

Igniting flare-up events in Cordilleran arcs

Mihai N. Ducea

Mark D. Barton

University of Arizona, Department of Geosciences, Tucson, Arizona, 85721, USA

ABSTRACT

High-flux pulses of magmatism that make up most of the exposed North American Cordilleran arcs are derived primarily from upper plate lithospheric source materials, and not the mantle wedge as most models would predict, based on a compilation of thousands of previously published Sr, Nd, and O isotopic data. Mass balance calculations show that no more than 50% of that mass can be mantle-derived. Flare-ups must have fundamentally developed simultaneously with crustal/lithospheric thickening, thus implying a connection. Subduction erosion from the trench side, and retroarc shortening from the foreland side are the main tectonic shortening processes that operate in conjunction with high flux magmatism during subduction, and therefore are likely triggers for flare-up events in arc. These arcs represent the sites of crustal differentiation, and thus contribute to net continental growth, only if dense residual lower crust was returned to the convective mantle. Isotopic data shown here suggest that if convective removal of batholithic roots takes place, it must be a consequence and not a cause of episodic flare-ups. The Altiplano-Puna Volcanic Complex in South America may be the most recent continental arc segment in flare-up mode.

Keywords: subduction, isotopes, arc magmatism, flare-up, delamination.

INTRODUCTION

Models that incorporate wet melting of the mantle wedge above a subduction zone followed by minor contamination with upper plate lithospheric materials have been proposed for the origin of both oceanic and continental arcs (Davies and Bickle, 1991; Eiler, 2003; Gill, 1981), however, they are fundamentally derived from studies of island arcs. These models have been successfully tested with experimental studies (Grove et al., 2006). This paper addresses some of the limiting constraints on the “exportability” of the island-arc template to arcs that formed on continental upper plate, particularly those arcs that reach the thermal and structural maturity of the Cordilleran orogen in North America. Cordilleran magmatism is manifested through the presence of large, pluton-flooded trench parallel areas (batholiths) that are thought to represent the intrusive roots of volcanic arcs found in subduction systems worldwide.

The Late Mesozoic–Early Cenozoic plutonic roots of the western North American arc system (Cordilleran coastal batholiths) are found along its convergent margin with the Pacific oceanic plate (Anderson, 1990). Four major coastal arc segments are known in North America: the Peninsular Ranges, the Sierra Nevada, the Idaho, and the Coast Mountains batholiths. Regional isotopic studies of continental arcs commonly stress the dominant contribution of upper plate materials to the arc (DePaolo, 1981; Farmer and DePaolo, 1983; Gromet and Silver, 1987; Hildreth and Moorbath, 1988; Taylor, 1988). They develop in relatively short, high-flux magmatic episodes separated by longer periods of relative quiescence (Armstrong, 1988). Possible changes in chemical and isotopic composition of batholiths during flare-ups could fingerprint triggering processes, but such temporal patterns have not been investigated in detail.

We interpret previously published age, flux, and isotopic data on the major North American batholiths. Some, but not all, of the conclusions presented here are not new—they are presented here because it appears that after a decade or two of new data acquisition, there is now overwhelming support for them over their competing alternatives.

DATA

We compiled a database that contains previously published petrographic, age, and Sr, Nd, and O isotopic compositions of North American Cordilleran plutonic rocks, in part building upon earlier efforts (Barton

et al., 1988). These compilation efforts have now merged into a unique format as the NAVDAT database (<http://navdat.kgs.ku.edu>; see the GSA Data Repository¹), which includes western North America plutonic and volcanic data (Walker et al., 2004). Radiogenic isotopic data were determined as whole-rock values, whereas in the case of oxygen isotopes, we used mineral and whole-rock data and calculated whole-rock $\delta^{18}\text{O}$ from mineral compositions and mode, where applicable.

A plot of ϵ_{Nd} initial (i.e., age-corrected) values against latitude is shown for North American batholiths in Figure 1. Palinspastic corrections were applied to arc segments that are out of place, such as Salinia

¹GSA Data Repository item 2007254, guide to using the NAVDAT electronic resources, and a bibliographic list of papers used in compiling data for Figures 1 and 2, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

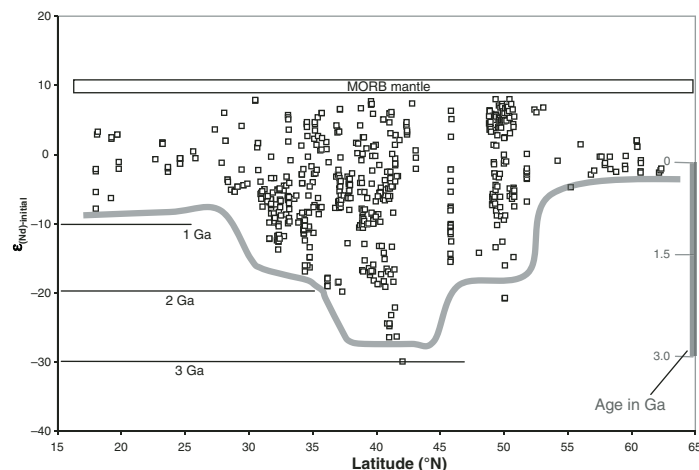


Figure 1. Initial ϵ_{Nd} whole-rock values for calc-alkaline rocks of North American coastal batholiths. Nd isotopic compositions of mid-oceanic ridge basalts (MORB) are also shown. ϵ_{Nd} of basement rocks of various ages were calculated using DePaolo (1988); see text.

in central California. There is an excellent correlation between the most negative pluton ϵ_{Nd} and the age distribution of basement rocks at any given location (Barton, 1996). There is also a good negative correlation between Nd and Sr isotopes (not pictured). The average initial ϵ_{Nd} for the Cordillera is -4.35 , and the average initial $^{87}Sr/^{86}Sr$ is 0.7075 . The great majority of the analyzed whole rocks and quartz separates in the Cordilleran batholiths display enrichments in $\delta^{18}O$ relative to mantle values. The average whole-rock $\delta^{18}O$ for the Cordillera is 8.5‰ (relative to SMOW), and the average quartz $\delta^{18}O$ is 9.0‰ , whereas mantle values worldwide are $5\text{--}6\text{‰}$ (Eiler et al., 2000; Taylor, 1988). Quartz $\delta^{18}O$ is significantly more robust to hydrothermal alteration than whole rock, feldspar, or other minerals found in granitoids, which is why it has been commonly measured as an alternative to whole-rock values in studies of granitoids. Values of quartz $\delta^{18}O$ that lie outside the range typical for the upper mantle indicate that the measured rock samples, or their precursors in the case of igneous rocks, have at some point interacted with the hydrosphere at or near Earth's surface; therefore they contain a significant crustal component.

The isotopic data were also used in combination with magmatic flux data (CONTACT88; Barton et al., 1988; NAVDAT does not contain flux data). The databases can be combined for parts of three arc segments where significant numbers of age and isotopic analyses exist: the Sierra Nevada, the northern Peninsular Ranges (combined here as one arc), and the Coast Mountains batholiths. There is a correlation between ϵ_{Nd} (and $^{87}Sr/^{86}Sr$) and magmatic flux in these arcs—episodes of high-flux magmatism coincide with negative ϵ_{Nd} excursions (Fig. 2). Secular isotopic excursions shown in Figure 2 are typically also spatial excursions toward the continental interior, which does not alter the interpretations discussed here.

MAGMATIC EPISODICITY AND ISOTOPES

All North American continental arcs record high-flux episodes separated by magmatic lulls (Armstrong, 1988; Barton, 1996; Barton et al., 1988). These flare-up episodes can generate as much as 80%–90% of the arc magmatic addition rates (Reymer and Schubert, 1984) within periods of 10–15 m.y. (Saleeby, 1990). Magmatic addition rates into the upper-middle crust are $\sim 75\text{--}100\text{ km}^3/\text{km m.y.}$ during flare-ups and $10\text{--}20\text{ km}^3/\text{km m.y.}$ during lulls (Coleman et al., 1992; Ducea, 2001; Silver and Chappell, 1988). What process triggers magmatic flare-ups in arcs? Correlations between magmatic fluxes and rates of plate convergence or plate margin obliquity are not obvious from the data. From a regional tectonic perspective, several drivers have been proposed to trigger flare-ups, and they fall into two main categories: (1) lithospheric extension and/or delamination (Lee et al., 2006), and (2) intra-crustal and/or lithospheric shortening (Ducea, 2001).

Extension or convective removal would likely result in an influx of “fresh,” asthenospheric mantle and related melts (Kay and Kay, 1991). However, Cordilleran rocks have low ϵ_{Nd} for all plutonic rocks during episodes of high-flux magmatism (Fig. 2), including mafic rocks, where avail-

able (Coleman et al., 1992; Kidder et al., 2003). It is therefore unlikely that any form of convective removal of the lower crust, upper mantle, or both, could be responsible for triggering Cordilleran flare-ups. The geologic record shows that all major flare-ups in North American batholiths formed during times of compression, in concert with a foreland fold and thrust belt, not with back-arc extensional basins. Crustal (lithospheric) thickening was proposed to be the cause of flare-up trigger in the California arc (Ducea, 2001). Specifically, shortening of the North American plate from the foreland side due to the Sevier orogeny could have ignited the late Cretaceous flare-up that built much of the Sierra Nevada arc, as a result of thickening and subsequent heating due to thermal relaxation (DeCelles, 2004). Large-scale, crustal-derived melting is complemented by a baseline, arc-mantle wedge flux of basalt, and heat from this flux contributes significantly to igniting a deep crustal flare-up (Dufek and Bergantz, 2005).

MOSTLY UPPER PLATE MAGMAS

The large number of negative ϵ_{Nd} in the North American plutons rules out the possibility that slab-derived melts (Drummond and Defant, 1990) could be a major contributor to the mass balance of batholiths (cf. DePaolo, 1981). Oceanic crust ϵ_{Nd} values and underlying lithosphere do not typically depart from MORB values of $+12(\pm 3)$, even after strong seawater interaction (Gregory and Taylor, 1981).

The isotopic compositions of North American batholiths correlate with the Nd model age of the local basement (Fig. 1) (Farmer and DePaolo, 1983). A crustal age corresponds very roughly to a value of $\epsilon_{Nd} = -10 \times t$ (DePaolo, 1988), where t is the crustal residence age in billions of years. These data indicate that the batholiths have not undergone major lateral transport from their source terrains following their emplacement. More importantly, the average batholith is a mixture of 15%–25% MORB ($\epsilon_{Nd} = 12$) and local basement, assuming equal Nd concentrations in the two end-member melts. Melts with MORB isotopic compositions could, in principle, be derived from the subducting slab, as well as other mantle reservoirs. In the limiting case where the MORB component is derived entirely from subducting oceanic crust, such a slab-derived component could not produce more than $\sim 20\%$ of the mass of North American batholiths. In this calculation, possible contributions from subducted sediments (Albarede, 1998; Davidson and Arculus, 2006; Plank, 2005) are ignored—they cannot be distinguished using the isotopes compiled here from framework continental, upper plate materials in arcs. This leaves open the possibility that sediments that undergo subduction erosion (Clift and Vannucchi, 2004; Scholl and von Huene, 2007) might be major contributors to the arc budgets. However, sediments are thought to undergo dehydration reactions at lower temperatures when the slab is still in a forearc position (Peacock, 2003), which should diminish their melt fertility under the arcs. North American average batholith compositions also require a bulk source that is mafic to intermediate in silica concentration and hydrous, equivalent to an amphibolite in the lower crust (Ducea, 2002). The average sedimentary input into a trench facing a large continent is unlikely to be “immature” or basaltic in composition. Their Nd isotopic composition is an average reflecting the mix of terrigenous (low ϵ_{Nd}) and pelagic (ϵ_{Nd}) inputs; there is no reason why subducted sediment, if it is a major source of magmatic flare-ups, would cause a negative excursion in the ϵ_{Nd} composition of the arc. Moreover, given typical sediment subduction fluxes (Plank and Langmuir, 1998), it is difficult to account for significant mass fractions of arc flare-ups by “en masse” melting of subducting sediments.

In summary, Nd isotopes provide strong evidence that Cordilleran arcs are derived primarily from the “upper plate,” that is, the overlying continental crust and mantle lithosphere. Shortening from the forearc side and subduction erosion processes can plausibly provide such materials in the source regions of arcs, and future work is certain to illuminate our understanding of this topic. Underthrusting from the back arc (continental) side is our preferred shortening model for delivering crustal materials to the arc-source regions during or prior to times of high magmatic

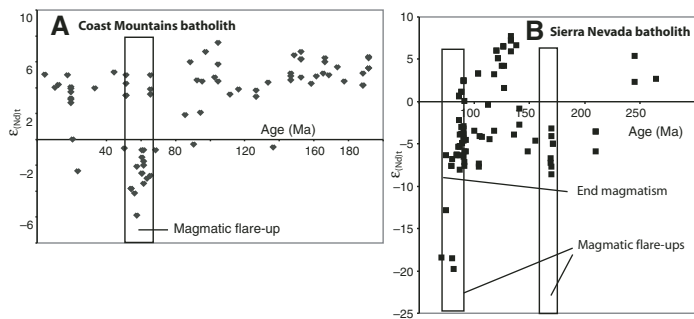


Figure 2. Initial ϵ_{Nd} whole rock values, as a function of crystallization age for plutons in the (A) Coast Mountains batholith (British Columbia) and (B) Sierra Nevada batholith.

fluxes, at least in the case of North American batholiths, although we do not exclude the independent effect of prolonged subcrustal thermal input during sustained subduction episodes.

HOW MUCH MANTLE-DERIVED MATERIAL?

Sorting out the mantle versus crustal contributions to the arcs has been an important task in isotope geochemistry of igneous rocks (Albarede, 1998), and has proven to be difficult because mantle and crustal signatures can overlap for several isotopic systems. Some of the mass added to the arc must come from the mantle wedge (Arculus, 1994), as evidenced by gabbroic and basaltic material in these arcs (Kidder et al., 2003) and required by heat budget considerations (Dufek and Bergantz, 2005; Sisson et al., 2005). However, the average composition of the Cordilleran upper 30 km is tonalitic to granodioritic, with relatively minor mafic rocks (Silver and Chappell, 1988).

The $\delta^{18}\text{O}$ data available for all batholiths suggest that there is a significant crustal component involved in magmatism. The average $\delta^{18}\text{O}$ for North American batholiths is 8.5‰, pointing to a significant crustal component by mass. For a cratonic North American crustal $\delta^{18}\text{O}$ average of ~10‰ (e.g., Taylor, 1988), and an upper bound mantle value of 6‰ (Eiler et al., 2000), at least some 50% of the arcs' mass must be recycled crust. The oxygen and radiogenic isotopic signatures are inherited primarily from the source regions, because assimilation of wall-rock materials at shallow or even mid-crustal depths probably produces only minor changes in the composition of magmas. This result has long been established for the northern Peninsular Ranges batholith (Gromet and Silver, 1987; Taylor, 1988), and appears to hold for the majority of the North American batholithic belts. Models that call upon extraction of batholithic rocks entirely by fractionation or re-melting of young mafic additions in the roots of the arcs (Petford et al., 1996) do not pass the oxygen isotope test for the North American Cordillera. A significant volume of source rock was at or near the Earth's surface prior to its transport in the "source region," regardless of the specific tectonic process that accommodated transport (subduction erosion, retroarc underthrusting, etc.).

In the case of some 30-km-thick felsic batholiths (Fliedner et al., 2000), the more their mass is distilled from new mafic additions from the mantle, the more residue is required. The mass-of-residue to mass-of-melt ratio in a batholith is 1/1 to 3/1 (Ducea, 2002). A batholith that contains 50% mantle-derived material requires at least 30 km of basaltic underplate in the arc, and a more reasonable estimate is twice that. For a reasonable average fraction of melt in the mantle wedge to be 5%, a mantle column of at least 600 km must have experienced melting beneath arcs (a similar conclusion was reached by Coleman et al. [1992]). The requirement that this enormous mass is produced in short periods of magmatic flare-ups is inconsistent with models that imply that "fresh," melt-fertile, wedge material is being fed to the sub-arc regions at plate motion rates.

All these observations point to the interpretation that mantle input to the North American arcs must be less important than some models suggest (Petford et al., 1996). Additional studies will be required to refine this estimate, but available data clearly point to a significant role of pre-existing crust in the mass budget of the North American arcs.

MODERN AND YOUNG EQUIVALENTS

A survey of compositional, isotopic, and age data for recent and modern continental arcs using the GEOROC database (<http://georoc.mpch-mainz.gwdg.de/georoc/>) indicates that there are no modern arcs currently at their peak of "flare-up" mode, unless large batholiths are presently forming in areas with relatively low volcanic fluxes; however, there is no seismic evidence that this might be the case. Some of the signature features of the North American arcs, such as the "enriched" isotopic ratios found even in gabbros and basalts, are also not typical of modern arcs, but rather, are exceptions. The majority of analyzed rocks, ranging in composition from basalt to rhyolites, have positive ϵ_{Nd} values.

One exception is the late Miocene to present-day volcanism in the Altiplano-Puna Volcanic Complex, located in the core of the Andean orogen (de Silva et al., 2006; Kay et al., 2005). An enormous outpour of calc-alkaline, mostly dacitic ignimbrites, peaked in the Pliocene and continues today in its waning stages. The upper to mid-crust is partially molten over an area ~200 km × 500 km (Zandt et al., 2003). The Altiplano-Puna Volcanic Complex has all the attributes typical of an arc flare-up product—it produced granodioritic magmas at a rate many times in excess of normal arc fluxes; it is located in an area where the crust became very thick, >65 km (Beck and Zandt, 2002), after significant shortening in the foreland; and it has a "lithospheric" baseline $^{87}\text{Sr}/^{86}\text{Sr}$ of ~0.705 (Kay and Mopodosis, 2001) in the more mafic products. The thick crust and mantle lithosphere and the presence of eclogite facies rocks of probable arc residual origin beneath the region (Gilbert et al., 2006) make it unlikely that a recent convective removal event has triggered this high-flux event. This example suggests that the flare-up events documented in the North American batholiths are most likely accompanied by a sizable volcanic equivalent.

RELEVANCE TO CRUSTAL GROWTH

Mantle plumes and/or island arcs are hypothesized to be the primary settings for crustal generation (e.g., Stein and Goldstein, 1996). However, melting processes associated with mantle plumes and island arcs generate mafic rocks, not the intermediate and felsic compositions of the continental crust (Rudnick, 1995). A second, "distillation" stage, probably in a continental-arc environment (Hollister and Andronicos, 2006), is required to refine ~30-km-thick crust with the felsic-intermediate, calc-alkaline composition of the North American arcs (Fliedner et al., 2000). Data summarized here point to a large amount of preexisting crust involved in the making of the North American arcs. Cordilleran magmatic events are important episodes of crustal distillation and less important sites of crustal addition from the mantle, particularly mantle that was not isolated from convection. The greatest unknown in deciphering crustal growth is the fate of residues that must complement granitoid magmatism at depth. The leading hypothesis is that these residues founder in the mantle because of their negative buoyancy (Kay and Kay, 1991). If this process does occur, as recent geophysical evidence seems to support (Zandt et al., 2004), it must take place after high-flux episodes. This is also evident from the fact that it is precisely those high-flux magmatic events that generate foundering-prone, sizable roots (Ducea, 2002).

ACKNOWLEDGMENTS

Supported by National Science Foundation grants EAR-0309885, EAR-0622334, and EAR95-27009.

REFERENCES CITED

- Albarede, F., 1998, The growth of continental crust: *Tectonophysics*, v. 296, p. 1–14, doi: 10.1016/S0040-1951(98)00133-4.
- Anderson, J.L., ed., 1990, The nature and origin of Cordilleran magmatism: Boulder, Colorado, Geological Society of America Memoir 174, 405 p.
- Arculus, R.J., 1994, Aspects of magma genesis in arcs: *Lithos*, v. 33, p. 189–208, doi: 10.1016/0024-4937(94)90060-4.
- Armstrong, R.L., 1988, Mesozoic and early Cenozoic magmatic evolution of the Canadian Cordillera, in Clark, S.P., Burchfiel, B.C., and Supper, J., eds., *Processes in continental lithospheric deformation: A symposium to honor John Rodgers*: Boulder, Colorado, Geological Society of America, Special Papers, v. 218, p. 55–91.
- Barton, M.D., 1996, Granitic magmatism and metallogeny of southwestern North America: *Transactions of the Royal Society of Edinburgh: Earth Sciences*, v. 87, p. 261–280.
- Barton, M.D., Battles, D.A., Bebout, G.E., Capo, R.C., Christensen, J.N., Davis, S.R., Hanson, R.B., Michelsen, C.J., and Trim, H.E., 1988, Mesozoic contact metamorphism in the western United States, in Ernst, W.G., ed., *Metamorphism and crustal evolution of the western United States: Volume 7: Englewood Cliffs, New Jersey, Prentice Hall*, p. 110–178.
- Beck, S.L., and Zandt, G., 2002, The nature of orogenic crust in the central Andes: *Journal of Geophysical Research*, v. 107, p. 2230, doi:10.1029/2000JB000124.

- Clift, P., and Vannucchi, P., 2004, Controls on tectonic accretion versus erosion in subduction zones: Implications for the origin and recycling of the continental crust: *Review of Geophysics*, v. 42, 31 p.
- Coleman, D., Frost, T., and Glazner, A.F., 1992, Evidence from the Lamarck granodiorite for rapid late Cretaceous crust formation in California: *Science*, v. 258, p. 1924–1926, doi: 10.1126/science.258.5090.1924.
- Davidson, J.P., and Arculus, R.J., 2006, The significance of Phanerozoic arc magmatism in generating continental crust, in Rushmer, T., and Brown, M., eds., *Evolution and Differentiation of the Continental Crust*: Cambridge, UK, Cambridge University Press, p. 135–172.
- Davies, J.H., and Bickle, M.J., 1991, A physical model for the volume and composition of melt produced by hydrous fluxing above subduction zones: *Philosophical Transactions of the Royal Society of London*, v. 335, p. 355–364, doi: 10.1098/rsta.1991.0051.
- de Silva, S.L., Zandt, G., Trumbull, R., Viramonte, J., Salas, G., and Jimenez, N., 2006, Large-scale silicic volcanism in the Central Andes—A tectonomagmatic phenomenon, in De Natale, P., Troise, C., and Kilburn, C., eds., *Mechanisms of activity and unrests at large calderas*: Geological Society of London, v. 269, p. 47–63.
- DeCelles, P.G., 2004, Late Jurassic to Eocene evolution of the Cordilleran thrust belt and foreland basin systems, western U.S.A.: *American Journal of Science*, v. 304, p. 105–168, doi: 10.2475/ajs.304.2.105.
- DePaolo, D.J., 1981, A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra-Nevada and Peninsular Ranges, California: *Journal of Geophysical Research*, v. 86, p. 470–488.
- DePaolo, D.J., 1988, Neodymium isotope geochemistry—An introduction: Berlin, Springer Verlag, 187 p.
- 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, Solid Earth and Planets*, v. 95, p. 21503–21521.
- Ducea, M.N., 2001, The California arc: Thick granitic batholiths, eclogitic residues, lithospheric-scale thrusting, and magmatic flare-ups: *Geological Society of America, GSA Today*, v. 11, p. 4–10.
- Ducea, M.N., 2002, Constraints on the bulk composition and root foundering rates of continental arcs: A California arc perspective: *Journal of Geophysical Research, Solid Earth and Planets*, v. 107.
- Dufek, J., and Bergantz, G.W., 2005, Lower crustal magma genesis and preservation: A stochastic framework for the evaluation of basalt-crust interaction: *Journal of Petrology*, v. 46, p. 2167–2195, doi: 10.1093/petrology/egi049.
- Eiler, J.M., ed., 2003, Introduction: Inside the subduction factory: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 138, 311 p.
- Eiler, J.M., Crawford, A., Elliott, T., Farley, K.A., Valley, J.W., and Stolper, E.M., 2000, Oxygen isotope geochemistry of oceanic-arc lavas: *Journal of Petrology*, v. 41, p. 229–256, doi: 10.1093/petrology/41.2.229.
- Farmer, G.L., and DePaolo, D.J., 1983, Origin of Mesozoic and Tertiary granite in the Western United States and implications for pre-Mesozoic crustal structure: 1. Nd and Sr isotopic studies in the geocline of the Northern Great Basin: *Journal of Geophysical Research*, v. 88, p. 3379–3401.
- Fliedner, M.M., Klempner, S.L., and Christensen, N.I., 2000, Three-dimensional seismic model of the Sierra Nevada arc, California, and its implications for crustal and upper mantle composition: *Journal of Geophysical Research, Solid Earth and Planets*, v. 105, p. 10899–10922, doi: 10.1029/2000JB900029.
- Gilbert, H., Beck, S., and Zandt, G., 2006, Lithospheric and upper mantle structure of central Chile and Argentina: *Geophysical Journal International*, v. 165, p. 383–398, doi: 10.1111/j.1365-246X.2006.02867.x.
- Gill, J., 1981, *Orogenic andesites and plate tectonics*: Berlin, Springer Verlag, 390 p.
- Gregory, R.T., and Taylor, H.P., 1981, An oxygen isotope profile in a section of Cretaceous oceanic-crust, Samail ophiolite, Oman—Evidence for $\delta^{18}\text{O}$ buffering of the oceans by deep (<5 km) seawater-hydrothermal circulation at mid-ocean ridges: *Journal of Geophysical Research*, v. 86, no. B4, p. 2737–2755.
- Gromet, L.P., and Silver, L.T., 1987, REE variations across the Peninsular Ranges batholith—Implications for batholithic petrogenesis and crustal growth in magmatic arcs: *Journal of Petrology*, v. 28, p. 75–125.
- Grove, T.L., Chatterjee, N., Parman, S.W., and Medard, E., 2006, The influence of H_2O on mantle wedge melting: *Earth and Planetary Science Letters*, v. 249, p. 74–89, doi: 10.1016/j.epsl.2006.06.043.
- Hildreth, W., and Moorbath, S., 1988, Crustal contributions to arc magmatism in the Andes of Central Chile: *Contributions to Mineralogy and Petrology*, v. 98, p. 455–489, doi: 10.1007/BF00372365.
- Hollister, L.S., and Andronicos, C.L., 2006, Formation of new continental crust in Western British Columbia during transpression and transtension: *Earth and Planetary Science Letters*, v. 249, p. 29–38, doi: 10.1016/j.epsl.2006.06.042.
- Kay, R.W., and Kay, S.M., 1991, Creation and destruction of the lower continental crust: *Geologische Rundschau*, v. 80, p. 259–270, doi: 10.1007/BF01829365.
- 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*, v. 117, p. 67–88, doi: 10.1130/B25431.1.
- Kay, S.M., and Mopodozis, C., 2001, Central Andean ore deposits linked to evolving shallow subduction systems and thickening crust: *Geological Society of America, GSA Today*, v. 11, p. 4–11.
- Kidder, S., Ducea, M., Gehrels, G., Patchett, P.J., and Vervoort, J., 2003, Tectonic and magmatic development of the Salinian Coast Ridge Belt, California: *Tectonics*, v. 22, p. 1058.
- Lee, C.T., Cheng, X., and Horodyskyj, U., 2006, The development and refinement of continental arcs by primary basaltic magmatism, garnet pyroxenite accumulation, basaltic recharge and delamination: Insights from the Sierra Nevada, California: *Contributions to Mineralogy and Petrology*, v. 151, p. 222–242, doi: 10.1007/s00410-005-0056-1.
- Peacock, S.M., 2003, Thermal structure and metamorphic evolution of subducting slabs, in Eiler, J., ed., *Inside the subduction factory*: Washington, D.C., American Geophysical Union, Geophysical Monograph Series, v. 138, p. 7–22.
- Petford, N., Atherton, M.P., and Halliday, A.N., 1996, Rapid magma production rates, underplating and remelting in the Andes: Isotopic evidence from northern-central Peru (9–11°S): *Journal of South American Earth Sciences*, v. 9, p. 69–78, doi: 10.1016/0895-9811(96)00028-4.
- Plank, T., 2005, Constraints from thorium/lanthanum on sediment recycling at subduction zones and the evolution of the continents: *Journal of Petrology*, v. 46, p. 921–944, doi: 10.1093/petrology/egi005.
- Plank, T., and Langmuir, C.H., 1998, The chemical composition of subducting sediment and its consequences for the crust and mantle: *Chemical Geology*, v. 145, p. 325–394, doi: 10.1016/S0009-2541(97)00150-2.
- Reymer, A., and Schubert, G., 1984, Phanerozoic addition rates to the continental-crust and crustal growth: *Tectonics*, v. 3, p. 63–77.
- Rudnick, R.L., 1995, Making continental crust: *Nature*, v. 378, p. 571–578, doi: 10.1038/378571a0.
- Saleeby, J.B., 1990, Progress in tectonic and petrogenetic studies in an exposed cross-section of young (~100 Ma) continental crust, southern Sierra Nevada, California, in Salisbury, M.H., and Fountain, D.M., eds., *Exposed crustal sections of the continental crust*: Norwell, Massachusetts, Kluwer Academic Publishers, p. 137–158.
- Scholl, D.W., and von Huene, R., 2007, Crustal recycling at modern subduction zones applied to the past—issues of growth and preservation of continental basement, mantle geochemistry, and supercontinent reconstruction: *Geological Society of America Special Paper* (in press).
- Silver, L.T., and Chappell, B., 1988, The Peninsular Ranges batholith: An insight into the Cordilleran batholiths of southwestern North America: *Transactions of the Royal Society of Edinburgh, Earth Sciences*, v. 79, p. 105–121.
- Sisson, T.W., Ratajeski, K., Hankins, W.B., and Glazner, A.F., 2005, Voluminous granitic magmas from common basaltic sources: *Contributions to Mineralogy and Petrology*, v. 148, p. 635–661, doi: 10.1007/s00410-004-0632-9.
- Stein, M., and Goldstein, S.L., 1996, From plume head to continental lithosphere in the Arabian-Nubian shield: *Nature*, v. 382, p. 773–778, doi: 10.1038/382773a0.
- Taylor, H.P., 1988, Oxygen, hydrogen, and strontium isotopic constraints on the origin of granites: *Transactions of the Royal Society of Edinburgh, Earth Sciences*, v. 79, p. 317–338.
- Walker, J.D., Bowers, T.D., Glazner, A.F., Farmer, G.L., and Carlson, R.W., 2004, Creation of a North American volcanic and plutonic rock database (NAVDAT): *Geological Society of America Abstracts with Programs*, v. 36, no. 4, p. 9.
- Zandt, G., Gilbert, H., Owens, T.J., Ducea, M., Saleeby, J., and Jones, C.H., 2004, Active foundering of a continental arc root beneath the southern Sierra Nevada in California: *Nature*, v. 431, p. 41–46, doi: 10.1038/nature02847.
- Zandt, G., Leidig, M., Chmielowski, J., Baumont, D., and Yuan, X.H., 2003, Seismic detection and characterization of the Altiplano-Puna magma body, central Andes: *Pure and Applied Geophysics*, v. 160, p. 789–807, doi: 10.1007/PL00012557.

Manuscript received 22 March 2007

Revised manuscript received 16 June 2007

Manuscript accepted 28 June 2007

Printed in USA