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

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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 m³/m²/yr (~ 0.0008 to ~ 0.001 km³/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 produces lower crustal, 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 $\delta^{18}\text{O}$ 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 km² and well temperatures upwards of 390°C (Hulen et al., 2002; Norton and Hulén, 2006). In 2004, the annual energy production from the SSGF was reported as ~ 3 TWh/yr (Bertani, 2005) and estimates of resource potential suggest that ~613 TWh/yr could be sustained for centuries (e.g., Norton and Hulén, 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 Hulén, 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 Hulén, 2006). Previous petrologic models have suggest 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 $< \sim 7$ 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 yield values of $\sim 140\text{-}170\text{ mW/m}^2$ (the high end includes the contributions from the geothermal areas; Lachenbruch et al., 1985). These values are more than triple the adjacent Sierra Nevada ($39\pm 12\text{ mW/m}^2$, Lachenbruch et al., 1985; Sass et al., 1971). The heat flow in the geothermal regions show 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 $>600\text{ mW/m}^2$ (Elders and Sass, 1988; Lachenbruch et al., 1985) and reaching maximum values of $>1200\text{ mW/m}^2$ (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, Stern, 1987) and Yellowstone ($1550\text{-}2100\text{ mW/m}^2$, 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 ($<5\text{ km}$) 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 is 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 meters (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, b).

2.3. Magmatism in the Salton Sea Geothermal Field

Magmatism at the surface is restricted to five rhyolitic domes called the Salton Buttes on the southeastern shore of the Salton Sea (Schmitt and Hulen, 2008). The domes lie over a 7 km-long horizon that is suggested to delineate the extensional processes at

depth, and likely share a common feeder dike at depth (Kelley and Soske, 1936; Robinson et al., 1976). Rhyolitic lavas from Salton Buttes contain xenoliths that include granophyres and amphibole-bearing basaltic xenoliths (Schmitt and Vazquez, 2006). In addition to xenoliths, data from wells that cut through dikes and sills also show bimodal magmatism: rhyolitic bodies and basaltic dikes, sills, and flows (Robinson et al., 1976; Schmitt and Vazquez, 2006). Schmitt and Vazquez (2006) note multiple populations of zircon crystallization, which they infer to be generated by multiple thermal pulses that caused melting and recycling of pre-existing basaltic intrusions.

3. Transient thermal model

A two-dimensional finite volume model is constructed to investigate the thermal and magmatic evolution of the crustal column below the SSGF from the initiation of rifting to the present day. The model is modified from Karakas and Dufek (2015) and includes extension of the crustal column, sedimentation at the surface, and basaltic magma injection into the lower crust (Fig. 2). Based on the results of Fuis et al. (1984), we consider an initial crustal column with three distinct layers: an uppermost sedimentary layer that is 4 km thick, a mid-level meta-sedimentary layer that extends from 4 km below the surface to 13 km, which is underlain by a thick crystalline basement (most likely amphibolite) that extends downward to 20 km (Fig. 2). Our simulations assume that rifting commenced 1 Ma (Brothers et al., 2009) or 0.5 Ma (Schmitt et al., 2013). We vary the extension rates and use 10 mm/yr (Brothers et al., 2009), 8 mm/yr, and 5 mm/yr in different sets of simulations for parametric analyses. In our model, the crust moves in response to tectonic extension and sedimentation by a defined velocity (kinematic

condition) that is informed by inferences of extension and sedimentation rates (e.g., Brothers et al., 2009; Schmitt and Hulen, 2008). Tectonic extension results in mantle upwelling and axial thinning of the crust. This is compensated in part by sedimentation on the surface, thickening the uppermost sedimentary layer as the lower layers subside. We do not include detailed topology of faults in the region.

We assume that lower-crustal magma injection started incrementally (as a series of basaltic dikes and sills) at the initiation of extension. The average flux into the crust is imposed through a mean injection frequency such that the exact timing of an individual intrusion is stochastic and described by a uniform distribution. To conserve mass, emplaced dikes are accommodated by laterally displacing crustal material to either side of the dike, and sills are accommodated by displacement of crustal material downward. Dikes are intruded from the base of the crust up to within 10 km of the surface (Fig. 2). These model emplacement depths are consistent with seismic observations of the crustal layering suggested by Fuis et al. (1984) and Barak et al. (2015). We make the assumption that due to the present-day (and temporally averaged) balance of extension and sedimentation that this maximum level of basalt ascent has remained consistent over time, although detailed constraints on the temporal variation of extension and sedimentation are limited. Although small shallower diabasic intrusions are observed in some boreholes, our assumption of lower crustal basaltic intrusions captures the long-term crustal thermal evolution to a first order, and gives a better understanding of the base level heat input to the crust.

The thermal evolution of the crustal column is calculated by solving time-dependent thermal advection-conduction equation. A full description of the methodology

is given in Karakas and Dufek (2015). Evolving melt geochemistry and latent and sensible heat of the system are calculated by parameterization of the non-linear melt fraction relationship as a function of temperature using rhyolite-MELTS thermodynamic model (Gualda et al., 2012) for appropriate crustal lithologies at upper, middle, and lower crustal depths and emplaced basalt at lower crustal depth (Fig. 3). The partitioning of sensible and latent heat in these non-linear relationships is done through an iterative approach (Voller and Swaminathan, 1991).

To specify the criteria for melting of sedimentary and meta-sedimentary layers, 500 MPa dry melting of pelites and quartzo-feldspathic rocks combining 1.0 wt.% H₂O locked in hydrous minerals as a function of temperature is parameterized from experimental results of Clemens and Vielzeuf (1987). Rhyolite-MELTS calculations are performed to determine the melt fraction - temperature relationship of crystallizing basalt (440 MPa and 0.5 wt% H₂O) and to determine the liquidus temperature of the lower amphibolite (2.0 wt% H₂O). The melt fraction as a function of temperature for amphibolite is parameterized using the experimental results of Rushmer (1991), Sisson et al. (2005), and Wolf and Wyllie (1994). We emphasize that we have specified a hydrous lower crust, and therefore our model represents a fertile end-member for lower crustal melting of igneous lithologies.

The composition for basalt injected into the lower crust is taken from the average of three XRF bulk chemical analyses of the most primitive mafic xenoliths found in Salton Buttes rhyolites (Herzig and Jacobs, 1991). Because the original dissolved water content of our modeled basalt is unknown, we chose a value of 0.5 wt% H₂O based on melt inclusion data from E-MORB (Sobolev and Chaussidon, 1996). We justify this choice by

noting that ϵ_{Nd} ratios in Salton Butte basaltic xenoliths are comparable to those reported for mid ocean ridge basalts from the East Pacific Rise and Alarcon Ridge (Herzig and Jacobs, 1994; Robinson et al., 1976; Schmitt et al., 2013). Since the average basalt flux is not constrained for the Salton Sea region, we consider a range of plausible values from diverse volcanic settings (10^{-3} to 10^{-2} $m^3/m^2/yr$, Crisp, 1984). We track melt composition, temperature, melt fraction, and surface heat flux through time. We recast the fraction of interstitial melt in the mush region as an equivalent 2-D uniform layer of melt, and then divide the two-dimensional domain by the injection width to give a normalized melt thickness.

4. Results

To illustrate features of our simulations, we present a snapshot that produced thermal and petrologic features consistent with observed heat flow and lower crustal melt. This snapshot shows crustal conditions at the end of a 0.5 Ma period of tectonic extension of 0.007 m/yr and basalt flux of 0.0085 $m^3/m^2/yr$ (Fig. 4a, b, c), as well as the gradual rise in surface heat flux that ensues (4d). From the surveyed conditions outlined earlier, we define a selection of optimal-fit models where the results of the final state of the system match the observations of crustal thicknesses, average surface heat flux (~ 140 mW/m²), crustal geotherm, petrology, and inferred presence of melt. From this, we can constrain the lower crustal heat source of the Salton Buttes volcanic region and give information about the initial conditions, long-term evolution, and basalt flux. A summary of the results from all scenarios is given in Table 1. We note that we model heat conduction and advection in the crust in response to the emplacement of mantle-derived magmas in the

lower crust during tectonic extension, and do not take into account upper crustal magma reservoirs and hydrothermal systems. As the total heat flux is ultimately controlled by the mantle flux, the upper crustal conditions will generate local variability, but will not influence the average behavior of the system that we set to model.

Overall, we see that repeated mantle-derived basaltic injections lead to construction of a lower-crustal mush region (Fig. 4c) composed predominantly of interstitial melt residua from basalt fractionation with little to no assimilation of crustally-derived melt for the lithologies we tested (Table 1). For many magma fluxes surveyed, solidification is rapid for basalt injected in the early time steps (~200 kyr). However, with repeated injections, crustal conditions get warmer and allow preservation of residual melt (in agreement with the conductive timescales, e.g., Petford and Gallagher, 2001). For magma fluxes of $<0.0085 \text{ m}^3/\text{m}^2/\text{yr}$, the amount of residual melt in the mush zone is equivalent to a uniform melt layer less than 150 m thick after 1 million years of basaltic injections and tectonic extension (Table 1). The energy supplied by dike and sill intrusion is insufficient to assimilate the amphibolite country rock. Transient, local melting of the crustal lithologies occurs immediately after the injection events, but, over the long-term, the ambient geothermal gradient does not support any crustal contributions at basalt fluxes $<0.0085 \text{ m}^3/\text{m}^2/\text{yr}$.

Intermediate to high basalt fluxes (0.0085 to $0.017 \text{ m}^3/\text{m}^2/\text{yr}$) coupled with rapid extension (0.010 m/yr) produce a mush zone with residual melt fractions equivalent to uniform melt layers up to ~500 m thick over 10-km width. In these scenarios, crustal melts form but in limited amounts, representing $<20\%$ of the total melt volume. For this range of conditions, the equivalent melt layer (residual melt + crustal melt) ranges

between 150 to 555 meters over 0.5 Ma (Fig. 5 and Table 1). At times longer than 0.5 Ma, the amount of crustal melt produced at high basalt fluxes is always at least ten times lower than the amount of residual melt derived from basalt fractionation (Fig. 5c, d and Table 1 at $0.0017 \text{ m}^3/\text{m}^2/\text{yr}$).

In summary, melt fractions of up to a maximum of 0.2 - 0.4 within a 10 km x 2 km model mush zone located at 16-18 km depth are seen in most of our simulations ($>0.0085 \text{ m}^3/\text{m}^2/\text{yr}$ and $>0.05 \text{ m/yr}$ in 10^5 yr timescales). Once the mush stabilizes, it remains over the lifetime of rifting (to the present state of the system) with incremental magma additions, provided the specified basalt flux of $> 0.0085 \text{ m}^3/\text{m}^2/\text{yr}$. The modeled residual melt fractions of <0.2 - 0.4 correspond roughly to andesitic-dacitic compositions as determined in the experimental work discussed below (Müntener et al., 2001; Sisson et al., 2005; Villiger et al., 2004).

5. Discussion

Repeated mantle-derived basaltic injections lead to the construction of a lower-crustal mush region composed predominantly of interstitial melt residua (<0.2 - 0.4) from fractional crystallization of basaltic dikes with up to 20% assimilation of lower crustal material. Rapid thinning ($>0.005 \text{ m/yr}$) and high basalt flux (0.008 - $0.010 \text{ m}^3/\text{m}^2/\text{yr}$) are required to match the present-day characteristics of the Salton Sea region (crustal thickness and surface heat flow). For mantle of equal fertility, extension and basalt flux are coupled—rapid tectonic extension enhances mantle melting, which in turn supports a higher flux of basalt into the lower crust (e.g., McKenzie and Bickle, 1988). We, however, note that melt volumes entering to the crust are controlled by several parameters (e.g.,

mantle potential temperature, melt extraction, porosity, strain rates; c.f., Karakas and Dufek, 2015; Ziegler and Cloetingh, 2004). We therefore use tectonic extension and basalt flux as independent parameters and quantify their coupled effect on melt evolution in the crust.

The relative paucity of crustal melting in our simulations indicate that the enthalpy transferred from dike emplacement mainly increases the sensible heat of the crustal material but rarely allows the pre-existing lower crust to rise above its solidus. In our model, the degree of crustal melting increases as a function of basalt flux (Table 1). We find that when the flux of basaltic magma is low ($<0.0085 \text{ m}^3/\text{m}^2/\text{yr}$), the heat supplied to the crust by the intruded magma is insufficient to drive any crustal melting, regardless of the tectonic extension rate. When the flux of basaltic magma is higher, the amount of crustal melt produced is equivalent to a melt layer of $<30 \text{ m}$ for all extension rates. This is consistent with previous thermal models that also find limited crustal melting in environments with thin crusts (e.g., Dufek and Bergantz, 2005; Karakas and Dufek, 2015; Petford and Gallagher, 2001).

We find melt fractions up to 0.2-0.4 in our best-fit models that exist for prolonged periods of time (10^5 to 10^6 yr) in the lower crust, in agreement with seismic observations (Barak et al., 2015), where the seismic reduction estimates were fitted via averaging over a large part of the lower crust. Although not considered in this study, the maximum melt fractions characterizing our optimal-fit conditions also overlap with efficient melt segregation and extraction processes at intermediate crystallinities (Dufek and Bachmann, 2010).

In our best fit 2-D simulations, a maximum lower crustal melt thickness of ~150-550 m³/m² is estimated by summing the interstitial melt in the mush region as an equivalent 2-D uniform body, and then dividing the two-dimensional domain by the injection width (Table 1). Similarly normalizing the total observed volume of Salton Buttes rhyolite (~0.5 km³, Robinson et al., 1976) gives 25 m³/m² of erupted rhyolite. As further differentiation is required in the upper crust, we can assume that only 10-20% of the melt escaping the lower crustal mushes will reach the surface as rhyolite. However, as the volumes of erupted rhyolite are very small, they are well within the modeled range.

5.1. Origin of silicic magmatism in the Salton Buttes

Published experimental data on crystallizing basalt at lower crustal pressures predict that for the melt fractions we compute (<0.2-0.4), fractional crystallization is likely to produce melt compositions ranging mostly from andesite to dacite, although small amounts of rhyolite can also form depending on conditions (melt fraction, water content, oxygen fugacity, and depth of the crystallization; Müntener et al., 2001; Sisson et al., 2005; Villiger et al., 2004). In mid-to-low crustal conditions (0.7 GPa experiments), hydrous melting experiments showed generation of rhyolite at low melt fractions (<0.2, Sisson et al., 2005). However, in dry and relatively low pressure conditions such as the Salton Sea magmatic system, the crystallization of plagioclase and pyroxene will slow down the evolution towards high silica melt (e.g., Wolf and Wyllie, 1994). Hence, we conclude that lower crustal generation of Salton Buttes rhyolite is unlikely, and requires further differentiation in the upper crust. Moreover, if rhyolitic melt compositions can be produced in the deeper crust within rift settings, they are likely to be diluted by more

mafic melts, such that aggregate composition in the mush zone is roughly intermediate.

Our thermal results are consistent with $\delta^{18}\text{O}$ and ϵ_{Nd} isotope ratios of Salton Sea rhyolites that indicate limited assimilation of meta-sedimentary rocks or pre-existing basement, and suggest a dominantly mantle-like magma source (e.g., Schmitt et al., 2013). Schmitt and Vazquez (2006) and Schmitt and Hulen (2008) suggested partial melting of hydrothermally altered material in the shallow crust to generate the rhyolitic magma. However, more recent work (Schmitt et al., 2013) has suggested a combination of fractional crystallization of MORB-like magma with <20% crustal assimilation (including some ingestion of hydrothermally altered intrusions at shallow depth). Additionally, more recent data show $\delta^{18}\text{O}$ values for feldspar (6.1-6.3 ‰) and pyroxene (4.7-5.5 ‰) that are likewise consistent with fractional crystallization of intruded magma (Wright et al., 2013).

To explain the eruption of rhyolite at the surface, we suggest that a deep basaltic mush zone episodically delivers coalesced andesitic to dacitic melt to an upper crustal reservoir (not modeled here), which subsequently undergoes further processing to reach rhyolitic compositions (Fig. 6); high silica rhyolite require low-pressure to form (Gualda and Ghiorso, 2013) and a polybaric differentiation column (with vertically-stacked reservoirs) is a likely situation in many magmatic provinces on Earth that produce silicic magmas (see Bachmann and Huber, 2016, and references therein).

5.2. Compositional gap in the Salton Sea system

If intermediate magmas are claimed to rise through the crustal column to shallow levels, why have only rhyolite lavas erupted at Salton Buttes and why are xenoliths and intrusive rocks only either rhyolitic or basaltic? Such compositional gaps are very

common in volcanic provinces (coined the “Bunsen-Daly” gaps), and are always puzzling in cases where differentiation dominantly through fractional crystallization is argued (e.g., Deering et al., 2011; Dufek and Bachmann, 2010; Szymanowski et al., 2015). In such magmatic provinces, we suggest that the intermediate magmas are stored as uneruptible crystal mushes (later forming plutons) in the upper crust while their differentiated melt-rich equivalents erupt at the surface.

Although only bimodal magmatism is observed in the Salton Buttes, interestingly, the adjacent extensional basins south of the Salton Sea do show intermediate compositions, which become progressively mafic along the pull-apart basins southward. The eruptive products of Cerro Prieto, the extensional basin south of the Salton Sea, reach rhyolitic to dacitic compositions (Schmitt et al., 2013). Intrusive rocks beneath Cerro Prieto are mafic, overlapping in composition with basalt xenoliths from the Salton Buttes (Schmitt et al., 2013). Still farther south (offshore, in the Gulf of California), the Roca Consag shallow intrusive plug is dacitic. Mafic eruptive compositions (andesitic with minor rhyolite volcanics and basaltic intrusives) are only observed to the south of Roca Consag (e.g. Ballenas Channel and lower Delfin basin; Martín et al., 2013). This difference in observed magma compositions are suggested to be related to the rate of sedimentation, where an increase in sedimentary thickness results in an increase in the degree of differentiation by controlling the neutral buoyancy level of magmas (Schmitt et al., 2013). However, assuming that the mafic endmembers are similar at all locations, we suggest an alternative explanation. An increase in the extension rate leads to a greater volume of differentiated compositions over time (e.g., Karakas and Dufek, 2015), as more heat and mass are advected in the lower crust (e.g., McKenzie, 1978, Fig. 5). A

similar situation may have happened in the Taupo volcanic zone in the last million years, where magmas have evolved from andesite-dominated to bimodal volcanism as the extension rate increased (e.g., Deering et al., 2011).

5.3. Focusing of magmatism

In our model, we restrict the tectonic extension and diking over a specified width (10 km) on the mantle-crust boundary. Lachenbruch et al. (1985) suggest that the extension should be distributed over a wide area (~150 km long and several tens of kilometers wide) in the Salton Trough in order to accommodate substantial magmatic addition with almost no crustal melting signatures and to explain the observed heat flux with the extension and sedimentation rates. However, this appears to be at odds with (1) the absence of any syn-rift magmatism outside the ~15 km zone around SSGF, (2) the age and stratigraphic depth of rhyolite bodies that are localized beneath the Salton Buttes since Mid-Pleistocene (Schmitt and Vazquez, 2006) and (3) the tectonic configuration of the Salton Trough-Imperial Valley System revealed by seismic interpretations (e.g., Barak et al., 2015; Brothers et al., 2009), all of which point to extension and magma injection localized in narrow zones. Our thermal model shows that localized continuous extension and repetitive magmatism over a million-year timescale can thermally accommodate large volumes of magma in the crust without producing a large amount of crustal melting (Fig. 5). It has been shown that the crustal melting rate is sensitive to the thickness of the crust (e.g., Dufek and Bergantz, 2005), compositional layering (fertile/refractory crustal compositions, e.g., Thompson et al., 2002), and initial conditions (e.g., Dufek and Bergantz, 2005; Karakas and Dufek, 2015). Therefore, in the SSGF, substantial melting of the crust is not thermally viable because it requires

excessive energy input and/or particularly fertile lower crust in this situation where the crust is very thin.

6. Conclusions

The present work uses a thermal model for the SSGF extensional system and captures the evolution of the lower crustal mush system under the SSGF to a first order, in agreement with petrologic studies on Salton Buttes volcanic products and seismic and heat flow studies in the Salton Through-Imperial Valley region. In the present model, we use values that have been constrained in the SSGF by various petrologic, field, and geophysical studies, and allow other poorly constrained variables to vary (e.g., basalt flux, tectonic extension). This approach provides us with quantitative estimates of the lower crustal melt thickness (0.5-1 km, assuming all the melt is extracted), average melt fraction in the mush zone (<0.2-0.4 over 16-18 km depth), and evolution (andesitic to dacitic melt formed in ~0.5 to 1 Myr mainly by fractional crystallization of basalt with <20% assimilation). We suggest that the pre-existing lower continental crust is thinned by extensional tectonics, and accompanied by intrusion of basalt with high flux in the lower crust to form an active magma column over 0.5 – 1 Ma. The magma generated in lower crust is intermediate in composition, which then must further differentiate in the upper crust to generate the high SiO₂ rhyolites that erupted at the surface.

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592

592

593 **Table 1.** Model results with varying basalt flux and tectonic extension rates

594

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

598

599 **Fig. 2.** Conceptual model for Salton Buttes magmatism. The computational domain is an
600 idealized proxy for crustal column and uppermost mantle, it consists of four layers: 0-4
601 km is unconsolidated sediments, 4-13 km is hydrothermally altered metasediments, 13-18
602 km is amphibolite, and 18-30 km is mantle peridotite. Sedimentation is restricted to a
603 given width at the surface (sedimentation width). Sedimentation at the surface subsides
604 lower crustal layers due to conservation of mass. Sedimentation and subsidence rate are
605 at near-equilibrium, which keeps the surface at sea level. Diking is localized over ~10
606 kilometers on the crust-mantle boundary (injection width). Sills are formed at the tip of
607 the dikes. The lengths of the dikes are randomized but the maximum length is set at ~6
608 km (10 km depth). Emplacement of dikes and sills are accommodated by displacement of
609 the crustal material to conserve mass. Crustal extension is accommodated by
610 displacement of the crustal column by the extension rate. Extension is accommodated by
611 thinning of the crust near-axis (tectonic width) by conservation of mass and induces
612 mantle upwelling. Drawing is not to scale.

613

614 **Fig. 3.** Melt fraction versus temperature relationship of 1) pelites and quartzofeldspathic
615 rocks at 5 kbar pressure and 1.0 wt.% water content. Melting relationships are
616 parameterized from fluid-absent melting experiments of Clemens and Vielzeuf (1987).
617 The solidus temperature for pelitic rocks is assumed to be 680°C; 2) amphibolite
618 experiments of Sisson (2005) and Rushmer (1991); 3) most primitive mafic composition
619 based on average of 3 bulk chemical analyses by XRF of mafic xenoliths of the Salton
620 Buttes erupted material (Herzig and Jacobs 1991) at 4.4 kbar. Melt fraction as a function
621 of temperature and water content (0.5 wt.% H₂O) is calculated with rhyolite-MELTS
622 (Gualda et al., 2012).

623

624 **Fig. 4.** An example simulation result with a basalt flux of 0.0085 m³/m²/yr and tectonic
625 extension of 0.007 m/yr. (a) compositional layering of the crust after 500 kyr of tectonic
626 extension, sedimentation and repetitive diking; (b) two-dimensional temperature
627 evolution; (c) two-dimensional melt fraction in the lower crustal mush; and (d) evolution
628 of surface heat flux over time, which matches average surface heat flow for Salton
629 Trough-Imperial Valley system (~140 mW/m²).

630

631 **Fig. 5.** Evolutions of crustal and residual mantle-derived melt thicknesses over time are
632 shown as a function of magma flux and tectonic extension. In (a, c) crustal melt
633 thicknesses at 500 kyr and 1 Myr, (b, d) residual melt thicknesses at 500 kyr and 1 Myr
634 are shown. In the first 500 kyr, crustal melting is not significant. Residual melt produced
635 by fractional crystallization of basalt is 100 meters thick when the tectonic extension is
636 0.010 m/yr. Some limited amount of crustal melting is observed when time is 1 Myr. The

relative amount of mantle-derived melt is at least an order of magnitude greater than the crustal melt. Note the different scales of color bars in (b), (c), and (d).

Fig. 6. Schematic representation of the generation and evolution of the Salton Sea Geothermal Field suggested by thermal modeling. Incremental dike emplacement and tectonic extension in the lower crust generates a mush with low melt fraction ($<0.2-0.4$) over 10^5 -yr timescale. Fractional crystallization of basaltic melt in the lower crust forms intermediate magma compositions that emplace in the upper crust. We infer that differentiation of intermediate magma in the upper crust generates rhyolitic melt that sometimes erupt at the surface. Hydrothermal water circulation in the upper crust transports heat from the magma body to the surface and develops the geothermal region that creates the peak surface heat flux ($600-1200 \text{ mW/m}^2$) measured at the SSGF.

- Clemens and Vielzeuf (1987)
- △ Rushmer (1991)
- △ Sisson et al (2005)

a **b** **c** **d**

Time (yr)	Intrusion frequency (yr)	Average basalt flux over time (m ³ /m ² /yr)	Tectonic extesion (m/yr)	Normalized residual melt volume (m)	Normalized crustal melt volume (m)	Crustal melting (%) (vol. crustal melt/ vol. total melt)
10 ⁶	10000	0.0043	-0.01	70	0	0
10 ⁶	10000	0.0043	-0.008	20	0	0
10 ⁶	10000	0.0043	-0.005	1	0	0
10 ⁶	7500	0.0057	-0.01	109	0	0
10 ⁶	7500	0.0057	-0.008	46	0	0
10 ⁶	7500	0.0057	-0.005	4	0	0
10 ⁶	5000	0.0085	-0.01	150	0	0
10 ⁶	5000	0.0085	-0.008	80	0	0
10 ⁶	5000	0.0085	-0.005	15	0	0
10 ⁶	2500	0.0170	-0.01	550	5	1
10 ⁶	2500	0.0170	-0.008	350	10	2.8
10 ⁶	2500	0.0170	-0.005	150	30	17