Reply to discussion

"The Ardara pluton, Ireland: deflating an expanded intrusion"

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Received 3 October 1994; revised and accepted 10 October 1994

1. Introduction

Morgan begins his discussion by stating that "the Ardara pluton is probably the classic example of a ballooning pluton". However, it is only a "classic example" if the ballooning model is correct! We agree with Morgan that careful evaluation of the ballooning model is needed, but we disagree with most of his statements. We will address each of Morgan’s points in the same order and using the same headings as in his discussion.

2. Field relationships

Morgan makes six points, a to f, which we will address. (a) Solid-state foliations (as opposed to non-penetrative solid-state deformation) generally are not well developed in the thin outer rind of the pluton and, where present, are not invariably parallel to the magmatic foliation (our fig. 5) or to the country-rock foliation. (b) There is no evidence that a solid-state foliation "lies in between two magmatically induced foliations". (c) We agree with this point. (d) In the north and north-west aureole, "aureole structures" do overprint "regional structures", but are in turn overprinted by regional folds and localized faults (Meneilly, 1982), as well as by shearing along the south-eastern margin. Late, localized "regional deformation" is also recognized in the northern aureole (Hutton, 1982; Meneilly, 1982). (e) We have no objection to this interpretation, but it should apply equally to both ballooning and non-ballooning models. (f) We agree with this point.

Morgan states that we offer no evidence for a post-intrusion regional event. Evidently he chose to ignore our evidence in support of Hutton's suggestion that a large ductile shear zone operated during and after emplacement along the south-eastern margin of the pluton, and the fact that Hutton (1982) has discussed another shear zone immediately to the north-east that was active after emplacement of the Ardara pluton. Morgan also did not comment on work published by Meneilly (1982), who noted that a regional D4 folding event "was synchronous with intrusion of the Ardara" and that D5 folding and shearing in the northern and southern aureoles post-date emplacement of the pluton.

As stated in our paper, we agree that conjugate shears in the pluton may reflect strain hardening during pluton expansion. However, we also note that these shears are very uncommon, largely occurring in a small region near the north-western margin, and that they could have formed during regional deformation. If the shears had resulted from expansion, we would expect them to occur everywhere along the margin of the pluton, which Morgan states applies to the Chindamora batholith, Zimbabwe. However, this is not the situation for the Ardara pluton.

We agree that age relationships in this region are incompletely understood. Field relationships suggest that the Main Donegal and Ardara plu-
tons are essentially of the same age, although intrusive relationships indicate that some of the Main Donegal Granite is younger (Pitcher and Berger, 1972; Hutton, 1982). Rb/Sr dates for both these plutons fall between 407 ± 23 and 386 ± 33 Ma (Halliday et al., 1980; O'Connor et al., 1982). U/Pb dates for the Main Donegal Granite and the related Trawenay Bay pluton are 407 and 411 Ma, respectively, whereas our initial U/Pb date for the Ardara pluton is 451 Ma. K/Ar ages and one 40Ar/39Ar cooling age of hornblende, biotite and muscovite from these plutons, fall between 414 Ma and 357 Ma (Pitcher and Berger, 1972 table 4-1; O'Connor et al., 1982). Additional dating of both plutons would be useful. However, the available data support our suggestion that post-emplacement regional deformation and metamorphism occurred around the Ardara pluton. The data do not require the solid-state deformation to be 50 Ma younger than the emplacement of the Ardara pluton, as stated by Morgan. Pitcher and Berger (1972) and Hutton (1982) have suggested, and we concur (Vernon and Paterson, 1993; Paterson et al., 1994) that shear zones in this region were long-lived and that shearing along the south-east margin of the Ardara pluton probably occurred before, during and after emplacement of both the Ardara and Main Donegal plutons.

Morgan cites the AMS data published by King (1966) and somehow reaches the conclusion “that by using the AMS data, regionally induced tectonic deformation can be distinguished from magmatic deformation”, and that the AMS data indicate that “magmatic expansion can create solid state foliations”. We strongly disagree with both statements. The AMS data of King (1966) only constrain the geometry of foliations and lineations. Particularly in the absence of information about the magnetic carrier, the AMS data do not indicate whether the foliations/lineations are of magmatic or solid-state origins, nor whether they formed in response to a particular impetus, such as magma ascent, ballooning or tectonism. However, if we accept Morgan’s suggestion that all horizontal lineations reflect later “solid state sinistral shearing”, King’s data plus the horizontal lineations seen in the tail of the pluton indicate that about half the pluton was affected by this post-emplacement deformation. In addition, Akaad (1956, fig. 5) noted that foliations in the pluton steepen inwards, which is incompatible with ballooning. Moreover, the presence of steep lineations favours piercement diapirism, not ballooning.

We have no objections to the suggestion of two periods of porphyroblast growth, but they do not necessarily imply separate pulses of intrusion during ballooning, and they could also be explained by other emplacement models. In this connection, we emphasize that we do not consider the Papoose Flat pluton to be a “classic example of forceful emplacement” (Paterson et al., 1991).

Morgan incorrectly states that the radial dykes in the Ardara pluton are undeformed or unfoliated (e.g., Akaad, 1956, p. 274, figs. 3, 4, 6b; Pitcher and Berger, 1972, p. 176). We agree with Akaad (1956) that foliations are absent from the youngest aplitic and pegmatitic dykes. However, the dykes we examined show evidence of minor solid-state deformation. These observations again emphasize the importance of distinguishing between magmatic foliations, solid-state foliations and minor solid-state deformation. Our work indicates that the radial dykes cut the magmatic foliation, and that they, though they are foliated in some places and not in others, do show evidence of minor solid-state deformation, comparable with that in much of the pluton. Again, we emphasize that, except at the very margin, the Ardara pluton shows the effects of only weak solid-state deformation, not a foliation superimposed on a strong magmatic foliation. Solid-state foliations in the south-east tail of the pluton post-date dyke emplacement. We did not find a radial dyke close to conjugate shears, and so we are uncertain of the timing of these shears relative to dyke emplacement.

3. Strain estimates and pluton expansion

Morgan incorrectly states that we ignored rigid body translation in our calculations of how much expansion occurred during emplacement. Strain data from individual samples do not record rigid body translations. However, we also used the de-
flection of pre-emplacement regional markers to calculate values of bulk shortening in aureoles, and these calculations do account for translations (Paterson et al., 1991; Paterson and Fowler, 1993; Fowler, 1994).

Morgan questions our decision to discard estimates of strain measured from enclaves "because they are not passive markers". In fact, we discarded enclave strains for a variety of reasons, and argue that microgranitoid enclave and xenolith shapes are functions of (1) initial shape and temperature, (2) residence time in the magma, (3) viscosity contrasts between enclave and host magma and (4) deformation path, which may include strain during ascent, convection, expansion and later deformation. His subsequent discussion makes it clear that he has simply assumed that enclave shape reflects only expansion, and so has ignored our observations of adjacent enclaves with different ratios and locally with different long-axis orientations near the pluton margin.

The crux of this issue is whether markers in plutons only give information on expansion, as assumed by Morgan, or whether they also reflect other processes in the magma chamber. In this connection, Morgan appears to have underestimated the importance of the papers of Cruden (1988) and Schmeling et al. (1988). These studies showed that magma convection, driven by viscous drag during diapiric ascent or by thermal and chemical gradients in an ascending or stationary chamber, cause an increase in the intensity of magmatic foliations, as well as in the magnitude of enclave flattening towards the chamber margin. Any chamber expansion would enhance this pattern, of course.

Morgan refers to a previous review of ours (Paterson et al., 1991) and claims that we stated that diapirism is not a viable mechanism. However, we made no such statement. We noted that "hot stokes" diapirism is a likely process at depth, but less likely in the upper crust. Instead, we argued that diapiric ascent was probably accompanied by a variety of country rock material transfer processes, not just ductile flow. In fact, we are at pains to emphasize the need for multiple emplacement processes for most plutons. Over-emphasis of single processes has led to many of the controversies about granite emplacement.

Morgan raises the interesting question of whether magma emplacement can cause augen gneisses in the outer rims of plutons. He also argues that if magma emplacement can deform metasedimentary rocks, why not other granitoids? He quotes the Tuolumne Intrusive Suite, Sierra Nevada, California, as an example. However, anyone who has examined pluton-pluton contacts in batholiths like the Sierra Nevada or published maps of these batholiths, knows that most of these contacts are sharp and highly discordant, and that the contact-rocks are relatively undeformed. Augen gneisses are not widespread and almost invariably are interpreted as having formed in post-emplacement shear zones (e.g., Tobisch et al., 1990). We are particularly confused about why Morgan mentioned the Tuolumne Intrusive Suite in this regard, because this batholith, though zoned, is a highly discordant body with largely undeformed margins, that is now viewed as a sequence of nested diapirs. Furthermore, magmatic foliations in this NW-SE trending batholith generally strike E-W and are not margin-parallel. Some solid-state foliations do occur locally, but are inferred to be fault-related (e.g., Hutton and Miller, 1994).

Furthermore, there may be large rheological differences between deforming quartz–mica-rich metasedimentary rocks and feldspar–hornblende-rich granitoids, as noted by others (e.g., White et al., 1976; Hine et al., 1978; Vernon and Flood, 1988). Metasedimentary rocks may be especially weak when undergoing dehydration reactions that pervasively release water, as in contact metatamorphic aureoles (Vernon et al., 1993).

We have recently submitted a paper with a much more extensive discussion of these plutons (Ardara, Papoose Flat, Tuolumne) and others, concluding that they are not "classical examples" of ballooning or "forcibly emplaced" plutons. On the contrary, their characteristics are better explained if they are viewed as asymmetrical, syntectonic, nested (where strongly zoned), piercement diapirs emplaced by the simultaneous operation of several country rock material transfer processes.
References


