Field and model constraints on silicic melt segregation by compaction/hindered settling: The role of water and its effect on latent heat release†

CIN-TY A. LEE1,*, DOUGLAS M. MORTON2, MICHAEL J. FARNER1 AND PRANABENDU MOitra1

1Department of Earth Science, MS-126, Rice University, 6100 Main Street, Houston, Texas 77005, U.S.A.
2Department of Earth Sciences and United States Geological Survey, 900 University Avenue, University of California, Riverside, California 92521, U.S.A.

ABSTRACT

To investigate how large volumes of silicic melts segregate to form granitic plutons, we conducted a case study of a zoned pluton, in which SiO₂ increases from intermediate (69 wt%) to highly silicic compositions (74 wt%) toward the contact with metasedimentary wallrock in the outer 25 m of the pluton. All other major, minor, and trace elements vary systematically with SiO₂ and indicate that outward increasing SiO₂ is due to a decrease in mafic elements and minerals. Whole-rock oxygen isotopes and elemental variation diagrams do not support mixing with wallrock as an explanation for the Si-rich boundary layer. Instead, mafic enclaves, which are common in the pluton, also decrease in abundance in the outer 25 m of the pluton, suggesting a mechanical origin for the Si-rich boundary layer. The coupling of mechanical and geochemical boundary layers, combined with geochemical modeling, indicate that the silica-rich, enclave-poor boundary layer formed by hindered settling or compaction of a crystal-rich (crystal fractions >60%) magmatic mush. Segregation of melts at high crystal fraction is known to be a slow process. However, petrography and Zr-based thermometry indicate that the residual Si-rich liquids were water-saturated. Water decreases melt viscosity, which helps expulsion, but equally importantly, water also delays much of the latent heat release to late in the thermal and crystallization history of a cooling magma. We show that the higher the water content, the longer the time interval over which a magma chamber resides at the stage when water-saturated, high-silica liquids form, allowing sufficient time for exfiltration of silicic liquids before the magma body freezes.

Keywords: Granite, rhyolite, batholith, pluton, cumulate, compaction, settling, xenolith

INTRODUCTION

The ubiquity of highly silicic igneous rocks, such as granites, at Earth’s surface makes our planet unique in the Solar System (Campbell and Taylor 1983; Taylor and McLennan 1985).

Of interest are how magmas with SiO₂ contents greater than 70 wt% are formed. Volumetrically, most magmatism on Earth occurs by melting of the ultramafic mantle, but this process produces basalts. Making silicic magmas from more mafic parental magmas requires a multi-stage differentiation process. For example, extreme fractionation (>95% crystal separation) is needed to make granites (Lee and Morton 2015). Numerous hypotheses have been suggested: crystal settling from more primitive parental magmas, partial melting (anatexis) of pre-existing crust or sediments, compaction-driven crystal segregation, Soret diffusion, zone refining, thermal migration, liquid immiscibility, or assimilation of Si-rich metasediments (Atherton 1993; Bachl et al. 2001; Bachmann and Bergantz 2004, 2008; Bacon and Druitt 1988; Baker and McBirney 1985; Beard and Lofgren 1991; Bowen 1928; Brown 1994; Brown et al. 1995; Castro 2013; Castro et al. 2010; Chappell 1999; Clemens and Stevens 2012; Glazner et al. 2008; Hildreth 1979; Hildreth and Wilson 2007; Jagoutz and Schmidt 2012; Lipman 2007; Lundstrom 2009; McBirney 1980; Noyes et al. 1983; Philpotts 1976; Roedder 1951; Tuttle and Bowen 1958; Van Tongeren and Mathez 2012). To contribute to this topic, we examine a well-exposed tonalitic pluton in which compositions grade from intermediate to high silica contents at the pluton margin. We combine geochemical, petrologic, and field observations to determine the mechanisms by which the Si-rich boundary layer formed. In this case study, the observations are best explained by compaction-driven segregation of silicic liquids. We combine our observations with thermodynamic models to define the compositional and physical conditions of the magmatic system over which compaction operated.

STUDY AREA: DOMENIGONI VALLEY PLUTON, CALIFORNIA

The study site is located within the Cretaceous 120 Ma Domenigoni Valley pluton in the northern Peninsular Ranges Batholith in southern California (Morton et al. 2014) (Fig. 1). The pluton comprises a minimum area of ~160 km² and intruded into a Jurassic meta-sedimentary unit composed of meta-greywacke, interlayered calcareous quartzite and phyllite-schist (Morton et al. 2014) (Figs. 1 and 2). The pluton consists of isotropic, medium-grained biotitehornblende tonalite with accessory zircon, titanite...