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(U-Th)/He zircon and archaeological ages for a late prehistoric eruption in the Salton Trough (California, USA)

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ABSTRACT

U-Th and (U-Th)/He zircon geochronology redefines the timing of volcanic activity in the Salton Trough (Southern California, USA), the subaerial extension of the incipiently oceanic Gulf of California. U-series disequilibrium corrected (U-Th)/He zircon analyses for a granophyre ejecta clast from the Red Island rhyolite dome indicate an eruption age of 2480 ± 470 a (calendric dates between 0 and 940 Before Common Era, BCE; error at 95% confidence). This eruption age is supported by U-Th zircon crystallization ages for two obsidian-bearing lavas: Red Island (the host for the granophyre) and Obsidian Butte, a prehistoric quarry for obsidian that is widely distributed in southern California and northern Mexico archaeological sites. Lavas and granophyre display overlapping zircon crystallization age distributions that support field and compositional evidence that they are cogenetic and contemporaneous. The (U-Th)/He eruption age is younger and significantly more precise than previous ages for these volcanoes, and is the first indication that the eruption of obsidian flows coincided with human presence in the region. A late prehistoric eruption age agrees with the absence of the Obsidian Butte lithic source among early prehistoric cultural artifacts, previously attributed to submergence of the quarry location during hypothesized persistent flooding by ancient Lake Cahuilla.

INTRODUCTION

Volcanic chronostratigraphy is essential in understanding the timing of human origins, migration, and exchange. Radiometric dating of volcanic rocks down to the historical realm is possible in favorable cases by K-Ar (^{40}Ar/^{39}Ar) geochronology (e.g., the 79 CE [Common Era] eruption of Vesuvius, Italy; Renne et al., 1997; Lanphere et al., 2007), but often accuracy is compromised by excess ^{40}Ar, parent-daughter mobility, or diffusive fractionation of ^{40}Ar/^{36}Ar (e.g., Cerling et al., 1985; Esser et al., 1997; McDougall and Harrison, 1999; Morgan et al., 2009; Flude et al., 2010).

(U-Th)/He geochronology of zircon, as one of the first radiometric dating techniques (Strutt, 1908), has had a revival as a thermochronometer, but it is equally suitable for rapidly cooled volcanic rocks without subsequent thermal disturbance (e.g., Tagami et al., 2003; Davidson et al., 2004; Schmitt et al., 2006; Blondes et al., 2007). Compared to K-Ar (^{40}Ar/^{39}Ar) geochronology, it offers the advantages of reduced excess ^{4}He due to rapid diffusion (Reiners et al., 2004), high daughter isotope production rates (^{4}He/^{40}Ar >20 per parent nucleus), and negligible atmospheric contamination (air Ar/He ~2000). Its application, however, has been limited by U-series disequilibrium effects, which, in the case of youthful zircon, typically cause severe age underestimation (Farley et al., 2002). To overcome this limitation, a novel combined U-Th ion microprobe crystal rim analysis and (U-Th)/He bulk crystal degassing analysis technique has been developed (to equal extent at the University of California, Los Angeles [UCLA] by Schmitt and Lovera, and at the University of Kansas by Stockli). Here we apply this technique to document an eruption in the Salton Trough (Southern California, United States) as recently as 0–940 BCE (Before Common Era). This age overlaps with human occupation of the Colorado Desert and adjacent regions, and agrees with the late onset of obsidian use from the Obsidian Butte resource in the Salton Trough (e.g., Schaefer and Laylander, 2007).

VOLCANISM IN THE SALTON TROUGH

The Salton Buttes together with Cerro Prieto and Roca Consag are morphologically the most pristine volcanoes in the northern Gulf of California and Salton Trough rift zone (Fig. 1). They form an ~7-km-long, northeast-southwest–trending lineament of 5 rhyolite domes (<1 km in diameter) along the dilatational San Andreas–Imperial fault step-over, immediately north of the active Brawley seismic zone (Fig. 1). The two largest domes are Red Island and Obsidian Butte; they consist of aphyric, glassy to devitrified rhyolite lava with rare oligoclase-anorthoclase phenocrysts surrounded by remnants of pyroclastic deposits. Where lavas developed obsidian textures, they were extensively quarried for production of lithic tools during late prehistoric and early post-Columbian time (Treganza, 1942; Hughes and True, 1985; Koerper et al., 1986; Schaefer and Laylander, 2007). They also contain diverse xenoliths comprising unconsolidated sediment, metasediment, basalt, and granophyre (Robinson et al., 1976; Schmitt and Vazquez, 2006). Granophyre xenoliths are leucocratic and phaneritic with interstitial glass. Their radiogenic and oxygen isotopic compositions demonstrate that they are cogenetic with the rhyolite host, and derived from remelting of juvenile mafic crust in an incipient oceanic spreading center (Schmitt and Vazquez, 2006), analogous to other transform fault–bounded rift segments within the Gulf of California (e.g., Lizarralde et al., 2007).

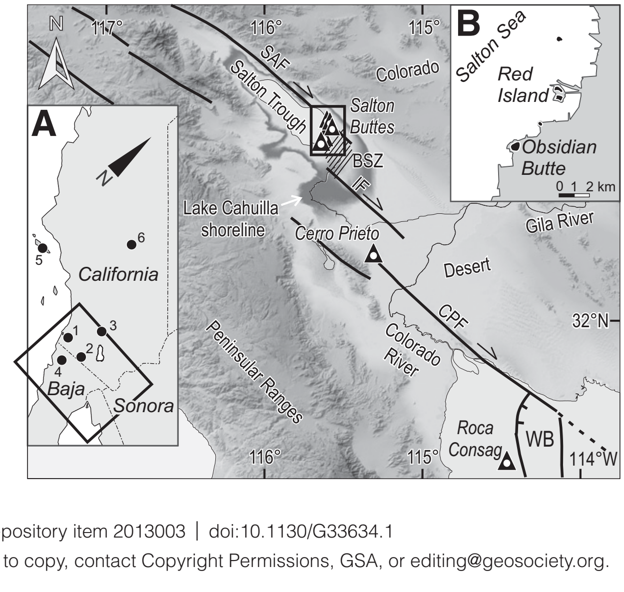

Figure 1. Map of northern Gulf of California (United States) and Salton Trough showing Quaternary volcanoes (triangles) and major faults (solid lines; SAF—San Andreas; IF—Imperial; CPF—Cerro Prieto). Maximum extent of Pleistocene–Holocene Lake Cahuilla (i.e., fill line at 12 m above sea level) is indicated (after Brothers et al., 2011). BSZ—Brawley seismic zone; WB—Wagner Basin. Inset A shows study region with archaeological locations (1—San Diego; 2—Anza-Borrego; 3—Coachella Valley; 4—Zaragoza, 5—Channel Islands; 6—Coso). Inset B details locations for Salton Buttes domes (red).

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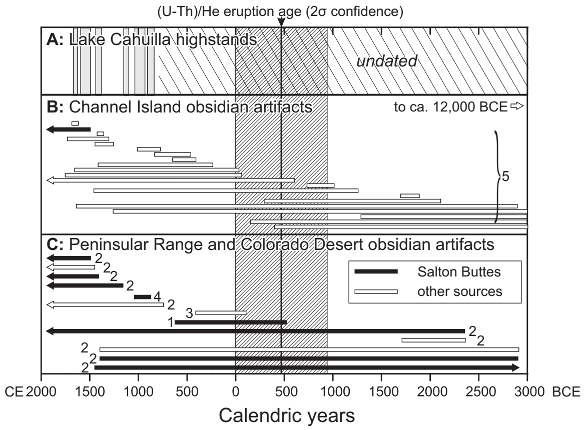

Figure 2. Comparisons with Red Island (U-Th)/He eruption age. A: ^{14}C-dated Lake Cahuilla (California) highstands (boxes; Philibosian et al., 2011). B: Obsidian artifacts from Channel Island. C: Peninsular Ranges and Colorado Desert sites. Artifact ages are calibrated ^{14}C calendar ages (2σ) from same stratum or section shown as exact or bracketing (bars), maximum (left arrows), or minimum (right arrows) ages. BCE—Before Common Era. Solid bars—Obsidian Butte; open bars—undifferentiated sources (Table DR3; see footnote 1). Numbers indicate references for archaeological data (locations in Fig. 1): 1—Kyle (1996); 2—McDonald (1992); 3—Love and Dahdul (2002); 4—Porcayo-Michelini (2006); 5—Rick et al. (2002), Erlandson et al. (2011).

PREVIOUS ERUPTION AGE CONSTRAINTS

Geological Ages

The most commonly cited age for Salton Buttes is 33 ± 35 ka (Friedman and Obradovich, 1981), which supersedes an earlier K-Ar age of ca. 16 ka reported in Muffler and White (1969). Obsidian hydration dating, now discredited (e.g., Anovitz et al., 1999), yielded surface exposure age estimates of 8.4 and 6.7 ka for Obsidian Butte and 2.5 ka for Red Island (Friedman and Obradovich, 1981). The emplacement of the Salton Buttes also closely relates to the chronology of cyclic flooding and desiccation of the Salton Trough. Flooding resulted from episodic northward diversion of the Colorado River, creating ephemeral lakes (ancient Lake Cahuilla) as natural precursors to the modern Salton Sea. Seismically detected sequences of coarse-grained deltaic sediment intercalated with lake deposits imply that at least in some instances the basin desiccated entirely prior to inundation (Brothers et al., 2011). Subaqueous pumice deposits, wave-cut benches, and raft zones of reworked pumice (Kelley and Soske, 1936; Robinson et al., 1976) indicate emplacement prior to the ca. 1650 CE desiccation of Lake Cahuilla (Philibosian et al., 2011; cf. Waters, 1983).

Archaeological Ages

Obsidian sourced from Obsidian Butte is distributed in the southwestern United States and northern Mexico, and in some cases has been documented at distances of 400–500 km from its source (e.g., California Channel Islands; Rick et al., 2002). Because the earliest use of this obsidian constrains a minimum age for Obsidian Butte, we have compiled ^{14}C ages concentrating on sites that preserve a protracted record of human presence. This includes proximal locations in the Colorado Desert, the Peninsular Ranges of southern California and northern Baja California, as well as distal sites in coastal California (Fig. 2). The earliest reliable artifact sourced at Obsidian Butte (Fig. 2) dates between ca. 510 BCE and 640 CE (Kyle, 1996). This excludes one putative Obsidian Butte artifact (Elko Eared dart point C9–309; recalibrated ^{14}C age 2350–1700 BCE; McDonald, 1992), which we reassigned to an unknown source because its Sr abundance is well below the 2σ limit for Obsidian Butte glass (Hughes, 1986). The conspicuously late onset of Obsidian Butte material preserved in the prehistoric record (Fig. 2) is in accordance with slightly younger ages previously suggested (ca. 940 to ca. 1600 CE; Hughes and True, 1985; Koerper et al., 1986). Older deposits in the region contain abundant obsidian artifacts procured dominantly from the Coso location (Fig. 1). The apparent temporal dichotomy for obsidian provenance from Coso versus Obsidian Butte has previously been explained by inundation of Obsidian Butte with ancient Lake Cahuilla prior to the late prehistoric period (e.g., Hughes and True, 1985; Koerper et al., 1986).

METHODS

Sampling

Several kilograms of lava were collected from outcrops at Red Island and Obsidian Butte (SB-04–01 and SB-04–02; Table 1). Granophyre I70–24 is a 1.5-m-diameter rounded ejecta clast from the southern Red Island dome (Table 1; see Robinson et al., 1976, their figure 5). All sampling locations were disturbed by 20th century quarrying, and lack evidence for a prehistoric lithic industry in the immediate vicinity. Abundant obsidian artifacts, however, occur as scattered surficial deposits in less disturbed areas of Obsidian Butte.

Analytical Procedures

Granophyre zircons were targeted for (U-Th)/He dating because they are more abundant and larger than those in coerupted lavas. Moreover, their (mostly) late Pleistocene crystallization ages obviate the need for ^{226}Ra disequilibrium corrections (Farley et al., 2002). Zircon was separated from ~150 g rock powder (<250 µm) using heavy liquids and hand-picked to select largely inclusion-free and intact euhedral crystals, which were pressed into indium metal flush with the mount surface for multicollection U-Th analysis using the CAMECA IMS 1270 ion microprobe at UCLA. After ~5-µm-deep ion sputtering of the crystal rims, grains were extracted from their mount, photographed, and wrapped in platinum foil for (U-Th)/He analysis. Separate aliquots were analyzed by isotope dilution with a quadrupole mass spectrometer at the University of Kansas and by peak height comparison with a pulse counting sector mass spectrometer at the California Institute of Technology. U-series disequilibrium corrections for (U-Th)/He include preeruptive magmatic residence (from U-Th zircon rim crystallization ages), and zircon-melt partitioning for Pa and U (D_{Pa}/D_U = 3; Schmitt, 2007). For comparison

TABLE 1. (U-Th)/He ZIRCON AGE SUMMARY FOR RED ISLAND GRANOPHYRE EJECTA CLAST I70–24

	(U-Th)/He age* (yr)	±	MSWD	(U-Th)/He age† (yr)	±	MSWD	n	U§ (ppm)	Th/U§	Mass§ (µg)	U-Th crystallization age** (yr)
Lab 1 (Caltech)	1440	500	3.2	2280	780	3.2	11	205–471	0.59–0.73	6.2–37	20000–37900
Lab 2 (KU)	1620	260	0.85	2650	600	2.2	16	143–1898	0.55–0.90	7.5–31	2980–34000
Combined	1520	260	1.8	2480	470	2.6	27	143–1898	0.55–0.90	6.2–37	2980–37900

Note: MSWD—mean square of weighted deviates; n—number of replicate crystals; Caltech—California Institute of Technology; KU—University of Kansas. All uncertainties 2σ (analytical) multiplied with square root of MSWD; sampling location N33°11′51.3′, W115°36′44.2″ (Robinson et al., 1976).

*U-decay series equilibrium.

†Corrected for U-series disequilibrium.

§Minimum–maximum.

**Rim ages determined at University of California–Los Angeles.

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with ^{14}C chronology, absolute (U-Th)/He ages were subtracted from the 2010 analysis date to yield calendric years (Fig. 2).

DATING RESULTS

Uncorrected for U-series disequilibrium, the average (U-Th)/He zircon age for Red Island granophyre I70–24 is ca. 1.6 ka (Table 1). U-series disequilibrium corrections (Farley et al., 2002) increase this age to 2.48 ± 0.47 ka (mean square of weighted deviates, MSWD = 2.6; n = 27; Table 1), or between 940 and 0 BCE in calendric years (at 95% confidence; Fig. 2). Error propagation includes uncertainties from ^{4}He, Th, and U isotope dilution analysis, morphometric measurements required for the α-ejection correction, and rim crystallization ages. The slightly elevated MSWD for the population, however, suggests a remainder of unaccounted error. We attribute this to internal zonation of the crystals, both with regard to age and U and Th abundance, which would affect disequilibrium and α-ejection corrections, respectively. Although it is conceivable to better constrain internal zonation through ion microprobe depth profiling, the lengthy analysis would make this impractical for a large number of crystals. We instead analyzed multiple crystals, rationalizing that this will empirically account for variations in crystallization ages and U and Th abundance. Excess scatter resulting from unaccounted analytical error is propagated by multiplying the weighted average age uncertainty with the square root of the MSWD (Table 1).

U-Th zircon rim crystallization ages for granophyre I70–24 (Fig. 3; Table DR1 in the GSA Data Repository[1]) display significant variations ranging from near eruption to ~30,000 a (MSWD = 25). The average rim crystallization age is 26.2 ± 1.0 ka (MSWD = 2.4; n = 35), with the exception of two younger rims, one of which overlaps with the (U-Th)/He eruption age (Fig. 3). The U-Th zircon crystallization ages in both lavas are statistically indistinguishable (Kolmogorov-Smirnov probability of equivalence = 0.55), but their overall age range exceeds analytical uncertainties, as indicated by the elevated MSWD for the population (MSWD = 3.2; n = 51). Unmixing models (Sambridge and Compston, 1994) deconvolve the U-Th crystallization age spectrum into 2 age peaks at 5.5 ± 1.2 ka and 12.1 ± 1.8 ka at subequal abundance (Fig. 3). The precision of individual crystal ages, however, is insufficient to distinguish discrete crystallization pulses versus continuous crystallization over this time interval. Regardless, the results from the unmixing model imply that a significant zircon population in both lavas continued to crystallize in the magma until immediately before the eruption.

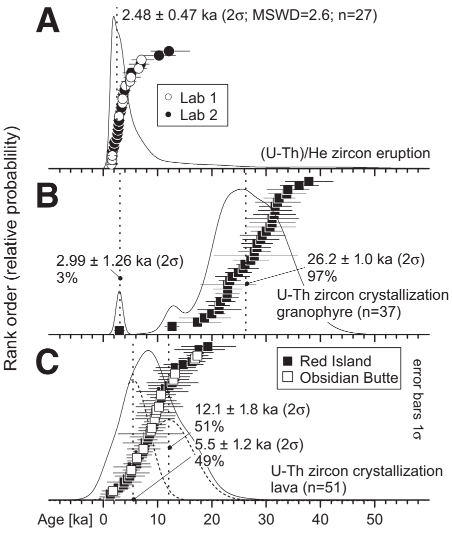

Figure 3. A: Rank-order and relative probability plots for (U-Th)/He zircon ages from Red Island (California) granophyre I70–24. MSWD—mean square of weighted deviates. B: U-Th crystallization ages from two-point zircon–whole-rock isochrons for granophyres. C: U-Th crystallization ages for lava samples. Gaussian curves in C indicate subpopulations from unmixing models. Lab 1—California Institute of Technology; Lab 2—University of Kansas.

DISCUSSION

Eruptive and Intrusive Activity in the Salton Trough

Because rapid cooling is expected after surficial emplacement of the granophyre xenolith in its host lava, the (U-Th)/He zircon age is reasonably interpreted to date the eruption of Red Island dome. The (U-Th)/He zircon eruption age is fully consistent with the U-Th crystallization ages, lending independent support to its accuracy. Both are younger than K-Ar ages. This is possibly due to excess ^{40}Ar in volcanic glass, whereas we do not expect excess ^{4}He in zircon due to rapid ^{4}He diffusion at magmatic temperatures undergone by the granophyre prior to eruption. Coincidentally, Red Island obsidian hydration ages agree with the (U-Th)/He age, but we refer to Anovitz et al. (1999) for a discussion of fundamental problems inherent to this method.

The similarity in U-Th crystallization ages for volcanic and plutonic samples implies that they collectively represent protracted zircon crystallization in a long-lived (relative to the time since the eruption) and hence potentially active magma reservoir. This commonality is underscored by zircon oxygen isotopic and trace element affinities between lavas and granophyres (Schmitt and Vazquez, 2006). Although the (U-Th)/He eruption age is strictly for Red Island, the similarity in composition and U-Th crystallization ages for Red Island and Obsidian Butte is permissive for both being coevally emplaced, in accordance with the notion that the Salton Buttes share a fault-controlled feeder dike at depth (Robinson et al., 1976).

Obsidian Cultural Availability and Holocene Lake Cahuilla

The (U-Th)/He zircon geochronology is a novel Quaternary dating tool, and although its application to archaeological samples is restricted by the destructive nature of crystal extraction from comparatively large samples (in particular for aphyric obsidian), it has potential for volcanic chronostratigraphy in an archaeological context. The young eruption age for Red Island is concordant with archaeological evidence for an exclusively late prehistoric (sensu lato) use of the Obsidian Butte lithic resource (Fig. 2). Under the assumption that "Obsidian Butte glass has been around for a long time" (Hughes and True, 1985, p. 329), the absence of Obsidian Butte artifacts in older deposits has been previously attributed to the persistent presence of ancient Lake Cahuilla, which would have submerged the lavas below nearly 80 m of water during its highstands (e.g., Hughes and True, 1985). A much more recent eruption age for Obsidian Butte, as proposed here, can explain this absence and obviate the need to postulate continuous inundation, a hydrologic pattern that would depart from frequent lake desiccation and filling cycles that have been documented for the past ~2000 a (Waters, 1983; Philibosian et al., 2011; Brothers et al., 2011).

CONCLUSIONS

By combining (U-Th)/He and U-Th zircon geochronology, we have dated quasi-continuous late Pleistocene to Holocene intrusive activity in the Salton Trough that culminated in explosive and effusive eruption of rhyolite at 2.48 ± 0.47 ka (between 940 and 0 BCE). The (U-Th)/He zircon eruption age for Red Island is one of the youngest in southern California, overlapping within uncertainty the phreatomagmatic eruption of Ubehebe Crater in Death Valley (Sasnett et al., 2012). It is the first reliable evidence that the Salton Trough has been recently volcanically active, overlapping with human presence in the Colorado Desert. Protracted zircon crystallization ages indicate magmatic longevity and imply potential for future activity. The consistency of combined U-Th and (U-Th)/He zircon chronology with archaeological ages for obsidian use underscores that this method has strong potential for Quaternary volcanic chronostratigraphy and archaeometry.

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[1] GSA Data Repository item 2013003, Table DR1 (U-Th analyses), Table DR2 [(U-Th)/He zircon analyses of Red Island granophyre], and Table DR3 (^{14}C age compilation for Obsidian Buttes artifacts), is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

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