Ages of Rhyolitic Magmatism in the Salton Sea Geothermal Field Determined by Ion Microprobe Dating of Zircon

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ABSTRACT

U-Pb and U-Th zircon ages for igneous rocks from the Salton Sea geothermal field (SSGF) help constrain the timing of magmatic and volcanic activity in this part of the Salton Trough. Two types of samples were age-dated: (1) drill cuttings from three geothermal wells that penetrated deeply-concealed extrusive and intrusive rhyolites in the current depth range 1.6 -2.7 km; and (2) flow/dome rocks and xenoliths from the Salton Buttes—four Quaternary rhyolitic volcanic centers exposed along the western margin of the geothermal field. The subsurface rhyolites yield U-Pb zircon ages between 417 ± 6 ka and 476 ± 23 ka (1σ). Average zircon crystallization ages are indistinguishable between the buried intrusive and extrusive rhyolites, and overlap (within the range of uncertainty) in two of the extrusive-rhyolite intercepts separated by ~300 m of intervening calcareous-siliciclastic strata. Zircons from the Salton Buttes rhyolites are much younger, yielding U-Th ages between 10 ± 1 ka and 18 ± 2 ka. The older ages closely overlap with those of granitic and finely-crystalline rhyolitic xenoliths (21 ± 2 ka and 18 ± 4 ka, respectively) in the exposed volcanics. Basaltic xenoliths in these volcanics host zircons, in remelt pockets, that yield ages between 30 ± 13 ka and 9 ± 7 ka. Subsurface-rhyolite zircon ages indicate that the inception of magmatism in this part of the U.S. Salton Trough was at least several 10^5 years earlier than indicated by the surface volcanic rocks and their xenoliths. Minimum sedimentation rates estimated from U-Pb zircon crystallization ages for the now buried but unambiguously extrusive rhyolites indicate that the rate of subsidence and sedimentation in the central portion of the SSGF—up to 4 mm/yr—was nearly twice as rapid as previously reported (2.4 mm/yr) for the northern part of the field. The ~30 - 9 ka age for the xenoliths of plutonic rock in the surface volcanics underscores the fact that heating in the modern geothermal system was initiated in the geologically recent past.

Introduction

Reliable knowledge of the thermal history of a geothermal system is critical for assessing the system's resource potential. Attempts to constrain that history for the Salton Sea Geothermal Field (SSGF) have utilized numerical modeling of static-temperature distributions from geothermal wells (Kasameyer et al., 1984; Norton and Hulen, 2006, this volume), radiometric dating of U-series isotopes in brines (Zukin et al., 1987), or detrital-K-feldspar thermochronology of reservoir sandstones (Heizler and Harrison, 1991). Results of these studies are in broad agreement that the modern manifestation of the Salton Sea hydrothermal system is very young indeed: variously and approximately 3 - 20 ka (Kasameyer et al., 1984); 10 - 40 ka (Zukin et al., 1987); 1 - 5 ka (Heizler and Harrison, 1991); and 10 – 50 ka (Norton and Hulen, 2006). However, there are clear indications of older magmatic-hydrothermal activity. Hulen and Pulka (2001) noted that deeply-concealed (1.7 km) but obviously extrusive rhyolites in one deep well in the Salton Sea field implied a corresponding felsic pluton and, in this geologic setting, that the pluton inevitably would drive circulation of magmatic-hydrothermal brines. Based on the previously estimated long-term sedimentation rate for the field (2.4 mm/yr; Herzig and Elders, 1988), Hulen and Pulka (2001) calculated that the buried rhyolites would have been emplaced about 700,000 years ago. Results of the present investigation show that this estimated age was too high by nearly a factor of two, and the corresponding sedimentation rate too low by an equivalent measure.

Previously, radiometric ages for surface volcanic rocks in the SSGF have been as a proxy for their less accessible intrusive counterparts (e.g, Kasamayer et al., 1984). Reliable primary magmatic ages, however, are in general difficult to obtain for youthful, active geothermal systems such as the SSGF. This is because Quaternary geochronology based on traditional radioactive decay systems, such as K-Ar, is in many cases affected by low radiogenic yield and/or contamination by extraneous daughter isotopes (excess ^{40}Ar). Moreover, the high ambient temperatures and intense fluid-rock interaction typical for active geothermal environments are unfavorable for preservation of magmatic crystalline phases, and may violate the closed-system assumptions generally required for calculating primary crystallization ages. This holds true to an even greater extent for subsurface igneous samples, whether in drill core or as cuttings from geothermal wells. Over the past few years, U-Pb and U-Th high-sensitivity and high-spatial-resolution ion microprobe geochronology of accessory minerals has demonstrated great potential to overcome these problems. Studies on The Geysers and Medicine Lake (California; Dalrymple et al., 1999; Lowenstern et al., 2000; Schmitt et al., 2003) successfully exploited the property of accessory zircons to preserve magmatic ages due to the mineral's outstanding chemical stability and extremely slow diffusion rates for radioactive parents and daughters (e.g., Cherniak and Watson, 2001).

We present the first U-Pb zircon ages for SSGF subsurface rhyolites, as well as an extensive set of U-Th zircon ages for surface lavas and xenoliths. The results indicate significant rhyolitic magmatism at ~450 ka, followed by a younger pulse of basaltic remelting, granite crystallization at shallow depth, and rhyolite volcanism between ~30 and ~9 ka.

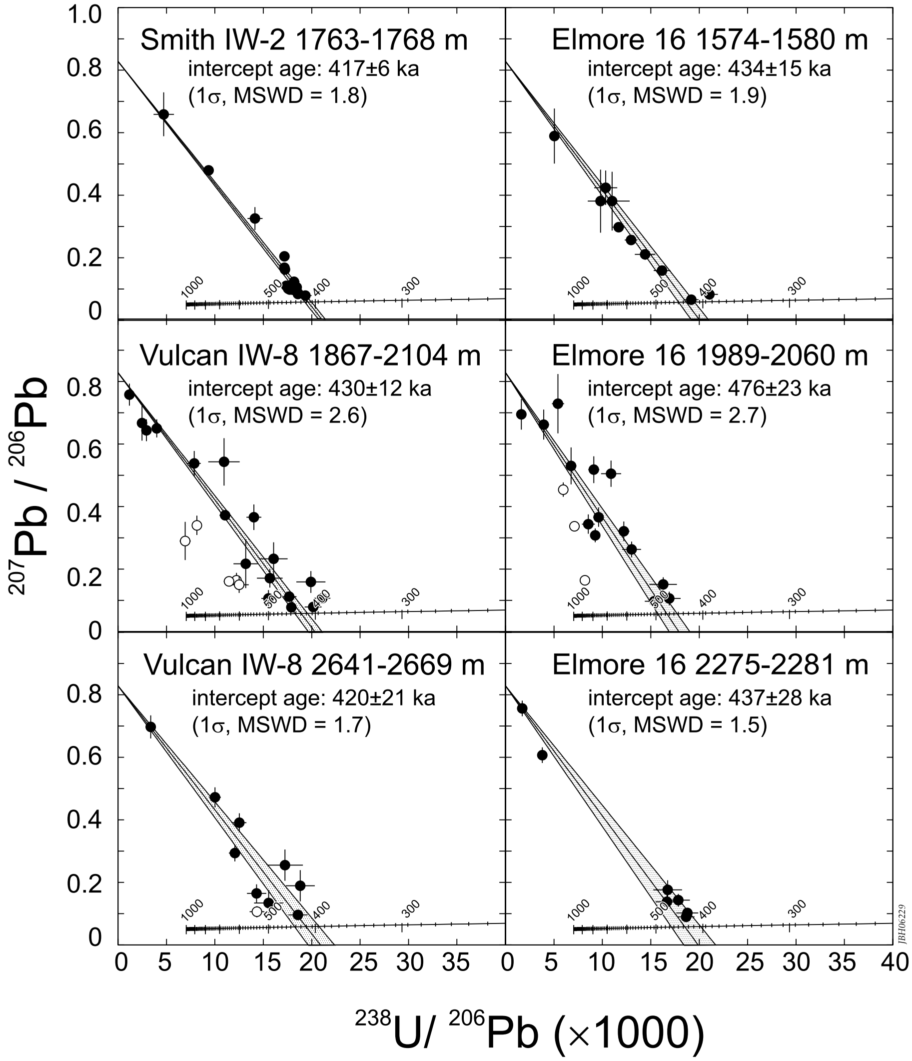

Figure 2. $^{207}Pb/^{206}Pb$ vs. $^{238}U/^{206}Pb$ ("Tera-Wasserburg") diagram with zircon results for subsurface rhyolites from the Salton Sea geothermal field (open symbols = older grains excluded from regression).

Previous Age Determinations

Four small-volume rhyolite flow/domes collectively known as the Salton Buttes crop out in the central portion of the SSGF (Figure 1). Scattered but young K-Ar age dates (between 33 ± 18 ka and <10 ka) were previously reported for Salton Buttes rhyolite samples (Muffler and White, 1969; Friedman and Obradovich, 1981). Obsidian-rind hydration ages for the same lavas are at the lower end of this age spectrum, but were also highly variable—between 2.5 and 8.4 ka (Friedman and Obradovich, 1981). Other age-dating attempts focused on xenoliths hosted by Salton Buttes flow/dome rocks: granophyric xenoliths have been inferred

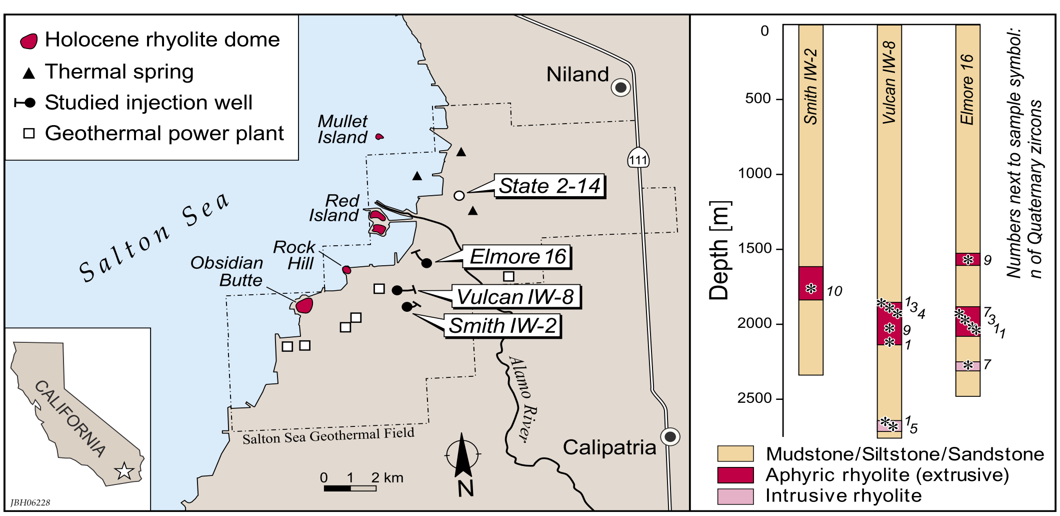

Figure 1. Map of surface rhyolites in the Salton Sea geothermal field (left) and simplified geothermal well logs showing subsurface rhyolite penetrations (right). Sampled intervals of ~3 - 6 m indicated by asterisks.

previously to be Late Quaternary in age based on the lack of detectable radiogenic ^{206}Pb, and K-Ar ages between ~1 and 4 Ma have been reported for basaltic xenoliths (Herzig and Jacobs, 1994).

Over the past several years, one of us (Hulen) has identified and described thick intercepts of hydrothermally altered intrusive and extrusive rhyolite deep (1.6-2.7 km) in at least three central SSGF geothermal wells including Smith IW-2 (Figure 1), the borehole in which the first of these thick older rhyolites was discovered (Hulen and Pulka, 2001). Prior to the present study, direct radiometric dating of these buried rhyolites had not been attempted, but Hulen and Pulka (2001) estimated a ~700 ka age for the Smith IW-2 rhyolite by extrapolating an average sedimentation rate calculated from the inferred occurrence of the 760 ka Bishop ash in well State 2-14 (Figure 1; Herzig and Elders, 1988), ~5 km to the northeast.

New Age Determinations

Subsurface rhyolites were sampled from three different wells in the SSGF (Smith IW-2; Vulcan IW-8; and Elmore 16; Figure 1). The sampling encompassed the full depth range, 1.6-2.7 km, in which the rhyolites were encountered. The rhyolite intercepts range in apparent thickness from ~100m to ~300 m. The available sample materials were drill cuttings, averaging about 1-3 mm in diameter, collected during drilling at intervals of ~3 m. Depending on the mass of available cuttings, one or two of these samples (between 10 and 200 g) were used for zircon separation. Due to sample-material limitations, the crystal-poor nature of the SSGF subsurface rhyolites, and frequent contamination by zircons derived from wall-rock fragments in the cuttings, the yield of magmatic zircon was generally poor (<10 zircons per individual sample). Because zircon ages for multiple depth intervals within a continuous section lack significant differences, and because replicate analyses on individual grains reproduced well (suggesting intra-grain homogeneity within limits of detection), we elected to combine spot analyses for individual sections (Figure 2). Due to the very young ages of SSGF zircons, the concordia curve in Figure 2 is corrected for initial disequilibrium (^{230}Th-deficit). Average zircon crystallization ages are obtained from the concordia intercept of the regression line through a common-Pb composition typical for anthropogenic laboratory contamination.

Our results yield average zircon crystallization ages between 417 ± 6 ka and 476 ± 23 ka (1σ). Two intrusive rhyolite sections in the deeper parts of wells Vulcan IW-8 and Elmore 16 yield overlapping ages of 420 ± 21 ka and 437 ± 28 ka, respectively. Despite the close agreement in average zircon U-Pb ages, there is evidence in some samples for age variability beyond analytical uncertainties, and individual zircon grains ~100 - 200 ka older than the main population are present.

In the case of the surface rhyolites of Salton Buttes, we collected two samples at the Obsidian Butte and Red Island locations for zircon extraction (Figure 1). In addition, two granophyre xenoliths, two basaltic xenoliths, and a xenolith of a previously unrecognized, fine-grained rhyolite with preserved spherulitic textures (for simplicity named "felsite") hosted by Salton Butte lavas were included in this study. Zircons from surface lavas and xenoliths proved to be too young to yield meaningful U-Pb ages, but were amenable to U-series disequilibrium dating. The wedge-shaped field for Salton Buttes zircons in the $^{230}Th/^{232}Th$ vs. $^{238}U/^{232}Th$ space (Figure 3) suggests protracted zircon crystallization or mixing between different populations. Best-fit results yield two isochron ages with 12 ± 2 ka and 19 ± 2 ka as upper and lower limits. Zircons from granitic xenoliths, by contrast, fall on a well-defined isochron with a 21 ± 2 ka age (Figure 3). This age is indistinguishable from the older ages for Salton Buttes zircons and the isochron age of zircons from the felsite xenolith (18 ± 4 ka; Figure 3). Interestingly, zircon is present in plagioclase-rich domains within amphibole-bearing basaltic xenoliths, suggesting remelting of altered basalts and subsequent zircon crystallization in pockets of evolved silicic melt. Isochron ages of 30 ± 13 ka and 9 ± 7 ka, respectively, were obtained for basaltic xenolith-hosted zircons (Figure 3).

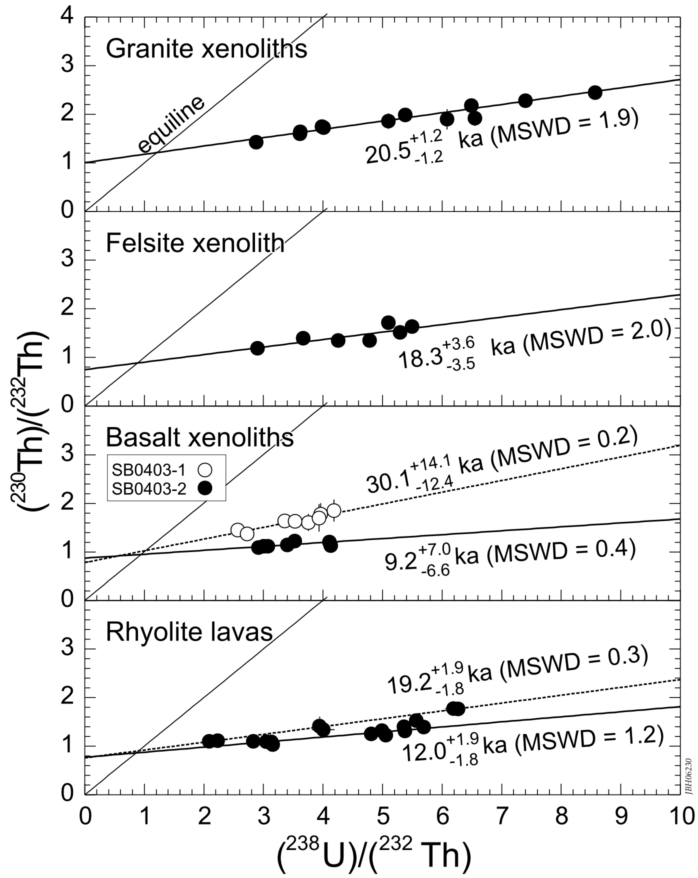

Figure 3. $^{230}Th/^{232}Th$ vs. $^{238}U/^{232}Th$ isochron plots with zircon results for surface rhyolite lavas and xenoliths from the Salton Sea geothermal field.

Significance of Zircon Ages and Implications for the SSGF Thermal History

Our U-Pb results for SSGF Late-Quaternary zircons show that an analytical precision of 2 - 3 % can be achieved under favorable circumstances (i.e., high U-abundance), comparable to K-Ar or Ar-Ar age uncertainties. Moreover, we are confident about the accuracy of our age results because zircon is stable over a wide range of crustal temperatures, including the ~235-400°C now prevailing at drilled geothermal-reservoir depths in the SSGF. As a test for potential Pb-loss or crystal surface reactions, we analyzed the outermost unpolished crystal faces of selected detrital and magmatic zircons to a depth of ~1 μm and subsequently repeated the analysis in the center of the same grains after grinding and polishing. Age results were in excellent agreement, suggesting that U-Pb systematics in zircon grains are robust even for the outermost rims likely to have experienced contact with hydrothermal fluids. K-Ar methods, by contrast, frequently fail to yield reliable primary magmatic crystallization ages for igneous rocks hosted by active geothermal systems (e.g., Schmitt et al., 2003), despite continued application of this method (e.g., Villa et al., 2006).

U-Pb closure in zircon at above-solidus temperatures is of great value because information on source rocks, assimilation, earlier episodes of magmatic zircon crystallization, or recycling of crystals from precursor intrusions may be extractable from the zircon record. By the same token, zircon ages may significantly predate the eruption of a magma. In fact, the agreement between the older ages for Salton Butte zircons and granitic xenoliths suggests that crystals in the rhyolite lavas became recycled from Late-Quaternary plutonic sources. By analogy, we hypothesize that the variability in some of the U-Pb ages of the subsurface rhyolites is due to recycling of zircons from yet to be recognized plutonic sources. In this context, it is also important to point out that pre-Quaternary zircons are scarce in surface rhyolite lavas (<10 %) and absent in granitic xenoliths. This underscores evidence from Nd- and Sr-isotopic data (Herzig and Jacobs, 1994) that a major role of basement granitoid or sediment melting can be dismissed for the origin of SSGF surface rhyolites and associated granites. Instead, remelting of young basaltic crust is a viable mechanism for producing SSGF silicic magmas.

Zircon crystallization ages constrain an upper boundary on the eruption ages for surface and subsurface rhyolite lavas in the SSGF. In the case of the Salton Buttes, our dates place a more tightly defined age limit on the eruptions compared to published K-Ar dates. This limit (<10 ± 1 ka) agrees within uncertainty with the oldest obsidian-rind hydration age (8.4 ± 1.6 ka; Friedman and Obradovich, 1981). We therefore strongly favor an early Holocene eruption age for the Salton Buttes. The short lag time (<8 ka) between zircon crystallization and eruption suggests that zircon crystallization ages may also be a reasonable proxy for the eruption age of the subsurface rhyolites. The caveat is that subsurface rhyolites contain zircons ~100 - 200 ka older than average zircon crystallization ages. Thus, magmatic zircon provenance may be more complicated in the subsurface rhyolites compared to the Salton Buttes lavas. For example, average zircon crystallization ages in two sections of buried extrusive rhyolite in well Elmore 16 differ by ~40 ka, consistent with their stratigraphic positions but with overlapping uncertainties. Caution is therefore required in extrapolating eruption ages from zircon crystallization ages, and we consequently infer maximum emplacement ages for subsurface rhyolites that are in the order of ~420 - 480 ka. Because subsurface rhyolite lavas with their pyroclastic carapaces (Hulen and Pulka, 2001) are now buried beneath 1.5 - 2 km of sediment, high average sedimentation rates of as much 4 mm/yr can be inferred for the central portion of the SSGF. If the implied, 2.4 mm/yr sedimentation rate for the State 2-14 site is realistic, then the center of the SSGF over time has subsided nearly twice as fast as the northern sector of the field.

In summary, two major implications with regard to the thermal evolution of the SSGF have emerged from our study: (1) a ~30 ka to Holocene age for the youngest identified plutonic proxies (granophyre and intrusive-rhyolite xenoliths; remelt pockets in basaltic xenoliths) for the Salton Buttes indicates that in the region of the Buttes, igneous intrusions are directly linked to the prograde heating observed in shallow portions of the SSGF today (see also Norton and Hulen, 2006, this volume). (2) Voluminous rhyolitic magmatism undoubtedly occurred here at ~450 ka. At that time, the Salton Trough sedimentary sequence at this location was only about two-thirds as thick as it is now. Nonetheless, beneath the older extrusive rhyolites at ~450 ka, that sequence was already being affected by magmatic-hydrothermal processes linked to cooling felsic plutons.

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