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Correlation between magnetic fabrics, strain and biotite microstructure with increasing mylonitisation in the pretectonic Wyangala Granite, Australia

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ABSTRACT

The Wyangala Granite is a foliated, porphyritic Silurian granite from the Palaeozoic Circum-Pacific type Eastern Lachlan Orogen (ELO) of Australia. It is a paramagnetic ilmenite-bearing, S/marginal I type two-mica- to mainly biotite–granite with different biotite contents and local chlorite alteration. Very highly strained quartz–epidote bands are present. In this contribution, anisotropy of magnetic susceptibility (AMS) is compared with independently measured intensity and 3D style of strain, biotite microstructure and degree of mylonitisation for low-strain granites with weak S-foliations, through medium-strain protomylonitic granites with moderate S- and C-foliations to a high-strain altered granite with a strong single foliation. The samples are further analysed for possible contributions from sample heterogeneity, magmatic flow and 'sub-magmatic' deformation.

A good correlation, $P'_{AMS} \sim 1.02 + 0.04 \ln P'(e)_{Qtz}$, is obtained between site-average degree of AMS (P'_{AMS}) in the granite and degree of finite-strain anisotropy ($P'(e)_{Qtz}$) from aspect ratios of quartz aggregates in S-foliations in hand specimen and outcrop (P'_{AMS} 1.03–1.14, $P'(e)_{Qtz}$ 1.4–19). The magnetic fabric ellipsoids agree with a kinematic regime between neutral and pure oblate predicted by the March model. The observed quartz strains, however, exceed the AMS March strains and are near neutral, plano-linear character. The geological factors that may have contributed to these differences include intra- and inter-crystalline deformation of biotite and bimodality in S and C.

Magmatic fabric is not clearly evident in either the AMS or the biotite data. New data for synkinematic oligoclase, low-titanium biotite and low-sodium K-feldspar show that conditions during deformation were approximately transitional greenschist–amphibolite facies: i.e., well below solidus. This agrees with published age data that put the granite emplacement in an extensional, back-arc setting in already deformed country rocks, and before later convergent regional deformation in Middle Devonian (Tabberabberan event) to Early Carboniferous (Kanimblan event) time.

1. Introduction

One of the techniques which is widely used to obtain the regional distribution of strain in granites is anisotropy of magnetic susceptibility (AMS). However, it is still often not known (1) how the intensity and shape of magnetic fabrics correlates quantitatively with strain in granites. Other related strain questions are (2) how the minerals responsible for the AMS acquired their preferred orientation (Passchier and Trouw, 2005; Vernon, 2004) and whether this can be used to predict strain (Oertel, 1983), and (3) how much of the observed magnetic fabric is due to magmatic flow and how much to solid state strain, especially in granites with weak magnetic fabrics (Benn, 1994, 2009). A separate question which is important for geological interpretation of AMS data is (4) whether, as frequently described for other granites, the present granite had been emplaced during the regional deformation or syntectonically (for commonly used criteria see Paterson et al., 1989; Vernon, 2004).

Early studies have established a correlation of strain intensity and magnetic fabric anisotropy in magnetite bearing (ferrimagnetic) granites (Cogné and Perroud, 1988). Such a correlation has been substantiated by Mamtani et al. (2011) who identified rigid body rotation of magnetite grains as a prevailing mechanism for magnetic fabric development in variably deformed ferrimagnetic granites. In paramagnetic granites the orientation distribution of mica is the main constituent of AMS. The relationship between mica-preferred orientation and magnetic fabric anisotropy has been well established in previous studies (Siegesmund et al., 1995; Hrouda et al., 1997; Lüneburg et al., 1999; Chadima et al., 2004). However, in granite, a complex microstructural fabric evolution is realized and so the relationship between strain and AMS needs a more detailed investigation.

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The Wyangala Granite in the Paleozoic Lachlan Orogen in eastern Australia is a foliated marginal S-type granite with paramagnetic biotite as the main constituent. The initial aim was to quantify the degree of strain in the granite, which had been mapped for degree of mylonitisation using the field criteria of White and Lennox (2010), with the help of AMS. As the study progressed, we came to better address questions (1) to (4) listed above. With its excellent foliations, good exposures and known time constraints, the Wyangala Granite is ideal for examining these points. This paper presents the mapping of PGL, the AMS data and documentation of those aspects concerning the interpretation of the AMS.

Given a sparse distribution of suitable geometrical markers such as xenoliths (Ramsay and Graham, 1970; Cogné and Perroud, 1988) or enclaves for independent estimation of finite strain, we devised a new method applicable to all of the samples which measures mesoscopic partial strain in granite from deformed quartz aggregates. This quantity reflects both the solid state degree of foliation development and the degree of biotite deformation because the foliation is mainly due to the deformation of quartz and biotite (Vernon and Flood, 1988). Correlations on a sample-by-sample basis are thus obtained between intensity of magnetic fabric, intensity of foliation, formation of S and C structure, degree of mylonitisation and strain determined from quartz aggregates.

A steep plano-linear S-foliation throughout the area, supported by measurements of 3D quartz-aggregate shape in some of the samples, allows us to compare also a near neutral and predominantly contractional deformation style in this granite with the ellipsoid shapes recorded by AMS.

To better understand the cause of the AMS fabric we report detailed optical analysis of biotite deformation styles and mechanisms in orthogonal oriented thin sections over the range of samples and strain states.

To test the magmatic versus solid state question we examined the biotite fabric in relation to a known magmatic foliation. We also use Benn's (1994) superposed strain models to determine whether there are regional variations of AMS that may be due to a variably oriented magmatic component.

Gneissic S-type granites are theoretically candidates for a number of proposed tectonic settings, one of which is the continental collision type (Barbarin, 1990; Pitcher, 1993) considered to have formed during regional orogenic deformation and metamorphism or syntectonically. The Wyangala Granite is an ideal case to test that possibility because of established chronologies of emplacement and regional deformations. Current age constraints place the emplacement as post Early Silurian deformation and pre-late Middle Devonian to Early Carboniferous deformation. Hence it is known to be pretectonic with respect to its foliation and metamorphism and not syntectonic. New electron microprobe data for minerals formed during deformation provide further support for that conclusion.

Finally, AMS data for limited samples of an unusual rock type dominated by weakly paramagnetic epidote provide an interesting contrast to biotite in their response to near plane strain deformation.

We begin with a review of the geological setting of the granite, including the recent mapping, and a description of the mineralogy, metamorphism and mesoscopic structures in the sampled granite rock types. This is followed by an account of the magnetic fabric, mesoscopic strain and microstructure and their respective correlations for the granite samples.

2. Geological setting and rock samples

2.1. Tectonic setting

The *Tasmanides* of Australia is one part of the 9000 km long series of convergent margin orogens along the southern and eastern margins of the Gondwana supercontinent from the Neoproterozoic till the Mesozoic (Coney et al., 1990; Cawood, 2005).

The *Lachlan Orogen* (LO) is a 700 km wide Early Paleozoic part of the Tasmanides in south-eastern Australia (Fig. 1a, b) that is thought to be an ancient convergent plate margin under which the paleo-Pacific oceanic lithosphere was continuously subducted (Aitchison and Buckman, 2012). It is considered an excellent example of an extensional accretionary orogen (Collins, 2002; Cawood et al., 2009) and to have always faced an ocean (Cawood et al., 2011).

The Lachlan Orogen (LO) is usually divided into three sections: the western, central and eastern belts reflecting the disparate deformation histories of these three sections (Fig. 1b). The *Eastern Lachlan Orogen* (ELO), the target of this study, is introduced in more detail in the following section.

2.2. Eastern Lachlan Orogen

The ELO consists of generally north–south elongated composite batholiths within previously east–west, then north–south folded Early Paleozoic sediments and volcanics (Fig. 1b; Glen and Wyborn, 1997). The Wyangala Granite lies in the Hill End Zone of the northern ELO (Fig. 1c) which in this area comprises mainly Ordovician metasediments and volcanic rocks of the Ordovician Macquarie Arc.

The geochemistry of the Macquarie Arc rocks indicates they formed in an intra-oceanic island arc settings (Glen et al., 2011) away from any pre-existing continental crust, or by rifting within a continental margin sequence upon an established marginal or back-arc basin (Quinn et al., 2014). They are surrounded by Ordovician marine, quartzose turbiditic sandstones and overlying siltstones with regionally persistent chert horizons (Percival et al., 2011) and contain zircon age populations different from the Macquarie Arc rocks (Meffre et al., 2007). The Ordovician turbidites and volcaniclastics were deformed during the two phases of the Late Ordovician–Early Silurian Benambran event *prior to* intrusion of the Wyangala Batholith, which was around 425 Ma (Lennox et al., 2014).

The various plutons within the batholith were deformed preferentially along their eastern margins *after intrusion* during the late Middle Devonian Tabberabberan event and Early Carboniferous Kanimblan event (Paterson et al., 1990; Lennox et al., 2014).

2.3. Wyangala Batholith and Wyangala Granite

The *Wyangala Batholith* consists of over 30 plutons spread over 160 km north–south and 30–40 km east–west (Fig. 1c). The Wyangala Supersuite constitutes the majority of the Wyangala Batholith and consists of three suites and twenty three plutons, including the Hovell Suite of ten plutons (Thomas and Pogson, 2012). The *Wyangala Granite* is the type pluton of this suite and covers 450 km^2 with the main body roughly square shaped and 35 km on each side (Fig. 1c). Across the generally north–south trending Wyangala Fault (Pogson and Watkins, 1998), also known as the Wyangala Dam Shear Zone (Close, 1978) is a NNE-trending part of the granite which is 1.5–4 km wide and 22.5 km long (Close, 1978; Pogson and Watkins, 1998) (Fig. 1c). This paper focusses on the more deformed eastern edge of the main body of the Wyangala Granite in the spillway of Wyangala Dam (GR 679600 6238200) west of, within and adjacent to the Wyangala Dam Shear Zone (Fig. 2). It also compares these mylonitised granites with less deformed granite in dimension stone quarries west and south of the spillway (Fig. 2a).

Thomas and Pogson (2012) describe the granite as a grey to cream or white, medium- to coarse-grained, equigranular to porphyritic, often megacrystic, generally foliated, cordierite–muscovite–biotite granite and granodiorite. It is an S-type granite although alteration is said to have moved its composition into the field of I type granites (Pogson and Watkins, 1998). Other writers have described the Wyangala Granite as a foliated, porphyritic biotite granite with megacrystic K-feldspar up to 10 cm across (Hobbs, 1966; Zee, 1983; Zee et al., 1985). The composition described by Thomas and Pogson (2012) is shown in Table 1 and is similar to that described by Close (1978) for samples east of the Wyangala Dam Shear Zone.