Is the Wasatch fault footwall (Utah, United States) segmented over million-year time scales?

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ABSTRACT

The Wasatch fault zone, Utah, is a 370-km-long segmented normal-fault system with topographic salients, depths of footwall exposure, geomorphic properties, and geophysical anomalies that suggest differential long-term footwall uplift and exhumation on segments that are partitioned by long-lived structural segment boundaries. Apatite (U-Th)/He ages from footwall samples along the range front from the five central footwall segments average 5.3 ± 1.0 Ma. Coupled two-dimensional thermokinematic and helium-diffusion models suggest average long-term (~5 m.y.) exhumation rates of 0.2–0.4 mm/yr for most of the Wasatch front. The exception is the southern end of the Salt Lake City segment, where exhumation rates are two times as great as elsewhere along the Wasatch front. The relatively invariant He ages and exhumation rates imply that most of the Wasatch did not behave kinematically as independent footwall-segment blocks with differential exhumation amounts over the past 5 m.y. The structural boundaries, such as salients and intrabasin highs that partially delineate segments, may have persisted since the Pliocene and controlled the locations of the surface-rupture segments.

Keywords: Wasatch Mountains, fault segmentation, exhumation, helium ages, thermochronology.

INTRODUCTION

Understanding fault segmentation in extensional terranes is important in terms of evaluating overall fault-system growth. For individual faults, displacement tends to scale with fault length (e.g., Walsh and Watterson, 1988), and the linkage of individual normal faults tends to form longer faults through time (e.g., Dawers and Anders, 1995; McLeod et al., 2000). Interpretations that shorter faults coalesce to form a single-acting fault system over time scales of 1 m.y. are suggested by numerical modeling (e.g., Cowie and Scholz, 1992) as well as studies of hanging-wall stratigraphic sequences (e.g., Schlische and Anders, 1996; McLeod et al., 2000). Fault segments are separated by boundaries (herein, ‘‘segment boundaries’’ refer to structural boundaries and not necessarily to barriers to earthquake rupture) that often are coincident with hanging-wall intrabasin highs, footwall salients, and footwall elevation variations. These boundaries have been interpreted as being persistent such that they separate regions of differential slip (e.g., Schwartz and Coppersmith, 1984; Wheeler and Krystinik, 1992) during overall fault growth; however, Anders and Schlische (1994) argued that there is not necessarily a slip differential at structural boundaries such as intrabasin highs.

Rock uplift, when combined with erosion, leads to exhumation of footwall rocks during prolonged normal-fault movement. Little work has been done to evaluate long-term segmentation of normal-fault systems by looking at footwall exhumation, even though segments often are recognized by footwall features that suggest persistent segmentation. We use apatite (U-Th)/He thermochronometry to evaluate along-strike variations in long-term (10^6 yr) footwall-exhumation rates adjacent to the Wasatch fault system, which has been the subject of many studies since the pioneering work of Gilbert (1928) and is arguably one of the most studied segmented normal faults in the world.

WASATCH GEOLOGY AND SEGMENTATION

The 370-km-long Wasatch fault zone is the major fault in the structural transition from the Basin and Range Province to the Colorado Plateau and Rocky Mountains (Fig. 1). The north-striking Wasatch fault zone consists of 45°–60° dipping normal faults that bound the western range front of the Wasatch Mountains. The Wasatch fault zone has been divided into at least 10 segments on the basis of geomorphic, topographic, geophysical, geodetic, and paleoseismic data (Swan et al., 1980; Schwartz and Coppersmith, 1984; Machette et al., 1991; McCalpin and Nishenko, 1996); the fault zone cuts rocks that range from Archean metamorphic to Tertiary sedimentary and volcanic rocks (Hintze, 1980). The five medial segments (Fig. 1) average 52 ± 13 km in length. Machette et al. (1992) outlined the main types of structural features of the boundaries as bedrock spurs that extend into the basin (salients), en echelon fault steps adjacent to bedrock, oblique intersections of fault traces, and long gaps in the fault zone. Salient and en echelon steps often are associated subsurface ridges, or intrabasin highs, in the hanging wall shown by gravity and magnetic anomalies (Zoback, 1983; Mabey, 1992). These structural boundaries are spatially coincident with the juxtaposition of rocks exhumed from deeper structural levels (e.g., Salt Lake City to Weber segments), major faults that cut across the range at segment boundary (e.g., Deer Creek fault at Salt Lake City to Provo segments) (Baker and Crittenden, 1961; Hintze, 1980; Bryant, 1990), changes in footwall drainage-basin properties (Mayer and Maclean, 1986), and changes in range-crest elevation (Fig. 2). Statistical analyses of the boundaries suggest that they have persisted since before the Quaternary (Wheeler and Krystinik, 1992), implying that the segments

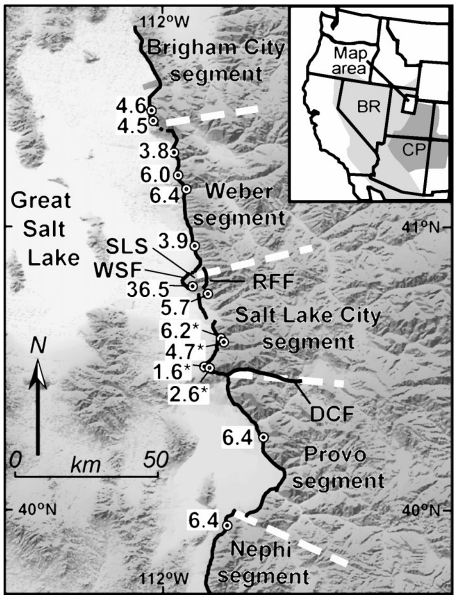

Figure 1. Map showing central Wasatch fault segments and apatite (U-Th)/He ages (in Ma). Solid line—Wasatch fault zone; dashed white lines—approximate segment boundaries; asterisks—ages from Armstrong et al. (2003). RFF—Rudys Flat fault; WSF—Warm Springs fault; DCF—Deer Creek fault; and SLS—Salt Lake salient. Inset map shows location of study area at boundary between Basin and Range (BR) and Colorado Plateau (CP) Provinces.

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Geology; May 2004; v. 32; no. 5; p. 385–388; doi: 10.1130/G20421.1; 3 figures; Data Repository item 2004064.

have independent, long-term uplift and exhumation histories, a hypothesis we test in this paper.

Considerable progress has been made in addressing Wasatch fault displacement rates for Holocene time scales (e.g., Machette et al., 1991, 1992; Chang and Smith, 2002) where vertical interevent displacement rates of well-constrained fault segments vary between 0.8 and 1.5 mm/yr. At 10^5 yr time scales, sparse displacement-rate estimates are low at 0.1–0.3 mm/yr (Machette, 1984; Friedrich et al., 2003), but displacement-rate variations on intersegment faults are poorly constrained. At 10^6 yr time scales, the southern Salt Lake City segment adjacent to the fault has been exhumed at a vertical rate of 0.8–1.2 mm/yr (Ehlers et al., 2003), but fission-track data from the Weber segment imply a slower exhumation rate of ~0.4 mm/yr (Naeser et al., 1983). Work on the Wasatch unroofing history has primarily focused on the southern Salt Lake City segment, where eastward tilt caused as much as 11 km of exhumation in the past 16 m.y. (Parry and Bruhn, 1987; John, 1989). Eastward tilt of the rest of the Wasatch is suggested by east-dipping Tertiary rocks along the east side of the Wasatch Mountains (Bryant, 1990; Coogan and King, 2001). Uplift of the southern Salt Lake City segment footwall is often used as an example to evaluate large-scale processes of extensional development, such as the role of isostasy (e.g., Wernicke and Axen, 1988); thus it is important to investigate along-strike variations in rate and magnitude of exhumation of the range front as a whole.

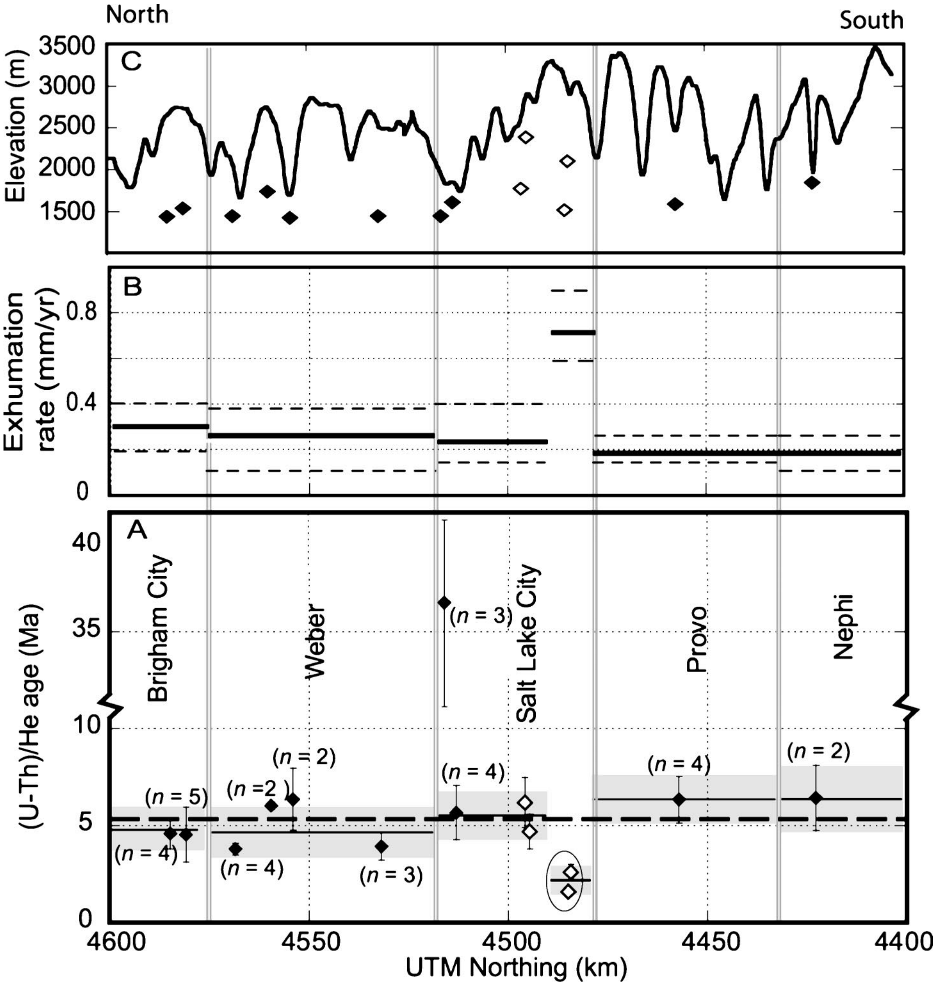

Figure 2. Plots of various data along trend of Wasatch fault. A: Average apatite (U-Th)/He ages. Solid horizontal lines and shaded areas show average ages and 1σ uncertainties for each segment; dashed line shows average age of 5.3 ± 1.0 Ma for all samples, excluding circled anomalous ages on southern Salt Lake City segment and 36.5 Ma age on Salt Lake City salient; *n* = number of single-grain ages for each sample. Hollow diamonds are multiple-grain furnace ages from Armstrong et al. (2003). Note that age scale is broken. B: Long-term (over ~5 m.y.) exhumation rates. Solid bold lines are average exhumation rates; dashed lines show possible range of rates based on spread of ages within each segment. C: Sample and range-crest (solid curve) elevations vs. distance (UTM—Universal Transverse Mercator).

APATITE (U-Th)/He THERMOCHRONOLOGY AND METHODS

(U-Th)/He dating is based on the diffusion and retention of ^{4}He produced by the radioactive decay of ^{235}U, ^{238}U, and ^{232}Th (e.g., Zeitler et al., 1987; Wolf et al., 1996; Farley, 2000). At geologic time scales, helium is completely expelled from apatite above 85 °C and is retained almost entirely below 40 °C, and the system has a closure temperature of ~70 °C (Farley, 2000). In the simplest sense, a helium age can be thought of as the time when a sample passed through the closure temperature during ascent to the surface; exhumation rate can then be deduced by assuming a geothermal gradient. Rather than assuming vertical exhumation and a simple closure temperature, we utilize the two-dimensional thermokinematic and He-diffusion model results of Ehlers et al. (2003), which was developed to predict exhumation rates across the southern Salt Lake City segment. The model accounts for the transient thermal regime across a normal fault during long-term displacement. It tracks the ascent of samples from depth to the surface for different fault slip (or exhumation) rates, and the He-diffusion algorithm accounts for He diffusion during cooling.

We report 10 new He ages and utilize 4 other He ages from Armstrong et al. (2003) for samples collected from the 5 central segments along the range front and adjacent to the Wasatch fault zone (Figs. 1 and 2), mostly at elevations between 1500 and 1800 m. Two samples from the southern Salt Lake City segment are from elevations of >2000 m (Fig. 2). A nearby He age versus elevation transect shows that He age versus elevation adjustments for this area are ~0.8 m.y./km of elevation increase (Armstrong et al., 2003). Thus, the He ages of the higher-elevation samples may be ~0.4 m.y. too high, but this possible error does not affect the results of this paper. For each segment, He ages were measured for 1–4 samples from sandstone, volcanic breccia, quartz monzonite, granitic gneiss, and granitic boulders in tillite (Table DR1[1]). Single-grain He ages (2–5 per sample) were determined by using laser heating at the California Institute of Technology (House et al., 2000) and then averaged to yield a mean sample He age (Table DR1; see footnote 1). The four samples from the southern Salt Lake segment (Figs. 1 and 2) are multiple-grain furnace He ages measured in the same laboratory as the single-grain ages (Table DR1; see footnote 1).

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[1] GSA Data Repository item 2004064, Table DR1, apatite (U-Th)/He ages and rock types with notes on techniques, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

He AGE RESULTS

Six samples from the Brigham City and Weber segments have He ages of 3.8 ± 0.3 to 6.4 ± 1.6 Ma (Fig. 2). Most of the age variability is in the Weber segment, where samples from the northern and southern ends of the segment have similar ages of 3.8 ± 0.3 and 3.9 ± 0.7 Ma and the samples closer to the center of the segment have overlapping ages of 6.0 ± 0.2 and 6.4 ± 1.6 Ma (Fig. 2). The average He ages for the Weber and Brigham City segments are 4.7 ± 1.3 Ma and 4.9 ± 1.1 Ma, respectively.

Salt Lake City segment He ages display considerable variation. A Tertiary volcanic breccia on the Salt Lake salient has an He age of 36.5 ± 5.1 Ma (Fig. 2), which is concordant with a zircon fission-track age of 35.3 ± 1.6 Ma and a biotite potassium-argon age of 37.7 ± 1.1 Ma (Van Horn, 1981). This He age records the age of deposition and indicates that this unit has been buried <1 km, because at greater depths He would diffuse out of the apatite, which would lead to younger ages. A sample from just east and across the Rudys Flat fault (Fig. 1) yields an age of 5.7 ± 1.4 Ma, which is consistent with ages of 6.2 ± 1.9 and 4.7 ± 0.9 Ma farther south (Figs. 1 and 2). The age discrepancy between the 36.5 Ma sample and other segment ages indicates that most of the long-term exhumation of this part of the Wasatch was accommodated on the Rudys Flat fault and prior to activation of the Warm Springs fault on the west side of the Salt Lake salient (Fig. 1). He ages at the southernmost end of the Salt Lake City segment are 1.6 ± 0.2 and 2.6 ± 0.4 Ma. These ages are about half of those farther north along the Salt Lake City segment (excluding AT00-18) and imply considerable differences in exhumation history along this segment. Farther south, the Provo and Nephi segment He ages are 6.4 ± 1.2 and 6.4 ± 1.7 Ma, respectively. Only one age was determined on each of the Provo and Nephi segments because of the lack of suitable rock types along the segments. These ages are thought to be representative of each segment because the rock types are consistent along the segments (mostly Pennsylvanian–Permian sedimentary rocks; Hintze, 1980), indicating a lack of structural relief change, and little exhumation difference, along each segment.

The average He age along the base of the Wasatch mountain front is 5.3 ± 1.0 (1σ) Ma when the anomalous ages at the northern and southern ends of the Salt Lake City segment are not considered (Fig. 2). This relatively narrow age range for most of the mountain front leads to important implications about long-term footwall segmentation of the Wasatch fault.

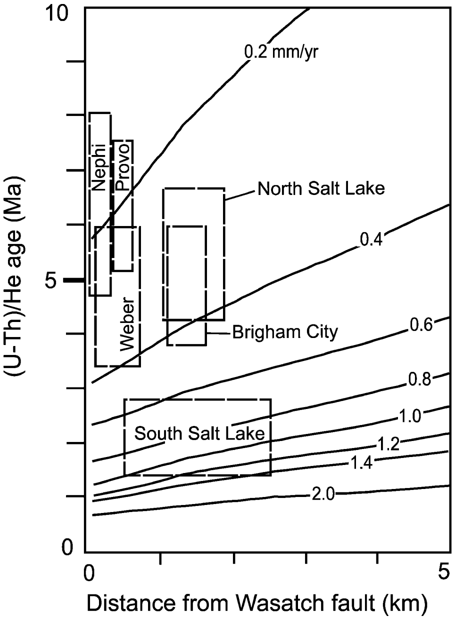

Figure 3. Predicted (U-Th)/He age for different range-front exhumation rates (labeled in mm/yr on diagonal lines) as function of distance east of surface expression of Wasatch fault (after Ehlers et al., 2003). Boxed regions encompass He ages and approximate distances from surface exposure of Wasatch fault within each segment. South Salt Lake box includes only two southernmost samples along Salt Lake City segment.

MOUNTAIN-FRONT EXHUMATION RATES

Exhumation rates in Figure 2 were determined by using modeled mountain-front exhumation rates from Ehlers et al. (2003) (Fig. 3). We assume that the entire Wasatch footwall block is tilted eastward in a manner similar to that of the southern Salt Lake City segment. Because this model assumes tectonic unroofing, depth locations where ascending samples cross the closure-temperature isotherm are under the hanging-wall valley rather than under the eroding footwall block (Fig. 3A), and the ages are influenced little by footwall ridges and canyons. For the Brigham City, Weber, and northern Salt Lake City segments, exhumation-rate estimates overlap and range from <0.2 to 0.4 mm/yr. This rate is consistent with the rate of 0.4 mm/yr based on Weber segment fission-track ages (Naeser et al., 1983). Southern Salt Lake City segment exhumation rates are 0.6–1.0 mm/yr. Farther south along the Provo and Nephi segments, exhumation rates are lower, 0.13–0.30 mm/yr. Thus, the mountain-front exhumation rate for most of the Wasatch Mountains is ~0.2–0.4 mm/yr, which is consistent with Pleistocene fault-slip rates of 0.1–0.3 mm/yr of Machette et al. (1992).

DISCUSSION AND IMPLICATIONS

The similar He ages and exhumation rates along most of the range front are consistent with the Wasatch footwall segments not acting independently, on average, over the past 5 m.y. The only exception is the Provo–Salt Lake City segment boundary, where there are significantly different long-term exhumation rates and where the east-striking Deer Creek fault extends across the footwall block (e.g., Baker and Crittenden, 1961; Bryant, 1990). The more rapid exhumation on the southern Salt Lake City segment seems to be local, such that this area tilted both eastward and northward (Armstrong et al., 2003), and so deeper structural levels are exposed at the south end of the segment.

The structural segment boundaries may have persisted for the past ~5 m.y., but there has been little difference in average segment-exhumation rate or magnitude; most of the central part of the Wasatch mountain front has been mechanically linked during this time. The structural boundaries and differences in exhumation magnitude must have formed earlier than ca. 5 Ma, perhaps during early to middle Miocene rapid unroofing elsewhere in the Great Basin (e.g., Dumitru et al., 1997).

The persistent structural boundaries can form rupture-propagation barriers (Bruhn et al., 1992) that control the locations of late Quaternary surface ruptures. Readjustment of the footwall block to capture or abandon hanging-wall sections, however, can cause changes in the structural boundaries that then cause changes in the surface ruptures. This type of readjustment is shown well by the Salt Lake salient, which is part of a persistent intrabasin high extending westward away from the Wasatch fault beneath the hanging-wall sedimentary rocks (Wheeler and Krystinik, 1992). The surface-rupture location changed at the same time as salient growth, as shown by the abandonment of the Rudys Flat fault to form the active strand of the Wasatch fault and uplift of the Salt Lake salient (Fig. 1). Prior to the abandonment of the Rudys Flat fault, rocks of the salient would have been buried <1 km (to not reset the He age).

Wasatch fault segments have been partly defined on the basis of range-crest elevation changes (e.g., Schwartz and Coppersmith, 1984) and correlated with variations in drainage-basin properties (Mayer and Maclean, 1986). The mostly invariant He ages indicate that footwall-block relief and other topographic characteristics are poor indicators of long-term segmentation. Topographic characteristics probably are controlled more by rock strength than exhumation rate. This interpretation is consistent with the landscape-evolution modeling of Ellis et al. (1999) that shows that relief is dominantly strength limited in Basin and Range topography. Additionally, footwall width perpendicular to range trend may also control overall relief. The Weber and Brigham City segments are made up of resistant metamorphic rocks, but display relatively low relief. These segments are narrow compared to the other footwall segments, and they may be unable to flexurally support the higher elevations that other, wider, segments can for the same long-term rate of uplift and exhumation.

ACKNOWLEDGMENTS

This project was funded by National Science Foundation grant EAR-9805073 and a California State University, Fullerton, minigrant. We thank K. Farley for sample analyses. L. Hedges helped with sample preparation and analysis. N. Dawers provided insightful comments.

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Manuscript received 15 December 2003
Revised manuscript received 14 January 2004
Manuscript accepted 16 January 2004

Printed in USA