Lithos 277 (2017) 131–153

Contents lists available at ScienceDirect

Lithos

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

Phase equilibrium modelling of granite magma petrogenesis: A. An evaluation of the magma compositions produced by crystal entrainment in the source

Marcos Garcia-Arias [a,b,*], Gary Stevens [b]

[a] Departamento de Geociencias, Universidad de Los Andes, Carrera 1 # 18A - 12, Bogotá, Colombia
[b] Centre for Crustal Petrology, Department of Earth Sciences, University of Stellenbosch, Cnr Ryneveld and Merriman Streets, Stellenbosch, Western Cape, Private Bag X1, Matieland, 7602, South Africa

ARTICLE INFO

Article history:
Received 17 December 2015
Accepted 17 September 2016
Available online 3 October 2016

Keywords:
Granite petrogenesis
Partial melting
Source-controlled processes
Pseudosections
S-type granites

ABSTRACT

S-type granites show strong positive or negative correlations for several elements and element ratios plotted against maficity (FeO + MgO), and the maficity of the granites is usually higher than that of experimental melts from metasedimentary sources. These compositional variations appear over a large range of scales within the same pluton and may reflect a strong influence of source-controlled processes in the composition of granites, i.e., the entrainment of a mafic mineral fraction to the melt, prior to co-segregation of the minerals and melt as magmas. This paper presents a thermodynamically constrained study of the magma major element compositions produced by the entrainment of a fraction of the mineral assemblage which coexisted with melt in the source, either the peritectic assemblage, the non-peritectic assemblage or mixtures of both, in several metasedimentary source compositions from 650 to 950 °C at 0.8 GPa. The compositions of the modelled magmas have been compared to a large dataset of S-type granites. Several potential factors that may control the composition of the magmas have been considered: melt loss, batch and fractional melting, spatially restricted equilibration of plagioclase during partial melting and the nature and amount of the entrained mineral assemblage. The results of the investigation show that, irrespective of the melting process, melts are too felsic to account for the more mafic granite compositions. When the entrainment of only the peritectic mineral fraction is considered, the modelled magmas are able to reproduce the geochemical trends defined by the granites with increasing maficity for most major elements. However, Ca-rich plagioclase must be present in the entrained mineral assemblage to reproduce the Ca content of granites. Ca-rich plagioclase is produced only when plagioclase equilibration is strongly spatially restricted, with a core of unreacted plagioclase not participating in the melting reactions and a rim of plagioclase reacting in equilibrium with the melting system. The amount of plagioclase participating in the melting reaction controls the Ca content of granites: the higher the amount of plagioclase involved, the higher the amount of Ca-rich plagioclase produced and the higher the Ca content of magmas. When the entrainment of both the peritectic and non-peritectic fractions is considered, the match between the composition of the modelled magmas and the granites is improved, but only if the peritectic fraction dominates over the non-peritectic fraction and spatially restricted equilibration of plagioclase occurs, with the residual Ca-rich plagioclase behaving in suspension within the melt. Modelling of the consequences of varying the relative proportions of the minerals in the peritectic assemblage shows that the geochemical trends defined by the granites are only achieved if the stoichiometric proportions of these minerals are maintained. Magmas produced at approximately the same temperature from several metasedimentary sources display variable compositions at the same maficity, but the trends produced by increasing amounts of entrained minerals are generally parallel, as well as parallel to the S-type granite trends. In summary, this study supports a source control on the composition of S-type granites, and indicates that this control is a consequence of entrainment of variable amounts of the stoichiometric peritectic mineral assemblage, including Ca-rich plagioclase. This process allows very similar compositional trends to be produced within magmas derived from metasedimentary sources of different compositions.

---

* Corresponding author at: Departamento de Geociencias, Universidad de Los Andes, Carrera 1 # 18A - 12, Bogotá, Colombia.
E-mail addresses: m.garcia@uniandes.edu.co (M. Garcia-Arias), gs@sun.ac.za (G. Stevens).

http://dx.doi.org/10.1016/j.lithos.2016.09.028
0024-4937/© 2016 Elsevier B.V. All rights reserved.

1. Introduction

Granites of the upper crust exhibit substantial major and trace element geochemical variation over scales that range from centimeters to hundreds of meters (e.g. Deniel et al., 1987; Farina et al., 2012; Hogan and Sinha, 1991; Pressley and Brown, 1999) and, in many cases, are not the expected leucocratic compositions that would form by the extraction of melts from their deeper sources rocks (e.g. Clemens and Stevens, 2012; Stevens et al., 2007). This compositional variation within plutons is very likely created by their incremental construction by many magma pulses, with compositional variation between batches (e.g. Ayres et al., 1997; Coleman et al., 2004; Farina et al., 2012; Glazner et al., 2004; Pressley and Brown, 1999), which may record a number of different processes that occur in the source: sequential batches of magma extracted from a single source composition with increasing temperature (e.g. Farina and Stevens, 2011; Patiño Douce and Johnston, 1991); different magma compositions produced as a consequence of compositional variation in the source (e.g. interlayered shales and psammites) (e.g. Deniel et al., 1987; Farina and Stevens, 2011; Patiño Douce, 1999); entrainment of variable amounts of solid material in the source (crystals and rock fragments) to the magma (e.g. Chappell et al., 1987; White and Chappel, 1977; White et al., 1999); entrainment of variable amounts of the peritectic assemblage produced by the incongruent melting reaction to the magma (e.g. Clemens and Stevens, 2012; Stevens et al., 2007), and variable degrees of disequilibrium during anatexis to produce magmas of different composition (e.g. Sawyer, 1991). Fractional crystallization from the margin of a magma chamber inwards is able to produce compositional trends, but only in a limited range (Garcia-Arias and Stevens, 2017-in this issue).

Considered collectively, the processes discussed above suggest that source composition and source melting behaviour exert a strong control on the composition of S-type granite magmas. Thus, studies seeking to explain the range of rock compositions within granitic plutons or eruptive complexes should first seek to understand what aspects of the geochemical variability can be explained as inheritance from the source, before invoking other petrogenetic scenarios. Currently, such an approach is hampered by the lack of systematic information on the ways in which the details of the partial melting process may control magma composition. This research attempts to address this lack of information, in the case of S-type granites, by using a phase equilibrium modelling approach to investigate the range of melt and magma compositions that can be produced by the range of processes defined above. This range of modelled compositions is then compared with rock compositions from typical S-type granite suites. The influence of other petrogenetic scenarios like fractional crystallization of magmas after segregation from the source has been dealt with by Garcia-Arias and Stevens (2017-in this issue), who found that, when a S-type magma crystallizes from the margin inwards, a compositional trend is produced, but this compositional variation is limited to a short range which is ultimately controlled by the bulk composition of the magma.

2. Source controls on the geochemistry of granitic magmas

The concept of grouping granites according to the nature of their sources (Chappell and White, 1992; Patiño Douce, 1999; White and Chappell, 1983) requires a chemical connection between source and magma. This connection is partly a consequence of the way in which source mineralogy controls melt composition, as illustrated by the compositions of experimental melts produced from different types of starting materials (e.g. Patiño Douce, 1999). However, natural and experimental melt compositions demonstrate that melts from crustal source rocks are usually very felsic. Indeed, common S-type granite compositions have considerably higher FeO, MgO, TiO_2 and CaO contents than do melt compositions from partial melting experiments on appropriate source compositions at temperatures for crustal anatexis (Stevens et al., 2007, and references therein) (Fig. 1, Appendix A). Experimental melts with high FeO, MgO, TiO_2 and CaO contents are achieved only for melt volumes in excess of 40% at temperatures above 900 °C (e.g. Patiño Douce and Johnston, 1991; Vielzeuf and Holloway, 1988). Such concurrent high temperature conditions and high melt fractions require complete breakdown of biotite before any melt loss occurs and this is exceptionally unlikely as it requires unrealistic physical properties of the source (Clemens and Mawer, 1992). Consequently, assuming that granite compositions are mostly established at the source region, they must involve the entrainment of ferromagnesian material to increase the maficity (FeO + MgO) of the magmas. Several processes have been proposed to explain the composition of S-type and I-type granites through the entrainment and co-segregation of minerals from the source.

2.1. Restite-unmixing

Chappell et al. (1987) and White and Chappel (1977) have proposed that most of the granitic plutons have not formed by crystallization of only melt but from a magma containing crystals (restite or residuum) from the source. The magma leaves the source once the melt fraction is high enough to shift the source from a solid framework to a liquid framework. The high viscosity and yield strength of the melt prevents a full segregation of the minerals, and thus the magma carry a variable amount of minerals from the source. With progressive separation from the source, the ascending granitic magma leaves behind part of the entrained restitic assemblage, thus producing granitic bodies that together show linear trends in Harker diagrams. Consequently, these linear trends represent all the possible compositions of the magmas, from a melt phase to the solid residuum, with the source plotting at some place around the middle of that line (see Fig. 2 of White and Chappel, 1977). This process was named the restite model by Chappell et al. (1987) and White and Chappel (1977), but as it involves separation (un-mixing) of part of the restite from the segregating magma, it is now more widely known as restite-unmixing (RU). Evidence in favour of this model is the presence of zircons of older age than the pluton, the existence of calcic plagioclase cores of generally uniform composition and the presence of refractory xenocrysts or xenoliths within the pluton. The magmas formed in this way would then ascend through dykes or via diapirism.

The RU model described above relies on two assumptions. Firstly, the only way melt can segregate from the source is by the breakdown of the solid framework, which implies melt fractions above 40–45 vol.% (e.g. Rosenberg and Handy, 2005; Vigneresse et al., 1996). Secondly, the mineral fractions (the restite or residuum) co-segregated with the melt and left in the source keep their modal proportions, with no variations in the mode of some minerals over other minerals along the whole process of segregation from the source and ascent. The second assumption is partly a consequence of the first one: if the mineral framework breaks down and is carried by the melt, it seems obvious that it must keep the modal proportions. The first assumption has been demonstrated not to be the most common scenario, as in the presence of syn-anatectic deformation, granitic melts are able to leave the source once they form an interconnected network in the source with around 5 wt.% melt (i.e., the first percolation threshold of Rosenberg and Handy, 2005), which then becomes permeable to melt migration (e.g. Brown et al., 1995). Moreover, the assumption requires a large melt production, whilst the amount of melt actually believed to be produced in the lower crust under fluid-absent conditions is 20–30 vol.% (e.g. Brown, 2013). If the melt can segregate from the source without breaking down the solid framework, the minerals in the restite entrained may not keep their modal proportions: there may be some minerals more likely to segregate than others, e.g. minerals in suspension within the melt versus minerals forming the solid framework.