



Primary crustal melt compositions: Insights into the controls, mechanisms and timing of generation from kinetics experiments and melt inclusions



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ARTICLE INFO

Article history:

Received 11 February 2016

Accepted 29 May 2017

Available online 3 June 2017

Keywords:

Crustal anatexis

Granite

Mechanisms

Kinetics

Primary melt composition

Nanogranitoids

ABSTRACT

We explore the controls, mechanisms and timing of generation of primary melts and their compositions, and show that the novel studies of melt inclusions in migmatites can provide important insights into the processes of crustal anatexis of a particular rock. Partial melting in the source region of granites is dependent on five main processes: (i) supply of heat; (ii) mineral–melt interface reactions associated with the detachment and supply of mineral components to the melt, (iii) diffusion in the melt, (iv) diffusion in minerals, and (v) recrystallization of minerals. As the kinetics of these several processes vary over several orders of magnitude, it is essential to evaluate in Nature which of these processes control the rate of melting, the composition of melts, and the extent to which residue–melt chemical equilibrium is attained under different circumstances. To shed light on these issues, we combine data from experimental and melt inclusion studies. First, data from an extensive experimental program on the kinetics of melting of crustal protoliths and diffusion in granite melt are used to set up the necessary framework that describes how primary melt compositions are established during crustal anatexis. Then, we use this reference frame and compare compositional trends from experiments with the composition of melt inclusions analyzed in particular migmatites. We show that, for the case of El Hoyazo anatectic enclaves in lavas, the composition of glassy melt inclusions provides important information on the nature and mechanisms of anatexis during the prograde suprasolidus history of these rocks, including melting temperatures and reactions, and extent of melt interconnection, melt homogenization and melt–residue equilibrium. Compositional trends in several of the rehomogenized melt inclusions in garnet from migmatites/granulites in anatectic terranes are consistent with diffusion in melt-controlled melting, though trace element compositions of melt inclusions and coexisting minerals are necessary to provide further clues on the nature of anatexis in these particular rocks.

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1. Introduction

Granitic magmas *sensu lato* play a critical role in both continental crust growth and its internal differentiation. However, the details of processes connecting granitic magmas in their source region with granitic intrusions, or their volcanic equivalents, are far from clear. Focused specifically on the differentiation of continental crust, field-based petrological and geochemical studies of migmatites and

allochthonous crustal granites, experimental studies, and phase equilibria modeling, constitute a “3-dimensional” approach to attack this problem (e.g. Brown, 2013; Clemens, 2006; Sawyer, 2008; White et al., 2007, 2011; and references therein). Each of these approaches, however, has drawbacks. Allochthonous granitoids and volcanic equivalents are the end products of anatexis and crustal differentiation, and their study provides a partial view of the process because primary melt compositions are established, and parental magmas generated, at deeper sites of melting. Although exhumed regional migmatitic terranes permit the direct observation of anatectic processes, classical petrological and geochemical studies of these terranes face a number of complexities, which make it difficult to retrieve the primary melt and parental magma compositions. These complexities include that (i) anatectic terranes record the

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superposition of prograde and retrograde processes, where partial melting occurs concomitantly to differential stress and deformation, (ii) primary melt may have fractionated and partially escaped the system, (iii) perfect segregation of melt from residue seems very unlikely, (iv) melt produced at deeper or adjacent crustal levels may have entered the system, (v) former melt present above the solidus has crystallized upon cooling, and (vi) H₂O dissolved in that melt has escaped and/or reacted with the residue (e.g. Brown, 2002, 2013; Sawyer, 2008, 2014; White and Powell, 2010; and references therein). Most of the experimental studies conducted on crustal anatexis provide equilibrium mineral and melt compositions at particular *P–T–X* conditions, whereas the continental crust is compositionally heterogeneous (Rudnick and Gao, 2003) and, so far, equilibrium melting seems to be the exception rather than the rule (e.g. Bea, 1996; Villaros et al., 2009a). Thermodynamic models also assume melt–solid equilibrium. In addition, there is a lack of precise thermodynamic data for several key phases, or end-members solid solutions related to minor components in the system. This produces, for instance, discrepancies between the compositions of model and natural or experimental melts (e.g. Bartoli et al., 2013a; Grant, 2009; White et al., 2011).

Some studies have concluded that compositional heterogeneities of crustal granitoids are inherited from the source region and, therefore, that somehow they reflect the composition of magmas present at the sites of generation (Clemens and Benn, 2010; Deniel et al., 1987; Glazner et al., 2004; Hogan and Sinha, 1991; Pressley and Brown, 1999). More commonly, however, it is concluded that compositions of crustal granitoids do not correspond to those of the primary anatectic melts produced during their genesis, due to one or a combination of several processes. These include: (i) magmatic differentiation due to e.g. “en route” fractional crystallization, that may start right at or relatively close to the source area (Barr, 1985; Brown et al., 2016; Carvalho et al., 2016; Chappell and White, 1992; Milord et al., 2001; Morfin et al., 2014; Sawyer, 1987, 2014); (ii) entrainment of residual (Chappell, 1996; Chappell et al., 1987), peritectic (Stevens et al., 2007; Villaros et al., 2009b) or both residual and peritectic (García-Arias and Stevens, 2017; Sawyer, 2014) minerals coexisting with the primary melt; (iii) mixing and mingling with mantle derived magmas (Collins, 1996; Gray and Kemp, 2009; Wall et al., 1987). As a consequence of the previous observations, we still have a limited understanding of the nature and intensity of crustal differentiation associated with the geodynamic settings where crustal granitic magmas are produced, including the ratio of crustal growth to crustal reworking (e.g. Brown, 2013).

This contribution seeks to provide information on the very first stages of crustal melting, and particularly on the mechanisms and time frames of melt generation, and controls on the composition of primary melts before segregation from the solid fraction. This represents the starting point of the process of generation of crustal granitoids. Recently, Sawyer (2014) has investigated in a contact metatextite migmatite the earliest stages of segregation of anatectic melts, and concluded that it is accomplished via the movement of melt from in situ neosomes into adjacent 0.5 mm-long micropores and 1 mm-long microleucosomes, that subsequently grow into longer (up to ≈ 10–20 mm) microleucosomes by progressive destruction of the bridges of matrix separating originally neighboring small microleucosomes. Our study refers to the earliest stages of melting, when melt forms and remains in contact with, or at short diffusion distances from, its residue. During this window of time, several processes leading towards mineral–melt equilibration and melt homogenization may occur, e.g. diffusion in minerals and melt, and recrystallization of minerals. Considering diffusivities of elements in granitic melts at anatectic conditions (e.g. Acosta-Vigil et al., 2012a), together with the shortest reported time frames for melt segregation (Harris et al., 2000; Sawyer, 1991), and estimations of segregation distances associated with the generation of leucosomes (Fig. 1a; Sawyer, 2008, 2014), our study describes the situation possibly before the segregation of melt into microleucosomes and, definitely, before migration of melt into cm–dm-scale in-situ

leucosomes. Nevertheless, this time window may vary depending on the tectonic setting and nature of (contact versus regional) anatexis. This contribution, therefore, deals with questions such as what are the controls on the compositions of initial melts generated in different microstructural locations of a protolith, how individual liquid aliquots at different microstructural sites evolve towards a homogeneous melt phase, what are the time frames of melt generation, melt homogenization and melt–residue equilibration, and how these time frames compare with those inferred for separation of melt from residue.

The most direct way to accomplish the investigation of the first stages of melting is through either studies of contact anatectic rocks that reached conditions at, or slightly above their solidus (Holness et al., 2005; Sawyer, 2014), or via experimental simulations (e.g. Acosta-Vigil et al., 2006a; Arzi, 1978; Brearley and Rubie, 1990; Buick et al., 2004; London et al., 2012; Mehnert et al., 1973). Considering the novel studies of melt inclusions (MI) or nanogranitoids in migmatites (Cesare et al., 1997, 2009, 2015), a **brand-new approach** that has the potential to increase our knowledge of the onset of crustal melting and mechanisms of anatexis in particular case studies of migmatites, is the combination of compositional data from MI and experiments on the kinetics of melting. In this contribution, we use previously published but never compared data sets from: (i) experimental studies on the kinetics of melting and diffusion in the granite system (Acosta-Vigil et al., 2012a), and (ii) melt inclusion studies documenting primary melt compositions in (ii.a) anatectic enclaves, where the process of regional partial melting has been frozen due to quenching upon ascent and extrusion within the host magma (Cesare, 2008), and (ii.b) in regional migmatites and granulites (Acosta-Vigil et al., 2016; Bartoli et al., 2016a; Cesare et al., 2015; Ferrero et al., 2015). Thus, we first set up a theoretical scenario describing the several processes acting concomitantly and controlling the nature of primary anatectic melt compositions prior to segregation (Section 2 of the paper); then, we review the results of kinetics experiments providing information on the interplay between, and role/imprint of each of these processes (Section 3); finally, and after discussing the main limitations of experiments to replicate and study natural anatexis (Section 4), we introduce the reader to the study of MI in anatectic rocks, and use the information provided by kinetics experiments as a framework to interpret the previously published compositions of MI in terms of nature and mechanisms of crustal anatexis in Nature (Section 5).

2. Processes and controls during the onset of partial melting: a theoretical scenario

We start by assessing the simplest route to producing a silicate liquid of granitic composition; that is, the melting of a near-minimum granite itself. Consider that a homogeneous, fine-grained crustal rock, such as an aplite, reaches some given *P–T* conditions at or just above its solidus (Fig. 1b). At equilibrium, a certain proportion of homogeneous melt will coexist with an assemblage of homogeneous minerals. However, the equilibrium proportions and compositions of phases will not form instantaneously, and each phase will likely follow a path in proportion (wt%)–composition (*X*)–time (*t*) space towards the conditions of equilibrium (Fig. 1d). It is the interplay between (i) the kinetics of processes governing the generation and homogenization of melt, and equilibration between melt and residue, versus (ii) the timing of melt segregation and extraction, that will determine the position in wt%–*X*–*t* space of every single phase at the time of melt–residue separation with respect to their equilibrium values, and hence the extent to which primary anatectic melts are homogeneous and at equilibrium with their bulk residue before leaving the source area.

It is commonly assumed that melting begins at multiphase grain junctions where all necessary reactants meet (e.g. Brown, 2010; Harris et al., 2000; Sawyer, 2014), and that the first melt produced has eutectic composition (e.g. Harris et al., 2000). Although we must be cautious when extrapolating experimental observations to Nature (see

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