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Re-examining pluton emplacement processes: Reply

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WE WERE pleased, and not surprised, to receive a comment about our article (Paterson & Fowler 1993) from someone working in the field of diapiric modeling. Our study was, in part, an effort to test pluton emplacement models proposed by laboratory work against the rock record—an important step in any geological modeling. We wish to note that our paper does not preclude the processes of diapirism (as defined in Weinberg's comment) or ballooning during final emplacement. We simply argue that other mechanisms besides ductile flow must operate during ascent and emplacement and that only a limited amount of expansion occurs during final emplacement.

Weinberg's main objections to our paper are as follows: (1) displaced volumes of country rock were underestimated because of difficulties in assessing shape and size of the three-dimensional flow field around plutons, particularly in the far field; and (2) narrow strain aureoles may result from ascent of plutons through 'power law' rocks. In stating these objections, Weinberg has chosen to ignore both the contradictory nature of these objections and implications that we have noted in our original paper. We completely agree with Weinberg that since plutons intrude country rocks that behave as power law materials and have temperature dependent viscosities, any ductile flow associated with emplacement will be concentrated in narrow aureoles. However, throughout his comment Weinberg ignores the implication that narrowing the aureole requires an *orders of magnitude* increase in the intensity of strain in the aureole. For example, for the width of aureoles in power-law materials proposed by Weinberg, X/Z strain ratios approaching or exceeding 1000/1 are needed. If these high strains are not present, as is the case around natural plutons, sufficient ductile flow for diapiric ascent or ballooning did not occur. Just as importantly, the rapidly increasing volume of country rock with distance from the pluton requires a rapid decrease of strain with distance from the pluton. Essentially, diapiric ascent or ballooning can only transmit strains to a wide outer aureole by having large strains in the inner aureole. It therefore seems unlikely for both mechanical reasons (thermal and power law behavior) and geometrical reasons that significant (any?) *ductile* flow will occur in a wide outer aureole, particularly at the time scales of pluton emplacement. Thus Weinberg incorrectly implies that lack of sufficient strain in inner aureoles can be compensated for by low intensities of far field strain.

We also do not feel as pessimistic as Weinberg does when he states that "determining the geometry of the flow cell is an impossible task". Ductile flow around a rising or expanding diapir *requires* simultaneous and volumetrically compatible flow everywhere around the diapir, assuming that large elastic strains do not occur. Thus, two-dimensional slices do provide important constraints on the three-dimensional flow field. By looking at many two-dimensional slices through different plutons, likely flow fields can at least be proposed. For example, we are presently examining the roofs and adjacent sides of tilted or vertically exposed plutons and almost invariably find that ductile strains decrease from sides to roof—in direct contradiction to Weinberg's suggestion that strains may be higher in the roofs. We have also found good examples of strain/structural discontinuities around the sides of the Papoose Flat and Ardara pluton which indicate that the intensity of ductile strains can abruptly drop short distances from pluton margins. Both of these observations indicate that the type of flow field envisioned by Weinberg is unlikely around natural plutons.

There are several other statements made by Weinberg that we feel are incorrect or misleading. (1) He suggests that "late deformation will mask the strain aureoles". We mentioned this in our paper but noted that this will in most cases *reduce* actual values of emplacement related strains. (2) He refers to an article by Guglielmo (1993) several times to argue for widths of aureoles around plutons and means of 'masking' intensities of strain in the aureole. Although Guglielmo's modeling is geometrically spectacular, it starts with an already emplaced pluton, only considers passive ductile strain with no thermal or power law effects, and assumes an aureole width rather than predicting this width. (3) Weinberg states that "estimated volumes are bound to be smaller than the volume of the plutons that displaced them", a statement for which we can find no substantiation and with which we completely disagree. (4) He implies that various mechanical responses of country rock somehow alter our results. Mechanical responses of country rock will determine the mechanisms and distribution of flow, but the required displaced volume stays the same. Volume constraints of needed country rock flow are independent of how flow is occurring. (5) He states that "high strain rate immediately around a sphere creates a region of low viscosity". What is the evidence? The modeling on which he bases this conclusion is only testing the viability of a single mechanism—power-law flow. Maybe high strain rates cause fracturing, as is predicted by other rock experiments, and thus increase the rate of stoping. Interestingly, while re-examining photos of Ramberg's centrifuge experiments (e.g. Ramberg 1967), we noted radial dilatant cracks with increasing margin-parallel displacement towards the pluton along with ductile flow. (6) Weinberg implies that the rim syncline around Arran granite is explained by power-law flow, but in his theoretical calculations (his fig. 1a) using an n value of 10 (well above predicted values for real rocks), his rim syncline goes out 1–2 body radii, while around the Arran granite the rim syncline is located only 0.2–0.4 body radii from the pluton. We are also somewhat confused by his choice of the Arran pluton because this is one documented example where multiple material transfer processes occurred during emplacement. (7) He states that "the strain aureole around Ardara pluton could be even narrower than it is without conflicting with the strain aureoles around experimental spheres rising through power-law fluids". This is incorrect—the required large increase in *intensity* of strain is completely ignored, is absent around the Ardara pluton, and thus invalidates this statement. (8) Finally, we note that Weinberg's values in his table 1 and fig. 1 do not agree with each other nor with statements in the text such as the width of aureoles in power-law materials "would be 45–150 times narrower than in Newtonian rocks", and that the Ardara aureole could be "even narrower . . . without conflicting with [power law models]". According to his table 1, aureoles in materials with power law exponents of 2.5 and 5 would be 18.2 and 25.8 times narrower than in Newtonian materials whereas the Ardara aureole is 193.1 times narrower than Newtonian and 7 times narrower than even Weinberg's power law material with an exponent of 10!

CONCLUSIONS

Weinberg finishes his comment by arriving at two conclusions based on faulty reasoning. He states that it is impossible to establish three-dimensional flow fields and implies that plutons must therefore rise as 'hot-Stokes' or 'power-law' diapirs. He also nicely shows that diapirism in power law country rocks should result in narrow aureoles but then uses this observation to conclude that space for the diapir was made completely by ductile flow. As stated above, we are not as pessimistic about placing constraints on three-dimensional flow fields around plutons, but simply note here that, even if he is correct, Weinberg certainly cannot use this observation in support of 'hot-Stokes' or 'power-law' diapirism. We also emphasize that his theoretical study, and most existing experiments, are not testing if and when different material transfer processes occur (e.g. fracturing vs ductile flow). They are only testing the feasibility of a single type of behavior given rather unrealistic boundary conditions.

We conclude by presenting a more global perspective of this issue. There are thousands of stocks and batholiths described in the literature that have extremely discordant margins, often down to the meter-scale. There are also many plutons with narrow ductile aureoles. Both regional markers and strains measured using small-scale markers indicate that ductile flow, even in the most impressive of these concordant structural aureoles, is usually rather small relative to the size of these plutons. Studies of both types of plutons indicate highly discordant roof contacts are the general rule. We therefore suggest that significant far-field ductile flow in the middle to upper crust is uncommon and that a more realistic query is whether or not parts of the inner aureoles have been somehow removed. Did most of the near field material transfer occur by return flow down the magma conduit?

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