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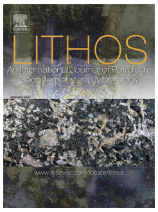

Invited review article

Experimental melts from crustal rocks: A lithochemical constraint on granite petrogenesis

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ABSTRACT

Many studies of experimental petrology have devoted to partial melting of crustal rocks. In order to provide lithochemical constraints on granite petrogenesis, this paper presents a compilation and synthesis of available experimental data for the major element compositions of felsic melts derived from partial melting of natural or synthetic materials in the compositional range of crustal rocks. The experimental melts are categorized into four types according to the species of hydrous minerals in starting materials: (I) amphibole-bearing; (II) amphibole- and biotite-bearing; (III) biotite-bearing; and (IV) biotite- and muscovite-bearing. If dehydration melting takes place at normal crustal conditions ($P = 5$–10 kbar, $T \le 1000$ °C), experimental melts are rich in SiO_2 but poor in $MgO + FeO_T$ except those from amphibole-bearing sources. A comprehensive comparison of compositions between experimental melts and starting materials indicates that geochemical fractionation is variable for different major elements and their ratios. Source composition and melting temperature exert stronger controls on the compositional variations of experimental melts than pressure and fluid. By comparing the experimental melts with natural granites, the following insights into granite petrogenesis can be got: (1) while peritectic assemblage entrainment may be the dominant mechanism for the compositional variations of garnet/cordierite-rich S-type granites, fractional crystallization of diverse melts from heterogeneous metasedimentary precursors probably governs the compositional variations of garnet/cordierite-poor S-type granites; (2) relatively K_2O-rich mafic to intermediate rocks are appropriate sources for calc-alkaline I-type granites. The compositional variations of calc-alkaline granites are jointly controlled by peritectic assemblage entrainment and subsequent fractional crystallization; (3) while dehydration melting at $T > 950$ °C is appropriate for the production of ferroan and alkali-rich granitic melts from intermediate magnesian tonalite or granodiorite, it is also possible for ferroan, alkali–rich and fluorine-rich granitic melts to be produced by dehydration melting of moderately magnesian mica–bearing materials at $T \le 900$ °C. Nevertheless, the low-T melts are more peraluminous than the high-T ones. Therefore, the composition of source rocks exerts the first-order control on the composition of granitic melts in closed systems. In addition, the dehydration melting of crustal rocks under different conditions is also responsible for variations in the composition of granites.

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1. Introduction

Granite (sensu lato) is the most important constitute of upper continental crust. The processes of producing granitic magmas play a significant role in the geochemical differentiation of continental crust. Partial melting of crustal rocks is a principal mechanism for the generation of granitic magmas (Clemens, 1990; Clemens and Watkins, 2001; Johannes and Holtz, 1996; Stevens and Clemens, 1993). In addition to fractional crystallization, such open-system processes as magma mixing and crustal contamination also play a role in granite petrogenesis. Although mantle-derived mafic magmas were considered important to the origin of granites, little studies of experimental petrology have been devoted to their assimilation of country rocks in changing the composition of granitic rocks. In contrast, a lot of melting experiments have been performed in past decades (see reviews by Castro, 2013; Clemens, 2006; Johannes and Holtz, 1996; Patiño Douce, 1999), providing a direct constraint on the origin of granites in closed systems. These experiments were made with starting materials of either natural crustal rocks or synthetic materials that are lithochemically similar to crustal rocks. The results were used: (1) to investigate the solidus, reactants and products, and melt productivity of natural or synthetic materials; (2) to determine the lithochemical compositions of experimental melts, the effects of chemical components, and melting conditions; and (3) to decipher the melting behaviours of common crustal rocks with the ultimate goal of understanding granite petrogenesis. However, a systematic investigation of the compositional fractionation between partial melts and starting materials during partial melting is still lacking. In particular, it is not clear yet what are the effects of source rock composition and experimental conditions (e.g., temperature, pressure, fluid, and oxygen fugacity) on the composition of granitic melts in closed systems.

With the accumulation of experimental data for the composition of granitic melts, various models have been proposed in the past decades for granite petrogenesis through the comparison between experimental melts and natural granites (e.g., Castro, 2013; Clemens and Stevens, 2012; Clemens et al., 2011; Johannes and Holtz, 1996; Patiño Douce, 1999; Roberts and Clemens, 1993; Stevens et al., 2007). While the results provide lithochemical constraints on granite petrogenesis in closed systems, a major divergence in these models is whether mantle-derived mafic magmas have supplied materials in the formation of granitic rocks. Patiño Douce (1999) considered that only peraluminous leucogranites can represent pure crustal melts which were formed by dehydration melting of muscovite-rich metasediments. However, all other granitic rocks, including metasedimentary rock-derived peraluminous granites, Cordilleran peraluminous granites, metaigneous rock-derived calc-alkaline granites, metaluminous, alkali-rich granites, and rhyolites associated with continental flood-basalt provinces, were observed to contain more ferromagnesian components and less silica than experimental melts from crustal rocks even at melting temperature up to 1000 °C. Such compositional discrepancies were ascribed to the involvement of mantle-derived magmas (Patiño Douce, 1999). On the other hand, Stevens et al. (2007), Villaros et al. (2009), and Clemens and Stevens (2012) noticed that natural granites not only exhibit compositional discrepancies of major elements relative to experimental melts, but also show regular compositional variations in most major elements and many trace elements in the Harker plots against Mg + Fe. In addition, individual granite plutons often display much less varied initial Sr and Nd isotope compositions than Mg + Fe (Clemens and Stevens, 2012). Therefore, the compositional variations of natural granites were ascribed to the entrainment of peritectic assemblages in various proportions by crustal rock-derived melts (Clemens and Stevens, 2012; Stevens et al., 2007; Villaros et al., 2009). In this regard, it is necessary to examine all available data from the experimental melting of crustal rocks and their artificial analogues, particularly those experiments carried out after the review of Patiño Douce (1999).

Many models for granite petrogenesis assume that only high-silica (SiO_2 generally >70 wt.%) granites are capable of representing pure melts derived from partial melting of crustal rocks, whereas low-silica ones could be added by mantle-derived magma or crustal source-derived peritectic and residual materials (e.g., Chappell et al., 1987; Clemens and Stevens, 2012; Patiño Douce, 1999). However, it is also known for a long time that the composition of source rocks exerts a substantial control on the composition of granitic melts. This difference is further enlarged by incongruent melting of crustal rocks due to the breakdown of different minerals. Through the comparison of compositions between experimental melts and natural granites, the validity of the above assumption can be testified by considering the possible factors that can cause the compositional variations of experimental melts. Furthermore, whether these factors are attainable at crustal conditions needs to be evaluated. In addition, it is also crucial to know the exact compositional ranges of granitic plutons, especially their dominant compositions. Attentions should be paid to know whether mafic rocks are spatially and temporally associated with granitic plutons and the exposed proportions of felsic plutons and mafic rocks. Such background knowledge is the first-order prerequisite to testify some models for granite petrogenesis.

This paper presents a compilation and synthesis of experimental data on the major element compositions of felsic melts that were produced by partial melting of natural or synthetic crustal materials at different conditions. With such an abundant dataset, we are in a position to understand the lithochemical fractionation between experimental melts and starting materials, to characterize the compositions of granitic melts and to investigate the possible factors that lead to the compositional variations of granitic melts in closed systems. Consequently, we are able to have a better understanding of granite petrogenesis. In doing so, we have differentiated the nature of source rocks into metasedimentary and metaigneous, respectively, corresponding to S-type and I-type granites as traditionally defined by Chappell and White (1974, 1992). As such, these parental rocks were metamorphosed to amphibolite-facies, eclogite-facie or granulite-facies prior to partial melting for granitic magmatism. Mineral abbreviations are after Whitney and Evans (2010).

2. Compilation of experimental data

The partial melting of crustal rocks to produce granitic melts usually takes place through dehydration melting reactions under fluid-absent conditions (Clemens, 1990; Clemens and Watkins, 2001; Stevens and Clemens, 1993). Three common hydrous minerals, muscovite (Ms), biotite (Bt) and amphibole (Amp), are generally involved in the dehydration melting. For this reason, four groups of starting materials can be classified in experimental petrology: (I) Amp-bearing rocks, which are basaltic and andesitic in lithochemistry; (II) Amp- and Bt-bearing rocks, which refer to tonalite, granodiorite, dacite, and metavolcaniclastic rocks; (III) Bt-bearing rocks, which include Bt gneiss, some metapelite and some metagreywacke; and (IV) Bt- and Ms-bearing rocks, which include