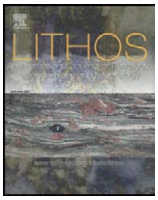
Lithos 116 (2010) 310–320

Contents lists available at ScienceDirect

Lithos

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



Melt-producing versus melt-consuming reactions in pelitic xenoliths and migmatites

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ARTICLE INFO

Article history:
Received 16 March 2009
Accepted 6 September 2009
Available online 24 September 2009

Keywords:
Migmatites
Xenoliths
Melt production
Melt consumption
Textures

ABSTRACT

Melt-producing reactions have operated both in pelitic xenoliths and in pelitic migmatites, but melt-consuming reactions, related to *in situ* melt crystallization, are largely restricted to migmatites. Hence, xenolith reaction textures may provide clues on the relative roles of both reaction types in migmatites. A comparison of xenoliths and migmatites results in a catalogue of textural and chemical features, some of which are argued to be diagnostic. The results have implications for the identification of restite in igneous rocks and for the relative importance of prograde and retrograde processes in different domains of layered migmatites.

1. Introduction

Anatectic migmatites commonly show both melt-producing and melt-consuming reactions (Cenki et al., 2002). The final textures, mineral modes and mineral chemistries are theoretically affected by four successive processes (Kriegsman, 2001a): (i) partial melting and small-scale differentiation into melt-rich domains and restitic domains; (ii) partial melt extraction; (iii) partial melt-consuming reactions between in situ crystallizing melt and the restite; and (iv) crystallization of remaining melt at the solidus, thereby releasing volatiles.

The "retrograde" (melt-consuming) overprint, which in some cases is pervasive, hampers the recognition and interpretation of "prograde" (melt-producing) reactions in many ways. First of all, early reaction textures may be partly to completely obscured by late reactions involving minerals and melt, which may, for example, reproduce assemblages that had disappeared during partial melting (Waters, 2001). Secondly, the exact melt composition is generally modified and difficult to retrieve (e.g. Ashworth 1985; Powell and Downes, 1990; Ellis and Obata, 1992; Whitney and Irving, 1994), which prevents proper balancing of reactions and in some cases prevents the distinction between alternative textural interpretations. Thirdly, solid phases are also affected by retrograde reequilibration, causing major changes in chemical compositions in the case of elements with high diffusion rates (notably Fe–Mg exchange: e.g., Spear, 1991; also Na–K exchange: e.g., Thompson, 1974), that may in extreme cases show little resemblance to the compositions during or immediately after melt production.

In contrast to migmatites, crustal xenoliths generally preserve original variations between individual reaction domains and can potentially characterize processes and reactions that operated during crustal melting (Grapes, 1986; Hanchar et al., 1994; Cesare et al., 1997; Álvarez-Valero et al., 2005, 2007). In addition, the chemical compositions of the melt and mineral phases are rarely modified by retrograde reequilibration and can thus help to constrain balanced melting reactions.

What has not yet been done, however, is to compare a large range of textural phenomena in primary migmatites, i.e. migmatites that record a single event of partial melting, and xenoliths with the aim to distinguish melt-producing from melt-consuming reactions in migmatites and to constrain "prograde" and "retrograde" components. This is, however, an important avenue for potentially resolving the following issues in migmatites:

- assessing the relative importance of melt-producing and melt-consuming reactions in melanosome domains of migmatites,
- the correct interpretation of trace element (re)distributions across leucosome–melanosome interfaces (e.g. Kriegsman and Nyström, 2003),
- the interpretation of age patterns in migmatites (e.g. Nyström and Kriegsman, 2003),
- estimates of melt loss from migmatites.

Under comparable conditions (e.g. similar P–T path, in terms of both shape and absolute values, similar starting material, similar heating rate), xenoliths may freeze in textures that are similar to the early stages of migmatisation. The remaining textures in migmatites

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0024-4937/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.lithos.2009.09.001

are expected to reflect the processes during subsequent restite–melt interaction. It has been postulated (Kriegsman, 2001a) that these processes mainly affect the melanosome domains of migmatites. Hence, the three hypotheses we intend to test through comparative petrology can be formulated as:

- (1) xenoliths show only or dominantly melt-producing reactions,
- (2) migmatites record both melt-producing and melt-consuming reactions,
- (3) melt-consuming reactions have mainly operated in melanosome domains.

Braun and Kriegsman (2001) compared textures in remelted xenoliths and migmatites, providing interesting details on a very particular case (remelted migmatites). The current paper differs from it by presenting a comparison of reaction textures in the far more common case of "primary migmatites".

We mainly, but not exclusively, use examples from the following high-grade provinces:

- xenoliths from fossil volcanic suites within the Neogene Volcanic Province (NVP) of the Betic Cordillera (SE Spain), extensively studied by Zeck (1970), Cesare et al. (1997, 2003a,b, 2009), Cesare and Gómez-Pugnaire (2001), Álvarez-Valero et al. (2005, 2007), Álvarez-Valero and Kriegsman (2007, 2008), and Álvarez-Valero and Waters (2010),
- granulite-facies migmatites from the Northampton Complex, so far only described in Kriegsman and Hensen (1998),
- granulite-facies migmatites from southern Finland well-known since Sederholm (1913, 1934) and studied in detail by Hölttä et al. (1994), Kriegsman (2001a,b), Johannes et al. (2003), and Nyström and Kriegsman (2003),
- granulite-facies migmatites from the Achankovil area in southern India (Cenki et al., 2002).

We restrict our analysis to cases of water (vapour)-absent melting, because the alternative case of water (vapour)-present melting leaves little textural evidence (see next section; for an alternative view, see Sawyer, 2010-this issue). In addition, the influence of deviatory stress is not considered, except for the spatial distribution of reaction textures (Section 2.2). Stress strongly influences the shape, location and direction of melt pockets, with deviatory stress favouring elongate shapes, regular spacing and long axes commonly parallel with or perpendicular to the main shortening orientation (e.g., Van der Molen, 1985; Hand and Dirks, 1992; Sawyer, 1999). In addition, deviatory stress exerts a strong influence on melt escape thresholds (Vigneresse et al., 1996) and thus, indirectly, on the progress of restite–melt back reaction. Stress is beyond the scope of this paper, however, because it does not influence the reaction balance, or which type of reaction texture is developed.

2. Partial melting: theoretical considerations and approach

2.1. On reaction paths and textures

There are two generic reaction types involving melt: water (vapour)-present melting and water (vapour)-absent dehydration melting. On any P–T path, the first melting occurs at the solidus, in suitable rock types, through a general equation A + V = M, where A are solid phases, V is water (vapour) and M is melt (see e.g., Thompson, 2001). An example in the KFMASH system is: Bt + Sil + Grt + Kfs + Qtz + V = M, (mineral abbreviations after Kretz, 1983), which requires that all five solid phases are in contact and start melting with vapour as the diffusion-controlling phase promoting contact and thermodynamic interaction between the phases. This is the reason why the term contact melting has been used. Water (vapour)-present melting quickly consumes the water present in the rock (e.g. Kriegsman, 2001a, and refs. therein), unless the system is open and a considerable influx of water occurs (e.g., Patiño Douce and Harris, 1998; Sawyer, 2010-this issue). Importantly, the only product phase at the solidus is melt and thus textural indications for this type of melting are not very strong. Instead, the arguments in favour rely heavily on geochemical analyses, including oxygen isotopes.

By contrast, water (vapour)-absent melting derives the necessary water from the breakdown of micas or amphiboles and is therefore also called dehydration melting. Generally, these reactions produce an incongruent phase that was not present prior to melting and the appropriate process is therefore also called incongruent melting. A well-known example in the KFMASH system is: Bt + Sil + Kfs + Qtz = Grt + Crd + M. The relative importance of water (vapour)-present and -absent melting has been debated extensively in the literature (e.g., Patiño Douce and Harris, 1998; Clemens and Droop, 1998; Spear and Daniel, 2001; Kriegsman, 2001a).

In addition to the above melt-producing reactions, Thompson (2001) also defined suprasolidus decompression dehydration reactions (SDDR) that consume melt + mica during decompression, producing an anhydrous assemblage and a vapour phase that is released from the system. In chemical systems dominated by univariant reactions, like many systems in experimental petrology, these reactions can be an important factor, but they may be less appropriate in more complex natural systems where shifting phase compositions lead to the dominance of mineral and melting reactions at higher variance (see, however, Section 3.3).

The P–T path determines which particular melt-producing and melt-consuming reactions are encountered. Different paths give different assemblages, but some phenomena are expected to be diagnostic, for example: inclusion textures (but see discussion in Vernon et al., 2008), single and multiple reaction rims or coronas, intergrowths, etc. In general, one may expect the following features during melt-producing reactions:

- leucosome present nearby, if the melt has not escaped from the system,
- mica breakdown, e.g. skeletal (corroded) biotite,
- growth of incongruent phases,
- mica inclusions in incongruent phases are separated from other phases,
- Plagioclase: Ab(-rich) breakdown, locally An(-rich) growth (see Álvarez-Valero and Kriegsman, 2010-this issue).

Melt-consuming reactions, besides including the presence of nearby leucosome as a common point, are more likely to show the following features:

- mica growth,
- breakdown of incongruent phases,
- coronas next to leucosome,
- impossibility to balance some reactions without involving a melt phase,
- Plagioclase: An(-rich) breakdown, locally Ab(-rich) growth,
- intergrowth of phases that had been consumed along the prograde path,
- fine-grained intergrowths, notably involving micas.

There are several complications to be expected before inspection of any thin sections: catalytical effects (Carmichael, 1969; see also Waters, 2001), where one partial equilibrium produces a phase that is consumed at the same rate by a second partial equilibrium. For example, a classical subsolidus reaction is the And–Ky transition that may make use of Ms as a reaction catalyser (Carmichael, 1969). In migmatites and xenoliths, similar complicated reactions may be expected that use biotite as a catalytic phase, giving rise to textures producing biotite and simultaneous textures consuming biotite. Reactants may be preserved by shielding in multivariant reactions if there are heterogenous rock domains ($f > 1$), which is a very common situation. In addition, there may be kinetic factors preventing nucleation.