Evolution of a shallow hydrothermal system in the Sierra Nevada batholith: records from a zoned, low-$\delta^{18}O$ skarn in the Mineral King Pendant

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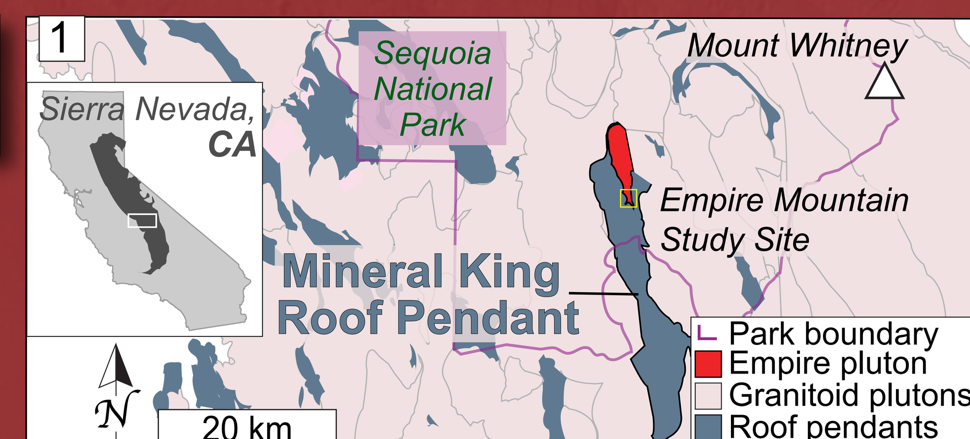
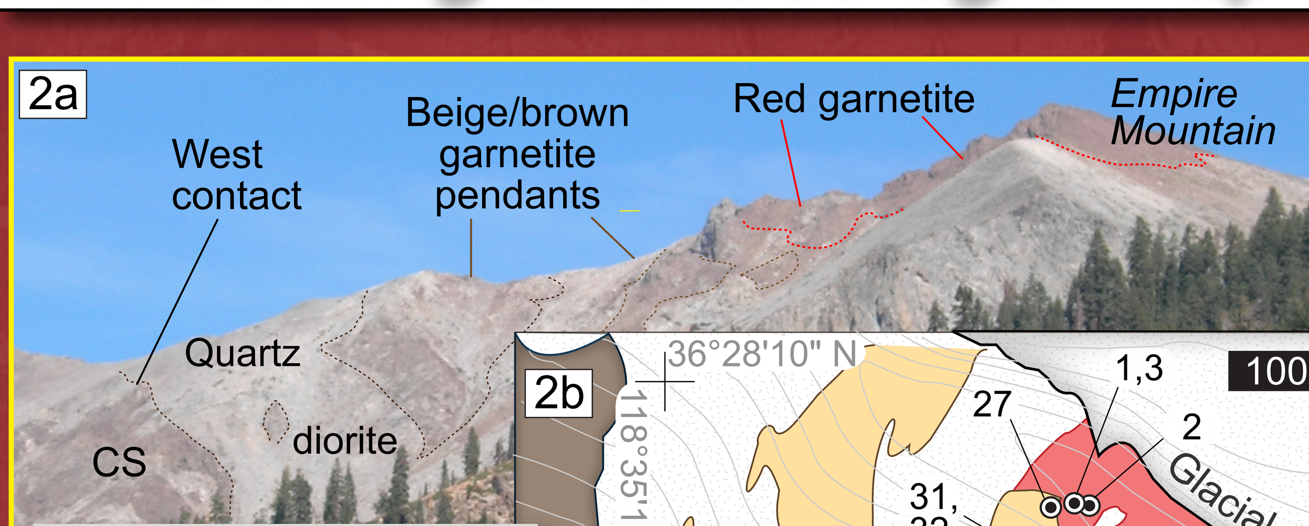
I. Introduction

Empire Mountain, located in the Mineral King pendant of the southern Sierra Nevada batholith, displays magnificent three-dimensional exposure of a shallowly intruded quartz diorite pluton and calc-silicate wallrocks, many of which are metasomatic skarn. In this study, we present field, geochronologic, compositional, and oxygen isotope analyses, showing that the voluminous skarns exposed at Empire Mountain are a newly recognized low-$\delta^{18}O$ locality, with both the pluton and skarn forming minerals recording continuous infiltration of surface-derived water throughout the evolution of the hydrothermal system. Fluid flow in the in the Empire Mountain hydrothermal system provides critical insight into the style of shallow decarbonation in convergent margin arcs.

II. Setting and Geologic Map





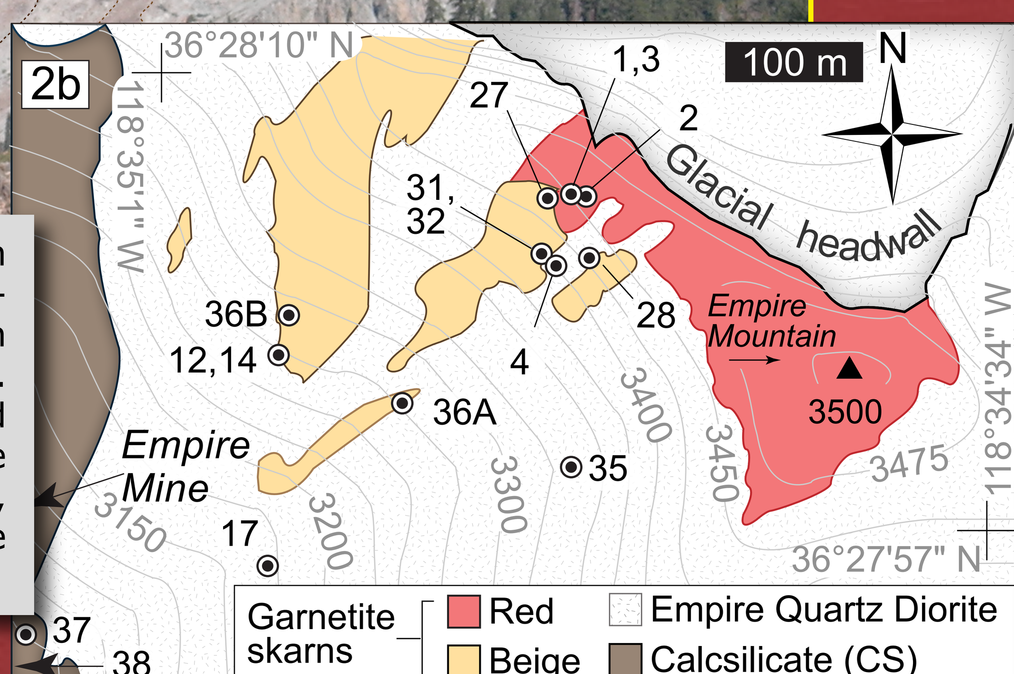


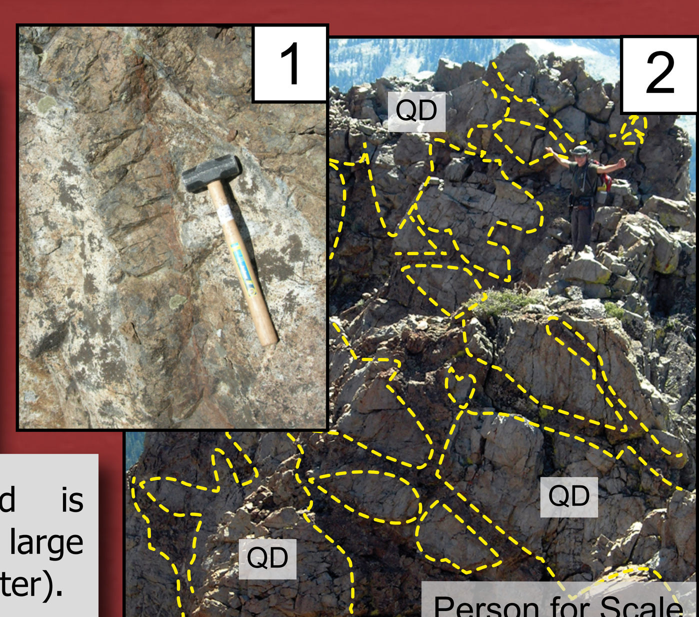
Fig. 2a (above) shows ~400 m of relief at the Empire Mountain study site and is an oblique view of Fig. 2b (right). Both figures show the isolated calc-silicate pendants, the Empire quartz diorite pluton, and color variations in the skarn rocks.

The Sierra Nevada batholith contains numerous roof pendants of Paleozoic to Cretaceous metasedimentary and metavolcanic rocks (Fig. 1, above). The Mineral King pendant is composed of marine sedimentary rocks deposited during significant felsic volcanic activity (Busby-Spera and Saleeby, 1987). At Empire Mountain, the pendant was intruded and contact metamorphosed by the ca. 109 Ma Empire Mountain quartz diorite (study area boxed in yellow in Fig. 1) and the hydrothermal system was unusually shallow compared to regional studies (1.5–2.5 kbar, 400–635°C; Brown et al., 1985, Ferry et al., 2001; Lackey and Valley, 2004).

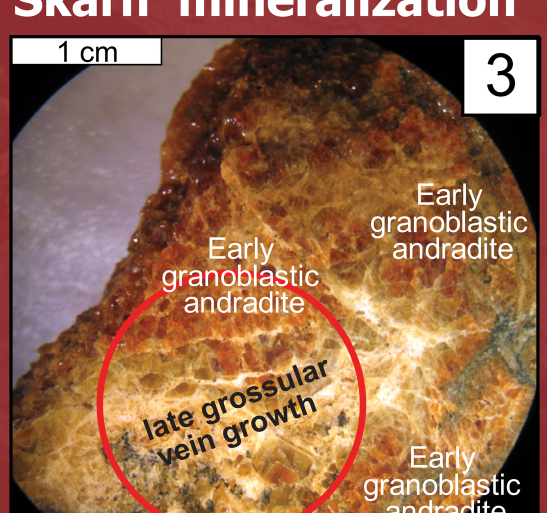
III. Field Relationships

Nature of the contact

The pluton-wallrock contacts are both sharp and gradational. Spalling pendant calc-silicate xenoliths become progressively garnet rich toward the contact over 5 – 50cm (1). In the cupola zone (2), the wallrock exhibits sharp contacts with several lens-like blobs of quartz diorite (QD, in yellow) and is coarse-grained, garnet-rich, with large calcite filled vugs (1 – 3 cm diameter).



Skarn mineralization

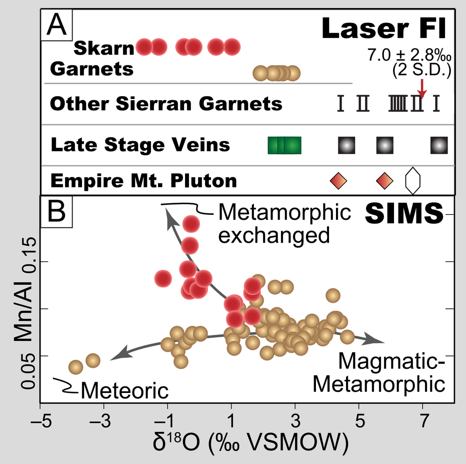


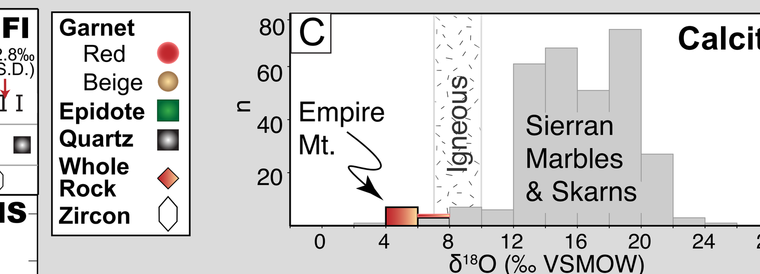
Petrogenetic sequence:

A) Early growth of distinct granoblastic red (locally andraditic) garnet, pyroxene, and wollastonite.
B) Secondary, overgrowth of beige garnet filling veins and fractures in the red garnetite (3)
C) Late stage, cross-cutting veins containing euhedral quartz + epidote ± calcite precipitated in open-space filling (4, 5).

IV. Oxygen Isotope Values at Empire Mountain

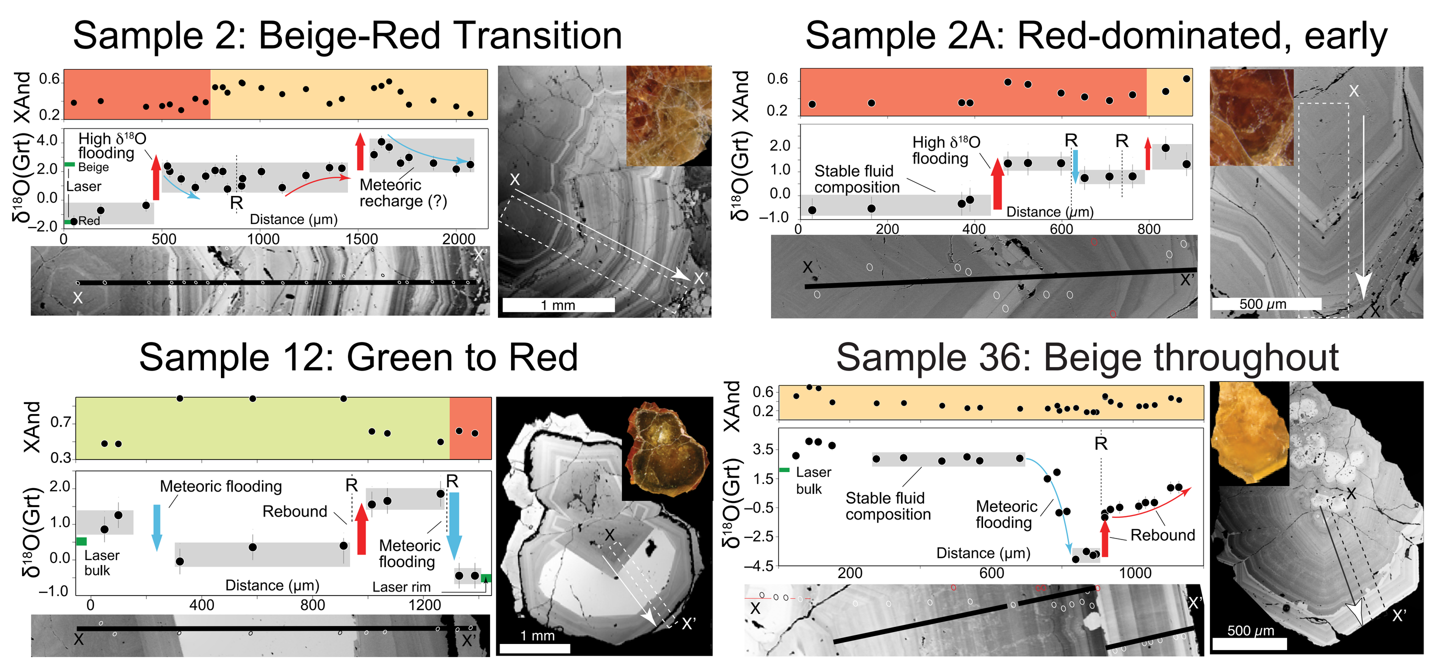
Skarn $\delta^{18}O$ values are controlled by and record the compositions of infiltrating fluid, typically in exchange equilibrium with an adjacent intrusion (Bowman, 1998; Clechenko and Valley, 2003). Our analyses reveal low-$\delta^{18}O$ skarn garnet values, with a marked transition from andraditic cores to grossular-rich rims (A, B). The three-way divergence of $\delta^{18}O$-Mn/Al values suggests that the fluid budget contained at least three components (B). These data support a hydrothermal system with a substantial component of Cretaceous meteoric water that controlled the low-$\delta^{18}O$ signal in the skarns.





All skarn minerals confirm the low-$\delta^{18}O$ signature. Zircon $\delta^{18}O$ value is typical of magmatic Sierran plutons, , but unexpectedly low in whole rock. Calcite values in the garnetites are below magmatic (Bowman, 1998), yet calcite in marbles elsewhere is 13–19‰ δ18O (C).

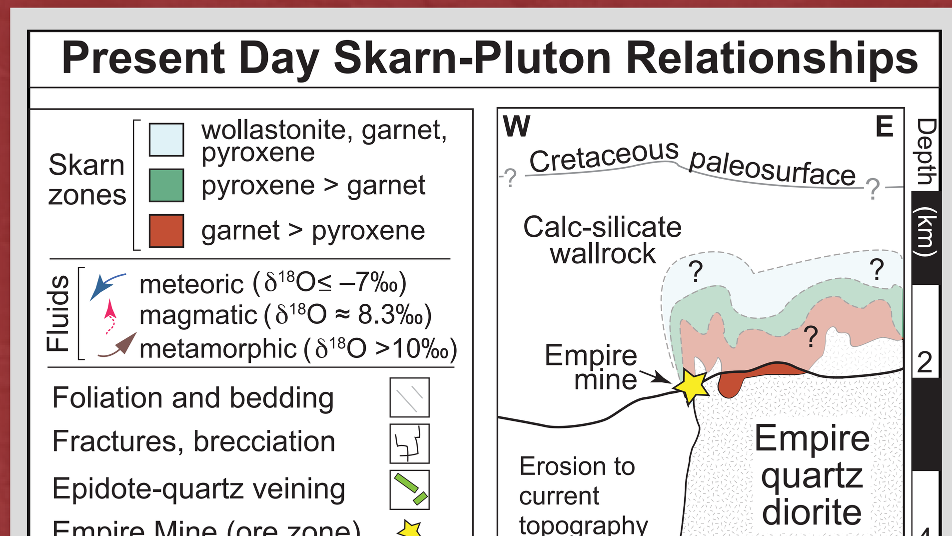
Single Garnet Transects



Single grain SIMS transects reveal:

- Single crystal zonation records changing fluid composition over time.
- Single grain $\delta^{18}O$ values vary from −4.0‰ to +4.4‰
- Zoning has both abrupt and gradual $\delta^{18}O$ shifts of up to 7‰ in a single grain.

Raidical changes in fluid composition are also supported by intracrystalline features like resorption surfaces (R), which are caused by fluid-related surface instability and dissolution (Jamtveit et al., 1993). In addition, although changes in Fe (andradite) values commonly correlate to changes in $\delta^{18}O$ values (Clechenko and Valley, 2003; Page et al., 2010), our data do not support a similar correlation.

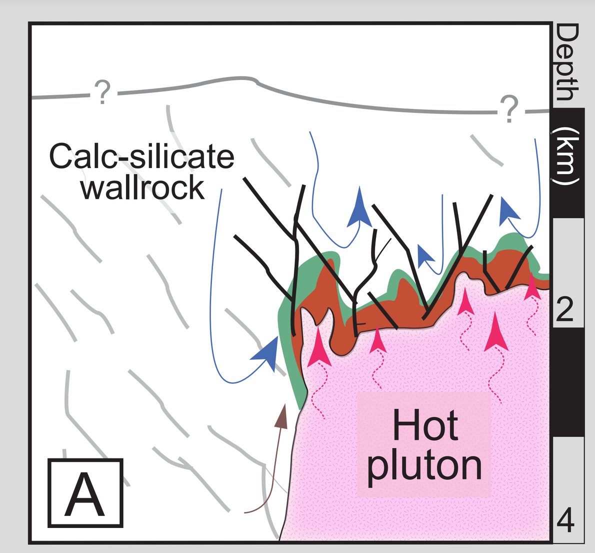


We present a model for the evolution of the Empire Mountain skarn, based our interpretation of the present-day exposure of the system (above) and all data (D'Errico et al., 2012). We describe this evolution in two steps: Early/Main Stage (A, right) and Late Stage (B, below).

V. Hydrothermal System Model

Early/Main Stage

Early-stage garnet has the lowest $\delta^{18}O$ values, suggesting that meteoric water made up a greater proportion of the early/main stage hydrothermal system's overall fluid budget. This significant meteoric fluid flux in the early and main stages is very unusual in the development of skarn systems; we hypothesize that shallow emplacement of the Empire Mountain quartz diorite is likely the reason for this early influx of meteoric water (see key, left, for symbols in Figs. A, B).



- Greater proportion of meteoric water than any other time
- Fluid mixing was confined to the cupola zone of the pluton that is preserved as the capping garnetite section above the pluton, atop Empire Mountain.
- Over time, sustained permeability due to negative volume change of reactions (Meinert et al., 2005).

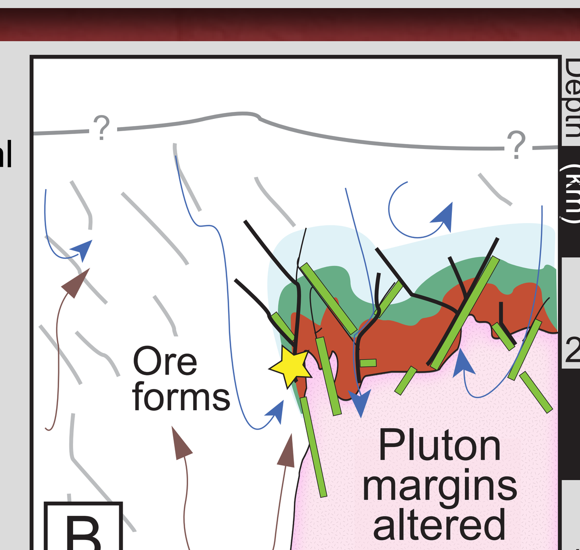
Magma emplacement estimate: <1kbar lith. pressure

- Large temperature contrast between intruding magma and cold pendant (far from main CA magmatism at 109Ma).
- Field relationships support the importance of brittle failure in the enhancement of permeability in the early and main stages of skarn formation.

Late Stage

The documented late-stage decrease of the meteoric water signal resulted from:
1. closure of permeability/porosity; or
2. greater input of the metamorphic water

- Continued meteoric water infiltration resulted in opened secondary fracture networks in the skarns and cooling pluton.
- Hydration of skarn minerals and pluton alteration by late fluids resulted in Pb-Zn ore deposition (a common feature of skarn ores in the Sierra Nevada, Newberry, 1980).
- Microthermometry of fluid inclusions late garnets yield minimum homogenization temperatures of 310–325°C, corresponding to increased $\delta^{18}O$ values of equilibrium fluids. (Sendek, this meeting).



Conclusions:

1. Empire Mountain skarn development involved a substantial component of Cretaceous meteoric water (low $\delta^{18}O$ values) that infiltrated in part due to shallow pluton emplacement.

2. The dynamics of skarn development appear to have resulted in more extensive decarbonation than is typical for skarn systems dominated by magmatic water.

Thus, we hypothesize that the voluminous Empire Mountain skarn represents a well-exposed, unrecognized model for efficient shallow level decarbonation that likely operated in convergent margin arc settings like those of the North American Cordillera.

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