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Skarn fluid sources as indicators of timing of Cordilleran arc emergence and paleogeography in the southwestern United States

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ABSTRACT

Oxygen isotope ratios of garnet provide well-established means to investigate crustal fluid histories. Traditionally, $\delta^{18}O$ values from skarn garnets have been used to track the hydrothermal evolution of an individual skarn body through time. We, however, use garnet from 14 skarns from the Jurassic (ca. 175 to ca. 148 Ma) Cordilleran margin arc (southwestern United States) to provide regional tectonic context to arc magmatism and hydrothermal activity. We document arc-wide garnet $\delta^{18}O$ variability of ~19‰ (–8.9‰ to +10.3‰, n = 159), providing a record of contrasting meteoric fluid ingress between northern (Sierra Nevada) and southern (Mojave Desert) arc segments. Strongly negative garnet $\delta^{18}O$ values (≤–3‰) are limited to the Mojave Desert arc segment and can only form in the presence of meteoric fluid, requiring shallow formation in subaerial crust. When combined with U-Pb garnet ages, the $\delta^{18}O$ data provide a minimum radiometric age of local subaerial arc emergence and temporal constraint on the migration of the Jurassic paleoshoreline in the Mojave Desert section of the arc.

INTRODUCTION

Skarns represent hydrothermally driven exchange of major elements (e.g., Si, Al, Fe, Ca) and trace elements (e.g., Zn, Cu, W) across chemical potential gradients at the interface of crystallizing magmas and carbonate bodies. Such exchange reactions liberate CO_2 and locally increase permeability, which focuses fluid flow and promotes further metasomatism (Bowman, 1998). The focused nature of flow generally limits skarns to volumetrically minor veneers between reactive rock types, but they are common in the crust where magmatic activity elevates geothermal gradients (e.g., Lee and Lackey, 2015; Ramos et al., 2020). Early-stage skarn domains are typified by calcic garnet, clinopyroxene, and wollastonite, whereas later-stage reactions produce hydrous minerals (e.g., epidote, amphibole) and endow skarns with base metals (Einaudi et al., 1981; Meinert et al., 2005). Physical resistance, refractory nature, and conspicuous growth zoning make skarn garnet an exceptional recorder of fluid compositions, particularly when oxygen isotope ratios ($\delta^{18}O$) are used to decipher fluid sources, which are dictated by tectonics and depths of intrusion (Jamtveit and Hervig, 1994; Crowe et al., 2001; Clechenko and Valley, 2003; D'Errico et al., 2012; Ryan-Davis et al., 2019). Because garnet generally grows early in skarns, the $\delta^{18}O$ values of such garnet preserve a snapshot of the hydrothermal conditions at the interface between plutons and their host rocks. Moreover, U-Pb geochronology of andradite-rich garnet (Seman et al., 2017; Gevedon et al., 2018) provides temporal constraints on skarn-forming conditions.

We combine garnet U-Pb ages and $\delta^{18}O$ values from 14 skarn systems along ~600 km of the Jurassic Cordilleran margin arc (southwestern United States; Fig. 1), highlighting contemporaneous lateral differences and emplacement conditions spanning ~25 m.y. of the Jurassic. The combined data provide constraints on the timing of local subaerial emergence in the arc section in the western Mojave Desert, which has implications for the timing of paleoshoreline retreat. Data indicate that regional patterns of skarn garnet $\delta^{18}O$ values provide insight into the prevailing conditions (e.g., relative depth, tectono-magmatic regime, paleogeography) at the time of pluton emplacement and peak hydrothermal activity in the crust.

GEOLOGIC SETTING AND BACKGROUND

The Jurassic was a critical period in the development of the North American Cordillera, with profound changes in tectonic style modulating magmatism and causing major changes to the paleogeography of the continental margin (Dickinson and Gehrels, 2010). Paleogeographic insight in particular benefits from studies of remnant calderas and intra-arc basins formed in a trans-arc graben system (Fig. 1; Busby-Spera, 1988; Busby, 2012). These caldera-basin settings are irregularly exposed along the ~1200-km-long arc-graben system in the Sierra Nevada and Mojave Desert and record subaqueous to subaerial deposition that chronicle the emergence of the Jurassic margin (Fig. 2; Schermer and Busby, 1994; Busby, 2012); however, the record is fragmental. In addition, extension during the latest Jurassic, shown by the age and footprint of the Independence dike swarm (ca. 148 Ma; Chen and Moore, 1982), is considered to be the result of geographically extensive transtensional tectonics that further modified the margin (Chen and Moore, 1982; Carl and Glazner, 2002). Paleobarometric constraints applied to the Independence dike swarm suggest differing intrusion levels are exposed across the arc (e.g., Glazner et al., 2008), with greater depths of exposure in the Sierra Nevada region compared to shallow and near-surface levels seen in Middle to Late Jurassic caldera systems in the Mojave Desert (Schermer et al., 2002). Though promising for their paleogeographic records, the central Mojave Desert rocks are altered by a shallow, regional (~1000 km^2) hydrothermal system whose duration and timing

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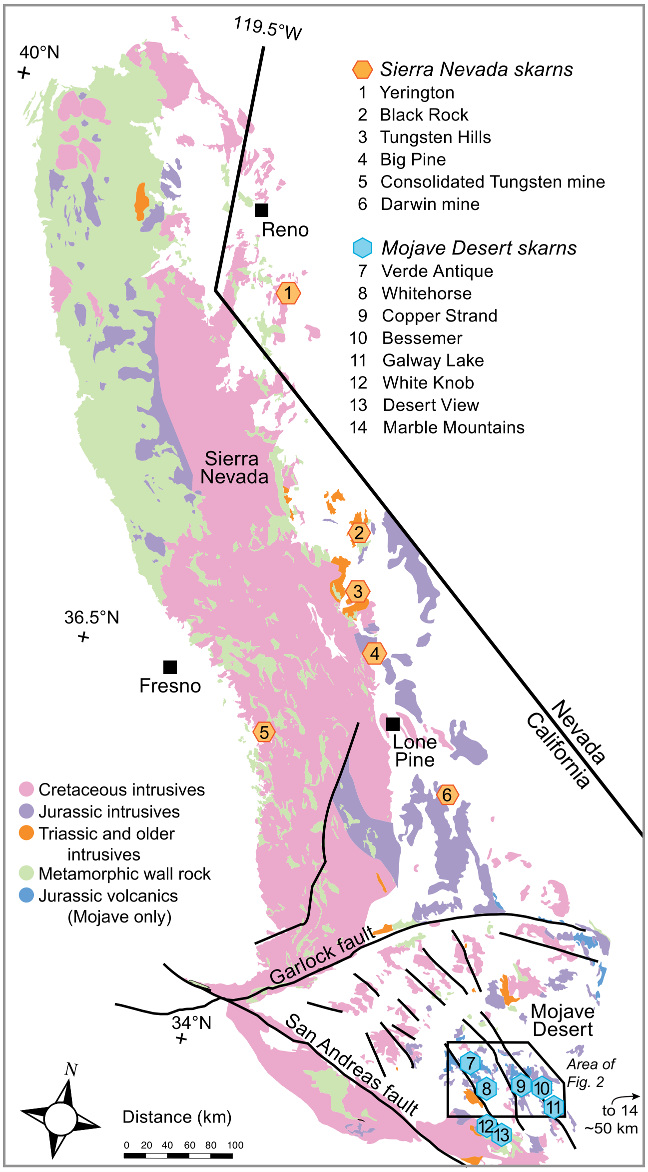

Figure 1. Location map of Mojave Desert and Sierra Nevada (southwestern United States) Jurassic skarn bodies included in this study (after Gevedon et al., 2018, and references therein). Skarn numbers here correspond to those in Figure 3.

are only loosely bound to the Jurassic (Solomon and Taylor, 1991; Fig. 2).

METHODS AND RESULTS

Garnet oxygen isotope data from 14 Jurassic skarns sampled laterally along ~600 km of the arc are paired with geochronologic data to illustrate along-strike variety among arc hydrothermal systems as controlled by tectonics. Garnet $\delta^{18}O$ values were measured by laser fluorination at the University of Texas at Austin (USA). Garnet from three skarns were U-Pb dated using the laser ablation–inductively coupled plasma–mass spectrometer (LA-ICP-MS) at Pomona College (Claremont, California) and combined with four skarn garnet ages from Gevedon et al. (2018). Zircon U-Pb ages of 22 plutons in the Mojave Desert and one in the Sierra Nevada were measured by LA-ICP-MS at the University of California Santa Barbara (USA) to provide additional skarn age context (see the Supplemental Material[1] for method details, and Tables S1 and S2 therein for all data).

Garnet $\delta^{18}O$ values from skarns we studied span ~19‰ (–8.9‰ to +10.3‰, $n = 159$; Fig. 3; Table S2). To our knowledge, this work constitutes the largest compilation of skarn garnet oxygen isotope data measured to date and includes some of the lowest skarn garnet $\delta^{18}O$ values observed globally (e.g., Crowe et al., 2001; Ryan-Davis et al., 2019). Negative $\delta^{18}O$ values are restricted to the Mojave Desert segment of the Jurassic arc (Figs. 2 and 3). Skarn garnet U-Pb ages from ^{18}O-depleted areas generally match the ages of neighboring plutons. New U-Pb zircon ages define a mid-Jurassic magmatic peak (ca. 175–162 Ma) and another in the Late Jurassic (ca. 152–148 Ma) (Fig. 2; Table S1, Fig. S1), typical of Jurassic plutonism in the arc (e.g., Barth et al., 2017). Zircon U-Pb ages of the ^{18}O-depleted Mojave Desert arc segment plutons confirm they are coeval with the Mojave Desert skarns, and unaltered plutons are confirmed to be Cretaceous (ca. 78 Ma) (Fig. 2; Solomon and Taylor, 1991; Table S1). Late Jurassic (ca. 152–148 Ma) skarns in the Mojave Desert, Tungsten Hills, and the Big Pine skarn are useful for examining fluid sources and flow in the crust during Independence dike swarm intrusion (Figs. 1 and 3; see Table S1 for ages of Tungsten Hill gabbro and Big Pine skarn garnet), whereas mid-Jurassic skarns are critical for understanding the timing of arc emergence.

DISCUSSION

Patterns in Skarn Garnet $\delta^{18}O$ Values: Sierra Nevada and Mojave Desert Arc Segments

Skarn garnet $\delta^{18}O$ values are largely controlled by fluid composition. Primary skarn garnet values commonly reflect the composition of their adjacent plutons (e.g., Bowman, 1998) typified by values between ~+4‰ and ~+9‰ (Meinert et al., 2005). Skarns with high ratios of fluids derived from dehydration and/or decarbonation of wall rocks results in garnet enriched in ^{18}O relative to its causative intrusions. Alternatively, influx of meteoric fluids and/or seawater in the early stages of skarn formation drives garnet $\delta^{18}O$ values toward 0‰; however, only the predominance of meteoric fluids can produce strongly negative garnet $\delta^{18}O$ values (≤–3‰). Variable conditions of emplacement and skarn formation parameters (e.g., wall rock ratio, composition, and heterogeneity, permeability, and evolving fluid budgets) contribute to isotopic variability in skarn garnets and can impart patterns of zoning that are meaningful for interpreting fluid histories (e.g., Jamtviet et al., 1993; Crowe et al., 2001; Ryan-Davis et al., 2019).

The ~19‰ range in garnet $\delta^{18}O$ values from this study and patterns of $\delta^{18}O$ ratios within that range provide information about these Jurassic skarn-forming paleo–hydrothermal systems. The Jurassic skarns of the Sierra Nevada yield a high and narrow range of $\delta^{18}O$ values (Fig. 3), many falling in the range expected for magmatic water (Bowman, 1998). For instance, despite formation during a period of transtension, garnet from 26 samples in five skarns of the Tungsten Hills (Figs. 1 and 2) records a narrow $\delta^{18}O$ range of +4.8‰ to +6.6‰ (mean +5.7‰ ± 0.75‰, two standard deviations) and little evidence of zonation within grains (Table S2), indicating a primarily magmatic fluid source (Fig. 1). Some skarns may occur as thin (1 cm) veneers of garnet and have high $\delta^{18}O$ values, as high as +12‰ (e.g., White Knob), controlled by proximity to

[1]Supplemental Material. A complete description of analytical methods used in this study and tables of all isotopic data. Please visit https://doi.org/10.1130/GEOL.S.14842722 to access the supplemental material, and contact editing@geosociety.org with any questions.

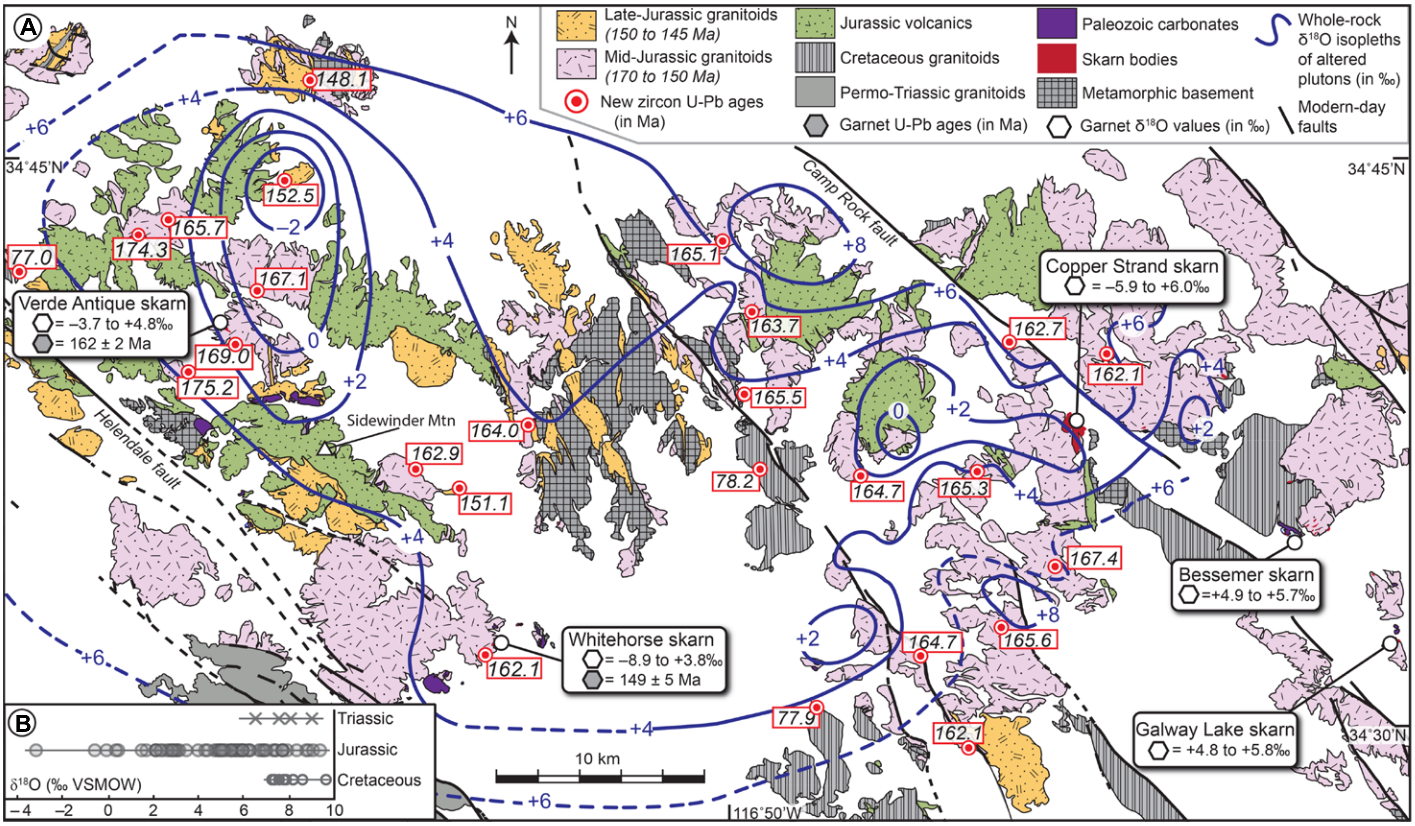

Figure 2. (A) Geology of central Mojave Desert (southwestern United States) and skarns of this study (modified from Walker et al., 2002, and references therein). Jurassic volcanic rocks are preserved in intra-arc basins (after Schermer and Busby, 1994). Contours represent bulk-rock $\delta^{18}O$ isopleths of altered Jurassic plutons (Solomon and Taylor, 1991) and mark the previously recognized regional extent of low $\delta^{18}O$ values. Garnet data extend the low-$\delta^{18}O$ zone to the west. New zircon U-Pb ages correlate to garnet U-Pb ages (Gevedon et al., 2018) and confirm Jurassic pluton alteration and coincident skarn formation. (B) Bulk-rock $\delta^{18}O$ values of Solomon and Taylor (1992). VSMOW—Vienna standard mean ocean water.

their carbonate host. Other skarns record high $\delta^{18}O$ values in garnet cores with decreasing values toward rims, indicating that garnet zonation reflects initial carbonate-dominated metamorphic fluids progressively diluted by magmatic fluids (e.g., Black Rock). Yerington skarn garnet $\delta^{18}O$ values are lower than expected of a magmatic-dominated system and demonstrate how a meteoric or marine fluid influx may expand the garnet $\delta^{18}O$ range in a predominantly igneous-controlled skarn system.

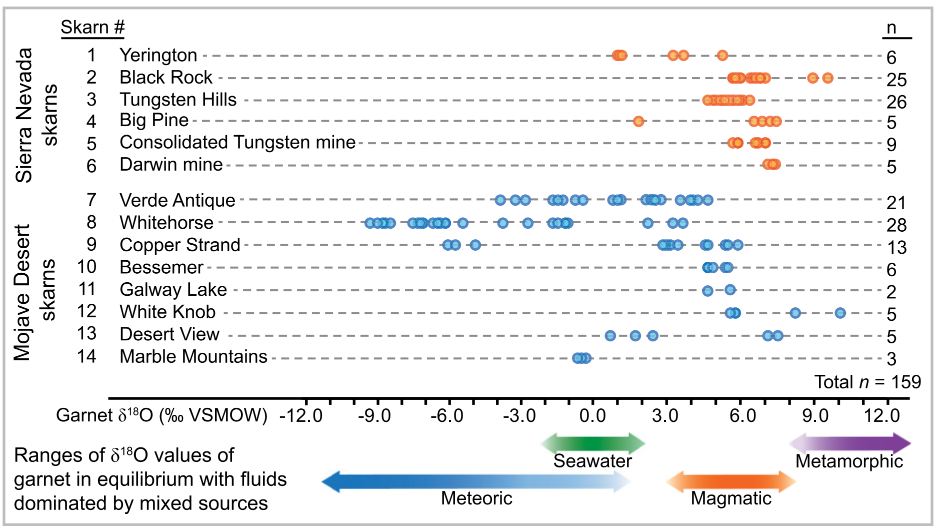

Figure 3. Jurassic skarn garnet $\delta^{18}O$ data. Symbols each mark one laser fluorination analysis. Sierra Nevada (southwestern United States) data suggest mixed magmatic- and metamorphic-derived fluids with a limited range of $\delta^{18}O$ values. Mojave skarn garnet values show mixed fluid sources heavily influenced by surface-derived fluid. VSMOW—Vienna standard mean ocean water.

The strongly negative garnet $\delta^{18}O$ values (<–3‰) of Mojave Desert skarns could only have been formed through interaction with meteoric water during the early stages of skarn formation (Fig. 3), typically between ~300 °C and ~600 °C (e.g., Bowman, 1998). Oxygen isotope fractionations between garnet and water are largest for end-member andradite, yet varying skarn formation temperatures from 300 °C to 600 °C produce at most 1.9‰ zoning in garnet assuming constant $\delta^{18}O$ values of fluid (Clayton et al., 1972; Matthews, 1994; Kohn and Valley, 1998). Observed intra-skarn isotopic ranges between +4.5‰ and +12.7‰ (Fig. 2; Table S2) require mixed fluid sources. Such conditions require that the skarn systems originated at shallow depths within a subaerial crustal column, providing constraints on Jurassic paleogeography.

Skarn Garnet $\delta^{18}O$ as a Record of Pluton Emplacement Conditions

Variation in skarn garnet $\delta^{18}O$ values highlights differences in pluton emplacement conditions and hydrothermal system formation. A lack of low $\delta^{18}O$ values does not inherently indicate

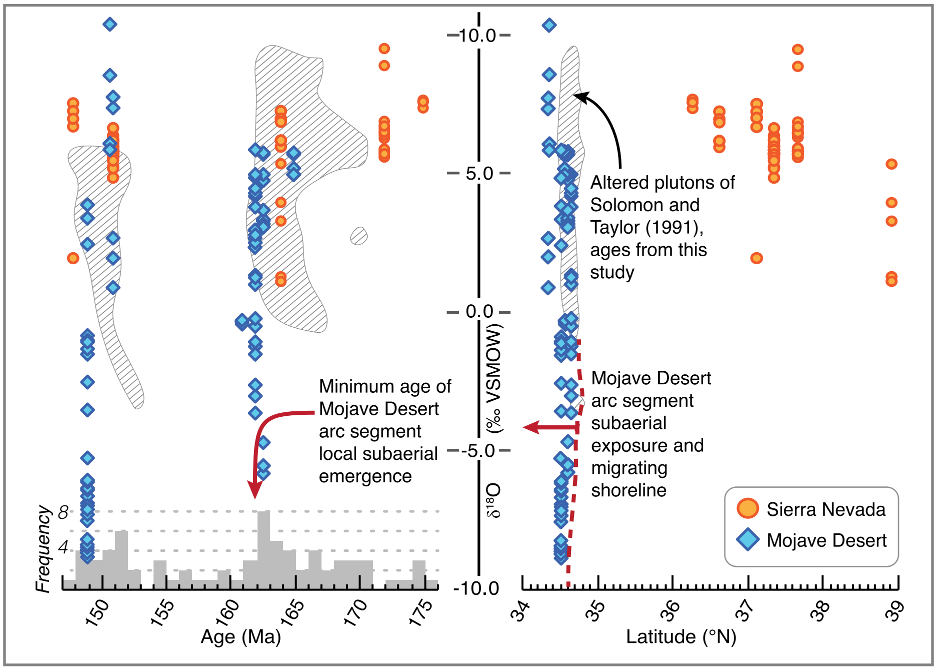

Figure 4. Ages and $\delta^{18}O$ values of Jurassic skarns and plutons of this study. Zircon U-Pb ages of Mojave Desert (southwestern United States) plutons paired with corresponding bulk-rock $\delta^{18}O$ values (hatched areas) of Solomon and Taylor (1991) reiterate the coeval nature of alteration of plutons and skarn formation and, by comparison, show skarn garnet to be a higher-fidelity record of hydrothermal activity. Histogram tabulates zircon U-Pb ages in Sierra Nevada from Klemetti et al. (2014). VSMOW—Vienna standard mean ocean water.

the lack of a subaerial or emergent crustal column. Multiple emplacement configurations may prohibit surface fluid from reaching skarn formation depths. In general, skarn formation below the brittle-ductile transition should diminish a hydrothermal system's ability to draw surface-derived water into the crust and thereby limit skarn $\delta^{18}O$ values to those of mixtures of magmatic and metamorphic fluids. Potential causes for the lack of a meteoric signature in the Sierra Nevada skarns may include (1) igneous-derived fluid locally dominating fluid-rock ratios (e.g., the hornblende gabbro host of the Tungsten Hills skarns) or by dehydrating wall rock; (2) comparatively deep emplacement, limiting significant infiltration of meteoric fluids; and/or (3) differences in crustal permeability limiting surface-water interaction with forming skarns.

Shallow emplacement and skarn formation depths are supported by the spatial and temporal occurrence (1) within the fossil hydrothermal system of Solomon and Taylor (1991) (Fig. 2), where normal faults associated with Jurassic extensional to transtensional tectonics thinned regional crust, allowing shallow intrusion and subsequent alteration of plutons (Solomon and Taylor, 1991; Barton et al., 2011; Busby, 2012); and (2) adjacent to calderas and intra-arc basins preserving the Sidewinder Volcanics (Schermer and Busby, 1994) (Fig. 4). An extensional or transtensional tectonic component would have provided a physical conduit for transportation of surface fluids to skarn formation depths and resulted in a steep thermal gradient, which would have facilitated the fluid circulation and requisite heat to produce the ^{18}O depletion of the altered Mojave plutons and low-$\delta^{18}O$ Mojave Desert skarns (Solomon and Taylor, 1991; Jamtveit and Hervig, 1994). In comparison, the magmatic-dominated $\delta^{18}O$ values of the Tungsten Hills skarn (Fig. 4) emphasize coeval differences in arc conditions between the Mojave Desert and Sierra Nevada arc segments.

Uranium-Lead Ages and Low-$\delta^{18}O$ Skarn Garnet Constrain the Timing of Arc Emergence

Contrasting $\delta^{18}O$ values between Sierra Nevada and Mojave Desert skarns indicate upper-crustal surface-water infiltration was limited to the Mojave Desert skarns. A garnet U-Pb age of ca. 162 Ma from the Verde Antique skarn (Gevedon et al., 2018) paired with negative $\delta^{18}O$ values indicates a Late Jurassic minimum age of local subaerial emergence for the central Mojave Desert segment of the arc. Our data contextualize the subaerial paleoenvironment recorded by the neighboring Sidewinder Volcanics series intracaldera fill (Fig. 2) (Schermer et al., 1994). Four ages from the >4 km package of the Sidewinder Volcanics series indicate periods of subaerial volcanic eruption between ca. 179 and 151 Ma (Schermer et al., 2002; Fohey-Breting et al., 2010). The U-Pb ages of altered plutons and skarns that formed near them indicate a robust regionally extensive hydrothermal system developed in response to the magmatism and that it periodically sampled meteoric water sources for ~14 m.y., despite likely subsidence associated with caldera systems and given coastal environment.

The Mojave Desert skarn record of arc emergence and surface-derived fluids has implications for the timing of Jurassic paleoshoreline retreat. Dickinson and Gehrels (2010) and Busby (2012) proposed the Jurassic paleoshoreline migrated through the region of the three newly recognized low-$\delta^{18}O$ systems (Figs. 3 and 4). Garnet ages and negative $\delta^{18}O$ values suggest migration of the Jurassic shoreline to the west of the Whitehorse and Verde Antique skarn localities (Fig. 4) occurred no later than ca. 162 Ma. Less-^{18}O-depleted garnet of some Mojave Desert skarns (e.g., Bessemer, Galway Lake, and Copper Strand; Fig. 3) may indicate infiltration of surface waters was localized and not as pervasive as Solomon and Taylor (1991) suggested, and is consistent with potential coastal alkaline lakes or marine basins and the trajectory of the paleoshoreline indicated by pre-Cretaceous Na ± Ca altered plutons (Battles and Barton, 1995).

CONCLUSIONS

Skarn garnet $\delta^{18}O$ values record the composition and sources of fluids present at pluton–host rock interfaces during emplacement and thus can serve as a nontraditional paleoenvironmental indicator useful for deciphering geographic and tectonic conditions. Skarn garnet of the Jurassic Cordilleran margin arc exhibits a wide range of $\delta^{18}O$ values (–8.9‰ to +10.3‰) controlled by differing depths of emplacement, host-rock composition, and tectono-magmatic regimes. When coupled with U-Pb ages, garnet $\delta^{18}O$ values reveal the regional extent, longevity, and fluid sources of such hydrothermal systems. In systems with surface connectivity, paired ages and low $\delta^{18}O$ values can provide additional spatio-temporal constraints on the migration of paleogeographic features such as shorelines or subaerial environments, including the timing of local arc emergence in the Mojave Desert. When compared to the record of hydrothermal alteration preserved by Jurassic Mojave Desert plutons, skarn garnet $\delta^{18}O$ values provides a more detailed and resilient record of the timing, magnitude, and regional extent of fluid sources that interacted with crustal rocks. The presence of surface-derived fluids in the Jurassic Mojave Desert skarns supports intra-arc extension and shallow emplacement and further supports the interpretation of the arc-graben style of magmatism.

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