Earth and Planetary Science Letters 405 (2014) 169–179

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Fe and Si isotope variations at Cedar Butte volcano; insight into magmatic differentiation

Thomas Zambardi [a,b,*], Craig C. Lundstrom [a], Xiaoxiao Li [a], Michael McCurry [c]

[a] Department of Geology – Natural History Building, University of Illinois at Urbana–Champaign, 1301 W. Green Street, Urbana, IL 61801, USA
[b] Géosciences Environnement Toulouse, CNRS – Université de Toulouse – IRD, 14 avenue Edouard Belin, 31400 Toulouse, France
[c] Department of Geology, Idaho State University, Twin Falls, ID, USA

ARTICLE INFO

Article history:
Received 5 April 2014
Received in revised form 8 August 2014
Accepted 12 August 2014
Available online 16 September 2014
Editor: T.M. Harrison

Keywords:
Si isotopes
Fe isotopes
magmatic differentiation
Cedar Butte

ABSTRACT

This study presents the stable isotopic variations of both Si and Fe recorded in a single well-characterized magmatic suite from Cedar Butte volcano (ID, USA), as well as a sill with progressive compositional change within Finland granophyre (Duluth Complex, MN, USA). Both isotopic systems show a significant enrichment in heavy isotopes in the more differentiated materials, in agreement with previous studies. In addition, the Finland granophyre sill shows a strong dependence between the isotopic composition and the sampling depth, suggesting the isotopic compositions follow a temperature gradient in which the cold part systematically enriches in heavy isotopes.

From these results it appears that at Cedar Butte, neither crystal fractionation, nor crustal contamination, nor late stage fluid exsolution can likely explain the isotopic variations we observe for both Fe and Si. We rather attribute these isotopic fractionations to a thermal migration process involving a top–down sill injection during which the isotopic distribution mostly follows a vertical temperature gradient.

1. Introduction

It is generally accepted that the continental crust has an andesitic bulk composition (e.g., Taylor and White, 1965) that is more silicic than the basaltic oceanic crust. Beyond this simple difference, the continental crust mainly contrasts with the oceanic crust in degree of compositional variability, with its vast scale making it difficult to identify the petrogenetic mechanisms responsible for making this silicic crust. Over the years, evolved silica-rich magmas have long been attributed to the somewhat blurry concept of magmatic differentiation, itself involving processes such as crystal fractionation, partial melting, fluid removal, and exogenous contamination.

Thanks to recent advances in mass spectrometry, several stable isotopic systems including Fe (e.g., Poitrasson and Freydier, 2005; Heimann et al., 2008; Schuessler et al., 2009) and Si (e.g., Douthitt, 1982; Ding et al., 1996; Savage et al., 2011, 2012; Zambardi and Poitrasson, 2011) now show analytically significant and systematic variations during magmatic differentiation. While these data provide new insight into magmatic differentiation, explanations of how the fractionations occur remain debated, in part due to different isotopic systems being used in separate studies. The behavioral contrast of the Si and Fe isotope systems provides a major constraint for assessing mechanisms of isotope fractionation and magmatic differentiation. A primary difference in behavior is that Si becomes more concentrated during magmatic differentiation while Fe depletes. As such, Si isotope variations are likely to reflect cumulative effects, in contrast to Fe. A second important difference is that whereas the Fe redox state can vary, possibly playing an important role in isotopic fractionation, Si is monovalent. In this study, we evaluate the most plausible processes for producing the isotopic variations observed.

Here we explore the combined stable isotopic compositions of Fe and Si from a single well-characterized magmatic differentiation suite from Cedar Butte, a small silicic volcano within the Eastern Snake River Plain (ESRP, Idaho, USA). To gain further insight into differentiation in A-type magmatic settings, we also provide data for a single sill layer within the Finland Granophyre (Duluth Complex, Minnesota, USA) to provide a possible intrusive analog to the magma reservoir of Cedar Butte prior to eruption. Together, these data lead to new views into magma differentiation and the production of silicic igneous rocks.

* Corresponding author at: Department of Geology – Natural History Building, University of Illinois at Urbana–Champaign, 1301 W. Green Street, Urbana, IL 61801, USA. Tel.: +1 33786272984.
E-mail address: zambardi@illinois.edu (T. Zambardi).

http://dx.doi.org/10.1016/j.epsl.2014.08.020
0012-821X/

2. Samples and methods

The ESRP volcanic province is an olivine tholeiite dominated volcanic field that lies coincident with and postdates the Yellowstone hot spot (Kuntz et al., 1992). Shervais and Vetter (2006, 2009) suggest that these basalts are derived mainly from lithospheric mantle sources, and that they are genetically linked to development of a mid-crustal layered mafic sill complex. The olivine tholeiite lavas are intruded, interlayered and overlain by a spectrum of more evolved mafic to high-SiO_2 rhyolites (e.g., McCurry et al., 2008). These evolved rocks also originated from post hot-spot magmatic activity starting ~1.4 Ma ago and share the distinctive geochemical features of A-type granites such as high Fe/(Fe+Mg) and low Sr concentrations (Chappell and White, 2001; McCurry et al., 2008).

Within the ESRP province stands Cedar Butte (CB), a 0.4 Ma polygenetic volcanic center which erupted ~10 km^3 of diverse lavas, beginning with eruption of high-SiO_2 rhyolite, and sequentially erupting more mafic lavas, ending with eruption of basaltic trachyandesite (75 to 55% range in SiO_2) (McCurry et al., 2008). The eruptive sequence follows a common compositional pattern thought to reflect the top to bottom drainage of a zoned crustal magma body (e.g., Hildreth, 1981). The CB series can be modeled straightforwardly by modified fractional crystallization (McCurry et al., 2008) and experiments indicate the endmember rhyolite is consistent with extreme fractional crystallization from the ESRP basaltic parent (Whitaker et al., 2008).

We analyzed the stable Fe and Si isotopic compositions of 8 samples from the CB differentiation suite as well as two other "end-members" from the ESRP volcanic area that tie in with this suite (compositions including Fe^{3+}/Fe_T given in Table 1). The CB suite consists of 1 basaltic trachyandesite, 1 trachyandesite, 3 trachydacites, and 3 rhyolites. The two additional samples, which bracket the CB suite in silica content, consist of a more primitive basalt from drill core within the Crater of the Moon (CM) basalt field and a high silica rhyolite from nearby Big Southern Butte (BSB). The sample from CM is an olivine tholeiite that is the most mafic end-member of our suite and could represent a basaltic parent magma from which the CB suite originates. The BSB sample represents the most extremely differentiated magma with Sr concentration of ~0.5 ppm (McCurry et al., 2008).

The Finland granophyre (FG), located in the northeastern portion of the Duluth Complex (MN), is a silicic intrusion lying immediately on top of a layered mafic intrusion (the Sonju Lake Intrusion) of the same age (Miller and Ripley, 1996; Vervoort et al., 2007; Paces and Miller, 1993). Originally mapped as a single concentrically zoned granophyric body, a drill core (AC-1) in the 1990's provided excellent detailed vertical stratigraphy through the middle of the FG, documenting a repeated sequence of differentiation in two sill-like bodies with the only sharp contact occurring at the contact between the two. Here, we focus on the uppermost sill sequence in the drill core, a 70 m thick layer which compositionally grades downward from high silica granite at its roof to monzodiorite at its base (major element data for samples AC1-16 (where AC1-xx refers to depth in feet) through AC1-178 are provided in Vervoort et al., 2007). We analyzed both Fe and Si isotope compositions for 4 AC-1 samples from 5 to 55 m depth. The Finland granophyre sill follows a classic A-type differentiation sequence with good general correspondence with the Cedar Butte series, as shown in Fig. 1. We thus use the Finland sill as a possible example of the Cedar Butte magma body prior to eruption. Maps and sampling locations for both CB and FG are given in McCurry et al. (2008) and in Vervoort et al. (2007) respectively.

Finally, we also measured the Si isotope composition of a 1 mg chip of microcrystalline material at the bottom of a thermal migration experiment in which andesite (AGV-1) with water was placed in the temperature gradient of the piston cylinder for 66 days. Details of this experiment are described in Huang et al. (2009) and Bindeman et al. (2013). This sample corresponds to the coldest part (350 °C) of the experiment and shares the compositional features of fine-grained granitic rocks. By comparing this data with the Si isotope composition of the starting material, this sample measurement will help us quantifying the Si isotope effect occurring along a thermal gradient under controlled conditions.

Iron purification was performed using standard purification methods involving anion chromatography in HCl media (e.g., Poitrasson and Freydier, 2005). The silicon sample preparation and analytical method is fully detailed in Zambardi and Poitrasson (2011). Fe and Si data were obtained using high resolution MC-ICP-MS methods using a NuPlasma HR (Nu instruments) or Neptune (Thermo) MC-ICP-MS. Further details about sample preparation and analytical methods for Fe and Si are given in Appendix A.

3. Results

All the isotopic data are reported in Table 1 using standard delta notation (see Appendix A). δ^{57}Fe varies significantly from 0.10 to 0.62 and increases hyperbolically at high SiO_2. Samples from basaltic to andesitic compositions (45 wt.% < SiO_2 < 60 wt.%) show insignificant δ^{57}Fe variations whereas trachydacites and rhyolites samples show a noticeable increase (+0.5 for δ^{57}Fe) toward heavier Fe isotopic compositions. These results are in good agreement with previous studies (Fig. 2) reporting Fe isotope signatures in igneous materials (Poitrasson and Freydier, 2005; Schuessler et al., 2009; Schoenberg and von Blanckenburg, 2006; Teng et al., 2008; Heimann et al., 2008; Telus et al., 2012; Sossi et al., 2012). Permil δ^{30}Si range from −0.31 for the most mafic end-member from CM to −0.10 for the most differentiated rhyolite from BSB. In between lie the CB data, increasing linearly with silica content from −0.25 to −0.11. These data follow trends with silica observed previously from Hekla volcano (Savage et al., 2011).

The FG sill shows δ^{30}Si ranging from −0.31 to −0.16 and δ^{57}Fe ranging from −0.09 to 0.48. Both systems show a consistent increase toward heavier isotopic ratios from bottom of the sill to the top (Fig. 3A & B). The single sample from the lowest temperature end of the Huang et al. (2009) experiment has a δ^{30}Si of $+0.54 \pm 0.04$ (2SE, $n = 6$), which indicates a significant enrichment in heavy isotopes relative to the isotopic composition of the bulk AGV-1 starting material (see Table 1; $\delta^{30}\text{Si} = -0.29$, Steinhoefel et al., 2011).

Measured ferrous over total iron decreases systematically through the sequence becoming very Fe^{+3} rich in the most differentiated samples (Fig. A.1). While this systematic change could be magmatic in origin, it is also possible that this reflects a post-eruption oxidation of these fine-grained samples by ascending fluids and gases (see Appendix A).

4. Discussion

The Cedar Butte trend whereby δ^{57}Fe increases only at >65 wt.% SiO_2 follows behavior observed previously in studies of co-genetic magmatic suites (e.g., Schoenberg and von Blanckenburg, 2006; Schuessler et al., 2009; Heimann et al., 2008) as well as genetically unrelated samples (e.g., Poitrasson and Freydier, 2005; see Fig. 2). In contrast, however, two studies of mafic tholeiitic differentiation (Teng et al., 2008; Sossi et al., 2012) show a clear relationship to δ^{57}Fe as SiO_2 changes from 43 to 57 wt.%. Interpretations of the origin of Fe isotopic variations range from crystal fractionation (e.g., Teng et al., 2008; Schuessler et al., 2009; Sossi et al., 2012) to loss of hydrous fluids during late stage differentiation (Poitrasson and Freydier, 2005; Heimann et al., 2008; Telus et al., 2012) to thermal diffusion isotopic effects