Earth and Planetary Science Letters 481 (2018) 338–349

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The effect of prior hydrothermal alteration on the melting behaviour during rhyolite formation in Yellowstone, and its importance in the generation of low-δ^{18}O magmas

Juliana Troch [a,*], Ben S. Ellis [a], Chris Harris [b], Peter Ulmer [a], Olivier Bachmann [a]

[a] Institute of Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, 8092 Zurich, Switzerland
[b] Department of Geological Sciences, University of Cape Town, 13 University Avenue, Rondebosch 7701, South Africa

A R T I C L E   I N F O

Article history:
Received 24 May 2017
Received in revised form 26 September 2017
Accepted 17 October 2017
Available online xxxx
Editor: T.A. Mather

Keywords:
rhyolite
bulk crustal melting
assimilation
hydrothermal alteration

A B S T R A C T

Constraining the contribution of crustal lithologies to silicic magmas has important implications for understanding the dynamics of these potentially highly explosive systems. Low-δ^{18}O rhyolite lavas erupted after caldera-forming events in Yellowstone have been interpreted as the products of bulk crustal melting of previously deposited and hydrothermally altered rhyolitic material in the down-dropped caldera roof. For lack of compositional data, the "self-cannibalisation bulk melting"-theory relies on the assumption that hydrothermally altered materials are near-cotectic and hydrous (>3 wt% H_2O) and will therefore readily melt at temperatures below 850 °C. In this study, we examine the drillcores Y2, Y9 and Y13 from a USGS drilling campaign in Yellowstone in order to characterise the hydrothermally altered material in terms of major and trace elements, oxygen isotopes and water contents. Rhyolite δ^{18}O values can decrease from "normal" (+5.8 to +6.1‰) on the surface to as low as −5‰ at depths of 100–160 m and probably lower as a function of increasing temperature with depth. While material in the drillcores is variably altered and silicified, oxygen isotope exchange in these samples is not accompanied by systematic changes in major and trace element composition and is independent of uptake of water. More than 75% of the drillcore samples have <0.5 wt% H_2O, making water the most limiting factor during melting. Modelled melting curves using rhyolite-MELTS suggest a maximum of 35% melt can be created at 850 °C, and that bulk melting would require extremely high temperatures >1100 °C. Therefore, large-scale bulk melting is unrealistic and low-δ^{18}O rhyolite magmas more likely result from assimilation of <30% partially melted altered crust with low δ^{18}O into a normal-δ^{18}O rhyolite magma from the main reservoir. This mechanism is supported by isotopic mass-balance models as well as thermal and volumetric constraints, and may be similarly applicable to other low-δ^{18}O settings worldwide.

1. Introduction

The relative roles of crustal melting and fractional crystallisation in the genesis of evolved magmas remain a topic of much debate in magmatic petrology, since their understanding is key to both the formation of the most explosive volcanic eruptions and the growth of continental crust on Earth. Oxygen isotope ratios in silicic magmas are powerful tracers of crustal involvement in magma genesis (Taylor, 1980) and can show values both above and below the nominal ~6.5‰ produced by closed-system differentiation to rhyolite from mantle-derived basalt (Bindeman, 2008). High-δ^{18}O magmas can result from assimilation of sedimentary rocks (δ^{18}O up to +25‰) or by the addition of materials produced during low-temperature alteration (Taylor, 1968, 1980). Low-δ^{18}O magmas require the addition of material that interacted with surface water, since only meteoric and sea water have δ^{18}O values significantly lower than MORB (Bindeman, 2008; Taylor, 1968). The mechanism by which this occurs is generally thought to involve the assimilation of hydrothermally altered rocks (Boroughs et al., 2012; Hildreth et al., 1984; Taylor, 1980).

In the Yellowstone volcanic field, USA, young low-δ^{18}O rhyolite lavas have been interpreted as the result of bulk melting (Bindeman et al., 2008; Bindeman and Valley, 2001) or assimilation (Hildreth et al., 1984) of hydrothermally altered lithologies. The source material has been inferred to represent earlier erupted materials from Yellowstone that were subsequently lowered in δ^{18}O during hydrothermal alteration by meteoric water and down-dropped via caldera faulting prior to remelting

* Corresponding author.
E-mail address: juliana.troch@erdw.ethz.ch (J. Troch).

https://doi.org/10.1016/j.epsl.2017.10.039

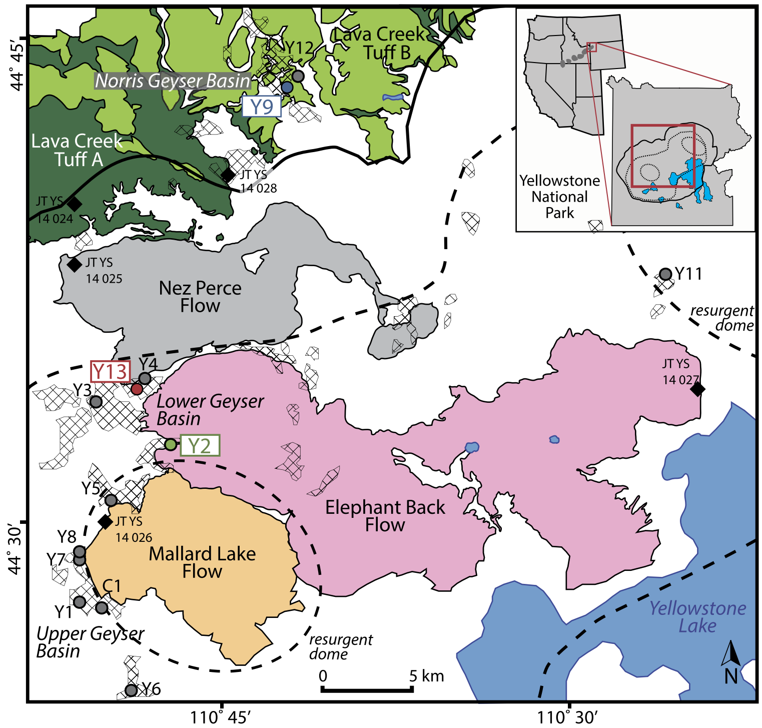

Fig. 1. Map of Yellowstone National Park showing extent of the units sampled in this study (after map from Christiansen, 2001) and the locations of drillcores used in this study Y2 (green circle), Y9 (blue circle) and Y13 (red circle). Data from other drillcores (grey-filled circles) was used for comparison. No data were used for drillcore Y10 because it is located north and away from the caldera. Black diamonds indicate sampling locations of unaltered surface equivalents of the units exposed in the drillcores. Thick black line marks caldera outline linked to eruption of Lava Creek Tuff, dashed lines show important ring faults associated with caldera collapse and resurgent doming (Mallard Lake dome and Sour Creek dome). Cross-hatched fields mark areas of intense hydrothermal activity. Blue areas mark major water bodies. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

(Bindeman and Valley, 2001). This “self-cannibalisation” model explains both the origin of the low-$\delta^{18}O$ signal and the temporal trends at an individual caldera. However, it requires that melting of altered rocks must occur within the upper crust (1–2 kbar) where comparatively low temperatures (<400 °C) limit assimilation and large-scale melting (e.g. Thompson et al., 2002). The “self-cannibalisation” model does not consider the natural compositions and water contents of the altered material, but assumes that altered rhyolite is hydrous (>3 wt% H_2O) and will thus readily melt extensively (>80%) at temperatures below 800–850 °C (Bindeman et al., 2008; Bindeman and Valley, 2001; Simakin and Bindeman, 2012). Here we use hydrothermally altered drillcore samples from the classic low-$\delta^{18}O$ location of the Yellowstone volcanic field, USA, to characterise the variably hydrothermally altered materials in terms of composition, oxygen isotopes and water contents and investigate their potential to be remelted and assimilated. By employing the thermodynamic software *rhyolite-MELTS*, we simulate the melting behaviour of these source materials as a proxy for the remelting behaviour of altered material at depth, and apply our findings to rhyolite generation models at Yellowstone.

Geological background

Silicic volcanism in Yellowstone has involved three voluminous ignimbrites, the Huckleberry Ridge Tuff (2.08 Ma), the Mesa Falls Tuff (1.30 Ma) and the Lava Creek Tuff (LCT; 0.63 Ma) interspersed with periods of relative quiescence dominated by the effusion of rhyolitic lavas (Christiansen, 2001; Girard and Stix, 2009; Stelten et al., 2015; Troch et al., 2017; Vazquez et al., 2009). A notable feature is the cyclic lowering in $\delta^{18}O$ (Bindeman and Valley, 2001; Hildreth et al., 1984; Troch et al., 2017). Following caldera collapse, variably depleted rhyolite lavas ($\delta^{18}O$ as low as +0.6‰) erupted prior to a recovery stage during which $\delta^{18}O$ values re-approached the +5.8 to +6.3‰ considered as “normal-$\delta^{18}O$”.

Yellowstone has been, and remains, the site of intense hydrothermal activity (Lowenstern and Hurwitz, 2008). In 1967–1968, thirteen research drill holes (Fig. 1) were completed by the US Geological Survey in the Yellowstone National Park (White et al., 1975). These drillcores provide the unique possibility to study how hydrothermal alteration varies with depth, across the volcanic field and between different volcanic lithologies (e.g. tuff vs. lava). The drillcores have been studied in detail for their hydrothermal mineral record (e.g. Bargar and Beeson, 1981, 1984; Bargar and Muffler, 1982; Keith et al., 1978; Sturchio et al., 1990 and others). However, little work has evaluated element mobility and isotopic changes occurring during alteration and their effects on the suitability of these materials as source materials during crustal melting.

2. Methods

2.1. Sampling

Samples were collected at the US Geological Survey Core Research Center (CRC) in Denver, CO, from drillcores Y2, Y9 and Y13 (Fig. 1), according to the initial mapping of White et al. (1975). Samples were selected that best capture pervasive alteration-related changes in the primary material; localised features such as breccias and veins were avoided. While possibly acting as nucleus for early melting, their role in large-scale melt production will likely be subordinate due to their limited volume (suppl. Fig. 5).

Drillcore Y9, the deepest drillhole (246.3 m) in Yellowstone, contains LCT A and B. Drillcore Y2 (maximum depth 158.5 m) penetrates the effusive units Elephant Back flow (EB, 0.153 Ma, all ages from Christiansen (2001) and references therein) and Mallard Lake flow (ML, 0.151 Ma). Drillcore Y13 (143.3 m depth) cuts