Application of (U-Th)/He Thermochronometry as a Geothermal Exploration Tool in Extensional Tectonic Settings: The Wassuk Range, Hawthorne, Nevada

Kyle E. Gorynski[1], Daniel F. Stockli[1], J. Douglas Walker[1], and Andy E. Sabin[2]

[1]Department of Geology, University of Kansas, Lawrence, KS
[2]Geothermal Program Office, China Lake, CA

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ABSTRACT

Geothermal exploration in the Basin and Range Province is often focused in extended terrains where heat has been transferred to the surface through advection in the footwall rocks of normal faults. Low temperature (U-Th)/He apatite ages of such footwall rocks can determine which areas have experienced the most recent, significant extension or have interacted with hot geothermal fluids. Apatite cooling ages from the footwall of the Wassuk Range, Hawthorne, Nevada have identified the presence of a known geothermal anomaly and associated structural complexities. The most recent pulse of exhumation along the Wassuk Range front occurred around 4-5 Ma. Range front apatite ages that deviate from this age range correspond to the location of the geothermal anomaly or highlight fault displaced blocks of Wassuk Range footwall. Constraints on the geometry and thermal evolution of the footwall can better focus exploration efforts therefore lowering the associated risks and costs of geothermal exploration.

Introduction

Extensional tectonic settings have long been a focus of geothermal exploration in light of the tectonic heat advection in the footwalls of normal faults coupled with magmatism and fracture permeability in the hanging wall rocks. Exploration for utility grade heat within the upper crust is generally focused where heat is expressed at the surface (i.e., hot springs). In the absence of such manifestations, logistic regression models have been used to focus regional-scale geothermal exploration to extensional areas with high strain accumulation (Blewitt, et al., 2003) and optimal fault orientation (Coolbaugh, et al., 2002). Specifically, the longevity of a geothermal field is contingent upon the ability to bring heat to the surface and the continuous reproduction of structural fluid conduits which is maximized when fault strike is oriented perpendicular to the direction of maximum extensional strain (Blewitt et al., 2003). Moreover, the relationship between high strain rates and geothermal production in extensional tectonic settings is likely the result of tectonic advection during rapid uplift and exhumation of the footwall in normal faults (Walker et al., 2005).

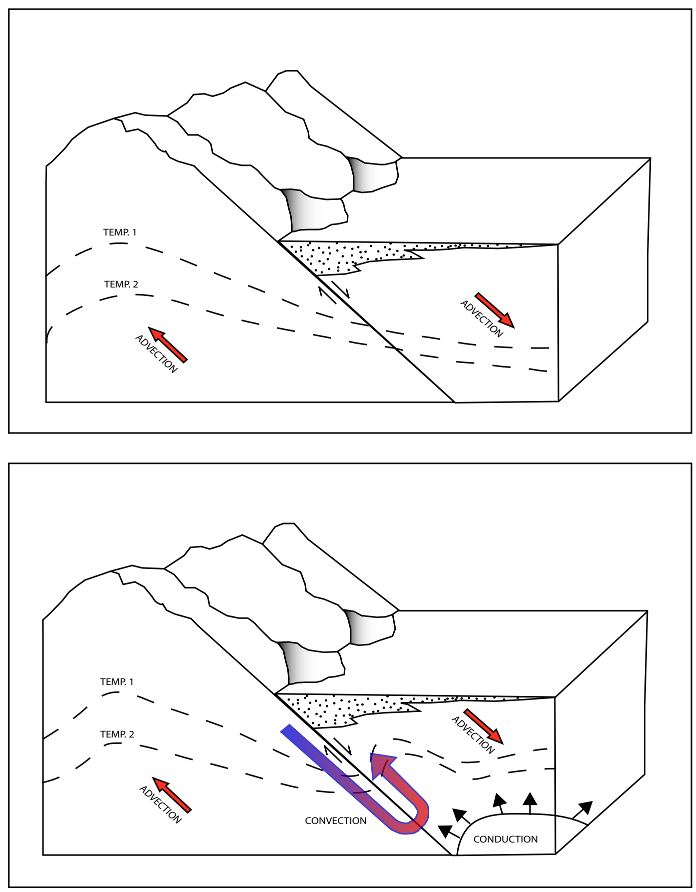

Figure 1. Two models for heat transport in extending crust. Each model can explain the presence of anomalously young apatite cooling ages along the range-front (Adapted from Elhers and Farley, 2003).

A more comprehensive study of extension, exhumation and therefore advection in the footwall rocks of normal faults can be used to pinpoint "blind" geothermal resources. Recent work on genetic occurrence models for geothermal resources (e.g., Walker et al., 2005; Sabin et al., 2005) has identified thermochronometric ages as a potentially key element in exploring for areas that contain sufficient heat to constitute a utility-grade geothermal resource. As geothermal resources require advection of heat to the upper crust, cooling ages give critical insight into whether such advection has occurred by faulting, flow of hot fluids, or very rapid erosion (Figure 1.). This paper presents new results from the footwall of the central Wassuk Range fault block, Hawthorne, Nevada, in an attempt to illustrate the utility of this approach.

Geologic and Tectonic History

The Wassuk Range (Figure 2.) is a nearly N-S trending mountain range on the western margin of the Basin and Range Province at the latitude of Lake Tahoe. The entire range is characterized by several intact fault blocks composed of Mesozoic age plutonic rocks and Jurassic metavolcanics bounded to the east by high-angle normal faults (Dilles and Wright 1988; Dilles, 1992; Dilles and Gans, 1995; Surpless, 1999). Mesozoic metavolcanics and plutonic rocks in the central Wassuk Range are nonconformably overlain by Oligocene to Miocene age silicic ash-flow tuffs (e.g., Mickey Pass and Singaste), andesite flows (e.g., Lincoln Flat Andesite) and later Tertiary Wassuk Group sediments and ashflow tuffs.

The onset of crustal extension in the Wassuk Range was accommodated along east-dipping, high-angle normal faults and is bracketed by the westward tilting of the overlying Tertiary units. Extension postdates the extrusion of the Lincoln Flat andesite (15-14.8 Ma) and is synchronous with the deposition of the Tertiary Wassuk Group sediments (McIntyre, 1990; Dilles and Gans, 1995; Surpless, 1999). Similarly, apatite fission track and (U-Th)/He data for the northern and central Wassuk Range show the onset of rapid exhumation at ~15 Ma followed by renewed range-front faulting after ~4 Ma (Stockli et al., 2002; Surpless et al., 2002).

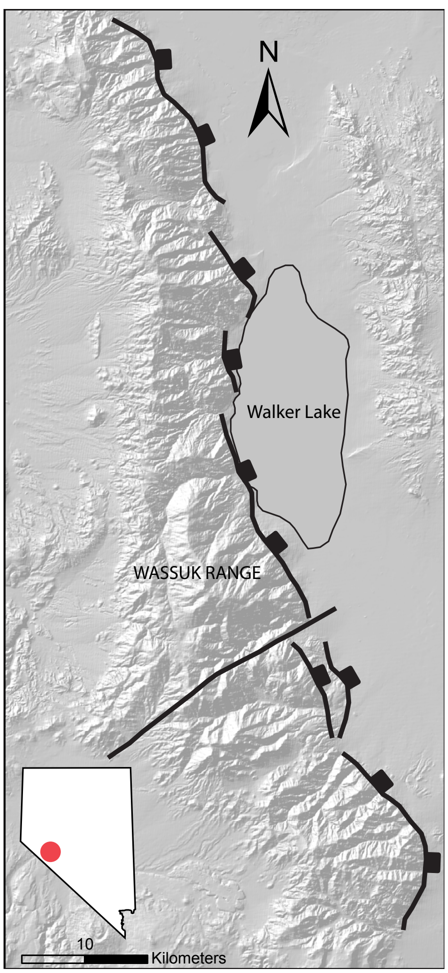

Figure 2. Generalized structure map of the Wassuk Range, Hawthorne, Nevada.

Methodology

(U-Th)/He dating of apatite is now a well-established thermochronometric technique and is widely applied in geological, stratigraphic, tectonic, and geomorphologic studies. (U-Th)/He dating is based on the decay of ^{235}U, ^{238}U, and ^{232}Th by alpha (^{4}He nucleus) emission. ^{4}He is completely expelled from apatite at temperatures above ~80°C and almost totally retained below ~40°C (termed the He Partial Retention Zone, PRZ). The thermal sensitivity of this system is lower than that of any other routinely used isotopic thermochronometer. Assuming a mean annual surface temperature of 10±5° C and a geothermal gradient of 25°C/km, the relevant temperature range is equivalent to depths of ~1 to 3 km (Stockli, 2005).

(U-Th)/He dating of zircon is also a well established thermochronometric technique. ^{4}He in zircon is completely expelled at temperature above ~193°C and retained below ~175°C (Dodson, 1973). (U-Th)/He dating of zircon, in conjunction with apatite cooling ages enables us to constrain thermal histories for samples within the upper ~8km of the crust.

Previous exploration has identified the presence of a geothermal cell within the hanging wall of the Wassuk Range block. A dense grid of (U-Th)/He thermochronometric samples were strategically collected along the range front and vertical transects in order to quantitatively assess the effects of the geothermal cell and to reconstruct tilting and exhumation history, respectively. (U-Th)/He ages were calculated for apatite and zircon crystals from each sample. Samples that experienced significant reheating due to percolation of hot geothermal fluids will be partially or completely reset during hydrothermal interaction. Spatial mapping of age deviations from expected results (e.g., volcanic emplacement age or depositional age) were constructed to better constrain the long-lived geothermal hotspot. Because of apatite's low-temperature thermal sensitivity, the apatite helium age profile for range front samples should mimic the lateral thermal gradient of the geothermal cell, where young ages correspond to areas which have been hottest most recently. Analysis of both the apatite and zircon (U-Th)/He thermochronometers with different closure temperatures allows for a more quantitative assessment of the thermal history of samples, magnitude of the thermal perturbation, and longevity of the thermal structure and hence the geothermal resource.

Discussion and Conclusions

Anomalously young apatite helium ages from the central Wassuk Range front clearly identify the presence of a geothermal cell (Figure 3.). Range front apatite cooling ages range between 15.5 and 1.9 Ma where the youngest ages correspond to those samples flanking the geothermal anomaly. The consequence of these data is increasingly apparent when apatite and zircon ages are compared with data across the entire range front, where again the youngest ages neighbor the geothermal cell.

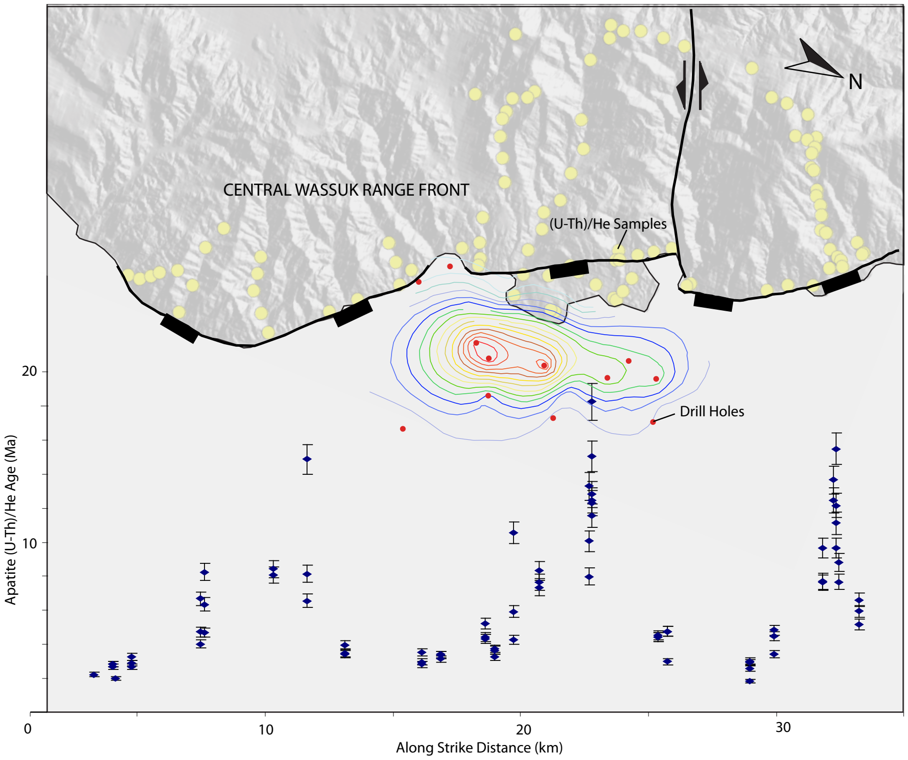

Figure 3. Along-strike apatite (U-Th)/He age distribution with relation to the Hawthorne geothermal anomaly. Apatite helium ages young as they approach the geothermal cell and highlight the location of a structurally displaced footwall.

Apatite helium ages of 8-15 Ma adjacent to the geothermal hot spot highlight structurally displaced slivers of Wassuk Range footwall. These faults were cut concurrently or subsequent to the latest stage of rapid exhumation at ~3.2 - 4.9 Ma (Figure 4.). The association of late-stage deformation with the geothermal cell is important since the production of structural fluid conduits is critical in the formation and longevity of a geothermal field.

It is currently unclear whether young apatite ages result from partial resetting by elevated temperatures in the hanging wall or are related to heterogeneous exhumation and therefore advection of footwall rocks. Zircon and apatite cooling ages along vertical transects reveal two structurally and temporally distinct fault blocks separated by an E-W trending fault with left-lateral oblique slip. Early extension (~15Ma) is evident throughout the range, but appears to be dominantly accommodated by westward tilting in the north and by E-W dip-slip in the south. Later extension (~4-6Ma), however, is prevalently accommodated south of the cross-fault. This late pulse of exhumation shows a significant geographical correlation with the Hawthorne geothermal anomaly.

Exploration for geothermal resources is expensive as it often requires the drilling of geothermal test holes to locate heat sources. This is especially true in areas where geothermal surface expressions are absent. (U-Th)/He dating of apatite can resolve complexities and unknowns in subsurface geometries and thermal evolution thereby significantly lowering exploration uncertainties and risks.

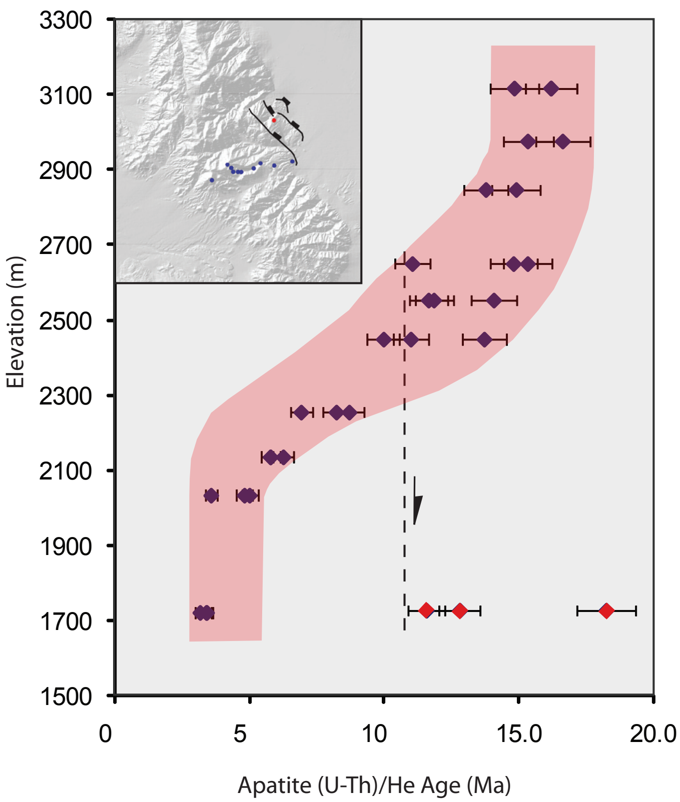

Figure 4. Plot of elevation vs. apatite (U-Th)/He cooling age showing the structural complexity of the Wassuk Range front and rapid exhumation of the footwall at ~ 15 Ma and ~3-5 Ma.

Acknowledgments

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