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Origin of enclaves in S-type granites of the Lachlan Fold Belt

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ABSTRACT

The more mafic S-type granites of the Lachlan Fold Belt contain a distinctive assemblage of lithic inclusions of deep crustal origin. Two types predominate, the schistose enclaves and the microgranular enclaves. There is also a small proportion of fragments of local country rock. All the features of the schistose enclaves are consistent with an origin as lithic restite fragments from the source. Their ubiquity in the mafic S-type granites and absence from both felsic S-type granites and I-type granites, conform with such an origin. The argument that these enclaves are not in chemical equilibrium with the host granite because they do not complement its composition is not valid, since they represent less fertile parts of the source that had different compositions that, as a result, melted to a lesser extent. Models that derived these enclaves from regions of the crust above the zones of partial melting, so that they are not restites, are complex, unnecessary, do not conform with their ubiquity in the more mafic S-type granites, and are not consistent with their chemical compositions.

The origin of the microgranular enclaves is controversial. In most S-type granites these enclaves have been recrystallized to a similar mineral assemblage to the host granite with a higher proportion of biotite. In a few places, such material is seen to be forming by recrystallization of material in the core of the enclave, which has the assemblage quartz + calcic plagioclase + orthopyroxene ± cordierite ± biotite with accessory ilmenite, sulfide and apatite. All of the microgranular enclave cores show pseudo-doleritic texture in which calcic plagioclase crystals ($>An_{60}$) and orthopyroxene crystals project into or are enclosed by quartz. Large plagioclase crystals are zoned, with some core compositions as calcic as An_{94}. The low Na contents of the microgranular enclaves are not consistent with an igneous origin. We consider that these enclaves were derived by metamorphism of calcareous mudstones or argillaceous limestones. The pseudo-igneous textures result from the presence of a partial melt during metamorphism. An analysis of a calc-silicate lens of upper amphibolite grade from the Wilsons Group of Victoria Land, Antarctica is remarkably similar in composition to the microgranular enclaves from Lachlan Fold Belt S-type granites. We suggest that rocks equivalent to that Group, which is of appropriate age and general composition, were the source rocks for the S-type granites of the Lachlan Fold Belt.

1. Introduction

S-type granites comprise a little over half of the 63,000 km^2 of granite that is exposed in the Palaeozoic Lachlan Fold Belt (LFB) of southeastern Australia. That the source rocks of these granites were at least dominantly sedimentary is shown by the strongly Al-oversaturated or peraluminous compositions of these rocks, with corresponding mineralogical features such as the presence of abundant cordierite, which is commonly altered, in the more mafic varieties. Such an origin is also consistent with the relatively evolved isotopic compositions. As is fairly generally (but certainly not universally) the case with less felsic granites, the more mafic S-type granites of the LFB invariably contain enclaves. The abundance of enclaves has been estimated for two locations of mafic S-type granites in the Kosciuszko Batholith. Chen et al. (1989) showed that enclaves with a diameter greater than 20 mm comprise 5% of the total volume of the Jillamatong Granodiorite at the locality which they studied. At Deddick, 60 km to the south, Maas et al. (1997) report that enclaves make up 4 to 7% of the exposure. The abundances of enclaves at these localities are characteristic of more mafic S-type granites of the LFB.

During mapping of the Berridale and Numbla 1:100 000 sheets, White et al. (1977) and White and Chappell (1989) described various types of enclave in the S-type granites, and the chemical compositions of 37 such enclaves were presented in those publications. Wyborn et al. (1991) reported data for 14 enclaves from the Cowra Granodiorite, 320 km north of Jillamatong. We have subsequently sampled 39 enclaves from the Young, Wagga and Maragle Batholiths of the LFB.

It is our view that while some accidental enclaves or xenoliths are present in these S-type granites, most of the enclaves represent lithic

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restite, that is they are pieces of largely solid material remnant from partial melting, which were transported from the source (Chappell et al., 1987; Chen et al., 1989; White et al., 1999; Wyborn et al., 1991). Some silicate melt may have been present in the enclave, and textural evidence shows that this was normally the case, but for the enclaves that are now present the amount of melt was insufficient for them to be disrupted. When fragmentation did occur, the former components of an enclave are seen as either smaller clusters of minerals or as individual crystals in the granite. Some of the other minerals in the granite may have been transported from the source as individual crystals of restite, or as small aggregates of such crystals. The relative proportions of single restite crystals in the granites that were transported from the source as such, or were derived from disaggregated lithic enclaves, is uncertain. The process of entrainment of solid material from the source, both as crystals and enclaves, was termed the restite model by Chappell et al. (1987).

This view of the origin of the enclaves in the S-type granites of the LFB differs from that of other workers (Elburg and Nicholls, 1995; Maas et al., 1997; Vernon, 1983, 1984, 1990, 1991, 2007; Waight et al., 2001). Those contributions are considered in the following discussion, where the restite model seems to provide a firmer basis for understanding the origins of the enclaves. In particular, this contribution shows how the restite model accounts in a much more satisfactory way for the fine-grained “microgranular” enclaves than do the widely accepted quenched mafic magma models.

2. Definitions of restite

Chappell and White (1991) used the term restite to refer to any solid material in a plutonic or volcanic rock that is residual from partial melting of the source and inferred that restite may occur as enclaves, or as single crystals either derived from the disintegration of enclaves or carried from the source as separate crystals. Vernon (2007) noted this definition and he stated that it implies that “source” means the specific parent rock that melted (we would say partially melted) to produce the granite magma under consideration. We agree that it has that implication and we will continue to use the term in that way.

White et al. (1999) discussed several types of restite minerals that may occur as individual crystals in S-type granites. First, they considered minerals which formed as a result of dehydration reactions, such as the incongruent melting of biotite (peritectic reaction)

$$\text{biotite} + \text{quartz} \rightarrow \text{orthopyroxene} + \text{melt}$$

The orthopyroxene is a restite phase, although it grows in the presence of melt and may form well-shaped crystals in that environment. When crystallization of that melt occurs, then additional orthopyroxene, indistinguishable from the restite crystals, could be produced. The reaction of biotite to produce orthopyroxene, followed by the later back-reaction to give biotite + quartz, has probably occurred in most S-type granites. In some cases the former presence of orthopyroxene is represented by quartz-biotite aggregates. Clemens et al. (2010) have proposed the term *peritectic crystal entrainment* for a process in which crystals, such as orthopyroxene, that have formed by a peritectic melting reaction are incorporated in the melt. Wyborn et al. (1981) described S-type volcanic rocks containing euhedral phenocrysts of orthopyroxene and cordierite, thought to be comagmatic and coeval with S-type granites of the LFB.

Second, plagioclase will be involved in partial melting processes. More calcic cores of plagioclase can result from partial melting, and likewise more magnesian cordierite. Both minerals will be restite, and again they will form in a melt environment and can have euhedral outlines. Chen et al. (1989) at Jillamatong and Maas et al. (1997) at Deddick have reported plagioclase in enclaves that is less calcic than the plagioclase in the host granite, and likewise for less magnesian cordierite. These data imply that the plagioclase and cordierite in the enclaves was not in equilibrium with the melt outside the enclaves, but this cannot be taken to mean that those minerals are not crystals of restite, nor can it be taken that the enclaves themselves were not residual from the source, i.e. restite.

Third, White et al. (1999) considered minerals that participate in the melt-forming reactions, but do not completely dissolve. Zircon is an excellent example in the S-type granites of the LFB, where the temperatures of the partial melts, given the compositions of those melt, were insufficient to produce complete melting of that mineral, in accord with the experimental data of Watson and Harrison (1983). Older zircon can always be found in those rocks (Williams, 1995), and it therefore was saturated in their melts and was, accordingly, a restite phase. Quartz was sufficiently abundant in the source rocks of the S-type granites for that mineral to be saturated in the melts and was therefore a restite phase in all but perhaps the most felsic rocks. The presence of the lumps of milky quartz, discussed below, testifies to that.

The reasons for considering that these individual crystals in the S-type granites of the LFB had a restite origin were discussed by Chappell et al. (1987). Our use of the term restite also encompasses all rock fragments that are carried from the source. These enclaves include completely infertile rocks that did not produce any melt phase, and rocks in which insufficient melt was produced for the enclave to disaggregate into the magma, although some melt could have been contributed (White et al., 1999). It is the enclaves, including material of such lithic restite that we are considering in more detail here. There is, of course, a general correlation between the abundance of these enclaves and the colour index of the host granite.

3. Enclaves in S-type granites of the Lachlan Fold Belt

An early account of enclaves from the LFB was of those from the Cowra Granodiorite by Stevens (1952). That pluton contains excellent exposures for examining enclaves in outcrop, at the Japanese Garden in Cowra (657037E 6255849N) (grid references in this paper are to zone 55 of the Geocentric Datum of Australia GDA94), where the use of water from the chlorinated city supply has removed lichen from the boulders, and nearby at Cowra Lookout (656828E 6255425N), where large boulders were blasted in creating the lookout.

3.1. The Cowra Granodiorite and Canowindra Volcanics

Ickert and Williams (2011) have reported a U-Pb zircon age of 428.5 Ma for the Cowra Granodiorite. The intrusion is elongated north–south and comprises garnet-cordierite granodiorite outcropping over an area of 72 km^2 (Fig. 1). It is representative of more mafic granites of the extensive (8750 km^2) Bullenbalong Supersuite (BSS) (see Chappell et al., 1987), and is its most northerly body. Despite its mafic character, contact metamorphic effects where it intrudes Silurian sedimentary rocks on its southeastern side are only seen within a few metres of intrusive contacts. Wyborn et al. (1991) have described the granodiorite as a medium- to coarse-grained rock with crystals of quartz, plagioclase, and white K-feldspar with cordierite up to 3 mm across and smaller commonly perfectly-shaped red-brown biotites 0.5-1 mm across. Large almandine garnets (mg 20–25) are sparse and surrounded by pinitized cordierite (Fig. 2). Plagioclase, which may appear as perfectly-shaped crystals, is complexly twinned and zoned with the composition mostly being in the range $An_{30–50}$, although there are some strongly sericitized cores. K-feldspar is weakly perthitic and there may be some granophyric texture when it is contact with quartz. Cordierite appears as pinite and/or mica pseudomorphs and there are small rosettes of secondary muscovite. Zircon, chunky prisms of apatite, and ilmenite are accessory minerals.