Dubious case for slab melting in the Northern volcanic zone of the Andes

Jennifer M. Garrison Department of Earth and Space Sciences, University of California, Los Angeles, California 90095, USA
Jon P. Davidson Department of Geological Sciences, University of Durham, South Road, Durham DH1 3LE, UK

ABSTRACT

It was first suggested by R.W. Kay that adakites may represent melts of subducted slab: since then, the term adakite has become synonymous with slab melts based on their unusual geochemical signature. This contribution, using the Northern volcanic zone of the Andes as an example, aims (1) to expose the weakness in simply associating a geochemical signature with a genetic mechanism and (2) to underline the importance of using several integrated lines of evidence in assessing the viability of slab melting. We conclude that although slab melting probably occurs in some arcs, regional geochemical trends in the Northern volcanic zone and their relationship to the subduction-zone architecture are not indicative of slab melting and can be accounted for by normal arc magmatic processes acting on wedge-derived basaltic magmas.

Keywords: Ecuador, subduction, adakite, Northern volcanic zone, slab melting.

BACKGROUND: SLAB MELTING AND ADAKITES

Melting of subducted basaltic crust was suggested by Kay (1978) as an explanation for a geochemically distinct class of subduction-related volcanic rocks, now widely known as adakites. The generation of adakites was subsequently examined by many researchers (Drummond and Defant, 1990; Drummond et al., 1996; Rapp and Watson, 1995; Sen and Dunn, 1994; Peacock et al., 1994). It was argued that subduction of young (typically 25 Ma or younger), consequently warm, lithosphere is needed for temperatures in the slab to rise above the solidus of wet basalt at high pressure and produce adakitic melts (a corollary to which is that most modern subduction-zone magmas with signatures quite distinct from those of adakites are produced by melting of the mantle wedge triggered by fluid addition from the subducted slab; Davidson, 1996). The characteristic adakite signature has now been identified in at least 13 arcs (Defant and Drummond, 1990), including the Northern volcanic zone of the Andes (Gutscher et al., 1999, 2000; Defant and Kepezhinskas, 2001), and the term ''adakite'' has come to be synonymous with melting of subducted lithosphere.

It is important to remember, however, that the geochemical signature represented by adakites is not unique to melting of subducted oceanic lithosphere, but more broadly corresponds to high-pressure melting of wet basalt (Drummond et al., 1996). This distinction is nontrivial, in that discerning between adakite production via slab melting versus melting of another basalt source (typically lower crust) is important if we are to recognize the individual components of arcs and to understand the importance of slab melting versus lower-crustal melting during formation of continental crust.

In light of the distinction just described, a case for slab melting based solely on geochemistry of erupted lavas is tenuous at best, particularly in regions where the geophysical data do not show that conditions are appropriate for slab melting. Because the geochemistry of slab and lower-crustal melts can be similar, distinguishing between them requires an integrated investigation of regional geochemistry along with tectonic setting and geophysical data.

COMPOSITIONAL CHARACTERISTICS OF ADAKITES

Experiments show that high-pressure melting of metamorphosed basalt produces a peraluminous Na-rich dacite with SiO_2 concentrations between 63 and 70 wt% (Sen and Dunn, 1994; Drummond et al., 1996; Rushmer, 1991; Peacock et al., 1994). These and similar melting experiments are important in that they demonstrate that adakitic melts can be generated from metamorphosed basalt at relatively low temperatures. A key point that can be made on the basis of these data is that any hydrous basalt at depth, be it subducted slab or lower crust, has the potential to produce melts with adakitic compositions.

The trace element signature most often used to classify rocks as adakites is high Sr concentration (>400 ppm) coupled with low Y (<19 ppm). This is because melting of wet basalt at pressures where plagioclase is not stable, or melting in the presence of high P_{H_2O}, will destabilize plagioclase and stabilize garnet. Because plagioclase is the primary phase that incorporates Sr, any melt that forms in the absence of plagioclase will be enriched in Sr (and Eu) with respect to the residue. For the same reason, absence of plagioclase leads to enrichment of Al_2O_3 in the melt. The presence of residual garnet, and, to a lesser extent, amphibole, will decrease Y concentrations in the melt, because heavy rare earth elements (REEs) (Dy to Lu) and Y are highly compatible in garnet, whereas the medium to heavy REEs (Gd to Lu) and Y are compatible in amphibole. Therefore, according to published data, an adakite as defined by a high Sr/Y ratio implies a basaltic source in a pressure-temperature field where garnet (and possibly amphibole) is stable but plagioclase is not, i.e., eclogite, amphibolite, or garnet amphibolite.

Rocks called high-Mg andesites are related to adakites. While some authors conclude that these rocks represent slab melts that have equilibrated with the mantle wedge, this distinction, like that of adakites, is based on geochemical signature. We do not address high-Mg andesites in this contribution because (1) they are not claimed to be direct slab melts, (2) the models we are discussing do not use high-Mg andesites as evidence for slab melting, and (3) none of the Northern volcanic zone samples are high-Mg andesites.

NORTHERN VOLCANIC ZONE

The Northern volcanic zone is the northernmost segment of active volcanism in the Andean arc, resulting from subduction of the Nazca plate beneath South America (Fig. 1). It extends from lat 5°N to 2°S and includes volcanoes in southern Colombia and Ecuador. The age of the plate beneath Ecuador is estimated to be from 10 Ma (Gutscher et al., 1999) to 27 Ma (Lonsdale, 1978), and it is subducting at ~59 mm/yr. Gravity data show that the thickness of continental crust beneath Ecuador is 50–70 km (Feininger and Seguin, 1983). The geometry of the subduction zone is uncertain owing to lack of seismicity in the slab and difficulty in identifying the Benioff zone; however, it has been suggested that the Nazca plate transitioned from steep to flat during the ongoing subduction of the Carnegie Ridge seamounts (Gutscher et al., 1999). More recently, it has been proposed that slab melting has contributed to the geochemical signature of lavas from Antisana volcano (Bourdon et al., 2002) (Fig. 1), and that slab melting and eventual cessation of volcanism are expected as the mantle wedge is squeezed out (Gutscher et al., 2000).

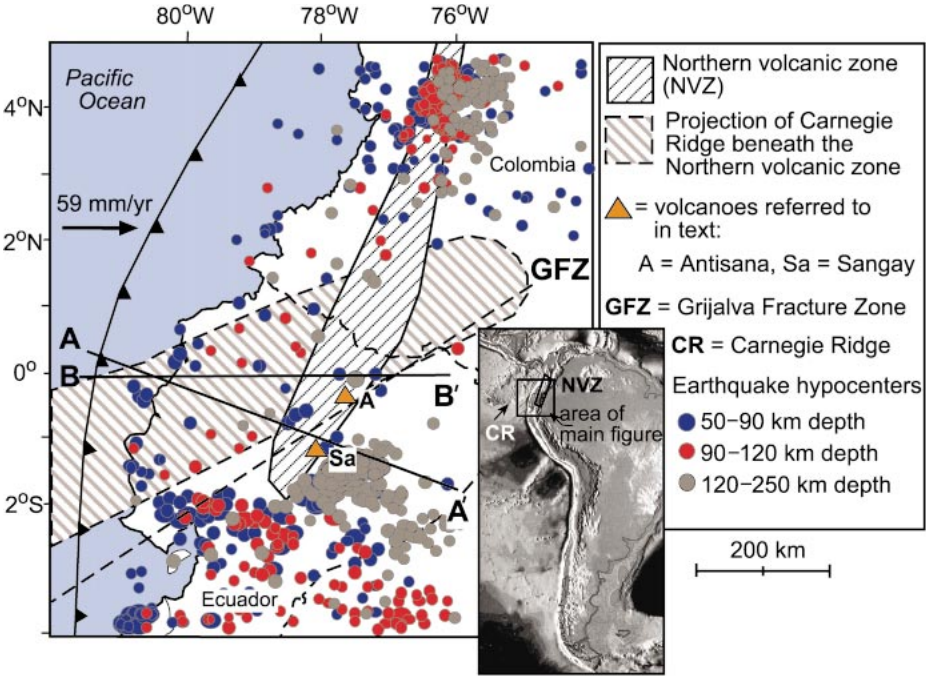


Figure 1. Map of Northern volcanic zone showing distribution of earthquake hypocenters and tectonic elements discussed in text. Cross sections along lines A–A′ and B–B′ are shown in Figure 4.

MODELS FOR ADAKITE GENERATION IN THE NORTHERN VOLCANIC ZONE

Gutscher et al. (1999) suggested that the slab dip is shallow only along the trajectory of the Carnegie Ridge, but folded or torn on either side such that the slab dips steeply to the north and south of the ridge. If the slab-tear model is correct, then a tear exists along the southern edge of the Carnegie Ridge, and edge melting has produced adakites in this region. Such a tear has been proposed where a northeast-trending fracture zone, the Grijalva fracture zone, intersects the Northern volcanic zone (Fig. 1). A more recent model invokes slab flattening beneath the Western Cordillera, where slab melts are produced owing to gradual warming of the slab at constant pressure (Gutscher et al., 2000). Slab-melt–metasomatized mantle wedge is then carried beneath the eastern cordillera by viscous drag, where the temperature increases and the mantle melts to produce the slab-melt signature claimed by Monzier et al. (1997) and Bourdon et al. (2002) to characterize some eastern volcanoes of the Northern volcanic zone.

These models of slab tearing or flat-slab subduction are useful in that they provide the basis of a hypothesis for testing the generation of adakites as slab melts in the Northern volcanic zone. It should follow that in areas where the subducted Carnegie Ridge seamounts have the most influence, there should be a more pronounced adakitic signature. Therefore, a north-south traverse along the arc should reflect an increase in adakite character near the Carnegie Ridge and the Grijalva fracture zone (Fig. 1) coupled with decreases toward the north and south where the slab is thought to be steep. If adakites are generated by melting of the exposed edge of the torn slab, then the signature should be most pronounced at the edges of this segment—i.e., prominent only at ~1°S and ~2°N.

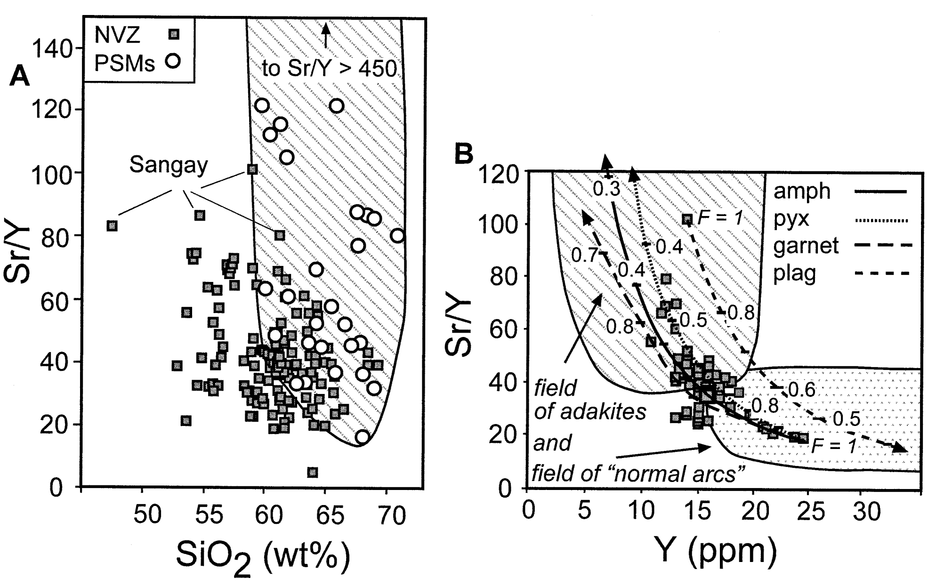


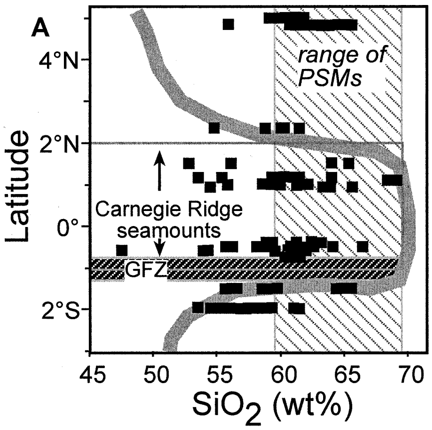
Figure 2. A: Graph of Sr/Y vs. SiO_2 for Northern volcanic zone (NVZ) volcanoes, showing gray ruled field for putative slab melts (PSMs) (for references to volcano and PSM compositions, see footnote 1 in text). B: Graph of Sr/Y vs. Y, filtered for samples with 63–69 wt% SiO_2, showing adakite (ruled) and “normal arc” (dot-patterned) fields as defined by Defant and Drummond (1990). Arrows show effects of plagioclase, pyroxene, amphibole, and garnet fractionation (*F*) on composition of melts. In general, PSMs have higher Sr/Y ratios than Northern volcanic zone rocks. Distribution coefficients are from Rollinson (1993).

TESTING THE SLAB-MELTING HYPOTHESIS: REGIONAL GEOCHEMISTRY OF THE NORTHERN VOLCANIC ZONE

We have compiled geochemical data from 14 volcanoes from 5°N to 2°S (Figs. 2 and 3) in the Northern volcanic zone.[1] We have also compiled adakite data from other areas that are, by virtue of their tectonic configuration, most convincingly the result of slab melting. (We refer to these as putative slab melts [PSMs] [see text footnote 1].) Our objectives are (1) to evaluate the degree to which the compositions of volcanic rocks of the Northern volcanic zone relate to high-pressure wet basalt melting in general and (2) to test the strength of the adakite signature (in terms of the SiO_2 concentration and Sr/Y ratio expected from high-pressure wet basalt melting, as described previously) and relate this to location along the arc. In this way we can test the relationship between adakitic character and the occurrence of slab dynamics that might favor melting. There are several points that can be made from the data along this traverse (Figs. 2 and 3).

1. If slab melts are a significant component of Northern volcanic zone lavas, only rocks with 63 to 70 wt% SiO_2 should have anoma-

[1]GSA Data Repository item 2003080, references for volcanoes used in graphs, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2003.htm.



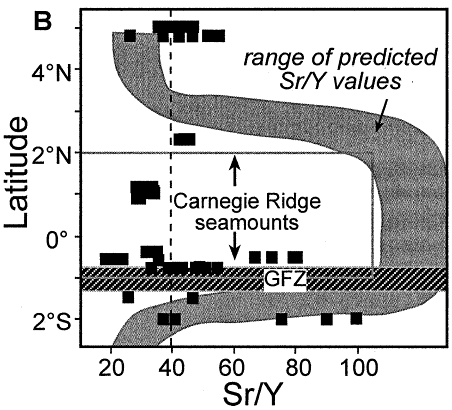


Figure 3. A: Graph of SiO_2 vs. latitude for Northern volcanic zone data. Range of putative slab melts (PSMs) (i.e., having predicted SiO_2 values and tectonic settings amenable to slab melting) is shown by gray ruled area. Subduction of Carnegie Ridge beneath Northern volcanic zone would affect area from 1°S to 2°N; subducted Grijalva Fracture Zone (GFZ) projects into continent at ~1°S. Predicted variation in SiO_2 with latitude, based on models of slab tearing and flat-slab subduction, is shown by broad gray curve. B: Graph of Sr/Y vs. latitude, filtered for SiO_2 = 63–69 wt%. Predicted range of Sr/Y values based on flat-slab models is shown by shaded gray region. Sr/Y values >40 (dashed line) are adakitic.

lously high Sr/Y ratios, corresponding to the expected compositions of slab melts. This does not appear to be the case (Fig. 2A); the Northern volcanic zone samples with the highest Sr/Y ratios are actually basalt and andesite from Sangay volcano, which is located above a steeply dipping slab and is therefore probably not producing a slab melt (Monzier et al., 1999). The remaining Northern volcanic zone samples do not show any particular association between Sr/Y and SiO_2, and, when compared with putative slab melts (Fig. 2A), the Northern volcanic zone rocks have overall lower Sr/Y ratios.

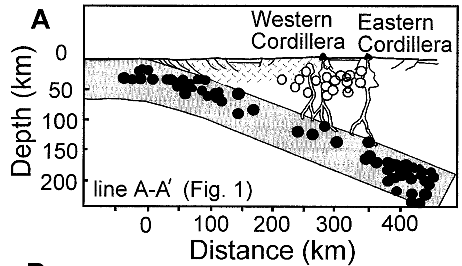
2. A graph of Sr/Y versus Y shows the Northern volcanic zone data and the ''adakite'' and ''normal arc'' fields as defined by Defant and Drummond (1990) (Fig. 2B). Compared to PSMs that have Sr/Y ratios ranging from 25 to 450, Northern volcanic zone volcanoes have Sr/Y ratios of <100 and in most cases <50. Those with Sr/Y > 50 have alternatively been suggested to be the result of low degrees of partial melting in the mantle wedge (Barragan et al., 1998). Thus, the case that Northern volcanic zone rocks are true slab melts is, at best, weak on the basis of geochemistry.

All other volcanoes in the data set straddle the boundary between adakite and ''normal'' arc rocks. This finding might suggest an evolutionary path from adakitic parents. This trend, however, can be readily explained by fractionation of amphibole, pyroxene, or garnet from normal arc magmas that depletes the melt in Y relative to Sr (Castillo et al., 1999) (Fig. 2B). Similarly, fractionation of plagioclase will create a similar trend but in the opposite direction by depleting the melt in Sr relative to Y. Although actual mineral assemblages are more complex, these models illustrate that control by fractionation of minerals expected to be stable in the deep crust may impart an adakitic signature.

3. If subduction of the Carnegie Ridge is controlling the formation of adakites, there should be a correlation between SiO_2 content and latitude: dacites should be concentrated in the area above the ridge but absent toward the north and south. Similarly, tearing of the slab should result in dacite compositions above the Grijalva fracture zone. A graph of SiO_2 versus latitude (Fig. 3A) shows that there is no significant correlation between SiO_2 content and the proposed trace of the Carnegie Ridge seamounts or the Grijalva fracture zone. This plot suggests that these features have little influence on distribution of dacite in the Northern volcanic zone. In fact, the samples with highest SiO_2, although located geographically above the ridge trajectory, do not have the corresponding Sr/Y that is consistent with an adakite signature (Fig. 3B).

A traverse of the Northern volcanic zone from north to south also shows no systematic latitudinal variation in adakitic signature defined in terms of Sr/Y (Fig. 3B). On this graph, Sr/Y ratios >40 are adakitic. If the Carnegie Ridge seamounts are the cause of flattening and this flattening is affecting volcanism, there should be a predominance of adakites in the arc segment above the ridge (1°S to 2°N), as predicted by the shaded region in Figure 3B. Samples from Sangay volcano have the most adakitic signature, although this signature has been attributed to lower-crustal melting. The most non-adakitic samples are from the region of the Carnegie Ridge.

For volcanoes in the Northern volcanic zone, given the lack of a consistent association between adakitic geochemistry and published flat-slab models, there is little compelling reason for calling on slab melting to produce the (albeit weak) adakitic signatures in some Northern volcanic zone magmas.



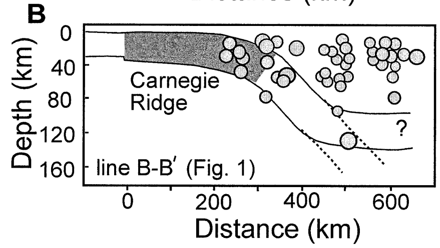


Figure 4. A: Steep-slab geometry projected onto line A–A′ (Fig. 1) overlying Carnegie Ridge, as interpreted by Lonsdale (1978). B: Flat-slab geometry as interpreted by Gutscher et al. (1999) along B–B′ (Fig. 1). Dashed lines added by us to illustrate no need for flat slab on basis of earthquake distributions.

TESTING THE SLAB-MELTING HYPOTHESIS: SUBDUCTION-ZONE ARCHITECTURE AND GEOPHYSICAL CONSTRAINTS

On the basis of seamount subduction studies and observed seismic data in the Northern volcanic zone, the large-scale effect of slab flattening owing to subduction of the Carnegie Ridge is questionable. Earthquake distribution in the Northern volcanic zone does not provide an unequivocal case for either steep or flat subduction angle (Figs. 1 and 4). Cross sections depicting slab angle (in Fig. 4A) have been used to show that the dip of the Nazca plate beneath Ecuador is steep (Lonsdale, 1978; Fig. 4A) or flat (Gutscher et al., 1999; Fig. 4B), depending on the latitude and azimuth of the traverse. The flat-slab interpretation is particularly unconvincing, given that this configuration is based on one earthquake. What is apparent from the seismic distribution is that earthquakes are sparse north of lat 1°S and that the deepest earthquakes (>150 km) cluster near central Ecuador and at 4°N (Fig. 1). Using seismic data to infer the subcrustal extension 400–600 km inland of the Carnegie Ridge (Spikings et al., 2001; Gutscher et al., 1999) leads to a somewhat circular argument, because the explanation for large (M > 7) earthquakes has been subduction of the Carnegie Ridge, and evidence for subduction of the ridge is the occurrence of these large earthquakes.

Although uplift in the Andean continental crust may reflect collision of the Carnegie Ridge seamounts with Ecuador, it does not necessarily reflect subduction of the ridge. Cahill and Isacks (1992) pointed out that although regions of flat subduction in the Andes correspond to a lack of volcanism, there is not an equally satisfying correlation between flat-slab locations and subducting seamounts. They suggested that the areas of flat-slab subduction in South America are more likely the result of variations in Gaussian curvature of the Nazca plate rather than ridge subduction. It has also been proposed that accretion may cause decoupling of the seamounts from the slab and mechanical underplating of basalt onto the base of the hanging wall (Ben-Avraham et al., 1981), or a seamount may subduct as an intact asperity (Kodiak Seamount; Eakins et al., 1999). Additional possibilities include shearing off of seamounts, underplating or subduction of seamounts piecemeal into the trench, accretion and/or erosion the front of the forearc region, and even subduction with no disruption in slab geometry whatsoever (Cloos, 1993, and references therein). It has been suggested that coupling of the seamounts to the crust and ''locking'' of the trench cause the seismic quiescence observed in other arcs (Scholz and Small, 1997).

ALTERNATIVE TO SLAB MELTING TO ACCOUNT FOR GEOCHEMISTRY OF NORTHERN VOLCANIC ZONE VOLCANOES

Both the geochemistry and distribution of volcanoes in the Northern volcanic zone can be explained by relatively simple models of mantle-wedge melting followed by assimilation and fractionation on ascent through the thick Andean crust. Melting of metamorphosed basalt, regardless of whether the source is the lower crust or the subducted slab, might be expected to produce a melt with high Sr/Y ratios ($>$40) and other geochemical characteristics typical of adakites. It has been shown that heating from mafic intrusions and latent heat of crystallization can initiate lower-crustal melting (Annen and Sparks, 2002; Petford and Gallagher, 2001). The thickness of the crust in the Northern volcanic zone is at least 50 km (corresponding to pressures of $\sim$17 kbar at the base of the crust), which, at temperatures above the wet basalt solidus, is in the eclogite to amphibolite facies (Cloos, 1993, and references therein).

We contend that a high Sr/Y signature is neither unique to slab melting nor insensitive to the residual mineral assemblage and fractionating phases. Caution should be used when applying the term ''adakite'' purely on the basis of the geochemical signature to imply a melt of subducted oceanic crust. Discerning between slab and lower-crustal melting presents a challenge to geochemists and would benefit from more compelling methods of discrimination than simple geochemical tests.

ACKNOWLEDGMENTS

The work was funded by National Science Foundation grant EAR-9980407 to Davidson. We have benefited greatly from logistical and geological assistance from Minard Hall and Patty Mothes of the Instituto de Geofisico, Quito, Ecuador. The manuscript was improved following reviews of Dennis Geist and Pat Castillo. We also thank Lisa Hammersley and Bill Moore for helpful discussions. Garrison acknowledges receipt of a dissertation year fellowship from the University of California, Los Angeles.

REFERENCES CITED

Annen, C., and Sparks, R.S.J., 2002, Effects of repetitive emplacement of basaltic intrusions on thermal evolution and melt generation in the crust: Earth and Planetary Science Letters, v. 203, p. 937–955.

Barragan, R., Geist, D., Hall, M., Larson, P., and Kurz, M., 1998, Subduction controls on the compositions of lavas from the Ecuadorian Andes: Earth and Planetary Science Letters, v. 154, p. 153–166.

Ben-Avraham, Z., Nur, A., Jones, D., and Cox, A., 1981, Continental accretion: From oceanic plateaus to allochthonous terranes: Science, v. 213, p. 47–54.

Bourdon, E., Eissen, J.-P., Monzier, M., Robin, C., and Martin, H., 2002, Adakite-like lavas from Antisana volcano (Ecuador): Evidence from slab melt metasomatism beneath the Andean Northern volcanic zone: Journal of Petrology, v. 43, p. 199–217.

Cahill, T.A., and Isacks, B.L., 1992, Seismicity and shape of the subducted Nazca plate: Journal of Geophysical Research, v. 97, p. 17,503–17,529.

Castillo, P.R., Janney, P.E., and Solidum, R.U., 1999, Petrology and geochemistry of Camiguin Island, southern Philippines: Insights to the source of adakites and other lavas in a complex arc setting: Contributions to Mineralogy and Petrology, v. 134, p. 33–51.

Cloos, M., 1993, Lithospheric buoyancy and collisional orogenesis: Subduction of oceanic plateaus, continental margins, island arcs, spreading ridges and seamounts: Geological Society of America Bulletin, v. 105, p. 715–737.

Davidson, J.P., 1996, Deciphering mantle and crustal signatures in subduction zone magmatism, *in* Bebout, G.E., et al., eds., Subduction: Top to bottom: American Geophysical Union Geophysical Monograph 96, p. 251–262.

Defant, M.J., and Drummond, M.S., 1990, Derivation of some modern arc magmas by melting of young subducted lithosphere: Nature, v. 347, p. 662–665.

Defant, M.J., and Kepezhinskas, P., 2001, Evidence suggests slab melting in arc magmas: Eos (Transactions, American Geophysical Union), v. 82, p. 65–69.

Drummond, M.S., and Defant, M.J., 1990, A model for trondhjemite-tonalite-dacite genesis and crustal growth via slab melting: Archean to modern comparisons: Journal of Geophysical Research, v. 95, p. 21,503–21,521.

Drummond, M.S., Defant, M.J., and Kepezhinskas, P.K., 1996, Petrogenesis of slab-derived trondhjemite-tonalite-dacite/adakite magmas, *in* Brown, M., et al., eds., The third Hutton symposium on the origin of granites and related rocks: Geological Society of America Special Paper 315, p. 205–215.

Eakins, B.W., Lonsdale, P.F., Massell, C.G., and Rathburn, A.E., 1999, Kodiak Seamount in the eastern Aleutian Trench: Submersible study of an intact guyot entering the subduction zone: Eos (Transactions, American Geophysical Union), v. 80, p. 1180.

Feininger, T., and Seguin, M.K., 1983, Simple Bouguer gravity anomaly field and the inferred crustal structure of continental Ecuador: Geology, v. 11, p. 40–44.

Gutscher, M.A., Malavieille, J., Lallemand, S., and Collot, J.Y., 1999, Tectonic segmentation of the north Andean margin: Impact of the Carnegie Ridge collision: Earth and Planetary Science Letters, v. 168, p. 255–270.

Gutscher, M.-A., Maury, R., Eissen, J.-P., and Bourdon, E., 2000, Can slab melting be caused by flat slab subduction?: Geology, v. 28, p. 535–538.

Kay, R.W., 1978, Aleutian magnesian andesites: Melts from subducted Pacific Ocean crust: Journal of Volcanology and Geothermal Research, v. 4, p. 117–132.

Lonsdale, P., 1978, Ecuadorian subduction system: American Association of Petroleum Geologists Bulletin, v. 62, p. 2454–2477.

Monzier, M., Robin, C., Hall, M.L., Cotten, J., Mothes, P., Eissen, J.-P., and Samaniego, P., 1997, Les Adakites d'Equateur: Modele preliminaire Académie des Sciences Comptes Rendus, ser. II, Sciences de la Terre et des Planetes, v. 324, no. 7, p. 545–552.

Monzier, M., Robin, C., Samaniego, P., Hall, M.L., Cotten, J., Mothes, P., and Arnaud, N., 1999, Sangay volcano, Ecuador: Structural development, present activity and petrology: Journal of Volcanology and Geothermal Research, v. 90, p. 49–79.

Peacock, S.M., Rushmer, T., and Thompson, A.B., 1994, Partial melting of subducting oceanic crust: Earth and Planetary Science Letters, v. 121, p. 227–244.

Petford, N., and Gallagher, K., 2001, Partial melting of mafic (amphibolitic) lower crust by periodic influx of basaltic magma: Earth and Planetary Science Letters, v. 193, p. 483–499.

Rapp, R.P., and Watson, B.E., 1995, Dehydration melting of metabasalt at 8–32 kbar: Implications for continental growth and crust-mantle recycling: Journal of Petrology, v. 36, p. 891–931.

Rollinson, H., 1993, Using geochemical data: Evaluation, presentation, interpretation: Essex, England, Pearson Education Limited, Prentice Hall Publishers, 352 p.

Rushmer, T., 1991, Partial melting of two amphibolites: Contrasting experimental results under fluid-absent conditions: Contributions to Mineralogy and Petrology, v. 107, p. 41–59.

Scholz, C., and Small, C., 1997, The effect of seamount subduction on seismic coupling: Geology, v. 25, p. 487–490.

Sen, C., and Dunn, T., 1994, Dehydration melting of a basaltic composition amphibolite at 1.5 and 2.0 GPa: Implications for the origin of adakites: Contributions to Mineralogy and Petrology, v. 117, p. 394–409.

Spikings, R.A., Winkler, W., Seward, D., and Handler, R., 2001, Along-strike variations in the thermal and tectonic response of the continental Ecuadorian Andes to the collision with heterogeneous oceanic crust: Earth and Planetary Science Letters, v. 186, p. 57–73.

Manuscript received 17 December 2002
Revised manuscript received 19 February 2003
Manuscript accepted 21 February 2003

Printed in USA