COMMENT

Weidong Sun
Shuguang Li
Department of Earth and Space Sciences, University of Science and Technology of China, Hefei 230026, People’s Republic of China

Zhang et al. (1997) documented very interesting and important changes in Pb isotopic compositions for granitoids in the North Qinling orogenic belt since the late Paleozoic time. On the basis of an out-of-date tectonic model of the Qinling orogenic belt, they suggested that the Yangtze craton accreted to the North China craton no later than 360 Ma.

We agree that Pb isotope compositions of granitoids from the North and South Qinling (Zhang et al., 1997) could provide important constraints on the history of collision along the North Qinling orogenic belt. However, we consider the data interpretation of Zhang et al. to be non-unique.

Figure 1 indicates that the lower Pb isotopic compositions of late Paleozoic and Mesozoic granitoids in North Qinling could also be the result of the North China craton being subducted under the North Qinling belt.

The Qinling-Dabie orogenic belt in central China is not a simple result of the collision between the North and South China cratons as Zhang et al. (1997) proposed. Recent research shows that there are several island arcs and so-called “microcontinents” between the North and South China cratons (e.g., Li and Sun, 1996; Li et al., 1996). The North Qinling arc consists of the Qinling continental block, Erlangping volcanic arc, and the Danfeng and Heihe volcanic arc. The higher radiogenic Pb isotope composition of the North Qinling arc compared with that of the North China craton suggests that the arc does not belong to the craton (Xue et al., 1997). New evidence also shows that the south edge of the North China craton is not an active margin, but a passive margin (Xue et al., 1996). South-dipping subduction of the North China craton along the Luonan-Luanchuan fault (see Fig. 1 in Zhang et al., 1997) led to the collision of the North China craton with the North Qinling island arc between 400 and 426 Ma (Li and Sun, 1996; Li et al., 1996; Sun et al., 1996a, 1996b; Xue et al., 1996), which could also have caused the changes in Pb isotopic compositions for granitoids in the North Qinling orogenic belt since the late Paleozoic.

It may also be worth considering that most of the late Paleozoic and Mesozoic granitoids (e.g., BJ, CH, ML in Zhang et al., 1997) in the North Qinling orogenic belt with $^{206}\text{Pb}/^{204}\text{Pb}$ lower than 18 lie along the Luonan-Luanchuan fault, the delimitation between the North Qinling orogenic belt and the North China craton, while those (TYP and KP) having $^{206}\text{Pb}/^{204}\text{Pb}$ higher than 18 lie along the Shang-Dan fault, the boundary between the South and the North Qinling orogenic belts (see Fig. 1 and Table 2 in Zhang et al., 1997). Erlangping is the only granitoid with $^{206}\text{Pb}/^{204}\text{Pb}$ lower than 18 that is not near the Luonan-Luanchuan fault. It lies in the Erlangping ophiolite, which belongs to the northern volcanic arc. These characteristics suggest that the unusual change in Pb isotopic compositions for late Paleozoic and late Mesozoic granitoids in the North Qinling orogenic belt developed from north to south. It is most likely the result of the subduction of the North China craton alone the Luonan-Luanchuan fault, as Xue et al. (1996) suggested. The collision between the North China craton and the North and South Qinling could have occurred in the Devonian (Li and Sun, 1996). Other evidence cited by Zhang et al. (1997)—e.g., change in provenance of clastic sedimentary rocks in the South Qinling belt (Gao et al., 1995) and change in benthic fauna distribution (Yin, 1994)—can be explained well by the Devonian collision.

The synollision granites, isochronal results of metamorphism, and other geological results suggest that the collision between the Yangtze craton and the South Qinling “microcontinents” took place at 206–223 Ma along the south margin of the South Qinling belt (e.g., Li and Sun, 1996; Li et al., 1996). The huge mass and momentum of the Yangtze and North China cratons caused a deep continental subduction and the formation of the ultrahigh-pressure metamorphic rocks in the Triassic collision. This multiblock collision model tallies better with geological evidence than does the model of two-continent collision with a two-stage subduction suggested by Zhang et al. (1997).

ACKNOWLEDGMENTS

This study is supported by the Chinese Natural Science Foundation (grant no. 49472144). We thank Shen-su Sun for his constructive reviews.

REFERENCES CITED


We welcome Sun and Li's Comment because it gives us an opportunity to discuss more evidence that the unusual Pb isotopic change of the North Qinling granitoids should be interpreted in terms of Devonian underthrusting of the South Qinling orogenic belt beneath the North Qinling belt, leading to accretion of the Yangtze craton to the North China craton (H.-F. Zhang et al., 1997a). Sun and Li interpret the Pb isotopic change to be due to subduction of the North China craton beneath the North Qinling belt. We are aware of the non-uniqueness in interpretation of the Pb isotopic composition, because the basement and granitic rocks in the North China craton also have less-radiogenic Pb isotopic composition (B.-R. Zhang et al., 1996). Accordingly, other geochemical and geological evidence must be considered.

As discussed in our paper (H.-F. Zhang et al., 1997a), the North Qinling late Paleozoic and Mesozoic granitoids with less-radiogenic Pb isotopic composition mostly have $\varepsilon_{Nd}(t)$ values that range from –1.5 to –4.5 at the time of formation and Nd model ages ($T_{DM}$) from 1.0 to 1.5 Ga (B.-R. Zhang et al., 1996; H.-F. Zhang et al., 1996). The values agree with those of the South Qinling granitoids [$\varepsilon_{Nd}(t) = –1.0$ to –8.5; $T_{DM} = 1.0$ to 1.7 Ga] and basement rocks [$\varepsilon_{Nd}(t) = –2$ to –14; $T_{DM} = 1.0$ to 2.2 Ga] (Huang and Wu, 1992; B.-R. Zhang et al., 1996; H.-F. Zhang et al., 1997b). The Yangtze craton displays a similarity in the distribution of Nd model age to that of South Qinling, except that 10% of the samples have Archean model ages (B.-R. Zhang et al., 1996). In contrast, $\varepsilon_{Nd}$ values of the Archean and Paleo-proterozoic basement rocks and Proterozoic-Mesozoic granitoids from the North China craton, including its southern margin, are calculated to vary from –10 to –25 in the late Paleozoic and Mesozoic. Nd model ages of the North China craton Precambrian basement rocks and Proterozoic-Mesozoic granitoids range from 2.0 to 3.6 Ga (Huang and Wu, 1992; Z.-Q. Zhang et al., 1994; B.-R. Zhang et al., 1996). These results clearly indicate that the North China craton crust is much older in Nd model age and more evolved in Nd isotopic composition than the South Qinling and Yangtze craton crust and North Qinling late Paleozoic and Mesozoic granitoids.

The North Qinling early Paleozoic granitoids with radiogenic Pb isotopic composition exhibit a clear compositional polarity. For example, their K$_2$O and incompatible-element (e.g., Rb and light rare earth element) contents and K$_2$O/Na$_2$O and La/Yb ratios show a systematic northward increase, if comparison is made on the basis of similar SiO$_2$. Correspondingly, $\delta^{18}O$ increases while $\varepsilon_{Nd}(t)$ decreases northward (B.-R. Zhang et al., 1994). A similar compositional polarity was also found for the Neoproterozoic to early Paleozoic Danfeng island arc volcanic rocks in North Qinling (B.-R. Zhang et al., 1994). These spatial changes in chemical and isotopic compositions resemble those found in circum-Pacific island arcs or active continental margins (e.g., Hildreth and Moorbath, 1988) and are interpreted to suggest the northward subduction of the Qinling paleoceanic crust beneath North Qinling during the early Paleozoic (B.-R. Zhang et al., 1994).

Sun and Li’s model of southward subduction of the North China craton beneath North Qinling has difficulty explaining data on Nd model ages and ages of detrital zircons as well as provenance studies of clastic sedimentary rocks. Analyses of clastic metasedimentary rocks from the ~1.0 Ga Kuanping Group (47 samples) and the early Paleozoic Erlanping Group (35 samples) of North Qinling reveal that rocks from both groups exhibit a similar, typical two-component mixing relationship in paired La/Co vs. Sr/Th and La/Co vs. Th/Co diagrams (B.-R. Zhang et al., 1994). The two components are constrained to be the Paleoproterozoic Qinling Complex from North Qinling and the Archean Taihua terrain from the North China craton. This conclusion is reinforced by the presence of detrital zircons from the Kuanting met-graywackes with ages as old as 2.8–3.3 Ga (Z.-Q. Zhang et al., 1994). These Archean zircons must have been derived from the North China craton, because no rocks older than 2.3 Ga have been confirmed in North Qinling (Z.-Q. Zhang et al., 1994). On the other hand, metapelites from the Sinian-Cambrian Taowan Group from the southernmost margin of the North China craton have uniform Nd model ages of 2.0–2.2 Ga, which are considerably younger than the predominantly Archean model ages of North China craton rocks, as described above, but are identical to values (1.9–2.2 Ga) of clastic metasedimentary rocks from both the Kuanping Group and the Qinling Complex. This requires a mainly North Qinling provenance for the Taowan Group (Z.-Q. Zhang et al., 1994). The above results suggest that the North Qinling belt and the southern margin of the North China craton had been in close proximity or accreted since 1.0 Ga.

In addition, the apparent southward increase in $^{206}$Pb/$^{204}$Pb ratio for the North Qinling late Paleozoic and Mesozoic granitoids, as claimed by Sun and Li, is artificial. As we pointed out (H.-F. Zhang et al., 1997a), the three (Tieyupu, Kuanping, and Wuguang) granites with radiogenic Pb isotopic compositions are distinct in occurrence and genesis from granitoids with less-radiogenic Pb isotopic composition. Thus, these two different types of granitoids cannot be compared.

Our provenance studies do support the microcontinent model for the Xichuan subunit in South Qinling during the Cambrian and Ordovician (Gao et al., 1995). However, our studies and the paleontological results of Yin and Huang (1995) both indicate that the South Qinling microcontinents, together with the Yangtze craton, accreted to the North China craton in Devonian time. Otherwise, it would be difficult to explain why lacustrine fish and plant fossils found in Middle–Late Devonian strata in the Zhongwei area, Ningxia province, of the western North China craton are characteristic of the Yangtze craton (Yin and Huang, 1995). Because of the relatively small mass, South Qinling microcontinents alone are not enough to underthrust North Qinling and produce granitoids in the overriding plate.

In summary, although Sun and Li’s interpretations are not at variance with the Pb isotopic compositions, they are incompatible with the above lines of geochemical and geological evidence. Therefore, we still favor the Devonian accretion model of the Yangtze craton to the North China craton. Further work is needed on dating of detrital zircons from the South Qinling Devonian sandstone and graywacke to better characterize the provenance.

ACKNOWLEDGMENTS
This study is co-supported by the National Nature Science Foundation of China, the State Commission on Education of China, the Open Laboratory of Constitution, Interaction and Dynamics of the Crust-Mantle System, and the Alexander von Humboldt foundation of Germany.

REFERENCES CITED

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.


860 GEOLOGY, September 1998
Vertical and lateral collapses on Tenerife (Canary Islands) and other volcanic ocean islands: Comment and Reply

COMMENT

E. Ancochea
Departamento de Petrología y Geoquímica, Facultad de Ciencias Geológicas, Universidad Complutense, 28040 Madrid, Spain

J. M. Fúster
Departamento de Geología, U.M.R. 6524, Université Blaise Pascal—CNRS, 5 rue Kessler; 63038 Clermont-Ferrand, France

N. O. Arnaud
Departmento de Petrología y Geoquímica, Facultad de Ciencias Geológicas, Universidad Complutense, 28040 Madrid, Spain

M. J. Huertas
Department de Géologie, U.M.R. 6524, Université Blaise Pascal—CNRS, 5 rue Kessler; 63038 Clermont-Ferrand, France

Marti et al. (1997) suggested “that the vertical collapses can play a major role in triggering lateral collapses” in Tenerife. This idea is based on the “coincidence between the formation of the Orotava and Icod valleys and two of the inferred caldera collapse events (Guajara and Diego Hernández)” which “suggest a mechanical connection between these processes.” In our opinion, the present data do not support their model. Moreover, the authors did not cite the work of Fúster et al. (1994) and Ancochea et al. (1995), in which another model of the stratigraphy, geochronology, and evolution of the Las Cañadas edifice is presented.

Continuous Volcanic Activity? Martí et al. (1997, Fig. 2), according to the stratigraphy from Martí et al. (1994), indicated the existence of three volcanic cycles of continuous activity during the last 2 m.y. Meanwhile, in the 1994 paper, these cycles were said to be separated by periods of dormancy of more than 100 k.y. The contradiction between both models is difficult to understand if the authors do not give new ages since 1994.

Mafic to Felsic Cycles? In their simple model (Martí et al., 1997), each cycle (Ucanca, Guajara, and Diego Hernández) begins with an important period of mafic volcanism (>40% in their Fig. 2). This is true for the post-caldera Pico Viejo–Teide formation (Navarro and Coello, 1989), but not for their three Upper Group cycles. In the Cañadas wall, where those formations are defined, the mafic rocks are more frequent at the top of the Diego Hernández sections, and there are almost no mafic lavas in the Guajara and Ucanca sections (Martí et al., 1994, Fig. 3). Nor are these cycles well established on the southern flank of the Cañadas edifice, where several tens of pyroclastic levels, often separated by paleosols, are exposed. These are older from southeast (0.15–0.6 Ma) to the southwest (up to 1.5–1.7 Ma). There is no conclusive evidence to prove that some (all or none) of these pyroclastic levels are correlated with great vertical collapse events.

Vertical and/or Lateral Collapses? The characteristics of the resulting calderas theoretically differ significantly, but in Tenerife the choice remains speculative. The volcanological structures are always incomplete, because the northern part of the caldera wall is lacking. Are the normal ring faults (incomplete and scarce) observed in the south Las Cañadas caldera wall bordering faults of a vertical collapse caldera, or instead the hanging end of great listric faults at the base of an avalanche caldera? The geological data “suggest that the caldera comprise several separate depressions” (Martí et al., 1997), but from these data it is not easy to deduce if the collapses were vertical or lateral, how many collapses took place, or if the depressions deal with the proposed collapses. It is not demonstrated that the faults (normal or inverse) were active at the time inferred for the formation of the three suggested calderas. At the base of the Tigaiga massif, the only preserved part of the Las Cañadas edifice in the northern sector of the island, there is a polygenetic breccia (Bravo, 1962) interpreted by Ancochea et al. (1990 and 1995) as a debris avalanche deposit. It is overlain by 2.3 Ma trachybasaltic flows. Thus it marks an old lateral collapse event and, to date, no vertical collapse has been proposed.

Age Relations Between Vertical and Lateral Collapses. Martí et al. (1997) gave an age of about 1 Ma for their Ucanca caldera and tentatively related this collapse to the formation of the Güimar valley, outside of the Cañadas edifice. Ancochea et al. (1990) demonstrated that this valley, formed by lateral avalanche from the essentially basaltic “Dorsal” edifice, is younger than 0.84 Ma. Thus the two collapse events cannot be associated. Similarly, Martí et al. (1997) gave an age of 0.57 Ma (0.65 Ma in Martí et al., 1994) to the final phonolite of the Guajara cycle (and their Guajara caldera). Ancochea et al. (1995) measured these phonolite at about 0.90 Ma, and Martí et al. (1994) found another equivalent phonolite date to date from 0.80 Ma. Therefore, the age of the suggested Guajara caldera could be older than that inferred by Martí et al. (1997). On the other hand, the age of the La Orotava valley, <0.78 Ma (Ancochea et al., 1990) or <0.73 Ma (Ibarrola et al., 1993), is not precisely constrained. Again, in this case, the temporal coincidence between the two collapses is not evident. Finally, there are no direct measurements for the Icod valley. Assuming it was generated during the formation of Las Cañadas caldera, Ancochea et al. (1990) proposed an age of about 0.15 Ma, which agrees with the estimation of <0.20 Ma from Watt and Masson (1995). The Icod valley–Diego Hernández caldera simultaneity remains to be corroborated.

In brief, the existence of three mafic-salic cycles and the ages of the three lateral and suggested vertical collapses are questionable. The coincidence in time and the connection between vertical and lateral collapses in Tenerife are not adequately demonstrated. The starting point of the calculated model by Martí et al. (1997, Fig. 3A) is certainly too simple and does not reflect the internal structure of the Las Cañadas edifice at the time considered, which was already the result of a very long and complex eruptive history. The proposed model is theoretically possible, but the existence in the Canary Islands of very frequent lateral collapses without connection with caldera collapses (Tigaiga breccia in Tenerife, El Golfo in El Hierro, etc.) indicates that vertical collapse is not requisite to generate large landslides. It is certainly too early to extend this model to other volcanic islands, Réunion Island included, where the existence and, of course, the simultaneity of the two types of collapse are not clearly demonstrated. The
“Grand Brulé–Enclos” system may be regarded as a single system derived from a seaward landslide (Lénat, 1990).

In any case, it is valuable that a part of the geological community concerned with Tenerife now considers avalanche processes in the evolution of the Las Cañadas after a long time of denying their importance (Martí et al., 1996).

REFERENCES CITED


REPLY

Joan Martí, Marcel Hürlimann, Giray Ablay
Institute of Earth Sciences, CSIC, Lluís Solé Sabaris s/n, 08028 Barcelona, Spain
A. Gudmundsson
Geological Institute, University of Bergen, Alléet, 41, N-5007 Bergen, Norway

Martí et al. (1997) proceeded from the assumption that vertical caldera collapses have played a major role in forming the Las Cañadas caldera to note a correspondence between the ages of the inferred paroxysmal pyroclastic eruptions of the last two Upper Group formations and the ages of the La Oratava and Icod valleys. We suggested that the valleys may have formed in response to the caldera collapses and provided theoretical support for this model. Ancochea et al. admit the plausibility of this hypothesis and, while not advocating an alternative, criticize it on four grounds: (i) that relevant references are not cited, (ii) that evidence for vertical collapses is lacking, (iii) that we contradict previous interpretations of the continuity of volcanism in central Tenerife (Martí et al., 1994), and (iv) that a relationship between the collapse events is not supported by available age data.

References. Ancochea et al. (1995) and Fuster et al. (1994) addressed the stratigraphy of the Las Cañadas edifice and divided its evolution into three phases. Phases 1 and 2 correspond to the Lower Group of Martí et al. (1994). Phase 3 is equivalent to the Upper Group (Martí et al., 1994), which includes the formations affected by the various collapse events. The Upper Group is considered by Fusté et al. (1994) and Ancochea et al. (1995) as a single constructional phase, whereas Martí et al. (1994) recognized three major Upper Group phonolitic formations in caldera wall exposures. Our model arises from a more detailed Upper Group stratigraphy than that proposed by Fuster et al. (1994) and Ancochea et al. (1995), which therefore makes theirs not directly relevant.

Continuity of Mafic and Felsic Activity. Martí et al. (1994) showed that central phonolitic activity was discontinuous during Upper Group times, whereas Martí et al. (1997) proposed that volcanic activity was continuous. Volcanism has been continuous in Tenerife, but central phonolitic volcanism has not; phonolitic cycles have been separated by periods of mafic to intermediate volcanism from flank and central vents. These mafic to intermediate volcanic rocks are interbedded with the Upper Group in the south of the island (Bryan et al., in press) and are presumably present beneath the Teide–Pico Viejo complex and on adjacent rift zones. The Upper Group edifices developed inside the Las Cañadas caldera, allowing only their youngest phonolitic products to exit the caldera or mantle the wall.

Occurrence of Lateral and Vertical Collapses. Martí et al. (1997) assumed that the Las Cañadas caldera formed originally by vertical collapses. Evidence for this has been presented elsewhere (Martí et al., 1994, 1996, 1997), as has evidence for the occurrence of large lateral collapses (Bravo, 1962; Watts and Masson, 1995; Teide Group, 1997). Here, we reiterate that the discovery of 500 m of Teide–Pico Viejo lavas below the present caldera floor makes a connection between the breccia deposits infilling the Icod valley and the central part of the caldera unfeasible, since this depth is lower than that at which the breccia deposits occur on the adjacent north flank.

The normal concentric faults referred to by Ancochea et al. are notable for having been exploited by phonolitic pyroclastic dikes. This supports their connection to shallow phonolitic magma chambers and suggests that they were active during caldera formation.

Correlation of Lateral and Vertical Collapses. The formation of the Guimar valley is not linked by Martí et al. (1997) to the formation of the Ucanca caldera. Our model is restricted to inferring a connection between the Guajara and Diego Hernández calderas, and the Oratava and Icod valleys, respectively. In our Figure 2 we placed a question mark next to Guimar only because its age is poorly constrained.

Concerning the age of the caldera forming Guajara eruptions, we note that the dates obtained by Ancochea et al. (1995) and Martí et al. (1994) are inconsistent. Ancochea et al. (1995) stated that the youngest Guajara rocks have an age of 0.90 Ma. However, inspection of Ancochea et al. (1995) shows that this sample does not come from the topmost Guajara unit. Martí et al. (1994) obtained an age of 0.65 Ma for one of the uppermost proximal Guajara units, located stratigraphically above the sample analyzed by Ancochea et al. (1995). However, new detailed studies have correlated the most distinctive Guajara and Diego Hernández units in the caldera wall with their distal equivalents to the south and north (Martí, 1996; Bryan et al., in press). This correlation enables us to infer the Granadilla pumice fallout deposit (0.57 Ma) as the caldera-forming product of the Guajara caldera, while Martí et al. (1994) have already inferred the El Abrigo ignimbrite (0.179 Ma) as the Diego Hernández caldera-forming products. We acknowledge the oversight in not citing the then unpublished age of 0.57 Ma, in light of which a coincidence of the formation of the Guajara caldera with the age of the La Oratava valley (<0.73 Ma) remains plausible. The youngest Diego Hernández eruption (0.179 Ma) and the putative age of the Icod valley (<0.17 Ma, Watts and Masson, 1995) remain better correlated.

REFERENCES CITED

Late-stage sinking of plutons: Comment and Reply

Scott R. Paterson
Department of Earth Sciences, University of Southern California, Los Angeles, California 90089-0740 (E-mail: paterson@usc.edu)

Glazner and Miller (1997) presented a provocative conclusion that plutons may sink immediately after crystallization and thus drag down their surrounding host rock. I remain puzzled by several aspects of this paper and hope that further discussion will clarify the implications of their hypothesis. I was surprised that, in presenting the hypothesis, Glazner and Miller chose to treat the problem as one dealing with a thin and relatively homogeneous horizontal section through a pluton and host rock rather than comparing heterogeneous vertical columns of magma and host rock. In the latter case, one might wonder what effect still-buoyant magma below the present surface might have. Or why the early-crystallizing magma (and thus more dense magma in their model) near walls and roofs doesn’t collapse and sink through the magma chamber rather than dragging down host rock outside the chamber.

I also found Glazner and Miller’s use of kinematic descriptions to be confusing. To my knowledge there is no evidence that any of the plutons discussed in their paper are sinking relative to their host rocks. Kinematic data are available only from host rocks and thus indicate only that inner aureoles are moving downward relative to outer aureoles, a conclusion with which I completely agree (e.g., Saleeby, 1990; Stein and Paterson, 1996; Paterson et al., 1996). These data say nothing about whether the pluton is going up or down during the downward movement of the inner aureole.

Given that there is little agreement on how space is made during the rise of plutons, I am curious about how and where Glazner and Miller imagine host rock is displaced during simultaneous pluton sinking and downward displacement of aureoles. Should we be looking for large flattening strains below plutons? Where does the downward-flowing host rock go when we get to the base of a pluton?

Finally, I was particularly surprised that Glazner and Miller did not attempt to test their hypothesis more rigorously. One simple test is to determine if the ductile aureoles formed before or after magma crystallization. One means of doing so is to determine if stopping (which requires the presence of magma) of the ductile aureole occurred, particularly along pluton margins where only magmatic fabrics exist. This test is further strengthened if preserved magmatic fabrics along these margins wrap around stopped blocks and are thus forming during or after sinking of these blocks (Fowler and Paterson, 1997). Detailed mapping of the margins of two of the plutons in Glazner and Miller’s (1997) Figure 1A, the Inyo Batholith located immediately north of the Marble Canyon pluton, and the Yerington batholith in Nevada (Fowler, 1996; Stein and Paterson, 1996), reveals that foliations formed in the ductile aureoles around these plutons are discordantly truncated by the pluton margins. There is no evidence of margin-parallel slip along these contacts and no solid-state foliation in the plutons adjacent to these contacts. In the Inyo batholith, nearby stopped blocks preserve the aureole foliation and, at least in the few I examined closely, have magmatic foliations wrapping around them. In the Yerington, ductile aureole structures are truncated by the pluton margin, and some potential stopped blocks exist (Fowler, 1996), but these have not been examined in detail. Thus, I believe that in both batholiths the ductile aureole is getting stopped out and locally completely removed along pluton margins along which only magmatic foliations are preserved. This implies that magma was still present along these margins after the ductile aureoles formed.

The maps and cross sections in Glazner and Miller (1997) suggest that the same process occurred in the Marble Canyon and Silver Zone Pass plutons. In their Figure 1B, the right end of the cross section shows a discordant margin along which gently dipping lithologic contacts are truncated by the Silver Zone Pass pluton. This is not at all the geometry I would expect at the margin of a sinking pluton. In their Figure 1C, the map pattern indicates that at both the north and south ends of the Marble Canyon pluton, lithologic contacts and locally the ductile aureole are truncated by the pluton margin, implying that they have been stopped out. Glazner and Miller imply that only magmatic foliations occur along these margins, which further emphasizes that the truncation at these margins formed by magmatic rather than postemplacement tectonic processes.

I agree with Glazner and Miller (1997) that another good test of their hypothesis is to look at pluton roofs. The only roof they mention is that above the Yerington batholith, where they noted that a graben of uncertain age has formed. This example is puzzling to me, because strata in this roof actually bend upward slightly, which would also explain graben formation due to bed lengthening. Furthermore, the most likely models for emplacement of the plutons described by Glazner and Miller (i.e., diapirism, ballooning, laccolith growth) typically involve arching of units above the pluton during emplacement. If these plutons then began to sink, layer shortening, not extension should occur in roof strata. Finally, my colleagues and I have mapped many other pluton roofs, in some cases above plutons where there is good evidence of downward flow of host rock along their sides (e.g., Paterson et al., 1994, 1996). We find either no deformation of the roofs or some minor upward deflections of host-rock markers.

Therefore, although I agree with Glazner and Miller (1997) that there is a great deal of evidence for downward flow of host rock around plutons, I see no evidence for pluton sinking. Alternatively, I suggest that downward flow of host rock is a natural process during magma ascent, that it helps make space during chamber growth, and that it transfers host rock down toward the region of growing crustal roots beneath arcs.
REFERENCES CITED

REPLY
Allen F. Glazner
Department of Geology, University of North Carolina, Chapel Hill, North Carolina 27599-3315
David M. Miller
U.S. Geological Survey, MS 975, 345 Middlefield Road, Menlo Park, California 94025

We (Glazner and Miller, 1997) offered an explanation for the puzzling observation that many plutons in the western United States lie in steep-sided synclines. This explanation conflicts with simple emplacement models which suggest that upward flow of magma should displace wall rocks upward, not downward. Noting that these plutons are typically denser than average and are surrounded by weak wall rocks (e.g., limestone and quartzite), we propose that the plutons sank as much as several kilometers after emplacement, owing to their high densities.

In trying to solve the mystery of the downward-displaced wall rocks, we have identified suspects (dense plutons), opportunity (ductile, low-density wall rocks), and motive (gravity). When these three act in concert, pluton sinking should result. If we fill a bathtub with tar and set a bowling ball upon the tar, we can be confident that the bowling ball will sink until it meets a stronger layer (the bathtub’s floor). The physics of sinking plutons is the same; therefore, dense plutons should sink in weak, low-density wall rocks (Glazner, 1994, 1998; Weinberg and Podladchikov, 1995).

Several of Paterson’s comments miss the big picture, we feel. For example, we are not surprised that foliation in a pluton’s aureole is locally truncated by the pluton. Foliation can form at many times in a pluton’s life cycle, including during ascent, and many plutons are multiphase, so local truncation is to be expected. A pluton may also become negatively buoyant before full crystallization. In contrast, we are impressed by the overall concordance of foliation shown in the examples we cited. Paterson asks if we should look for large flattening strains below plutons. Yes; this is what is observed in the aureoles around eastern California plutons (e.g., Morgan et al., 1998).

Paterson proposes that aureole kinematics are best explained by “downward flow,” an ill-defined process that is presumably capable of sucking a thin cylinder of wall rocks down adjacent to a rising pluton. The key kinematic difference between pluton sinking and downward flow is that sinking requires that the pluton move down relative to the aureole, whereas downward flow requires the opposite.

We are surprised by Paterson’s statement that he is unaware of any pluton-down kinematic indicators. The steep, asymmetrical anticlines that bound the plutons in question are most simply interpreted as pluton-down folds. Had the latest pluton movement been upward relative to the aureole, we would expect at least some upward drag adjacent to them. We also cited Sven Morgan’s dissertation work, which shows abundant pluton-down kinematics (e.g., Morgan et al., 1998). In fact, these eastern California examples show pluton-down shear bands defined by fibrolite cutting andalusite-bearing assemblages, consistent with the increasing temperatures and pressures that pluton sinking would bring.

Our simple calculations indicate that, late in their emplacement history, relatively dense plutons should sink through weak, low-density wall rocks. We are unaware of anything that would prevent this from happening and therefore are unsurprised by field relations that are compatible with the process. We do not believe that the hypothesis is invalidated by the observations that Paterson cites, and we welcome further evaluation. On the other hand, we are unaware of evidence for downward flow of contact aureole rocks relative to plutons, as Paterson proposes. We find this downward flow process to be sufficiently vaguely defined that it is unclear how it might otherwise be tested.

REFERENCES CITED