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Thermal and petrologic constraints on lower crustal melt accumulation under the Salton Sea Geothermal Field

Ozge Karakas[a,b,*], Josef Dufek[b], Margaret T. Mangan[c], Heather M. Wright[d], Olivier Bachmann[a]

[a] Department of Earth Sciences, Institute of Geochemistry and Petrology, ETH Zurich, Switzerland
[b] School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, USA
[c] U.S. Geological Survey, California Volcano Observatory, Menlo Park, CA, USA
[d] U.S. Geological Survey, Cascades Volcano Observatory, Vancouver, WA, USA

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ABSTRACT

In the Salton Sea region of southern California (USA), concurrent magmatism, extension, subsidence, and sedimentation over the past 0.5 to 1.0 Ma have led to the creation of the Salton Sea Geothermal Field (SSGF)—the second largest and hottest geothermal system in the continental United States—and the small-volume rhyolite eruptions that created the Salton Buttes. In this study, we determine the flux of mantle-derived basaltic magma that would be required to produce the elevated average heat flow and sustain the magmatic roots of rhyolite volcanism observed at the surface of the Salton Sea region. We use a 2D thermal model to show that a lower-crustal, partially molten mush containing <20–40% interstitial melt develops over a $\sim 10^5$-yr timescale for basalt fluxes of 0.008 to 0.010 $m^3/m^2/yr$ (~ 0.0008 to ~ 0.001 km^3/yr injection rate) given extension rates at or below the current value of ~ 0.01 m/yr (Brothers et al., 2009). These regions of partial melt are a natural consequence of a thermal regime that scales with average surface heat flow in the Salton Trough, and are consistent with seismic observations. Our results indicate limited melting and assimilation of pre-existing rocks in the lower crust. Instead, we find that basalt fractionation in the lower crust produces derivative melts of andesitic to dacitic composition. Such melts are then expected to ascend and accumulate in the upper crust, where they further evolve to give rise to small-volume rhyolite eruptions (Salton Buttes) and fuel local spikes in surface heat flux as currently seen in the SSGF. Such upper crustal magma evolution, with limited assimilation of hydrothermally altered material, is required to explain the slight decrease in $\delta^{18}O$ values of zircons (and melts) that have been measured in these rhyolites.

1. Introduction

Quantification of the mass and heat balance in the crust during magmatic episodes is essential for understanding magma evolution and crustal construction. Up to now, many studies have focused on the petrological and geophysical aspects of magma emplacement in the crust, but numerical studies constraining the thermal evolution of the coupled magma–crust system from the mantle to the surface remain few and controversial (e.g., Annen et al., 2006; de Silva and Gregg, 2014; Dufek and Bergantz, 2005; Gelman et al., 2013; Glazner et al., 2004). In particular, linking the magma flux into the crust with the heat flow measured at the surface can be informative but relatively few studies have made this link (see, however, Wohletz et al., 1999).

As demonstrated quantitatively in Karakas and Dufek (2015), the coupled influence of tectonic extension and magma injection strongly influences the thermal, and hence mechanical and chemical structure of the crust in rift zones (e.g., Buck, 1991). The Salton Sea region of the western USA is an exceptional environment to study how tectonic extension and lower crustal magma injection act in concert to modify the crustal structure of such rift zones and advect large quantities of heat to the surface to fuel geothermal systems and drive eruptions of differentiated magmas. The Salton Sea Geothermal Field at the southern end of the Salton Sea is one of the hottest and largest geothermal systems on Earth, with a thermal-gradient anomaly covering 72.4 km^2 and well temperatures upwards of 390 °C (Hulen et al., 2002; Norton and Hulen, 2006). In 2004, the annual energy production from the SSGF was reported as ~ 3 TW h/yr (Bertani, 2005) and es-

* Corresponding author at: Department of Earth Sciences, Institute of Geochemistry and Petrology, ETH Zurich, Switzerland.
E-mail address: ozge.karakas@erdw.ethz.ch (O. Karakas).

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timates of resource potential suggest that ∼613 TW h/yr could be sustained for centuries (e.g., Norton and Hulen, 2006).

A number of studies explain the tectonic and magmatic evolution of the Salton Sea region (e.g., Brothers et al., 2009; Lachenbruch et al., 1985; Schmitt and Hulen, 2008). Controversy remains, however, on the nature of the magmatic heat source fueling SSGF and the generation of rhyolite magma. Conceptual heat flow models have postulated two, although potentially not mutually exclusive, mechanisms for the SSGF—one deep and mafic (Elders et al., 1972; Lachenbruch et al., 1985), the other shallow and felsic (Hulen et al., 2002; Norton and Hulen, 2006). Previous petrologic models have suggested several different mechanisms to form the silicic magmas: 1) partial melting of mantle peridotite that formed first rhyolitic and then basaltic melts (Robinson et al., 1976), 2) melting of the crustal lithologies in response to basalt emplacement (e.g., Hulen et al., 2002), 3) fractional crystallization of parental magma (e.g., Herzig and Jacobs, 1994), 4) partial melting of previously intruded, hydrothermally altered basalt stalled at depths between 4 and 12 km (Schmitt and Vazquez, 2006), and 5) a combination of fractional crystallization of the mafic parent and assimilation of hydrothermally altered mafic intrusions at depths <∼7 km (Schmitt et al., 2013). The key to understanding the heat budget and compositional evolution of magmas in this system is to constrain the energy and mass influx from the mantle in the form of basalt intrusions. In this study, we use a thermal model (Karakas and Dufek, 2015) to evaluate the conditions from which the SSGF and rhyolitic volcanism ultimately derive. Motivated in part by the inference of melt in the deep crust based on seismic studies (e.g., Barak et al., 2015), we focus on the consequences of lower crustal intrusion/differentiation in a rifted crust, and how the resulting melt might feed a shallower differentiation level.

2. Geologic setting

2.1. Tectonic evolution of the Salton Trough

The Salton Sea Geothermal Field is located along one of the three northernmost pull-apart basins (Fig. 1) generated by extension and subsidence due to offset between the San Andreas Fault (SAF) and the Imperial Fault (IF) (Elders et al., 1972; Lonsdale, 1989). The present day tectonic configuration of the Salton Sea is suggested to be a result of two-stage tectonic evolution that started ∼500 ka by block rotation between San Jacinto Fault (SJF) and SAF (Brothers et al., 2009). The second stage of evolution developed the SAF-IF step-over that concentrated extension in two locations: the Mesquite Basin and the southeastern shore of the Salton Sea. The extension rate in SSGF in the last 500 ka, calculated by subsidence and sedimentation rates, is 11.5 mm/yr (Brothers et al., 2009). Subsidence has been approximately matched by sedimentation (2.2–3.8 mm/yr, Schmitt and Hulen, 2008) and kept the surface elevation near sea level (Lachenbruch et al., 1985). By compiling 322 measurements, the average surface heat flow of the entire Salton Trough-Imperial Valley region yields values of ∼140–170 mW/m^2 (the high end includes the contributions from the geothermal areas; Lachenbruch et al., 1985). These values are more than triple the adjacent Sierra Nevada (39 ± 12 mW/m^2, Lachenbruch et al., 1985; Sass et al., 1971). The heat flow in the geothermal regions shows much higher values over limited areas due to focused advection controlled by hydrothermal systems and/or the presence of shallow melt, with SSGF locally exceeding >600 mW/m^2 (Elders and Sass, 1988; Lachenbruch et al., 1985) and reaching maximum values of >1200 mW/m^2 (Elders and Sass, 1988). These high heat flows measured in SSGF are comparable to the largest geothermal systems in the world, such as the Taupo Volcanic Zone (800 mW/m^2 in Central Volcanic Region,

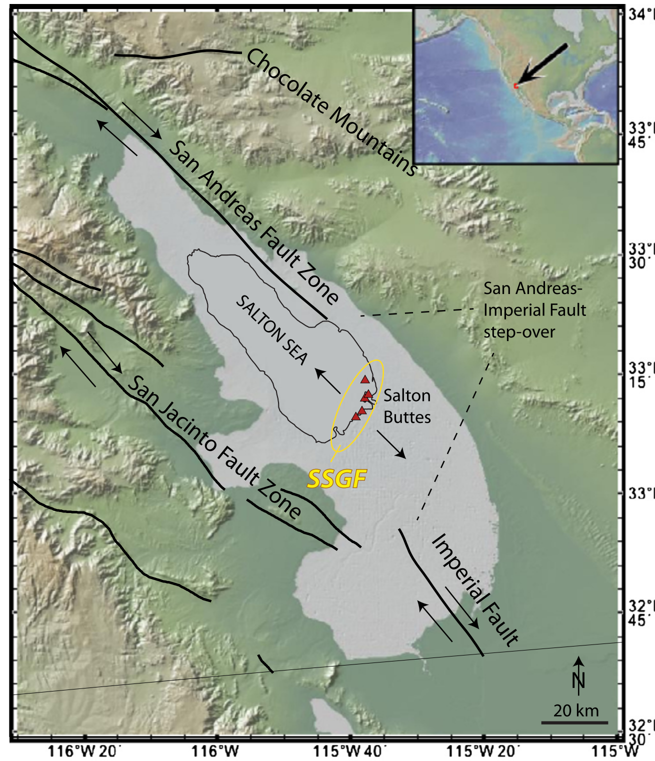

Fig. 1. Map of the Salton Trough (30 m DEM) produced using GeoMapApp (http://www.geomapapp.org). Major faults in the area and location of the Salton Buttes are shown.

Stern, 1987) and Yellowstone (1550–2100 mW/m^2, Lowenstern and Hurwitz, 2008).

2.2. Crustal lithologies in the Salton Sea region

The compositional crustal layering in the Salton Sea area (Fig. 2) is constrained by seismic experiments (e.g., Barak et al., 2015; Fuis et al., 1984), scientific boreholes, and xenoliths present in the erupted products (Schmitt and Vazquez, 2006). The uppermost part of the crust (<5 km) is unconsolidated sediments deposited from Colorado River, mainly sand, silt, clay, sandstone, siltstone, and claystone (Fuis and Kohler, 1984; Herzig and Elders, 1988a). This layer is underlain by metamorphosed sediments (Muffler and White, 1969), which are mainly composed of greenschist facies metasedimentary rocks (Herzig and Jacobs, 1994; Robinson et al., 1976). Below 10 km, seismic wave velocities increase gradually with depth while retaining physical continuity, suggesting progressive hydrothermal alteration and thermal metamorphism of sediments due to rapid burial and heating (Fuis et al., 1984; McDowell, 1987; McKibben and Hardie, 1997). The lower 10–18 km of the crust are inferred to be a gabbroic layer, formed by extension-related magma emplacement (Lachenbruch et al., 1985).

Scientific boreholes cut diabasic sills at 2.5 to 3 km depth (undated; Elders and Sass, 1988) and three extrusive rhyolitic sequences with thicknesses between 100 and 300 m (Schmitt and Hulen, 2008). These rhyolite intervals provide stratigraphic markers from which sedimentation rates can be calculated. High resolution U–Pb zircon dates from these units yield ages between 479 and 420 ka (Schmitt and Hulen, 2008). Approximately 5 km north of the SSGF, distal fallout deposits from the eruption of Bishop Tuff that created Long Valley Caldera (dated as ∼0.76 Ma, Chamberlain et al., 2013; Van den Bogaard and Schirnick, 1995) are found beneath 1.7 km of sediment (Herzig and Elders, 1988a, 1988b).