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# (U–Th)/He thermochronometry reveals Pleistocene punctuated deformation and synkinematic hematite mineralization in the Mecca Hills, southernmost San Andreas Fault zone

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ABSTRACT

The timing, tempo, and processes of punctuated deformation in strike-slip fault systems are challenging to resolve in the rock record. Faults in the Mecca Hills, adjacent to the southernmost San Andreas Fault, California, accommodate active deformation and exhumation in the Plio-Pleistocene sedimentary rocks and underlying crystalline basement. We document the spatiotemporal patterns of San Andreas Fault-related deformation as recorded in crystalline basement rocks of the Mecca Hills using fault microstructural observations, geochemical data, and hematite ($n = 24$) and apatite ($n = 44$) (U–Th)/He (hematite He, apatite He) thermochronometry data. Reproducible mean hematite He dates from minor hematite-coated fault surfaces in the Painted Canyon Fault damage zone range from ∼0.7–0.4 Ma and are younger than ∼1.2 Ma apatite He dates from adjacent crystalline basement host rock. These data reveal concomitant Pleistocene pulses of fault slip, fluid flow, and synkinematic hematite mineralization. Hematite textures, crystal morphology, and hematite He data patterns imply some damage zone deformation occurred via cyclic crack-seal and creep processes. Apatite He data from crystalline basement define distinct date-eU patterns and indicate cooling across discrete fault blocks in the Mecca Hills. Uniform ∼1.2 Ma apatite He dates regardless of eU are located exclusively between the Painted Canyon and Platform faults. Outside of this fault block, samples yield individual apatite He dates from ∼30–1 Ma that define a positive apatite He date-eU correlation. These patterns reveal focused exhumation away from the main trace of the San Andreas Fault at ∼1.2 Ma. Low-temperature thermochronometry of fault-related rocks provides an unprecedented window into the $10^5$–$10^6$-yr record of San Andreas Fault-related deformation in the Mecca Hills and documents hematite deformation mechanisms that may be operative in other strike-slip faults world-wide.



## 1. Introduction

Establishing the spatiotemporal patterns of deformation in fault systems is critical for informing fault zone evolution, the geodynamic processes that shape modern fault systems, and the seismic hazards of active faults (e.g., Fialko, 2006; Dolan et al., 2007; Pérouse and Wernicke, 2016). Punctuated exhumation and associated deformation processes may be a key characteristic of fault zone dynamics in strike-slip fault systems, particularly in transpressional regimes (e.g., Frost and Rose, 1996; Dolan et al., 2007). In the southernmost San Andreas Fault (SAF) system, extensive but spatially-isolated, rapid exhumation of discrete fault blocks has been documented over greater than million-year timescales (e.g., Spotila et al., 2001, 2007; Niemi et al., 2013). Identifying shorter-duration ($10^5$–$10^6$-yr) deformation pulses and deformation mechanisms is challenging, but is needed to bridge long-term structural and geologic histories with geodetic and paleoseismic datasets.

The Mecca Hills lie adjacent to and northeast of the southernmost SAF. Active deformation and exhumation in this area results from transpression on the Coachella section of the SAF (Fig. 1; Dibblee, 1954; Sylvester and Smith, 1976). The geology of the Mecca Hills is well established (Sylvester and Smith, 1976; McNabb et al., in press); geodetic data constrain modern-day asymmetric strain rates across the southernmost San Andreas Fault, as well as creep localization on discrete structures in the Mecca Hills (Fialko, 2006; Lindsey and Fialko, 2013; Lindsey et al., 2014). Prior work in the Mecca Hills focuses on the Late Pliocene to Pleistocene sedimentary record of basin development and deformation (Sylvester and Smith, 1976; McNabb et al., in press). A suite of dextral and dextral-normal faults sub-parallel to the

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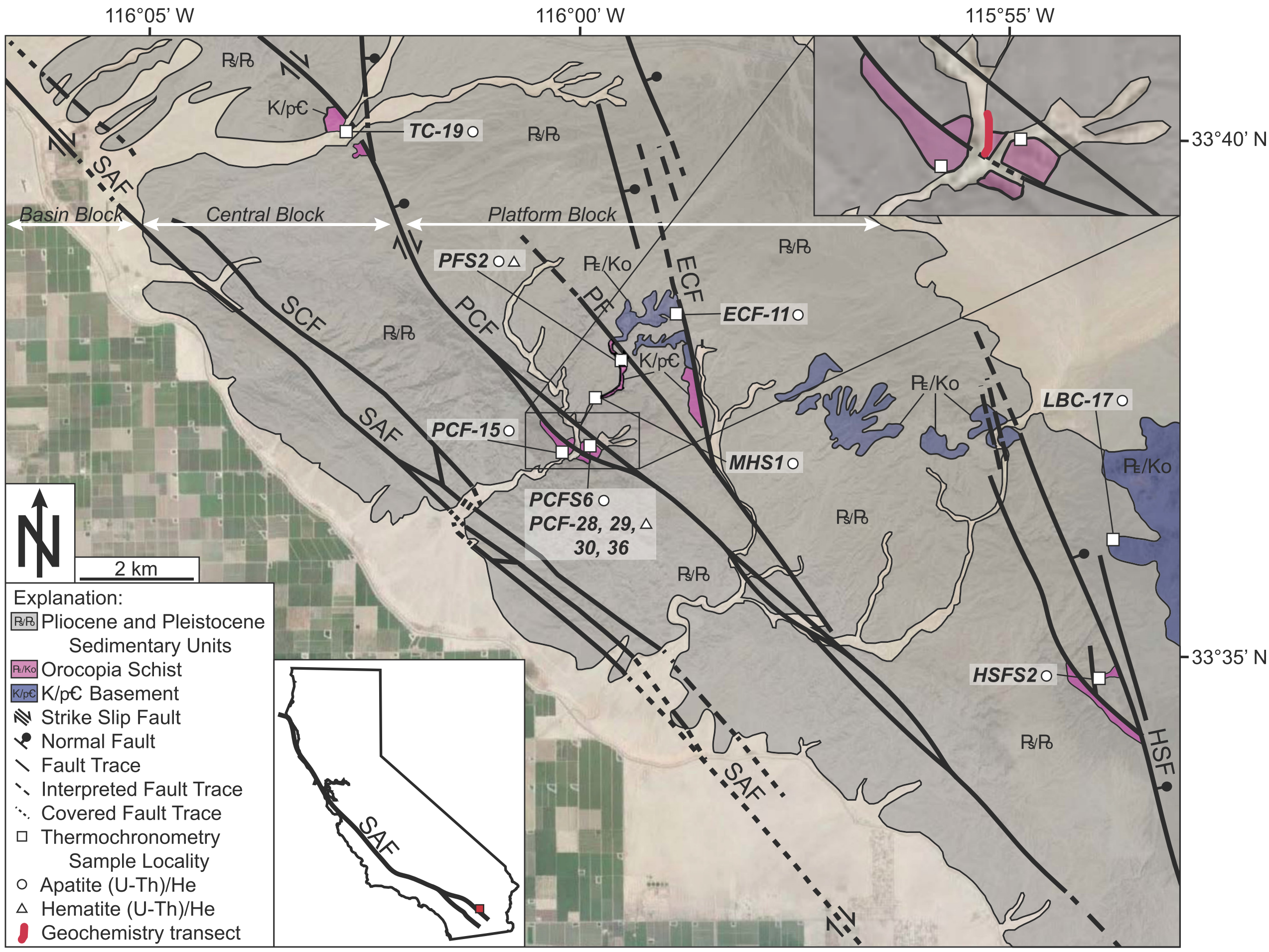


**Fig. 1.** Mecca Hills location, geology, and thermochronometry sample localities. White circles and triangles indicate bedrock apatite He and slip-surface hematite He samples, respectively. Basin Block, Central Block, and Platform Block are structural domains defined by Sylvester and Smith (1976). Bold red line shows the location of the geochemical transect shown in Fig. 2 and Fig. 5. SAF – San Andreas Fault, SCF – Skeleton Canyon Fault, PCF – Painted Canyon Fault, PF – Platform Fault, ECF – Eagle Canyon Fault, HSF – Hidden Springs Fault. Underlying imagery is from Google Earth. Geology modified from Fattaruso et al. (2014) and McNabb et al. (in press). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SAF cut the previously studied sedimentary rocks and Precambrian and Cretaceous crystalline basement rocks exposed in the canyons and drainages of the Mecca Hills (Fig. 1; Dibblee, 1954; Sylvester and Smith, 1976). These exhumed fault zones hosted in crystalline basement rocks preserve a critical thermal, geochemical, and microstructural record of the spatiotemporal evolution of the dynamic southernmost SAF system.

Low-temperature thermochronometry is sensitive to thermal and mechanical processes in the upper crustal portions of fault systems and can potentially provide a window into the timing, mechanisms, and significance of short-duration ($10^5$–$10^6$-yr) deformation phases. In this contribution, we integrate multi-scale fault zone geochemical and structural characterization with low-temperature thermochronometry of fault-related rocks to present a basement perspective of SAF-related deformation in the Mecca Hills. We target the fault-related rocks themselves, acquiring hematite (U–Th)/He (hematite He) thermochronometry data from hematite-coated minor slip surfaces in major fault damage zones that cut the crystalline basement rocks in the Mecca Hills. We compare these results with apatite (U–Th)/He (apatite He) data from adjacent, comparatively unaltered crystalline basement that record cooling patterns related to discrete fault block development and exhumation in the Mecca Hills. The hematite and apatite He data patterns reveal Pleistocene phases of syntectonic hematite mineralization in the Painted Canyon Fault damage zone during active and rapid fault block exhumation. Our data provide new insight into the evolution of SAF-related structures in the Mecca Hills, deformation processes in hematite-coated fault systems, and the ability of low-temperature thermochronometry of fault-related rocks to record the timing of these vertical deformation phases and fault zone processes.

## 2. Geologic setting

The SAF in California is the major fault system that accommodates much of the relative transform plate motion between the North American and Pacific tectonic plates (e.g., Atwater, 1970). The recent tectonic history of this region is complex and includes tectonic reorganization and the resulting inception of the complementary San Jacinto, Elsinore, and San Felipe fault zones at ~1.3–1.1 Ma (Janecke et al., 2011; Dorsey et al., 2012). Evidence for tectonic reorganization at approximately this time has also been recognized at Durmid Hill, near the southern termination of the SAF (Markowski, 2016). The southernmost SAF consists of several major strands including the Coachella section of the SAF. This fault section extends from the Banning-Mission Creek branch point in the northwest to the termination of the SAF fault proper in the Brawley Seismic Zone near Bombay Beach (Rogers, 1965; Shearer et al., 2005). The Coachella section, and the southernmost SAF in general, has not had a large earthquake rupture in historic time (Sieh, 1986). Geophysical and paleoseismologic datasets