°S and at Chaltén near 49.5°S (Ramos et al., 2005). These adakites, which also erupted east of where the Chile ridge collided at ~ 12 Ma, have chemical characteristics (65-66% SiO_2, 1370-1440 ppm Sr, $^{87}Sr/^{86}Sr$ = 0.7032-7033, $^{143}Nd/^{144}Nd$ ~ 0.51289, La/Yb 28-30) similar to the Cerro Pampa adakite. New $^{40}Ar/^{39}Ar$ plateau ages from laser incremental heating of hornblendes show that the 3 adakitic centers progressively get younger to the north (Chaltén at 14.50±0.29 Ma, Puesto Nuevo 13.12±0.55 Ma, and Cerro Pampa at 11.39±0.61 Ma) as expected if they are associated with melting of the trailing edge of the Nazca plate as ridge collision progressed northward.

In contrast to these adakites, the ~ 16 Ma Moyano andesite which erupted further south near 50° 16'S, east of where the Chile Ridge collided with the trench at ~ 13 to 15 Ma, lacks slab melt characteristics (Ramos et al., 2005). A big difference between these regions is that Miocene mafic plateau lavas are associated with the adakites in the north, but not with the Moyano andesite. Gorring et al. (1997) suggested that a thermal anomaly in the asthenospheric mantle was needed to explain why mafic magmas formed by decompression melting erupted through the slab-window associated with the ridge collision at 12 Ma, but not with the one created at 15 to 13 Ma. This situation suggests that extreme thermal conditions are required to produce slab melt adakites. These conditions are achieved in Patagonia only when a very young subducting slab that is coupled with additional heat from a thermal anomaly in the asthenospheric mantle.

SUBDUCTION EROSION ADAKITES

Outside the Andes, previously well-accepted slab-melt adakites are being reinterpreted as having an association with melting of crust introduced into the mantle wedge through forearc subduction erosion. The leading example is the high Mg andesitic lavas from the type locality at Adak Island in the Aleutian arc (Kay, 1978). Among problems with a slab-melt interpretation for this adakite are: a) the lack of subduction of a hot young oceanic crust near the time that the 11 Ma adakite erupted, and b) evidence for mixing of the adakitic magma with a typical mantle wedge-derived arc magma. An alternative model attributing the origin of this adakite to melting of forearc oceanic basement incorporated into the mantle wedge by forearc subduction erosion solves these problems (Kay, 2004). Additional evidence for an association with forearc subduction erosion comes from the Adak adakite erupting at a time of frontal arc migration. A similar case can be made for Miocene adakites in Costa Rica in the Central American arc that was formerly interpreted as slab melts (Goss et al., 2003).

Andean magmas with adakitic characteristics that erupted over old, cold portions of the subducting Nazca plate are common in the Central Andes. All have steep REE patterns, but none have the depleted isotopic signatures and high Sr contents of the Cerro Pampa, Cook and Adak adakites. A significant number have steeper REE patterns. Support for the adakitic characteristics of some of these magmas being related to forearc subduction erosion comes from regionally anomalous and marked changes in isotopic and trace element signatures in magmas erupted during and after periods of frontal arc migration. The feasible explanation is a component derived from partial melting of continental crust introduced into the mantle wedge and subjected to high-pressure metamorphism in a peak period of subduction erosion during arc migration. Examples come from magmatic rocks in the Southern Volcanic Zone (SVZ) near 34°S (Kay et al., 2005) and the Central Volcanic Zone (CVZ) near 27°S (Kay and Mpodozis, 2002; Kay, 2003).

Evidence for subduction erosion components in southern CVZ adakitic arc magmas near 27°S (Fig. 1) comes from transient changes in trace element signatures in ~ 7 to ~3 Ma magmas erupted coincident with a time of ~ 40 km of eastward frontal arc migration. These adakitic magmas are characterized by very steep REE patterns and marked high field strength element depletion (high La/Ta ratios). Attributing these features to melts of thickened crust is at odds with the transient nature of the chemical changes. A simpler explanation is that these chemical signatures result from melting of forearc crust introduced into the magma wedge at the time of arc migration. Support for incorporation of forearc crust into the mantle wedge comes from chemical and isotopic contrasts in mantle-derived early Miocene backarc and Pleistocene arc magmas erupted before and after frontal arc migration.

Evidence for crustal components removed by forearc subduction erosion also playing a role in the origin of adakitic Miocene to Holocene arc magmas in the northern SVZ near 34°S (Fig. 1) comes from chemical and isotopic contrasts (Stern, 1991; Kay et al., 2005). Support for a subduction erosion component comes from: 1) relatively abrupt changes in εNd values in a whole range of mafic to silicic magmas that correlate with two episodes of arc migration at ~ 20 to 16 and ~ 7 to 3 Ma, 2) transient steep REE patterns and high Sr and Na contents in magmas erupted during the two periods of frontal arc migration, and 3) mafic lavas that erupted through < 45 km thick forearc crust having chemical characteristics like similar age arc magmas erupted in 60 to 70 km thick crust to the east. Kay and Mpodozis (2002) pointed out other anomalous transient chemical changes in central Andean arc adakites between ~ 26°S and 32°S that erupted at times of arc migration and that could reflect forearc subduction erosion processes.

ADAKITES RELATED TO MELTING OF THICKENED CRUST

The most common way to produce adakitic magmas in the Andes is through interaction of mantle derived magmas with thickened garnet-bearing crust. Importantly, a majority Andean adakites have erupted through crust which has been thickened in response to crustal shortening and ductile flow of the deep crust. Partial melting at the base of this crust in association with injection of mantle-derived basaltic arc magmas in a high-pressure MASH (melting, assimilation, storage and homogenization – Hildreth and Moorbath, 1988) zone leads to magmas with adakitic characteristics. This process is supported by temporal correlations of deformation in foreland fold/thrust belts with eruption of adakitic magmas whose isotopic ratios are best explained by crustal contaminants (e.g., Kay et al., 1999).

In the ultimate case, backarc southern Puna adakites (Fig. 1) with extreme REE characteristics (La/Yb to 100, Sm/Yb > 8) are associated with melting of over thickened lower crust that became negatively buoyant relative to the underlying mantle (Kay et al., 1994). Rapid sinking ("delamination") of this gravitationally unstable granulitic to eclogitic crust along with the underlying mantle lithosphere produced a void in the mantle wedge that was filled by asthenosphere. Mafic magmas that segregated in this asthenosphere caused transient heating and partial melting of the crust, including the delaminating lower crust. These melts left eclogitic residues that are denser than the pre-existing (unmelted) lower crust.

CASE AGAINST A GENERAL RELATION BETWEEN SLAB-MELT ADAKITES AND SHALLOW SUBDUCTION ZONES

The origin of some Andean adakites became clouded with the publication of Gutscher et al. (2002) that argued that slab melting was a common consequence of shallow subduction. Proposed examples of slab melting in the paper were from the Chilean flatslab region (Fig. 1) and Ecuador. The principal chemical evidence to support the proposed slab melting model came from Miocene to Holocene magmatic rocks over the Chilean flatslab (see summary in Kay and Mpodozis 2002). The slab melting model proposed for the Chilean flatslab adakites has a number of very serious problems: 1) the Miocene backarc magmas attributed to slab-melting do not have adakitic chemical characteristics; 2) the melting model presented cannot explain the presence of basaltic andesites among the proposed backarc slab melts, 3) there is no evidence for the ~ 70 km thick lithosphere at 20 Ma that is needed to produce the shallow 1300°C isotherm that allows the slab melting model to work and 4) the only magmatic rocks with adakitic characteristics are < 16 Ma andesites and dacites in the principal Cordillera whose origin is best explained by interaction with thickened crust and forearc subduction erosion. There is no convincing evidence for slab melting in the Chilean flatslab region and all of the adakites in region that are far better explained by being related to thickened continental crust and forearc subduction erosion.

CONCLUSIONS

Most adakites in the Andes as well as elsewhere are best explained by equilibration of mantle wedge derived arc magmas with thickened garnet-bearing continental crust or incorporation of forearc crust into the mantle wedge by subduction erosion rather than by melting of subducted oceanic slabs. Strong support for this statement in the Andes comes from the positive temporal correlation between abundant adakitic magmas and patterns of crustal thickening and eastward arc front migration. Marked increases in Andean adakite production at ~ 19 to 16 Ma and again at ~ 8 to 4 Ma can be correlated with peaks in crustal thickening and forearc subduction erosion that are likely linked to convergence parameters between the Nazca and South American plate and the motion of South America over the mantle in the hotspot reference frame. The least common origin of Phanerozoic adakites on Earth appears to be slab melting. The clearest possible case for slab melt adakites in the Andes are Miocene and Holocene adakites in Patagonia that are tectonically related to an extremely young subducting oceanic slab near the time of a ridge-trench collision as well as a hot asthenospheric mantle.

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REFERENCES CITED

Defant, MJ and Drummond MS, (1990), Derivation of some modern island arc magmas by melting of young subducted lithosphere. Nature 347, 662-665.

Gorring, M.L., Kay, S. M., Zeitler, P.K., Ramos, V.A., Rubiolo, D., and Fernandez, M.I. (1997). Neogene Patagonian plateau lavas: Continental magmas associated with ridge collision at the Chile triple junction. Tectonics 16, 1-17.

Goss, A.G., Kay, S.M., Mpodozis, C. (2003). Subduction erosion controlled adakites: Examples from the Bonete/Incapillo-Central Andean and Middle American margins, X Congreso Geológico Chileno Actas, Concepción, Chile, electronic files.

Gutscher, M.A., Maury, R., and Eissen, J.P. (2000). Can slab melting be caused by flat subduction? Geology 28, 535-538.

Hildreth, W. and Moorbath, S. (1988). Crustal contributions to arc magmatism in the Andes of Central Chile. Contributions to Mineralogy and Petrology 98, 455-489.

Kay, R.W. (1978). Aleutian magnesian andesites-melts from subducted Pacific Ocean crust. Journal of Volcanology and Geothermal Research 4, 117-132.

Kay, R.W. (2004). Subduction erosion and recycled components at convergent margins: the Aleutian adakites. 32° International Geological Congress, Abstracts (electronic), Florence, Italy.

Kay, S.M. (2003). Trace element and isotopic evidence for a forearc subduction erosion component entering Andean arc magma sources during frontal arc migration. Third State of the Arc Workshop, IAVCEI Magmatic Studies Group, Timberline, Oregon, SOTA website.

Kay, S.M. and Mpodozis, C. (2002). Magmatism as a probe to the Neogene shallowing of the Nazca Plate beneath the modern Chilean flatslab. Journal of South American Earth Science, 15, 39-59.

Kay S.M., Coira B., and Viramonte, J. (1994). Young mafic back-arc volcanic rocks as indicators of continental lithospheric delamination beneath the Argentine Puna Plateau, Central Andes. Journal of Geophysical Research 99, 24323-24339.

Kay, S. M., Godoy, E., and Kurtz, A. (2005). Episodic arc migration, crustal thickening, subduction erosion, and magmatism in the south-central Andes. Geological Society of America Bulletin 117, 67-88.

Kay S.M., Ramos, V.A., and Marquez, M. (1993). Evidence in Cerro Pampa volcanic rocks for slab melting prior to ridge-trench collision in southern South America. Journal of Geology 101, 703-714.

Peacock, S.M., Rushmer, T. and Thompson, A.B. (1994). Partial melting of subducting oceanic crust. Earth and Planetary Science Letters 1212, 227-244.

Ramos, V.A., Kay, S.M., and Singer, B. (2004). Las adakites de la Cordillera Patagónica: Nuevas evidencias geoquímicas y geocronológicas. Revista de la Asociación Geológica Argentina 59, 693-706.

Stern, C.R. (1991). Role of subduction-erosion in generation of Andean magmas. Geology 19, 78-81.

Stern, C.R. and Kilian, R. (1996). Role of the subducted slab, mantle wedge and continental crust in the generation of adakites from the Andean Austral Volcanic Zone. Contributions to Mineralogy and Petrology 123, 263-281.