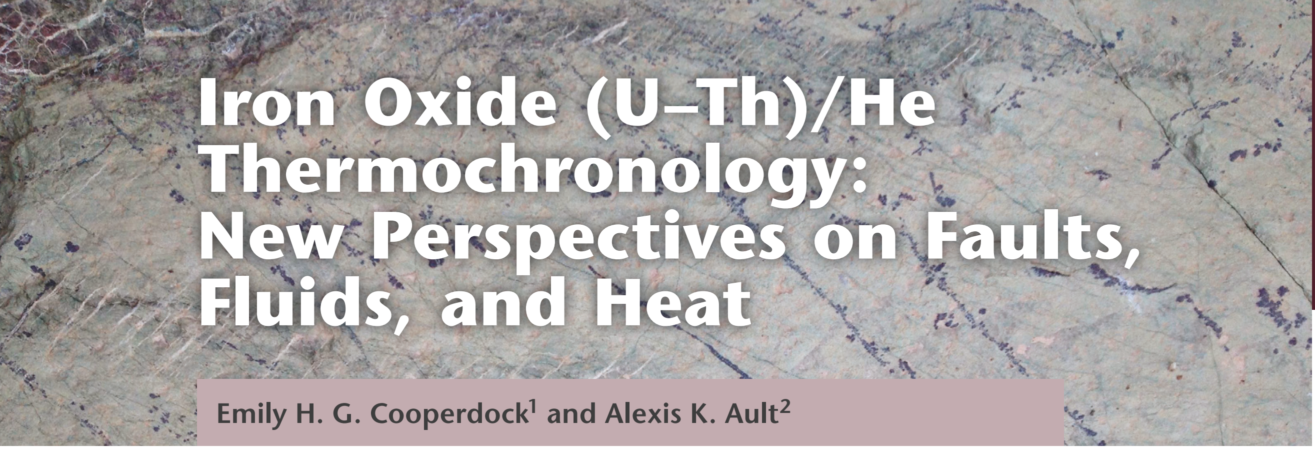

Iron Oxide (U–Th)/He Thermochronology: New Perspectives on Faults, Fluids, and Heat

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Magnetite (black) in a deformed serpentinite from Oman. Credit: Emily H. G. Cooperdock

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Fault zones record the dynamic motion of Earth's crust and are sites of heat exchange, fluid–rock interaction, and mineralization. Episodic or long-lived fluid flow, frictional heating, and/or deformation can induce open-system chemical behavior and make dating fault zone processes challenging. Iron oxides are common in a variety of geologic settings, including faults and fractures, and can grow at surface- to magmatic temperatures. Recently, iron oxide (U–Th)/He thermochronology, coupled with microtextural and trace element analyses, has enabled new avenues of research into the timing and nature of fluid–rock interactions and deformation. These constraints are important for understanding fault zone evolution in space and time.

Keywords: iron oxide, thermochronology, faults, heat, fluid–rock interaction, hydrothermal mineralization

INTRODUCTION

Faults are dynamic environments that can be active over temporal and spatial scales that span several orders of magnitude. Deformation along faults occurs by creep, microseismicity, and/or mega-earthquakes (e.g., Scholz 2002). Faults also serve as pathways for fluids (e.g., Sibson 1981). Textural and geochemical transformations of fault materials are associated with these diverse processes and depend on the mineralogy and rheology of the lithologies present (i.e., continental crust, oceanic crust, or mantle), the ambient conditions (i.e., depth, geothermal gradient), fluid composition, and strain rate. Reconstructing the deformation and fluid–rock interaction histories of these systems is central to understanding fault zone evolution, earthquake mechanics, and how Earth material properties change through time.

Minerals used for more conventional thermochronological applications, such as apatite and zircon, can track cooling of rocks from fault-related processes, such as exhumation. Most applications quantify variations in exhumation rates that are broadly linked to fault activity over million-year timescales and require kilometer-scale offsets. Recently, (U–Th)/He thermochronology of zircon and apatite entrained within, or adjacent to, fault zones has been used to decipher the timing of shear heating and thermal fluid flow (e.g., Maino et al. 2015; Louis et al. 2019). Minerals that grow on fault surfaces, on the other hand, can directly record changes in temperature, geochemistry, and strain rate during deformation.

Iron (Fe) is the fourth most abundant element on Earth and iron oxides (i.e., hematite, magnetite, goethite) are common in many geologic environments, from Earth's surface to deep magmatic systems (e.g., Cornell and Schwertmann 2003) (Fig. 1). Hematite (Fe_2O_3), goethite ($FeOOH$), and magnetite (Fe_3O_4) often grow as microcrystalline aggregates, concretions (hematite, goethite), or up to centimeter-sized single crystals (magnetite, hematite), depending on conditions at the time of mineralization. The ubiquity of Fe oxides makes them attractive targets for constraining the timing of diverse geologic processes. In this contribution, we highlight Fe oxides in fault zones and fractures; however, we note that hematite and goethite also precipitate from oxidizing fluids as diagenetic cements, hydrothermal deposits, and deep weathering horizons (e.g., laterites) (Fig. 1). Magnetite can form as a primary mineral in igneous rocks or as an alteration product in metamorphic and hydrothermal systems (Fig. 1).

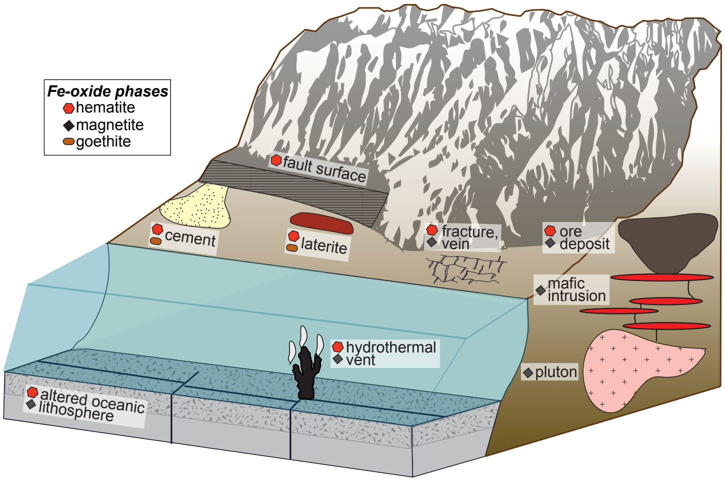

Figure 1 Simplified block diagram showing geologically diverse occurrences of hematite (hexagons), magnetite (diamonds), and goethite (ovals) in continental and marine settings.

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Iron oxides are suitable for (U–Th)/He thermochronology because they incorporate measurable U and Th, negligible initial He, and are generally He-retentive on geologic timescales at near-surface temperatures (e.g., Strutt 1909; Bahr et al. 1994; Farley and Flowers 2012). Early applications of hematite and magnetite (U–Th)/He dating focused on high-temperature hydrothermal systems and igneous rocks, respectively (e.g., Fanale and Kulp 1962; Wernicke and Lippolt 1997; Blackburn et al. 2007). These studies demonstrated that Fe oxide (U–Th)/He thermochronology can constrain simple thermal histories, such as mineralization or volcanic eruption ages.

Analytical advances and improved understanding of He diffusion kinetics has enabled research using Fe oxide (U–Th)/He thermochronology to document more complicated thermal histories and diverse processes, such as exhumation, diagenesis, and soil development (Shuster et al. 2005; Evenson et al. 2014; Reiners et al. 2014). The low-temperature sensitivity of Fe oxide (U–Th)/He thermochronometers, coupled with their occurrence in faults, provides the unique opportunity to investigate the thermal and deformation histories of fault systems. Here, we review the Fe oxide (U–Th)/He systematics that make this analytical tool distinct from other noble gas thermochronometers. We highlight methodological advances and complementary data that have improved our ability to accurately interpret Fe oxide (U–Th)/He dates. We then illustrate how hematite and magnetite (U–Th)/He thermochronology can be applied to document fluid–rock interactions, mineralization, and deformation on faults.

IRON OXIDE (U–TH)/HE TEMPERATURE SENSITIVITY

British physicist Robert John Strutt (1875–1947) measured the first hematite U–He date in 1909 and concluded that the lower-than-expected age was the result of He loss from the mineral. Subsequent step-heating ^{4}He diffusion experiments revealed that specular and botryoidal hematite have relatively low closure temperatures between ~100 °C and 300 °C (e.g., Bahr et al. 1994). The magnetite (U–Th)/He system has a reported closure temperature of ~250 ± 50 °C, based on a diffusion experiment using internal fragments from a single igneous magnetite crystal (Blackburn et al. 2007). These hematite and magnetite closure temperatures are calculated using a 10 °C/My cooling rate and the assumption that the He diffusion domain is the entire grain. However, this assumption may lead to incorrect interpretations in samples composed of different grain sizes or subdomains. For example, aliquots of hematite (or goethite) analyzed for (U–Th)/He dating are commonly aggregates of individual tiny crystals that may record a range of closure temperatures within a single sample (Farley and Flowers 2012; Evenson et al. 2014).

Our understanding of He diffusion in minerals was advanced by the ability to generate a spatially uniform distribution of ^{3}He by proton bombardment. By incrementally heating an aliquot of sample and measuring the synthesized ^{3}He that degasses, we can determine a ^{3}He Arrhenius relationship (the relationship between the diffusion coefficient and temperature) (see Gautheron and Zeitler 2020 this issue) that characterizes the diffusion domain(s) and diffusion kinetics of He for that aliquot of sample (e.g., Farley and Flowers 2012; Farley 2018). Moreover, by measuring the naturally occurring ^{4}He that degasses at the same time as ^{3}He, we can use the measured ^{4}He/^{3}He ratio to constrain the spatial distribution of ^{4}He in a single grain or aggregate (e.g., Shuster and Farley 2005). Information about the spatial distribution of ^{4}He can be used to place tighter constraints on the geologic thermal histories of samples than is possible from a bulk ^{4}He measurement and a (U–Th)/He date alone.

Atom-scale diffusion calculations and ^{4}He/^{3}He diffusion experiments indicate that polycrystalline hematite exhibits polydomain He diffusion, or simultaneous He loss from individual crystallites in the aggregate (Farley and Flowers 2012; Evenson et al. 2014; Farley and McKeon 2015; Balout et al. 2017). New single-crystal ^{4}He/^{3}He and bulk (U–Th)/He data from different-sized crystals confirm that each hematite grain in an aggregate constitutes a diffusion domain (Farley 2018; Jensen et al. 2018). Hematite ^{4}He/^{3}He diffusion experiments refine the closure temperature to ~50–250 °C, given a range of typical grains sizes (0.01–1,000 µm) and assuming a 10 °C/My cooling rate, thereby confirming the strong dependence of closure temperature on grain (domain) size (Farley and Flowers 2012; Evenson et al. 2014; Farley 2018).

Iron oxide ^{4}He/^{3}He data have also enabled researchers to interpret increasingly complex geologic histories. For example, ^{4}He/^{3}He thermochronology of hydrothermal hematite has been applied to reconstruct the long-term burial and erosion history of the eastern Grand Canyon (Arizona, USA) (Farley and Flowers 2012), the rapid exhumation and evolution of the Buckskin–Rawhide detachment system of Arizona (USA) (Evenson et al. 2014), past fluid movement in the vicinity of the Moab Fault in Utah (USA) (Garcia et al. 2018), and the mineralization history of banded iron formations (Farley and McKeon 2015).

IRON OXIDE GROWTH, COOLING, AND HE LOSS IN FAULTS AND FRACTURES

Iron oxide (U–Th)/He thermochronology can document a variety of fault-related processes, such as fluid flow and mineralization, tectonic exhumation, or thermal resetting from frictional heating or hydrothermal processes (Fig. 2A). These diverse interpretations are, in part, possible because Fe oxides in fault rocks are secondary minerals. Thus, they can form above or below their closure temperature, making them distinct from other minerals traditionally used for (U–Th)/He thermochronology. Apatite and zircon, for example, crystallize in igneous or metamorphic systems well above their respective closure temperatures and, thus, yield (U–Th)/He dates that record subsequent cooling through their closure temperatures. In this section, we will explore the implications of variable formation temperatures and subsequent thermal histories that induce He loss on the interpretation of Fe oxide (U–Th)/He thermochronology data.

Iron oxide (U–Th)/He data patterns and interpretations depend on a sample's specific closure temperature, formation conditions, and the postformation thermal history (Fig. 2B). For example, if an Fe oxide crystallizes and remains at temperatures below its closure temperature, such as in some upper crustal faults or hydrothermal systems, then the associated (U–Th)/He date will record the time of mineral growth (i.e., mineralization, formation age) (Fig. 2B) (Moser et al. 2017; Garcia et al. 2018; Jensen et al. 2018; Cooperdock et al. 2020). Alternatively, if an Fe oxide experiences or forms at temperatures higher than its closure temperature, then the (U–Th)/He date captures subsequent cooling due to tectonic or erosional exhumation (Fig. 2B) (Calzolari et al. 2018). Furthermore, a sample may contain multiple Fe oxide generations that, depending on the aliquot-specific closure temperature, will reflect formation and/or cooling (Cooperdock and Stockli 2016).

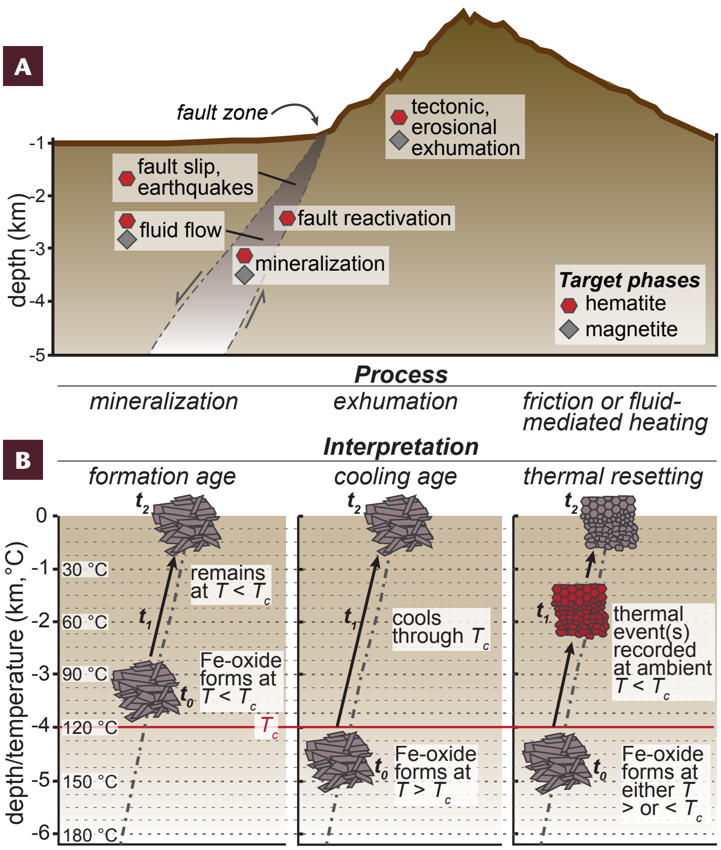

FIGURE 2 (**A**) Schematic cross-section showing potential processes recorded by hematite (hexagons) and magnetite (diamonds) (U–Th)/He thermochronology in fault and fracture systems. (**B**) Potential processes and their interpretations in terms of Fe oxide (U–Th)/He thermochronology data from fault zones. Simplified cross-sections show a polycrystalline Fe oxide aliquot, with a hypothetical associated 120 °C closure temperature (T_C). Iron oxide (U–Th)/He dates can represent either a formation age, a cooling age, or thermal resetting, depending on the ambient temperature at which the hematite formed relative to T_C, and also the post-formation thermal and deformation history. Symbols: t = time; T = temperature; T_C = closure temperature.

Fault and fracture systems host thermal, chemical, mechanical, and/or fluid-mediated processes that may cause open-system behavior (i.e., He loss and/or parent isotope gain or loss) (FIG. 2B) that also must be considered. For example, friction-generated heat during fault slip may induce He loss from hematite on fault surfaces by thermally activated volume diffusion or recrystallization (FIG. 3) (Ault et al. 2015; McDermott et al. 2017; Calzolari et al. 2020). Hydrothermal fluids present in a fault zone may also cause thermal resetting (He loss) from existing hematite (FIG. 3) (e.g., Ault et al. 2016), analogous to documented He loss from apatite in fault rocks (Louis et al. 2019). Similarly, hydrothermal magnetite may grow intermittently from fluid pulses driven by tectonic fracturing, or hot fluids may thermally reset He in existing magnetite within veins (FIG. 3) (Cooperdock and Stockli 2016; Cooperdock et al. 2020). Fluids can also add or remove U from Fe oxides, or precipitate U-bearing interstitial phases (e.g., Evenson et al. 2014; Reiners et al. 2014). These complexities can be identified with complementary textural and geochemical data, which, in some cases, reveal new information on the geologic history of the sample.

STRATEGIES FOR DATA INTERPRETATION

The fact that Fe oxides can grow above or below their closure temperature and experience He loss and/or parent isotope gain presents unique challenges for interpreting Fe oxide (U–Th)/He thermochronology data, but also opportunities for achieving deeper insight into fault zone processes. How do you know if an Fe oxide (U–Th)/He date reflects mineralization, exhumation, or a superimposed thermal process such as frictional heating (FIG. 2)? Is there geological significance to scattered dates from aliquots of a single sample or from across multiple samples? Addressing these questions requires: (1) knowing aliquot-specific closure temperature estimates; (2) providing detailed Fe oxide textural analysis and aliquot characterization; (3) determining the mineralization temperature and/or background thermal conditions that the Fe oxide experienced.

Estimating an aliquot-specific closure temperature involves knowledge of the aliquot's grain size distribution. Micron to submicron hematite platelets or particles commonly observed on fault surfaces and in some fault veins are below the resolution of a petrographic microscope and require field-emission scanning electron microscopy (SEM) for imaging (e.g., Ault et al. 2016). Magnetite grain sizes, however, can typically be measured using an optical microscope (Cooperdock and Stockli 2016) (FIG. 4). The range of potential aliquot closure temperatures is inferred from the grain size distribution, the assumption that the plate half-width or grain radius is the diffusion domain length-scale, and the application of available diffusion kinetics (Blackburn et al. 2007; Farley 2018). Aliquots with variable grain sizes or an evolving grain size distribution with deformation may experience variable He loss, which will lead to intrasample data scatter over their thermal history (FIG. 5).

Textural, grain quality, and chemical characterization are also critical to addressing these questions. Scanning electron microscopy, energy dispersive X-ray spectroscopy, X-ray computed tomography (micro-CT), and electron microprobe analyses are used to characterize aliquot quality and chemistry. For example, these methods can reveal the presence and abundance of non–iron oxide phases introduced during or after Fe oxide mineralization from fluid circulation, or via mechanical mixing during deformation. These phases may be U-bearing and/or have a

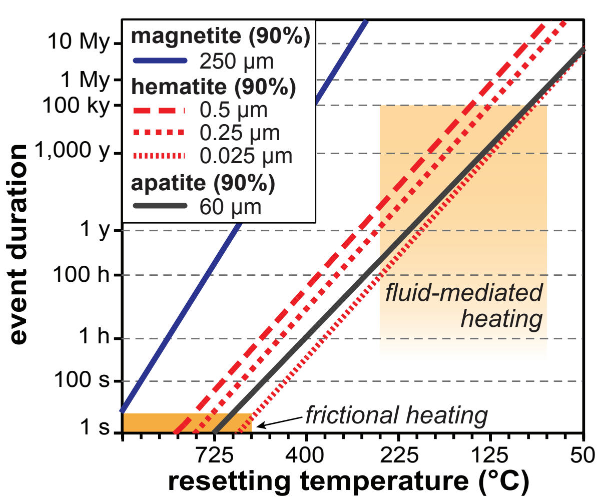

FIGURE 3 The temperature and time, from seconds (s) to millions of years (My), that are required to reset (i.e., induce 90% He loss) the (U–Th)/He systems in magnetite, hematite, and apatite, taking into account grain sizes as denoted in legend. Shaded boxes highlight thermal resetting conditions for frictional (i.e., earthquake) and fluid-mediated heating. MODIFIED FROM AULT ET AL. (2015, 2016).

different He retentivity compared with Fe oxide, and, thus, contribute to Fe oxide (U–Th)/He data scatter (e.g., Evenson et al. 2014). Alternatively, U that is added to existing Fe oxides by subsequent fluid interaction may be revealed by a negative relationship between Fe oxide (U–Th)/He date and Th/U ratio within a sample (Reiners et al. 2014). In addition, the shape of these individual micro- to nano-scale crystals can yield key insights into the (de)formation and related thermal processes from fault slip. Textures can be linked to Fe oxide (U–Th)/He data patterns within individual samples and/or across multiple samples in a larger dataset to infer complex thermal histories (Fig. 4) (McDermott et al. 2017; Moser et al. 2017).

Hydrothermal or igneous magnetite can be rife with inclusions, fractures, or intergrowths, all of which have the potential to introduce excess He, modify the He diffusion kinetics, and otherwise complicate data interpretation (Cooperdock and Stockli 2016). Iron oxides cannot be screened for internal inclusions or fractures using transmitted light. Reflected light microscopy or SEM imaging can provide a 2-D view of a grain, but this requires a thin section and polishing away part of the crystal. In contrast, micro-CT provides a nondestructive, 3-D view through an entire mineral grain at micron-scale resolution, and can identify inclusions of other minerals, fluid inclusions, or fractures (Fig. 4). This technology does not heat or alter the sample during preparation or scanning, so that the same grains screened by micro-CT can be used for subsequent (U–Th)/He analysis (e.g., Cooperdock and Stockli 2016).

Together with image analysis, fault rock data interpretation is augmented by independent thermometry and constraints on the postmineralization ambient thermal history.

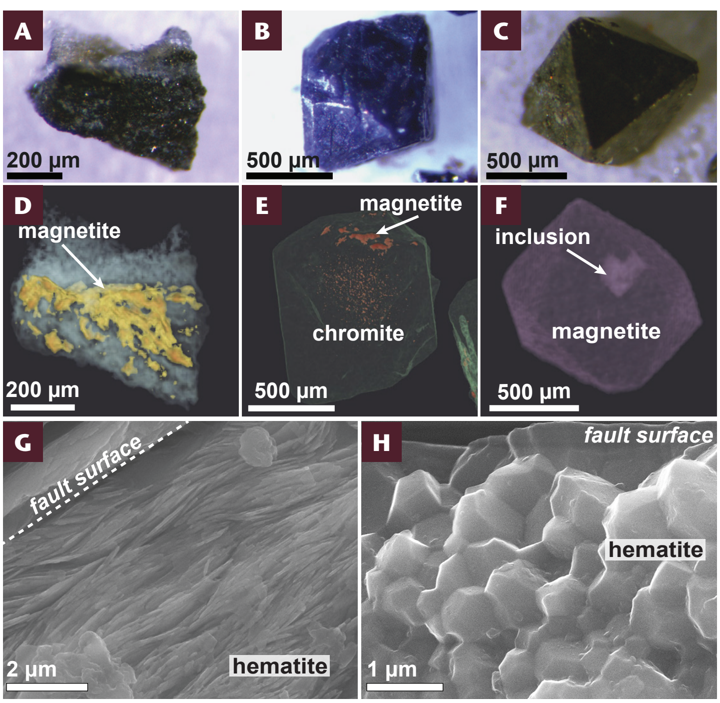

Figure 4 (**A–C**) Optical microscope images of three opaque minerals, initially presumed to be homogenous magnetite. (**D–F**) Grains in Figures A–C, respectively, are rendered visible by reconstructed micro-computed tomography (micro-CT) data. Figure 4D shows a magnetite crystal aggregate surrounded by matrix; Figure 4E shows chromite with magnetite surface alteration; Figure 4F shows magnetite with a mineral inclusion. Note how internal heterogeneities are revealed by micro-CT. (**G–H**) Scanning electron microscopy images of hematite from fault surfaces showing different textures and crystal morphologies, including plates (Fig. 4G) and polygonal grains (Fig. 4H).

Mineralization temperature estimates can be made by Ti-in-quartz thermometry of cooccurring phases, fluid inclusion microthermometry of hematite and/or coprecipitated calcite or quartz, and stable or clumped isotope analysis of coeval carbonates (Jensen et al. 2018; Cooperdock et al. 2020). Thermal history constraints from apatite or zircon (U–Th)/He or fission track thermochronology of nearby undeformed rocks are compared with Fe oxide (U–Th)/He dates and corresponding closure temperature estimates. Thus, aliquot-specific closure temperature estimates, microtextural observations and aliquot screening, and information on the ambient thermal history, collectively provide context for interpreting Fe oxide (U–Th)/He dates as recording mineralization or some other postmineralization thermal process.

BREAKTHROUGHS IN APPLICATIONS TO FAULT SYSTEMS

Advances in our understanding of He diffusion in Fe oxides, coupled with textural analysis, have enabled emerging applications of Fe oxide (U–Th)/He thermochronology that sit at the intersection of deformation and fluid–rock interaction processes within fault zones. Here, we highlight novel Fe oxide thermochronology data interpretations in fault systems over a spectrum of conditions from low-temperature mineralization to high-temperature thermal resetting.

Mineralization Events in Fault and Fracture Systems

Fault and fracture zones enhance fluid–rock interactions, which can form new minerals by direct replacement or by precipitation from fluids. Hematite (U–Th)/He studies have focused on the timing of mineralization in hydrothermal systems (Wernicke and Lippolt 1997; Farley and Flowers 2012). For example, Jensen et al. (2018) extracted individual crystals from specular hematite veins associated with basement-hosted, fault-controlled sandstone injectites in the Colorado Front Range (USA). Hematite (U–Th)/He dates exhibit a positive relationship with hematite plate thickness, and the oldest Cryogenian dates are interpreted as recording a minimum formation age. In this study, coeval sand injection and hematite mineralization may reflect fluid circulation during extensional tectonics.

Cooperdock and Stockli (2016) applied (U–Th)/He thermochronology to date magnetite in serpentinite, which is a fluid-altered mantle rock. Magnetite grains were sampled from a kilometer-scale shear zone within an exhumed subduction complex on Syros (Greece). A combination of textural and geochemical analyses reveals two magnetite populations that record distinct fault-related events based on variations in grain size, (U–Th)/He date, trace element chemistry, and field context. A millimeter- to centimeter-diameter grain size population enriched in Mg, V, Ti, and Al, which were mobilized via hot (400 °C) subduction-related fluids, yield middle Miocene (U–Th)/He dates consistent with cooling through the magnetite closure temperature during tectonic exhumation (Fig. 5). A second, submillimeter-diameter grain population, found exclusively within a localized slip surface defined by talc, are depleted in Mg, V, Ti, and Al and yield ~3 Ma magnetite (U–Th)/He dates, significantly younger than ~10 Ma zircon (U–Th)/He dates from the same regional shear zone. Due to their grain size, the ~3 Ma magnetite grains should have a higher closure temperature than the zircon (U–Th)/He system, and, therefore, these magnetite (U–Th)/He dates are interpreted as mineralization below the magnetite closure temperature along a Pliocene-age fault surface (Fig. 5). Trace element–depleted rims on the

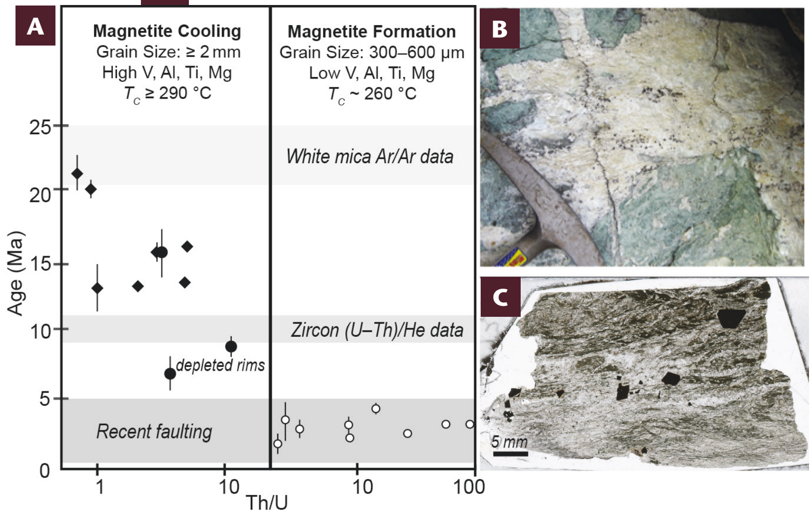

FIGURE 5 (**A**) Magnetite (U–Th)/He data (black and white data points) from serpentinite on Syros (Greece). Two populations are distinguished by (U–Th)/He date, grain size, and grain chemistries. One population (black data circles and diamonds) reflects magnetite cooling ages between existing white mica Ar/Ar data and zircon (U–Th)/He cooling ages. This is consistent with a magnetite He closure temperature between mica Ar/Ar and zircon (U–Th)/He closure temperatures (T_C). A younger, chemically and texturally distinct population (white circles) grew below the magnetite closure temperature and reflects magnetite mineralization along a Pliocene fault surface. MODIFIED FROM COOPERDOCK AND STOCKLI (2016). (**B**) Fault slip surface from the Syros serpentinite displaying black magnetite crystals growing in white talc and surrounded by green serpentinite. Hammer for scale. (**C**) Photomicrograph of a thin section from the rock in FIGURE 5B showing variations in grain size of magnetite (black).

large magnetite grains located on the slip surface provide further evidence for two growth events in this fault zone. This study demonstrates that magnetite (U–Th)/He can be used both as a thermochronometer and to date mineralization within fault zones, and it highlights the ability of serpentinites to episodically grow new magnetite in the presence of repeated fluid pulses.

Thermal Resetting in Fault Zones

Fault zones host a variety of thermal processes from coseismic friction-generated heat during an earthquake to fluid-mediated heat advection. Progressive deformation and strain localization create thin (millimeter-scale) slip surfaces in fault zones. During fault slip, the rate of heat generation can outpace heat dissipation, leaving a thermal and textural fingerprint on fault surface minerals such as hematite. For example, a network of hematite "fault mirrors", or high-gloss, light-reflective thin slip surfaces, in the exhumed, seismogenic Wasatch Fault damage zone (Utah) preserve textural and thermochronometric evidence for transient, elevated temperatures during microearthquakes (Ault et al. 2015; McDermott et al. 2017). Plio-Pleistocene hematite (U–Th)/He dates from fault mirrors are associated with polygonal hematite crystals, a high-temperature texture reflecting annealing and/or grain growth. These textures and hematite (U–Th)/He dates, when compared with host-rock apatite (U–Th)/He data, are best explained by flash heating (T > 1,000 °C) at rough patches (i.e., asperities) on the slip surface causing He loss by diffusion and/or recrystallization (McDermott et al. 2017).

Laboratory deformation experiments on hematite at earthquake slip rates confirm that hematite (U–Th)/He thermochronology can serve as a fault slip paleotemperature proxy (Calzolari et al. 2020). Experimentally generated fault surfaces develop fault mirror–like patches comprising sintered nanoparticles similar to some natural fault surfaces (FIGS. 6A, 6B). Comparison of hematite (U–Th)/He dates from undeformed and deformed hematite reveal that fault mirror zones exhibit >70% He loss during seismic slip in the laboratory (FIG. 6C). The magnitude of He loss is consistent with asperity flash heating to temperatures >900 °C that occurs during fault slip (Calzolari et al. 2020). These examples reveal how hematite (U–Th)/He thermochronology can be used to identify earthquakes in the rock record.

Minerals precipitated in or trapped within faults can also be thermally reset by fluids (e.g., Ault et al. 2016; Louis et al. 2019). For example, hematite (U–Th)/He dates from fault-related fissures exposed in Devonian and Carboniferous rocks on the Gower Peninsula (Wales) are ~141–120 Ma and overlap with ~131 Ma detrital apatite fission track (AFT) data from sediments infilling the fissures (Ault et al. 2016). Burial history reconstructions are inconsistent with both hematite (U–Th)/He and AFT dates reflecting cooling due to erosion alone. Early Cretaceous thermal fluid circulation, coeval with North Atlantic rifting, may have reset the hematite (U–Th)/He and AFT systems or, alternatively, new hematite was precipitated from those thermal fluids. This highlights how high-permeability faults and fractures can serve as conduits for fluid and heat transfer, even long after these structures originally formed.

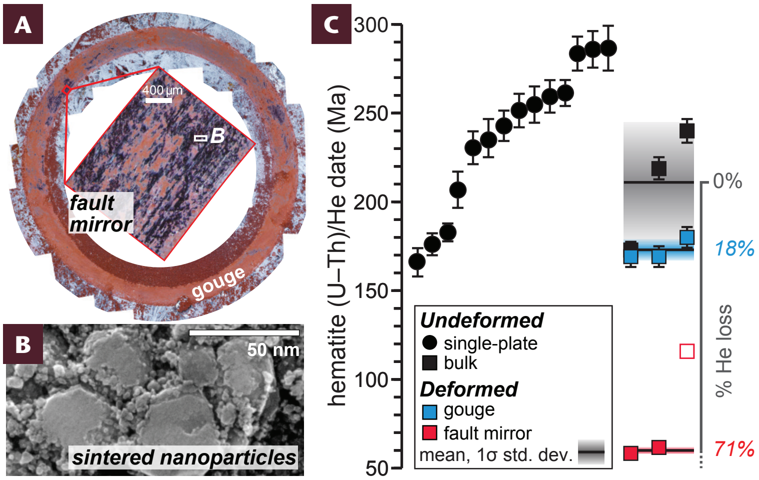

FIGURE 6 (**A**) Experimentally generated hematite fault surface from a laboratory deformation experiment at earthquake slip rate of 0.32 m s^{-1}. Fault mirror zones and gouge were produced during the deformation of originally coarse-grained hematite. (**B**) Scanning electron microscope image of sintered nanoparticles from the fault mirror in FIGURE 6A. (**C**) Comparison of hematite (U–Th)/He dates from undeformed starting material (single-plates and bulk) with deformed fault mirror and gouge material. Fault mirrors show up to 70% He loss. Data point with white fill was not included in the He loss calculation due to U volatilization during laser degassing of the aliquot. Thermochronology data patterns require that He loss occurs via localized asperity flash heating during earthquake slip. MODIFIED FROM CALZOLARI ET AL. (2020).

CONCLUSIONS

Recent analytical and data interpretation advances in Fe oxide (U–Th)/He thermochronology enable application of this tool to constrain the timing of a variety of geologic processes: in particular, those in fault zones. The range of temperature sensitivities that can occur within a single sample, due to grain size variations, allows for reconstruction of a broader swath of a sample's, and, thus, a fault's, history. The fact that Fe oxides can mineralize or lose He below their He closure temperatures provides an opportunity to investigate thermal histories of both high- and low-temperature processes in fault systems. This also means that Fe oxide (U–Th)/He thermochronology should be viewed and approached differently from more traditional thermochronometers. In fact, Fe oxide (U–Th)/He data is more powerful when combined with them.

Although there has been much progress over the past decade, opportunities exist for growth and new research directions. Iron oxide $^{4}He/^{3}He$ thermochronology will provide additional insight into He diffusion and how the kinetics might vary for different grain morphologies, crystal structures, and chemistries. Further developments that link Fe oxide (U–Th)/He thermochronology with microstructures, chemistry, and thermometry will allow us to better understand the significance of (U–Th)/He dates in fault systems and other environments. Iron oxide (U–Th)/He and $^{4}He/^{3}He$ thermochronology can be coupled with other direct dating techniques, including $^{40}Ar/^{39}Ar$ dating of clay gouge (e.g., Fitz-Diaz and van der Pluijm 2013) or U–Pb dating of syntectonic calcite (e.g., Nuriel et al. 2017), to document kinematics and rates of fault slip in heterogeneous fault rocks. Earth is also not the only planet rich in iron. Mars, the red planet, has abundant hematite and other Fe oxides on its surface. With the success of the *Curiosity* rover and planned future missions, hematite (U–Th)/He analysis may be a way to date aqueous activity on the Martian surface (Kula and Baldwin 2012).

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