Is stoping a volumetrically significant pluton emplacement process?:
Discussion

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Glazner and Bartley (2006) suggest that stoping is an insignificant to potentially nonexistent process in the emplacement and evolution of magmatic systems. We strongly disagree with this conclusion and present here a number of alternative perspectives, which we group into three categories: after a brief discussion of the definitions of stoping and rafts versus stoped blocks, we discuss (1) the characteristics and interpretation of pluton–host rock contacts, (2) the characteristics and interpretations of host rock xenoliths in plutons, and (3) several general issues raised by their paper.

RAFTS VERSUS STOPED BLOCKS: A MISLEADING DISTINCTION?

Historically, the idea of stoped blocks and rafts in plutons extends back to Goodchild (1892). Goodchild described the presence of inclusions in plutons but did not ascribe any movement to these inclusions; thus, this first description identifies what would now be called a raft. He stated “lines of stratification, the false bedding [presumably a foliation], and the joints of the original quartzite are distinctly traceable through the included blocks in their present position” (p. 449). However, he also stated that the inclusions appeared to have been detached across joint planes. Daly (1903, 1933, p. 268) stated “here the term stoping will mean subsidence or ascent of included blocks because they have densities contrasted with that of the inclosing melt.” His statement, that during “continued fracturing of wall or roof, continued immersion of corresponding fragments, the magmatic chamber is enlarged….” (p. 268) indicates that a chamber may grow upward, sideways, or both. To our knowledge, all subsequent papers about stoping refer back to the original Daly (1933) definition.

Here, we provide our own working definitions that have been slightly modified from Pignotta and Paterson (2007):

Magmatic stoping—the process of completely disconnecting and surrounding a piece of host rock (xenolith, if original host rock, or cognate inclusion, if older plutonic phase) by magma, resulting in movement of the block relative to its position prior to emplacement; stoping may occur along magma chamber roofs, sides, and floors at any crustal level, and blocks may form through a number of different processes (e.g., thermal cracking, diking, tectonic stresses, focused porous flow).

Stopped block—a host rock xenolith or cognate inclusion disconnected from its site of origin, surrounded by magma, and rotated and/or translated in this magma; stoped blocks commonly show evidence of physical disaggregation and sometimes melting and may be displaced downward (sinking) or upward (floating) depending on the density contrast between block and magma.

Raft—a host rock xenolith that is surrounded in two dimensions by plutonic material where no discernible rotation and/or translation (relative to in situ host rock) of that xenolith can be demonstrated. However, we note here that this definition, as also defined in the Glazner and Bartley (2006) paper, potentially propagates an incorrect but widespread belief regarding the differences between “rafts” as in situ pieces of host rocks and “stoped blocks” as translated and/or rotated pieces of host rock. If more than one raft exists, this requires either every other raft to have been at least laterally displaced as new magma intruded between them, or every raft to have been separated by zones of stoping, which removed the formerly contiguous host rock as magma surrounded each new raft. The former process requires displacement of rafts and the latter requires stoping (we ignore the unlikely case of complete assimilation of intervening material). Furthermore, the first process is “dilatational” in that rafts can only be moved apart from one another as new magma pulses intrude between formerly contiguous host rock pieces. This is a very testable scenario since it prevents lithologically unrelated host rock pieces from...
ever being brought together, particularly along the strike of bedding in each raft. Thus, accumulations of lithologically heterogeneous xenoliths (rafts or blocks) should not form by either of these processes. Figures 1 and 2 show situations where this test fails.

CHARACTERISTICS AND INTERPRETATION OF CONTACTS

We suggest that the existence of displaced and rotated xenoliths in plutons is only one observation that supports stoping. Discordant magma-host rock contacts, which truncate pre-placement host rock markers and show a lack of ductile deformation, are highly suggestive of host rock removal by a brittle process such as stoping. In some plutonic bodies, the total length of discordant intrusive contacts ranges from 50% to nearly 100% of exposed pluton-host rock contacts (Paterson et al., 1996; Žák et al., 2006). More specifically, we often find discordant, rectangular-shaped, stepped contacts along pluton margins, where the steps commonly approach 90°, rather than tapered shapes suggestive of dike tips. Most of these steps show no evidence of faulting at their corners (Paterson and Fowler, 1993; Fowler and Paterson, 1997; Yoshinobu et al., 2003), show no evidence of melting or assimilation along the contacts, do not have dikes along their margin, and show no evidence of internal contacts between dikes along the projection of the stepped walls into the pluton. We conclude that these steps represent locations of removed (by stoping) host rock blocks that were successfully transported out of the plane of observation. We see no evidence in these steps for the dike termination model of Glazner and Bartley (2006), nor do these stepped contacts support a sill or laccolith model of chamber growth, particularly for plutons with discordant, stepped margins, such as those in the Cascades core emplaced as deep as ~30 km, where roof uplift is difficult. Therefore, we believe that stoping remains one of many viable processes for host rock displacement during transport of magma.

CHARACTERISTICS AND INTERPRETATION OF XENOLITHS IN PLUTONS

Glazner and Bartley (2006) address evidence of rotation or nonrotation of xenoliths in plutons. We agree that this is an important criterion (however, please see our cautionary note regarding the definition of a raft), but it is one that must be evaluated through detailed observation and mapping. We have found many examples where xenolith long axes and preserved internal structures (bedding, foliation, lineation) have been rotated >90° from nearby potentially in situ host rock structures (however, even large pendants may be rotated or displaced, e.g., Memeti et al., 2005). We also have found examples of more subtle evidence of rotation. Many xenoliths have long axes roughly parallel to their internal foliation. These long axes are locally closely aligned to the magmatic foliation and track any changes in orientation made by this foliation (see also Wolak et al., 2005). This suggests that the xenolith long axes rotated parallel to the foliation due to the strain that caused this foliation. If the nearby margin of the pluton is roughly parallel to the structure of “in situ” host rock pendants (very common along the sides of plutons), then there may be an apparent, but misleading parallelism between xenolith and nearby pendant structures. We have found a number of these examples, including xenoliths (we interpret them as stowed blocks) along the eastern margin of the May Lake pendant, Tuolumne Batholith, Sierra Nevada (Fig. 2), one location referred to by Glazner and Bartley (2006). The following tests may be applied to our hypothesis: (1) block long axes should statistically parallel the magmatic foliation, even where this foliation curves into nonparallelism with the nearby pendant structures; (2) some block long axes should be at high angles to the magmatic foliation, as is predicted for tumbling objects during rotation caused by strain (Ildefonse et al., 1997); and (3) mixtures of juxtaposed, lithologically distinct blocks may be found in these xenolith accumulations (Figs. 1 and 2).

We find item three above to be a very telling observation, that is, the occurrence of mixed populations of xenoliths, including mixtures of microgranodiorite enclaves and host rock xenoliths, at the meter to 10 m scale. It is particularly telling if lithologically distinct blocks are in close proximity along the projected strike of bedding, since this precludes their being in original stratigraphic continuity or pieces of relict folds (Figs. 1 and 2). We suggest that such occurrences represent the accumulation of xenoliths and subsequent movement and alignment during flow of the surrounding magma (e.g., Tobisch et al., 1997).

Glazner and Bartley (2006) suggest that the existence of large populations of stowed blocks, as well as data on their dimensions and fractal characteristics, has not been recognized. In contrast, we have several such data sets, at least two of which are known to Glazner and Bartley through formal review or informal discussions. Examples are the large number of blocks preserved in the Mitchell Intrusive Suite in the southern Sierra Batholith (Pignotta, 2006; Pignotta and Paterson, 2007) and in the Kodiak Batholith, Alaska (Farris, 2006; Farris et al., 2006; Farris and Paterson, 2007). Both have a bifractal, xenolith frequency-size distribution: one slope of the curve fits the predictions that Glazner and Bartley (2006) make for block fracturing, and the other slope suggests that additional processes played a role in block disintegration. In addition, the Kodiak Batholith has large zones of partly digested and metamorphosed xenoliths in the pluton and geochemical and isotopic data that indicate ~80% of the magma formed from melted crustal material (Hill et al., 1981; Ayuso et al., 2005; Farris, 2006). Although we cannot establish the magnitude of in situ digestion of xenoliths due to the overall crustal contamination, the preservation of partly digested xenoliths indicates that this process played at least some role in the contamination of these magmas (Tangalo et al., 2003; Farris, 2006; Farris et al., 2006).

The concern Glazner and Bartley (2006) have about the lack of “stowed block graveyards” at pluton floors is an interesting one. In our experience, very few pluton floors are exposed, except for the base of sills and dikies, which may not do a great deal of stoping (however, see Fig. 3). Furthermore, we are not yet sure what features to look for at pluton floors, since the behavior of stowed blocks in chambers is complex (e.g., Clarke et al., 1998; Sparks et al., 1977; McLeod et al., 1998; Wolak et al., 2004). If blocks partially melt, we may find only refractory remnants (e.g., Dunand et al., 2005). If they mechanically disaggregate, as Glazner and Bartley (2006) argue they should in order to get fractal block-size distributions, we may need to look for piles of small xenoliths or even xenocrysts at any subhorizontal boundaries (i.e., Hawkins and Wiebe, 2004) or find cumulates of individual crystals at pluton floors or, for that matter, dispersed throughout the pluton. Pieces of blocks may also get trapped at other rheological boundaries in the chamber; or they may get swept off floors if continued movement of magma occurs (Fig. 3)(e.g., Hawkins and Wiebe, 2004). For example, magma flow in large dolerite sills exposed in the Dry Valleys of Antarctica (Fig. 3) ripped off pieces of Beacon Sandstone along both the roof and floor of the sill, rotating these pieces within the sill, but not obviously depositing them on the floor (Fig. 3).

The mechanism, if stoping was a minor process in these sills, or if blocks were removed elsewhere, is unknown. Finally, examples of stowed blocks well below pluton roofs (e.g., Paterson and Miller, 1998b) and block “graveyards” on intrusion floors do exist, such as in the Sázava pluton, Bohemian Massif, where closely packed blocks of older refractory plutonic rocks have accumulated ~1 km below the pluton roof (Fig. 9c in Žák et al., 2006).
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Figure 1. A collection of lithologically diverse and variably oriented xenoliths located near the Benson Lake pendant, Sierra Nevada. Compositions include metasedimentary, metavolcanic, and plutonic blocks. We interpret all of these xenoliths to be stoped blocks collected elsewhere and transported to this site; during transportation, some alignment of blocks occurred.

Figure 2. Lithologically diverse xenoliths in the Kuna Crest unit of the Tuolumne Batholith adjacent to the May Lake pendant, Sierra Nevada. Compositions include metapelites, metapsammite, amphibolite, and one of uncertain protolith. We interpret all of these to be stoped blocks transported to this location.

Figure 3. Dolerite sills (dark rock) in the Dry Valleys, Antarctica, intruding the well-bedded Beacon Sandstone. Blocks of sandstone formed at both the roof and base of the sill, and smaller pieces (lower right arrow) were ripped off larger blocks and rotated along the sill floor. Middle and left arrows point to pieces of clearly rotated blocks in the center of the sill. The upper piece of Beacon Sandstone has stratigraphic units that match well to the lower piece of Beacon Sandstone. This example shows that sheetlike bodies can certainly break off pieces of host rock from both their roof and floor during emplacement and not necessarily result in a pile of blocks on the floor of the sill. Picture was taken from helicopter: cliff is >500 m high in photo.
show little to no evidence of extensive annealing in the Tuolumne Batholith, nor is it clear to us how annealing at the mineral scale would in fact remove evidence of an internal contact (Vernon, 2006, personal commun.).

From the Glazner and Bartley (2006) paper, readers might conclude that there is little reason to consider the process of magmatic stoping. In contrast, we suggest that block formation and the behavior of blocks in magma chambers are very informative pursuits. Our studies indicate that a careful examination of block formation provides insights into a natural experiment on the relationships among high-temperature cracking, local focused porous flow, local assimilation, dike formation and propagation, the high-temperature rheological importance of grain size and anisotropy, and the interplay between thermal versus regional stresses. These processes occur around all plutons, whether or not stoping is widespread, and understanding them will certainly improve our knowledge of the high-temperature rheological behavior of the lithosphere. Furthermore, once blocks are in chambers, they continue to act as useful tools such as paleo–plumb bobs and timing markers, particularly in regard to the timing of magmatic fabric formation, and as rheological indicators of the relative strength of magmas (e.g., Paterson and Miller, 1998b).

In summary, we suggest that stoping is widespread in all types of plutons, but there is a range of magnitudes, and that there is much to be gained by studying the process of stoping in regard to high-temperature rheological behavior and magma emplacement. However, we suggest that careful field studies (e.g., meter-scale grid-mapping), microstructural observations, and detailed geochemical analyses, combined with sophisticated modeling, are needed rather than the broad speculations presented by Glazner and Bartley (2006).

REFERENCES CITED


Gerbi et al. (2004) noted that this magnitude of stoping can remove a large portion, if not all, of ducile aureoles developed around plutons, thus removing evidence for the earlier emplacement history. We have also recognized examples where younger pulses of magma have broken off (stope) pieces of older highly viscous magmas as they moved into a magma chamber, thus changing the final physical, geochemical, and potentially chemical patterns preserved in the pluton (e.g., Zák and Paterson, 2005; Zák et al., 2006; Matzel et al., 2005).

We also find Glazner’s and Bartley’s (2006) arguments that the Tuolumne Batholith consists of a large number of dikes, that host rock xenoliths only occur along dike contacts, and that these dike contacts are now cryptic because of extensive annealing rather startling. Two of us (Paterson and Fowler, 1993; Paterson and Vernon, 1995; Gerbi et al., 2004). However, even this amount of stoping can considerably modify a number of aspects of pluton–host rock systems. For example, Gerbi et al. (2004) noted that this magnitude of stoping can remove a large portion, if not all, of ducile aureoles developed around plutons, thus removing evidence for the earlier emplacement history. We have also recognized examples where younger pulses of magma have broken off (stope) pieces of older highly viscous magmas as they moved into a magma chamber, thus changing the final physical, geochemical, and potentially chemical patterns preserved in the pluton (e.g., Zák and Paterson, 2005; Zák et al., 2006; Matzel et al., 2005).

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