spread phenomenon, these studies may have overestimated the role of tectonic denudation as a cause of cooling. If rapid cooling reflects the infiltration of cold, surface-derived fluids, then cooling rates cannot be used to constrain uplift rates. Rather, the timing of rapid cooling reflects the transport of lower plate rocks into the zone of fluid infiltration. Thus, quantitative constraints on uplift rates associated with extensional detachment faults should be determined with the use of well-constrained field relations and pressure-temperature-time data based on thermobarometry and radiogenic age determinations.

REFERENCES AND NOTES

1. M. D. Crittenden, P. J. Coney, G. H. Davis, Eds., *Geol. Soc. Am. Mem.* **153** (1980).
2. B. Wernicke, *Nature* **291**, 645 (1981).
3. R. L. Armstrong, *Annu. Rev. Earth Planet. Sci.* **10**, 129 (1982).
4. B. Wernicke, *J. Geophys. Res.* **100**, 20159 (1995).
5. E. M. Anderson, *The Dynamics of Faulting* (Oliver and Boyd, Edinburgh, ed. 1, 1942).
6. J. A. Jackson, in *Continental Extensional Tectonics*, M. P. Coward, J. F. Dewey, P. L. Hancock, Eds. (Geological Society of London, Special Publ. 28, London, 1987), pp. 3–18.
7. W. R. Buck, *Tectonics* **7**, 959 (1988).
8. B. Wernicke, *Can. J. Earth Sci.* **22**, 108 (1985).
9. ____ and G. J. Axen, *Geology* **16**, 848 (1988).
10. W. R. Buck, F. Martinez, M. S. Steckler, J. R. Cochran, *Tectonics* **7**, 213 (1988).
11. A. Yin, *ibid.* **8**, 469 (1989).
12. G. A. Davis and G. S. Lister, *Geol. Soc. Am. Spec. Pap.* **218**, 133 (1988).
13. G. J. Axen, *J. Geophys. Res.* **97**, 8979 (1992).
14. R. K. Dokka and S. H. Lingrey, in *Cenozoic Paleogeography of the Western United States*, J. M. Armentrout *et al.*, Eds. (Pacific Section of the Society of Economic Paleontologists and Mineralogists, Los Angeles, 1979), pp. 141–146.
15. D. A. Foster, T. M. Harrison, C. F. Miller, K. A. Howard, *J. Geophys. Res.* **95**, 20005 (1990).
16. D. K. Holm and R. K. Dokka, *Earth Planet. Sci. Lett.* **116**, 63 (1993).
17. R. J. Scott, D. A. Foster, G. S. Lister, *Geol. Soc. Am. Bull.*, in press.
18. R. K. Dokka, *Geology* **21**, 711 (1993).
19. G. A. Davis, J. L. Anderson, E. G. Frost, T. J. Shackleford, *Geol. Soc. Am. Mem.* **153**, 79 (1980).
20. We extracted oxygen from silicate minerals using the CO_2 laser-probe system [Z. D. Sharp, *Geochim. Cosmochim. Acta.* **54**, 1353 (1990)]. Silicate samples (~0.2 to ~1 mg) were loaded into individual wells 2 mm in diameter in a solid Ni sample holder and heated in the presence of BrF_5 with a 20-W CO_2 laser. The liberated O_2 gas was converted to CO_2 by reaction with hot graphite. The CO_2 gas was analyzed on a VG Prism gas-ratio mass spectrometer. Accuracy and precision were assessed by 26 analyses of the Gore Mountain garnet standard [J. W. Valley, N. Kitchen, M. J. Kohn, C. R. Niendorf, M. J. Spicuzza, *Geochim. Cosmochim. Acta.* **59**, 5223 (1996)], which yielded a mean value of 5.81 ± 0.16 per mil (accepted value, 5.8 per mil).
21. A. Matthews, *J. Metamorph. Geol.* **12**, 211 (1994).
22. R. T. Gregory and R. E. Criss, in *Stable Isotopes in High Temperature Geological Processes*, J. W. Valley, H. P. Taylor, J. R. O'Neil, Eds. [*Reviews in Mineralogy* **16**, Mineraology Society of America, Washington, DC, 1986), p. 91.
23. J. L. Anderson, in *Metamorphic and Crustal Evolution of the Western United States*, W. G. Ernst, Ed. (Prentice-Hall, Englewood Cliffs, NJ, 1988), pp. 503–525.
24. M. J. Bickle and D. McKenzie, *Contrib. Mineral. Petrol.* **95**, 384 (1987).
25. K. P. Furlong, R. B. Hanson, J. R. Bowers, in *Contact Metamorphism*, D. M. Kerrick, Ed. [*Reviews in Mineralogy* **26**, Mineralogy Society of America, Washington, DC, 1991), p. 437.
26. M. S. Roddy, S. J. Reynolds, B. M. Smith, J. Ruiz, *Geol. Soc. Am. Bull.* **100**, 1627 (1988).
27. J. E. Spencer and J. W. Welty, *Geology* **14**, 195 (1986); J. Wilkins, T. Heidrick, R. Beane, *Ariz. Geol. Soc. Dig.* **16**, 108 (1986).
28. S. J. Reynolds and G. S. Lister, *Geology* **15**, 362 (1987).
29. R. Kerrich and W. Rehrig, *ibid.*, p. 58.
30. R. D. Halfkenny, R. Kerrich, W. A. Rehrig, *Ariz. Geol. Surv. Bull.* **198**, 190 (1989).
31. B. M. Smith, S. J. Reynolds, H. W. Day, R. J. Bodnar, *Geol. Soc. Am. Bull.* **103**, 559 (1991).
32. J. Morrison, *J. Metamorph. Geol.* **12**, 827 (1994).
33. S. Losh, *Geol. Soc. Am. Bull.* **109**, 300 (1997).
34. J. L. Anderson, A. P. Barth, E. D. Young, *Geology* **16**, 366 (1988).
35. E. DeWitt, J. F. Sutter, G. A. Davis, J. L. Anderson, *Geol. Soc. Am. Abstr. Prog.* **118**, 584 (1986).
36. C. Ruppel, L. Royden, K. V. Hodges, *Tectonics* **7**, 947 (1988).

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Suppression of Volcanism During Rapid Extension in the Basin and Range Province, United States

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Continental extension and volcanism are generally thought to be complementary. Stratigraphic and structural data from some highly extended parts of the Basin and Range province reveal instead that rapid extension appears to have suppressed volcanism. This relation may reflect enhanced crystallization of midcrustal magmas during extension resulting from exsolution of magmatic volatiles, increased interaction of magmas with meteoric water, and dispersal of magma into smaller bodies. Some rift environments may thus be characterized by voluminous synextensional plutonism with little or no concomitant volcanism.

The Basin and Range province of western North America (Fig. 1) has been extended by 50 to 100% (200 to 300 km) and was the locus of voluminous mafic to silicic volcanism throughout the mid- to late Cenozoic (*1*). The relation between extension and volcanism in the province, however, is controversial (*2*, *3*). In more highly extended domains, volcanism often preceded short-lived episodes of large-magnitude extension (*3*). Such a progression supports an active rifting model, wherein ascent of mantle-derived magmas triggers extensional collapse of the lithosphere (*3*). In a passive rifting model, stretching and thinning of lithosphere cause decompression melting in the asthenosphere, such that volcanism follows the onset of extension (*4*). Implicitly, the generation, ascent, and eruption of magma ought to be enhanced once extension is under way in both models. Here, we document the relation between extension rates and eruption rates in the northern Colorado River extensional corridor (CREC) in the Basin and Range province and show that rapid extension suppressed rather than enhanced volcanic activity.

The CREC (*5*) is a 50- to 100-km-wide region of highly extended upper crust (Fig. 1), characterized by pervasive normal faulting and steep tilting of upper crustal sections. Both volcanism and rapid extension migrated northward from near the Whipple Mountains at 22 to 17 million years ago (Ma) to near Las Vegas, Nevada, at 14 to 12 Ma (*6*, *7*), but the inception and peak of volcanism typically predate the peak of extension (*3*). This relation is best documented in the Eldorado Mountains (*8*) (Figs. 2 and 3). Volcanic rocks here include the following: 18.5- to 15.1-Ma trachyandesite to dacite lavas and breccias, a 15.1-Ma dacite ignimbrite, 15.1- to 14.1-Ma basalt and trachydacite flows intercalated with coarse clastic debris, and 14.1- to 13.0-Ma capping basalts and trachyandesites that unconformably overlie the older rocks (Fig. 2). The Eldorado Mountains represent a major eruptive center (*8*), and the entire 4-km-thick volcanic section is locally derived. Average volcanic accumulation rates increased from less than 1 mm/year at 17 Ma to a peak of 3 mm/year between 15.8 and 15.0 Ma, and then abruptly dropped at 15.0 Ma (Fig. 3A). Volcanic activity resumed after 14.2 Ma, but average accumulation rates were slower by an order of magnitude (~0.3 mm/year).

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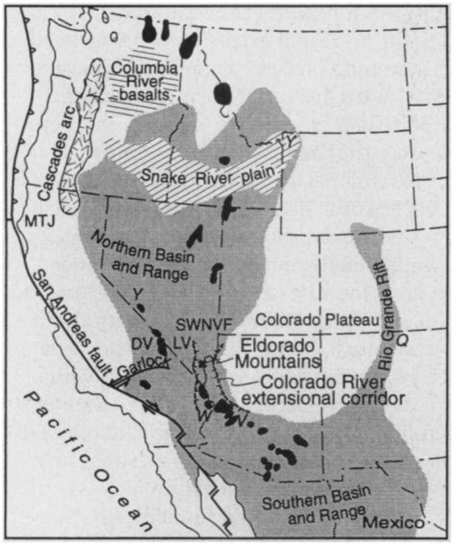

Fig. 1. Generalized map and key Cenozoic tectonic features of the western United States. Gray shading is the approximate extent of the Basin and Range physiographic province; patterned areas are the major late Cenozoic volcanic provinces (Cascades arc, Columbia River basalts, and Snake River plain). Black splotches indicate Cordilleran metamorphic core complexes. MTJ, Mendocino triple junction; LV, Las Vegas, Nevada; Y, Yerington, Nevada; DV, Death Valley; SWNVF, southwest Nevada volcanic field; W, Whipple Mountains; V, Vulture Mountains; Q, Questa, New Mexico.

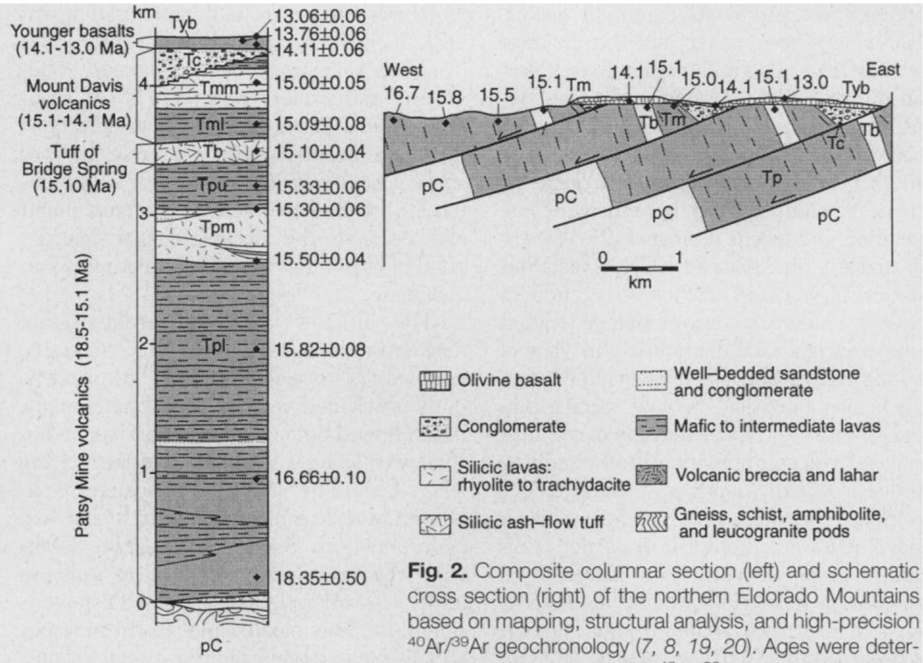

Fig. 2. Composite columnar section (left) and schematic cross section (right) of the northern Eldorado Mountains based on mapping, structural analysis, and high-precision $^{40}Ar/^{39}Ar$ geochronology (*7, 8, 19, 20*). Ages were determined from more than 100 $^{40}Ar/^{39}Ar$ mineral and whole-rock step-heating experiments performed at the University of California, Santa Barbara (UCSB), and at Stanford University during 1991 to 1996 (methods and a table summarizing the $^{40}Ar/^{39}Ar$ data are available at www.sciencemag.org/feature/data/975101.shl). Most ages shown are weighted means of multiple determinations and are listed in units of Ma. Stratigraphic nomenclature is modified from (*9*). Abbreviations: pC, Precambrian crystalline basement; Tp, Tpl, Tpm, and Tpu are undifferentiated, lower, middle, and upper members of Patsy Mine volcanic rocks; Tb, tuff of Bridge Spring; Tm, Tml, and Tmm are undifferentiated, lower, and middle Mount Davis volcanics; Tc, volcaniclastic conglomerate; Tyb, younger capping basalts.

The volcanic sections in the Eldorado Mountains are steeply tilted to the east and are cut and offset by closely spaced, gently west-dipping normal faults (Fig. 2) (*9*). Palinspastic reconstructions indicate a stretching factor of ~2.0, oriented 80° east of north. The age of extension can be assessed directly by means of cross-cutting relations and by angular unconformities within syntectonic deposits. There is no evidence for faulting and tilting before eruption of the 15.1-Ma ignimbrite. In 15.0- to 14.1-Ma volcanic and sedimentary rocks, tilts decrease abruptly upsection, individual flows thicken on the downthrown sides of faults, and offsets along faults decrease progressively upsection (Fig. 2). These relations demonstrate that extensional faulting was under way by 15 Ma (*8*). Coarse clastic intervals in some of these syntectonic deposits record erosional unroofing of older rocks in adjacent footwall blocks. Younger (14.1 to 13.0 Ma), gently tilted olivine basalt, trachyandesite, and rare silicic flows unconformably overlie the previously faulted and tilted units and provide an upper age bracket for most of the extension (Fig. 2). Collectively, these observations suggest that extension began at 15.1 to 15.0 Ma and that the area was stretched by a factor of 2.0 by 14.1 Ma. Extensional faulting and tilting continued after 14.1 Ma at a greatly reduced rate along widely spaced high-angle faults.

The antithetical relation between the extensional strain rate and the eruption rate (Fig. 3B) that we have documented in the Eldorado Mountains cannot be attributed to analytical error because the $^{40}Ar/^{39}Ar$ ages tightly bracket the timing of both the shutoff of volcanism and the inception of extension to within about 100,000 years. Neither is it a consequence of incomplete sampling or the episodicity inherent in large-volume eruptions. The cumulative thickness curve (Fig. 3A) reflects eruptions of hundreds of thin, locally derived mafic lava flows over several million years, where the recurrence interval was ~5000 to 10,000 years. More than 50 flows were erupted between 15.5 and 15.0 Ma, whereas no flows have yet been identified with ages between ~14.9 and 14.3 Ma. Indeed, this antithetical behavior was first suggested by field relations: Volcanic rocks in the area are mostly either preextensional and steeply tilted or postextensional and flat-lying; flows that are demonstrably synextensional and that have intermediate dips are volumetrically insignificant.

The tectono-magmatic evolution of the northern CREC can thus be divided into three phases. Volcanism preceded the inception of extension by several million years and increased in vigor until extension began (Fig. 4A). After the onset of rapid extension, volcanic eruptions in the area virtually ceased (Fig. 4B). The abrupt waning of eruptive activity implies that extension evidently

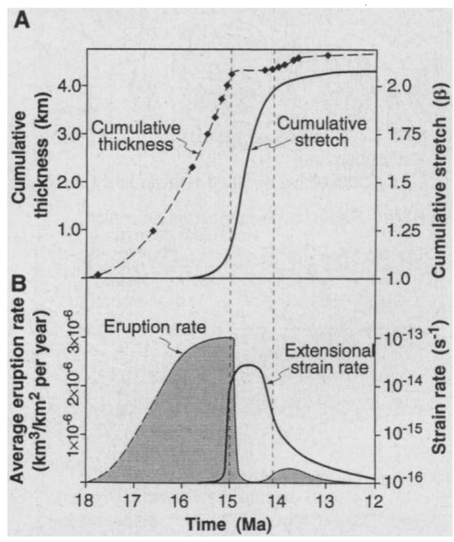

Fig. 3. Eruptive and structural history of the Eldorado Mountains area. (**A**) Cumulative thickness of volcanic rocks and cumulative stretching factor (β) versus time, averaged from many fault blocks. The diamond symbols are the $^{40}Ar/^{39}Ar$ ages. Uncertainties are about equal to symbol size. (**B**) Estimated average eruption rates (volume per unit area per unit time) and extensional strain rate (ln $\beta/\Delta t$, where t is time).

suppressed volcanism. As extension waned, volcanic activity resumed, albeit at a slower rate (Fig. 4C). The abrupt shutoff of volcanism during rapid extension is the most remarkable feature of this three-part history, because it runs counter to conventional wisdom that predicts that extension ought to increase volcanic activity by enhancing the generation and ascent of melts (*10*). We suspect that the time scale (±100,000 years) for cessation of volcanic activity is too short to represent a natural waning of melt generation in the mantle source, particularly in view of the long history and vigorous level of volcanism before extension. Several mechanisms could explain why rapid extension of the crust suppressed volcanic activity. Active fracturing and faulting of the upper crust might reduce confining pressures on hydrous magmas ponded at the ductile-brittle transition, thus causing abrupt exsolution of volatiles and crystallization of magmas. An elevated flux of magmatic volatiles in some rift environments has been suggested on the basis of $^4He/^3He$ data (*11*). Increased fracturing would also increase permeability and potentially allow meteoric water to penetrate to midcrustal depths (*12*). Such enhanced fluid-magma interaction would convect heat away and promote solidification rather than eruption (*13, 14*). Conduit systems in the lower and middle crust may have been physically disrupted by flow and anastamosing low-angle shear zones. Extension in the lower and middle crust might also decrease the likelihood that magmas pond in large reservoirs, promoting instead an abundance of dikes and sills.

The ultimate cause of preextensional magmatism remains conjectural. Convective removal (*15*) or delamination (*16*) of previously thickened mantle lithosphere might have allowed hot asthenosphere to ascend to shallower levels and induce partial melting (Fig. 4A). The concomitant increase in buoyancy and temperature of crust that had been previously thickened may have weakened the crust and caused it to collapse under its own weight (Fig. 4B). Postextensional capping basalts and trachyandesites locally have more primitive compositions, which may reflect the inception of decompression melting of asthenosphere (*17, 18*) (Fig. 4C).

Data from other highly extended areas in the Basin and Range province commonly reveal eruptive and extensional histories that closely resemble that of the Eldorado Mountains, despite major differences in absolute timing and geographic position [Fig. 5; see also figure 19 in (*3*)]. Although the exact ages and rates are not as well constrained, volcanic activity often peaked before most of the local extension, and rapid extension was associated with a waning or even a shutoff in volcanic activity. We suggest that the primary causes of the cessation of eruptive activity in these areas were the thermal and baric consequences of extensional fracturing and thinning of the upper crust. If rifting can suppress volcanic activity, even though generation of melts continues unabated or is even enhanced, then eruption rates are an inaccurate proxy for magma production in continental rift environments. Some rifts may have widespread synextensional plutonism for which there is no volcanic equivalent. Rapidly extending rifts that lack significant volcanism may be characterized by elevated heat flow or hydrothermal activity. Geophysical profiling of modern and ancient rifts may provide evidence that magmas ponded at lower to middle crustal levels during extension. Further field and numerical investigations are needed to critically evaluate the relation between volcanism, plutonism, and strain rate in extensional environments.

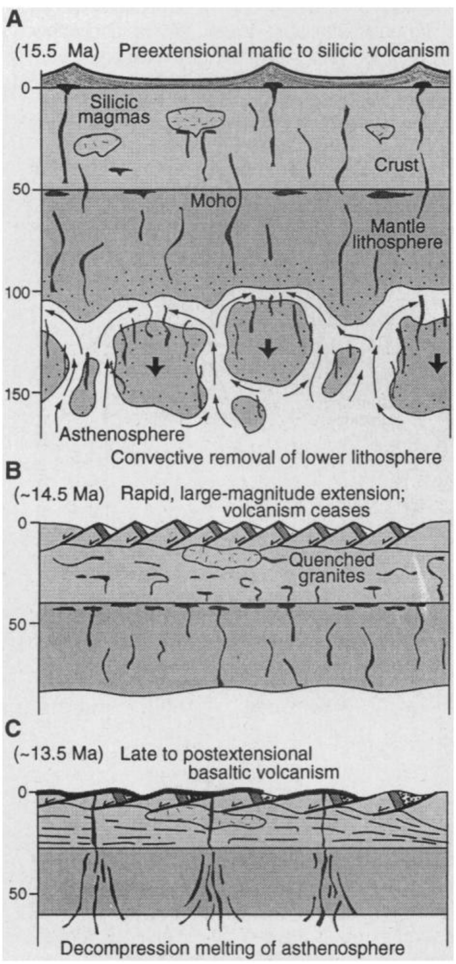

Fig. 4. Sequential lithospheric cross sections illustrating the tectono-magmatic evolution of the northern CREC.

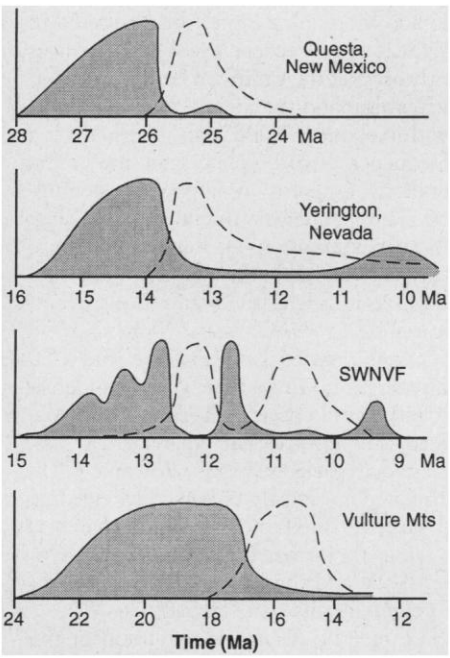

Fig. 5. Estimated eruption rates (shaded) and strain rates (dashed line) for selected areas in the Basin and Range province. Sources of data: Questa, New Mexico (*21*); Yerington, Nevada (*22*); SWNVF (*23*); and Vulture Mountains, southwest Arizona (*24*).

REFERENCES AND NOTES

1. R. L. Christiansen and R. S. Yeats, in *Decade of North American Geology: Cordilleran Volume* (Geological Society of America, Boulder, CO, 1992).
2. M. G. Best and E. H. Christiansen, *J. Geophys. Res.* **96**, 13509 (1991).
3. P. B. Gans, G. A. Mahood, E. Schermer, *Geol. Soc. Am. Spec. Pap.* **233**, 1 (1989).
4. A. M. C. Sengor and K. Burke, *Geophys. Res. Lett.* **5**, 419 (1978).
5. K. A. Howard and B. E. John, *Geol. Soc. London Spec. Pub.* **28**, 299 (1987).
6. A. F. Glazner and J. M. Bartley, *Tectonics* **3**, 385 (1984).
7. P. B. Gans, P. Darvall, J. Faulds, *Geol. Soc. Am. Abstr. Prog.* **25**, 108 (1992).
8. P. B. Gans, B. Landau, P. Darvall, *ibid.* **26**, 53 (1994).
9. R. Anderson, *Geol. Soc. Am. Bull.* **82**, 43 (1971).
10. D. McKenzie and M. J. Bickle, *J. Petrol.* **29**, 625 (1988).
11. E. R. Oxburgh, R. K. O'Nions, R. I. Hill, *Nature* **324**, 632 (1986).
12. H. P. Taylor, in *Magmatic Processes: Physiochemical Principles*, B. O. Mysen, Ed. (Geochemical Society, University Park, PA, 1987), vol. 1, pp. 337–358.
13. H. M. Bibby, T. G. Caldwell, F. J. Davey, T. H. Webb, *J. Volcanol. Geotherm. Res.* **68**, 29 (1995).
14. C. J. N. Wilson *et al.*, *ibid.*, p. 1.
15. J. P. Platt and P. C. England, *Am. J. Sci.* **293**, 307 (1993).
16. P. Bird, *J. Geophys. Res.* **84**, 7561 (1979).
17. T. K. Bradshaw, C. J. Hawkesworth, K. Gallagher, *Earth Planet. Sci. Lett.* **116**, 45 (1993).
18. E. E. Daley and D. J. DePaolo, *Geology* **20**, 104 (1992).
19. K. Howard, P. Gans, B. John, G. Davis, J. Anderson, *U.S. Geol. Surv. Open File Rep. 94-0246* (1994).
20. P. Gans and P. Darvall, in preparation.
21. J. Meyer and K. Foland, *Geol. Soc. Am. Bull.* **103**, 993 (1991).
22. J. H. Dilles and P. B. Gans, *ibid.* **107**, 474 (1995).
23. D. A. Sawyer *et al.*, *ibid.* **106**, 1304 (1994).
24. J. E. Spencer *et al.*, *J. Geophys. Res.* **100**, 10321 (1995).
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