Lithos 120 (2010) 277–292

Contents lists available at ScienceDirect

Lithos

journal homepage: www.elsevier.com/locate/lithos

# Selective entrainment of peritectic garnet into S-type granitic magmas: Evidence from Archaean mid-crustal anatectites

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ARTICLE INFO

*Article history:*
Received 16 March 2010
Accepted 10 August 2010
Available online 15 August 2010

*Keywords:*
Peritectic garnet entrainment
Anatexis
Granite geochemistry
Granite petrogenesis

ABSTRACT

Entrainment of restite is commonly invoked to explain both the origin of relatively mafic granites and granodiorites, as well as the chemical connection between granite magmas and their sources. This concept has become linked to models for magma migration out of the source, as restite entrainment is considered to take place when diatexitic sources mobilise *en masse*. This is at odds with the common occurrence of relatively mafic granites as high level intrusions in the crust or their eruptive equivalents that must have formed from markedly water-undersaturated magmas that ascended through narrow conduits. We investigate pelitic migmatites from the Mkhondo Valley Metamorphic Suite (MVMS) in Swaziland, where a mid-crustal heating event produced metatexitic migmatites with minimal post-anatectic recrystallisation. In these rocks all the garnet is peritectic, having arisen through biotite fluid-absent melting, which produced garnet poikiloblasts characterised by inclusions of melt, quartz and biotite. Leucosomes that represent sites of melt transfer carry similar, smaller (typically <1 mm), entrained garnet poikiloblasts, which were capable of amalgamating to form larger composite grains. In anatectic structures where melt was present for longer, entrained garnet was extensively recrystallised, via a dissolution-precipitation process, to adopt a more magmatic character. The peritectic garnet in the pelitic source appears to have grown out of equilibrium with feldspar and HREE-rich accessory phases, while the recrystallised garnet in the larger melt-filled structures became progressively better equilibrated with these minerals. Thus, peritectic garnet in the source grew sufficiently rapidly to prevent trace element equilibrium with the bulk-rock composition, and, concurrent rapid magma segregation prevented the development of diatexitic source conditions. The segregated magma consisted of melt, the peritectic assemblage (principally garnet) and the accessory minerals monazite and zircon. These rocks illustrate that mafic granites may arise purely as mixtures of melt and the peritectic assemblage produced by the incongruent melting reaction. Importantly, under the circumstances which produced the MVMS anatectites, peritectic garnet is entrained as <1 mm poikiloblasts, demonstrating how mafic granitic magmas can migrate out of the source without the source becoming diatexitic.



## 1. Introduction

Several studies have highlighted the fact that relevant experimental melt compositions are typically more leucocratic than most granites and granodiorites (e.g. Montel and Vielzeuf, 1997; Stevens et al., 2007). Additionally, relatively mafic granites and granodiorites appear to faithfully image the composition of their sources, as evidenced by the applicability of the S- and I-type classification scheme (Chappell and White, 1974) in certain areas of the world, such as the Lachlan Fold Belt (LFB) of south-eastern Australia and the Cape Granite Suite of South Africa. This chemical memory of the source has been interpreted to reflect the entrainment of solid source material to the melt (e.g. Chappell and White, 1974; Stevens et al., 2007). Our current understanding of how this process might occur in the anatectic crust is strongly linked to the 'restite entrainment' model of Chappell and White (1974) and the 'restite unmixing' model of White and Chappell (1977), Chappell et al. (1987), Chappell (1997), and Chappell et al. (2000). In combination these models propose that restitic fractions of the source are entrained to the melt and that the subsequent fractionation of this entrained material accounts for the systematic compositional variations observed within granitoid suites of the Lachlan Fold Belt (LFB). Thus the term 'restite' in these models includes a variety of different source components, i.e. minerals not involved in the melting reactions (e.g. the pre-anatectic anhydrous ferromagnesian and oxide minerals), the remains of the minerals partially consumed by anatexis (e.g. plagioclase), the solid products of the typically incongruent melt-generating reactions (e.g. peritectic garnet, cordierite, orthopyroxene, K-feldspar), as well as unmelted or less melted fragments of rock. The latter category commonly manifests as amphibolite facies enclaves in granites, which has led

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doi:10.1016/j.lithos.2010.08.015

to the suggestion that such granites arise by relatively low-temperature melting involving elevated water activity in the source (Chappell et al., 2000). Restite entrainment is proposed to occur once melt fractions in the source are sufficiently high to break down the rigid rock framework (i.e. once the Critical Melt Fraction of van der Molen and Paterson, 1979 is reached) and the crystal/rock fragment-rich magma can move *en masse*, systematically freeing itself of restite as it ascends to higher levels in the crust (White and Chappell, 1977; Chappell, 1997).

Further coupling between the restite models for granite petrogenesis and source processes has been achieved by models for melt segregation developed by Sawyer (1994, 1996, 1998, 2001), which consider the contamination of melt by residual phases, the possibility of entrainment of a whole-source component in the melt and the progressive separation of these entrained components during magma flow. Sawyer (1996) suggested that efficient melt-residuum segregation is mainly restricted to metatexitic migmatites where melt fractions are low and where segregation is generally deformation-assisted. Under such conditions there is sufficient melt present to form an interconnected network through which melt can move, i.e. ≤10% (First Percolation Threshold of Vigneresse et al., 1996), but insufficient to mobilise the solid fraction in the source. Magma mobility on the other hand, defined as the movement of melt plus entrained source material, is only considered to take place with the development of a pervasive melt fraction throughout the whole rock volume, i.e. in diatexitic migmatites. The solid matrix framework then looses cohesion and bulk flow of the melt plus the entire residue may occur, producing the residuum enriched granites described by White and Chappell (1977) and Chappell et al. (1987).

Mobilisation of a diatexitic source prior to magma segregation from entrained restite is at odds with several important lines of evidence concerning the conditions of anatexis in granite source areas and the mechanisms by which granite magmas ascend. Firstly, some granite magmas can be demonstrated to have left their source areas rapidly enough that trace element equilibrium between the melt and residuum is not attained (Ayres and Harris, 1997; Bea et al., 2006; Villaros et al., 2009b). Secondly, granite magmas which intrude at high-levels in the crust and/or erupt, very likely ascend through dykes and narrow conduits propagated by magma buoyancy (Clemens and Mawer, 1992; Petford et al., 1993). Such magmas must be markedly water-undersaturated, and arise through high-temperature, fluid-absent melting reactions (e.g. Clemens, 1992). The plutons and eruptive products that these magmas produce typically display a wide range in chemistry from leucogranites to mafic granodiorites, thus necessitating a mechanism for mafic granite production by fluid-absent melting.

Recently, ‘selective peritectic phase entrainment’ has been proposed as an alternative model to explain the petrogenesis of mafic, peraluminous granites (Stevens et al., 2007; Villaros et al., 2009a,b). The process involves the entrainment of only the solid peritectic products of the melting reaction to the melt. Specifically, the entrainment of garnet and ilmenite arising through high-temperature, incongruent, fluid-absent melting of biotite in metapelites is suggested to control the chemistry of the strongly peraluminous, mafic granites studied by Stevens et al. (2007). Thus, the admixture to melt is controlled by the stoichiometry of the melting reaction and this is proposed to explain the very tight inter-element correlations displayed by some granites as a function of increasing maficity (Fe + Mg), namely an increase in A/CNK, Mg# and Ca, a decrease in Si and K, as well as the very focused positive correlation of Ti with maficity (Stevens et al., 2007). Selective entrainment of the peritectic assemblage to the melt therefore appears to be a viable mechanism for producing hot, water-undersaturated, mafic granitic magmas. Consequently, we follow Sawyers lead and investigate appropriate

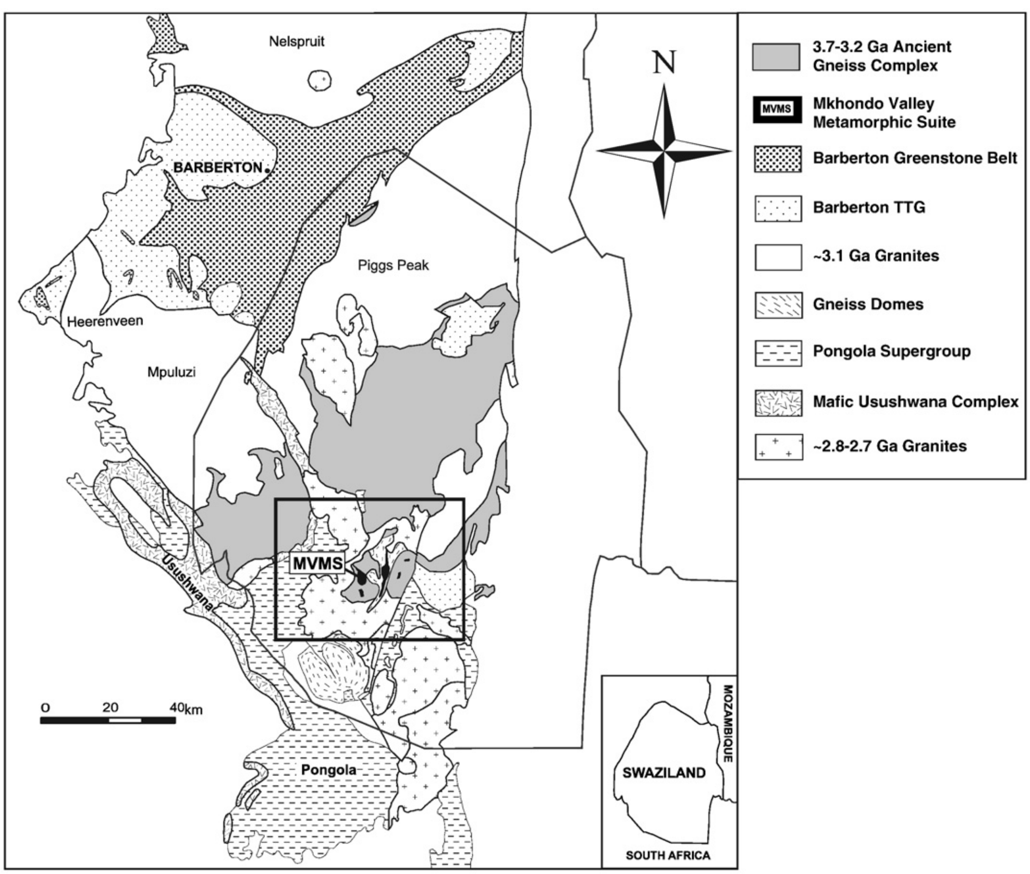


**Fig. 1.** Schematic geological map of Swaziland modified after Wilson (1982), showing the AGC and location of the Mkhondo Valley Metamorphic Suite (MVMS) study area.