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Tectonics from topography: constraining spatial and temporal landscape response rates to Teton fault activity using low-T thermochronology, quantitative geomorphology, and limnogeologic analyses

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Abstract Understanding how landscapes respond to tectonic and climatic forcing over a range of timescales remains a top priority for studies in tectonics, geomorphology, and geodynamics. To examine this, we are attempting to separate signals that define uplift, drainage incision, and sediment flux at multiple timescales (10^7 to 10^2 yrs). The Teton Range serves as an ideal natural laboratory for filtering this interplay due to its comparatively small size and consistent along-strike climatic variation. Recent studies indicate that Teton fault motion first initiated near Mount Moran at ∼13 Ma in the northern portion of the range and slip onset gets younger to the south. No major climatic variations occur along strike, so tectonic forcing is interpreted to be the primary driver of landscape evolution. To test this hypothesis, we are evaluating 'lag' between fault slip onset and incision of drainages using AHe techniques combined with quantitative landscape analysis to constrain long-term response and analyzing seismic reflection and core data from range front lakes to determine sediment volume flux over shorter intervals. Preliminary data from a seismic survey completed in August 2018 reveals multiple depocenters in Jackson Lake. Results from the seismic survey and AHe analysis should be available in Spring 2019.

Introduction

The rate of landscape response to changes in tectonic forcing determines how landscapes 'record' tectonic processes, and thus the sensitivity of this response represents a fundamental hurdle to accomplishing the longstanding goal of deriving 'tectonics from topography' (e.g. Wobus et al., 2006; Miller et al., 2012). Ultimately, understanding this time-integrated coupling between tectonic (or climatic) forcing and the subsequent landscape response remains one of the greatest challenges in tectonics and geomorphology (Tucker, 2009). This enigma persists primarily because interactions between tectonics, climate, and the landscape response is two-way coupled (Whittaker, 2012) and understanding the nature and rate of landscape response across a range of timescales requires that these processes can be documented in landscape features that represent a variety of nested temporal scales (e.g. Dadson et al., 2003). At the temporal wavelength of mountain range growth and decay, low-T thermochronologic techniques such as apatite U-Th/He (AHe) and apatite fission track (AFT) yield long-term 'averaged' response times. However, it remains unclear if these time averaged rates are representative of erosional and exhumational processes operating over shorter temporal wavelengths, such as those documented by cosmogenic and radiochemical techniques and those preserved in the detrital record of Quater-

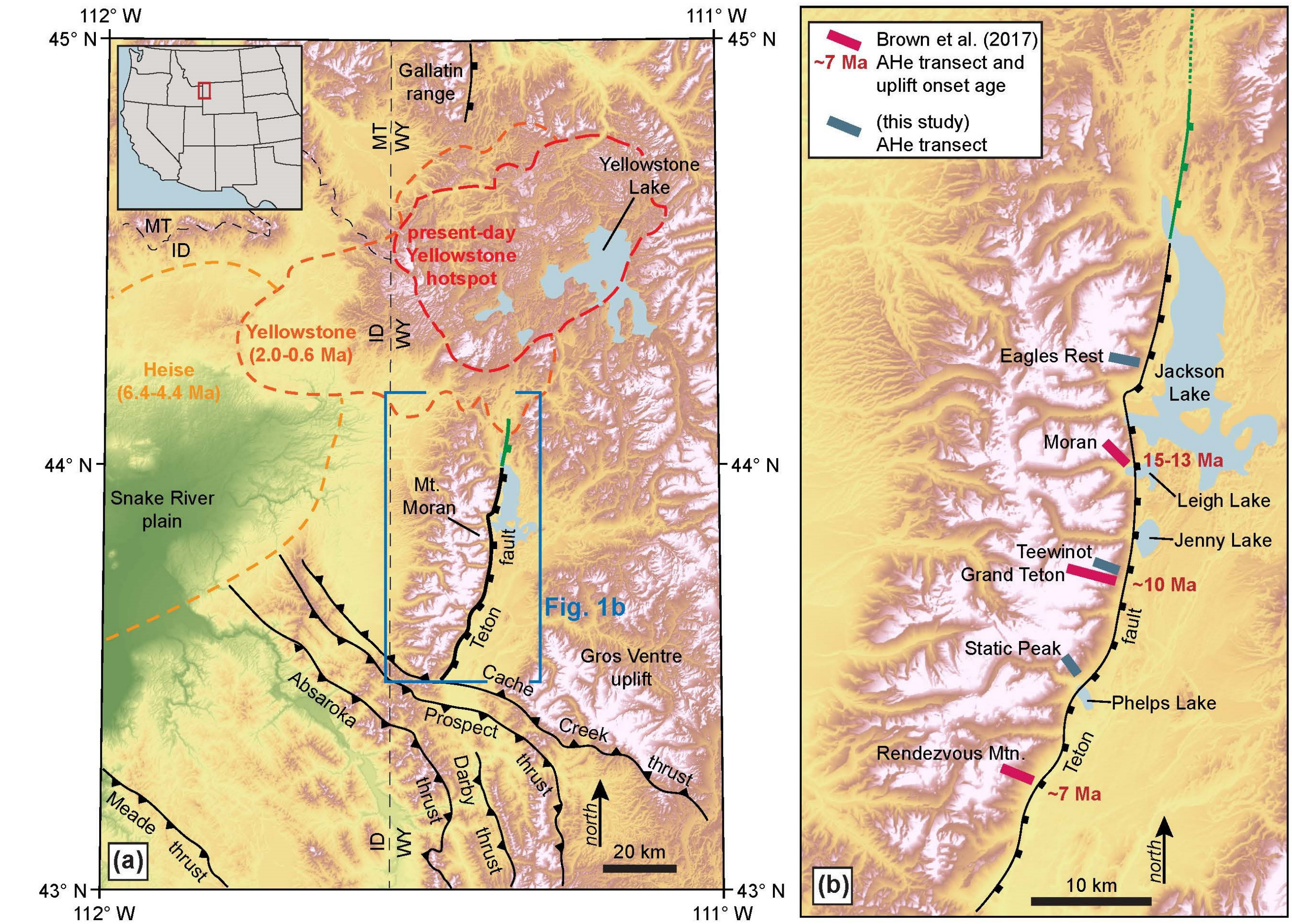

Figure 1. (a) Regional digital elevation model (DEM) of the Greater Teton-Yellowstone region. Positions and time intervals of the Yellowstone plume is shown. Apparent truncation of the Sevier belt by the Heise (6.4-4.4 Ma) volcanic center is also shown. (b) DEM of the Teton Range overlain with the positions of subvertical AHe transects of Brown et al. (2017) and the modeled fault slip onset ages (red) that were used to identify Mount Moran as the likely center of the Teton fault. Subvertical transects shown in blue were collected during this study and are still being analyzed.

nary moraines and even more recent lake sediments (Twichell et al., 2005; Larsen et al., 2016). Thus, to execute these natural experiments and resolve these signals, it is necessary to identify study areas that allow for first-order boundary conditions such as tectonic forcing to be constrained independently (Tucker, 2009; Whittaker, 2012).

The Teton Range in Wyoming (Figure 1a), which results from motion on the crustal-scale Teton fault, represents an idealized natural laboratory to examine linkages between these processes. In this region, pronounced along-strike variations in long-term fault slip onset timing, duration, and rate are carefully documented (Brown et al., 2017), thus constraining this first-order tectonic boundary condition. Additionally, there are few places in the world where such a simple active structural system is preserved and the along-strike variability in this first-order tectonic boundary condition provides a unique opportunity to examine how the landscape response varies with changes in tectonic forcing across a range of temporal scales.

Research Plan and Methods

In order to reconcile the long-term and short-term landscape response to variations in tectonic forcing, it is necessary to examine the along-strike vari-

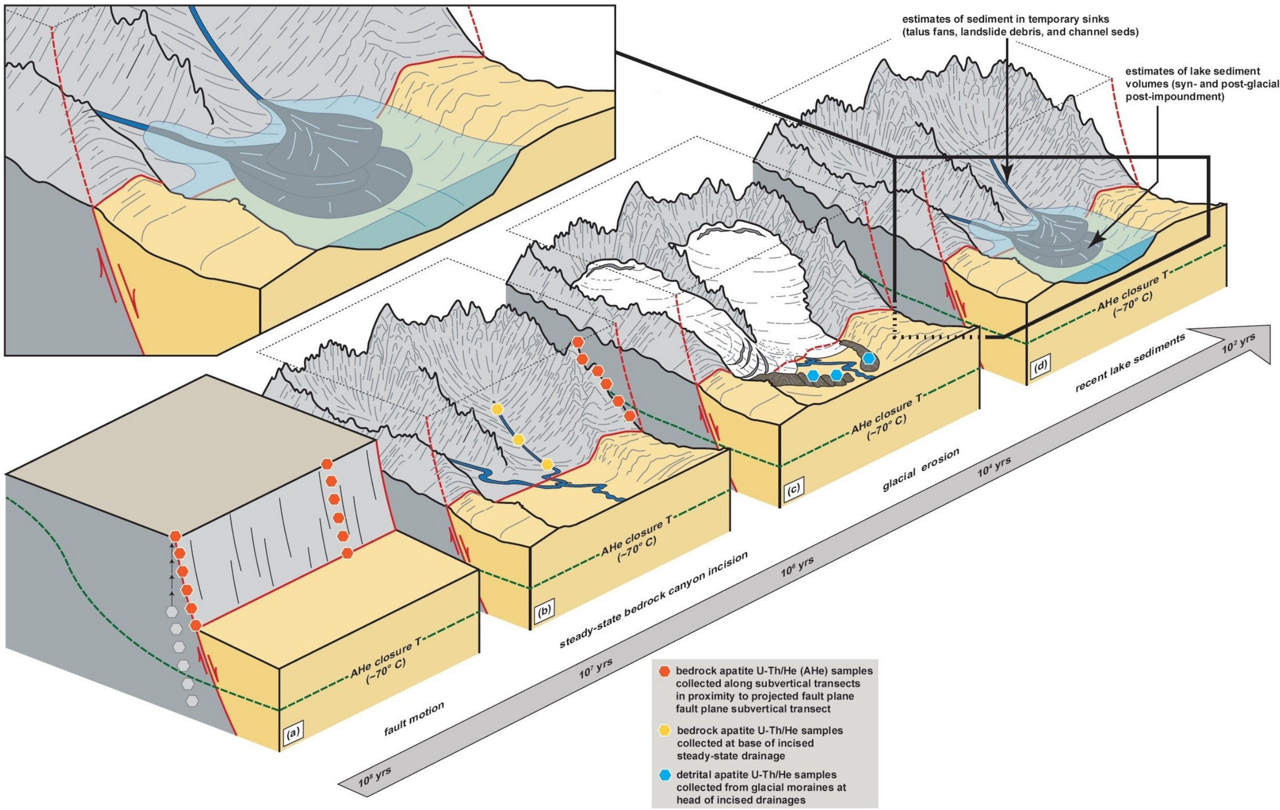

Figure 2. Understanding the nature and rate of landscape response due to tectonic forcing across a range of timescales requires both that the tectonic forcing is well-characterized and that these processes can be documented in landscape features that represent a variety of nested temporal scales. (a) Theoretically, low-T thermochronologic (AHe) analysis of samples collected along subvertical transects on or structurally adjacent to the projected fault plane can record the timing of fault motion and the variability in such motion along strike. (b) At the longest erosional timescales of 106-7 years, comparison of bedrock AHe ages collected along the floor of major drainages with ages of fault-related uplift onset provides the long-term 'lag' of landscape response. (c) At erosional timescales of 104-5 years, erosion and valley incision rates can be derived from detrital AHe age signals preserved in glacial features such as moraines. (d) At the shortest timescales, the erosional mass efflux removed from the uplifted system is recorded in lake sediment packages. Such lake fan packages record the efflux at the 103 and 102 year timescales for volumes of sediment preserved between the pre-glacial, post-glacial, and post-modern impoundment surfaces. To document these volumes, this project will use seismic CHIRP surveys of the glacial lakes on the east side of the Teton Range. Seismic stratigraphy will be tied to lithofacies descriptions of long-cores collected in representative sedimentary packages identified during seismic surveys.

ation in the erosion rate and system mass efflux in a range of bedrock and detrital features that serve as proxies for different nested temporal scales and across a range of drainage morphologies (Figure 2). To do this, we have begun a number of research objectives, including: (1) supplementing the Brown et al. (2017) AHe dataset with three new subvertical transects at Eagles Rest, Teewinot, and Static Peak (Figure 1b) to refine the spatial variability in fault slip onset, duration, and rate, (2) continuing quantitative landscape analysis, including 3-D thermal-kinematic surface modeling, river longitudinal profiles and knickpoint identification, to determine the distribution of steady versus non-steady state drainages in the Teton Range, (3) using the analysis from (2), identifying steady-state drainages to be

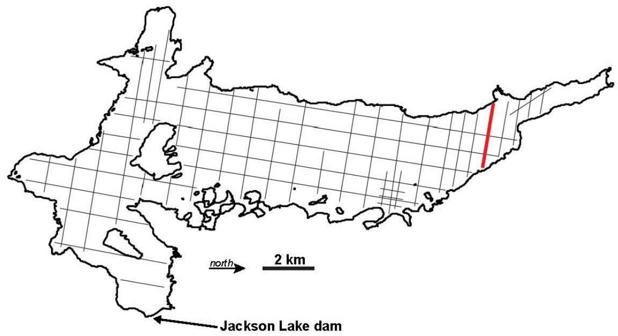

Figure 3. August 2018 seismic reflection survey track line map for Jackson Lake.

sampled for bedrock AHe thermochronology to establish the long-term landscape response (10^6 to 10^7 years) by comparing ages of fault slip and drainage incision in adjacent locations, and (4) determining the volume of sediment preserved between syn- and post-glacial (104 years timescale) and post-modern impoundment (10^2 years timescale) surfaces using CHIRP seismic reflection profiling (Larsen et al., 2016; Twichell et al., 2005).

During the summer 2017 field season, we collected samples for AHe analysis from three new subvertical transects, including Static Peak, Teewinot, and Eagles Rest Peak to address objective 1. Additionally, we collected samples for AHe analysis from Granite, Death, Avalanche, Cascade, Paintbrush, and Webb Canyon, to address objective 3 (Figure 1b). $^{4/3}$He, ^{238}U, ^{235}U, and ^{232}Th were measured at the University of Illinois Helium Analysis Laboratory. Individual grains were packed in Nb tubes and He was measured in each sample by outgassing in a Santa Cruz laser microfurnace at ~1000° C for three minutes. U and Th were measured using isotope dilution and quadrupole mass spectrometry. Results from these samples are still being analyzed and should be available in Spring 2019, thus they are not discussed in this contribution.

The final component of this work was to use lake seismic surveys to address objective 4. Profiles were spaced ~1 km apart and were collected in both the range strike and dip direction (Figure 3). Higher resolution infill surveys were conducted where necessary. All seismic CHIRP data was collected using an Edgetech SB-0512i sub-bottom profiler with a model 3200 topside processor and integrated dGPS. Shot points were collected every 2 seconds (~3 kt underway speed), and digital signals were recorded as SEG-Y files. The Edgetech 3200 acquisition system allows the source frequency to be modified within the range of 0.5-12.0 kHz. Our experience in glacial lakes has found the swept frequency range of 0.5-2.7 kHz provides an excellent balance between vertical resolution and penetration depth in both lacustrine muds and underlying/intercalated glacial or deltaic sands and gravels (McGlue et al., 2017). Given the coarse sediment supplied to the northern axis of Jackson Lake by the Snake River delta and the dense lacustrine clays reported by Pierce and Colman (1986), this requires coherency filtering, gain controls, and muting. All processing is being carried out at the University of Kentucky using HYPACK and Seisware software.

Preliminary Results

During the summer 2018 field season, we collected a high-resolution geophysical survey of Jackson Lake (Figure 3) to accomplish the first phase of objective 4. A total of >70 km of seismic profile data was collected. Although a number of these lines are still being processed, we have included example results (Figure 4). In this survey, we had two primary goals. Our first goal was to capture the geometry and volume of sediments exposed above the acoustic basement, which we interpreted to possibly represent the glacial-post glacial sediment boundary that will be verified by later core acquisition and geochronologic analysis. The second objective was to use seismic stratigraphic analysis to identify the "Dambrian" surface, representing the transition from pre- to post-impoundment sedimentation, and determine the volume of sediment stored above this boundary to produce estimates of sediment flux for the past 100 years. As with the glacial-post glacial surface, ground truthing this contact with a core acquisition program and geochronologic analysis represents the next phase of this work.

In Jackson Lake, sediment distribution is clearly controlled by the evolution of major structures associated

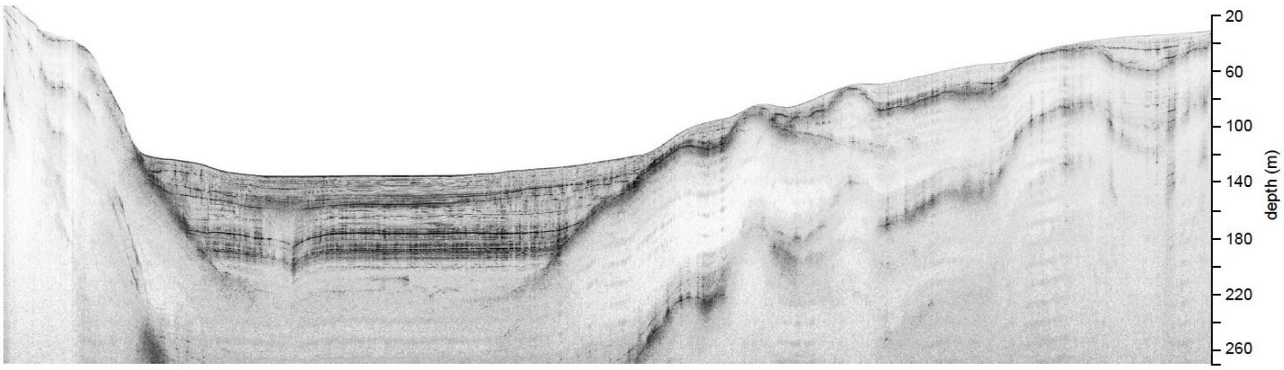

Figure 4. Preliminary CHIRP seismic reflection profile from Jackson Lake. Depths based on time-depth conversion that includes a sediment velocity of 1500 m/s.

with the Teton fault system. In our preliminary results, there are multiple major depocenters and numerous smaller sediment accumulations, including 'perched' basins on the edge of the larger faulted depocenters (Figure 4). Future seismic processing and mapping will allow us to further define the sedimentary and structural architecture of this basin. Also, core acquisition and geochronology will allow us to define the intervals and determine the eroded volume of material derived from the range from the short-term timescales, which can then be compared to estimates of long-term erosion determined by Brown et al. (2017) and for AHe analysis of samples collected by this study.

Conclusions

Understanding how landscapes respond to changes in tectonic and climatic forcing remains as one of the greatest challenges in tectonics and geomorphology. Specifically, the rates at which landscape erosion and exhumation are able to respond to transient changes in forcing (such as fault slip and subsequent tectonic uplift) over multiple timescales remains poorly constrained. To better understand feedback relationships between tectonics, climate, and landscape response, we separate the signals that define uplift, drainage incision, and sediment flux at multiple timescales. The Teton Range serves as an ideal natural laboratory for filtering this complex interplay due to its comparatively small size and consistent along-strike climatic variation. Recent AHe data collected along multiple subvertical transects in the Teton Range indicate that Teton fault motion first initiated near Mount Moran at ~13 Ma in the northern portion of the range and slip onset gets younger south of Mount Moran (10 Ma and 7 Ma at the Grand Teton and Rendezvous, respectively). As there are no indications that major climatic variations occur along strike, tectonic forcing is interpreted to be the primary driver of landscape evolution. When complete, this study will test this interpretation by comparing landscape response times over multiple temporal scales. To do this, we will: (a) evaluate 'lag time' between fault slip onset and deep incision of major drainages using AHe techniques to determine long-term ($10^{6\text{-}7}$ yrs) landscape response, (b) using quantitative landscape analysis, including river profile analysis and 3-D thermal-kinematic modeling calibrated to AHe ages from incised drainages to further evaluate the long-term landscape response, (c) analyze seismic reflection profiles calibrated by sediment cores from the range front lakes to determine the volume flux of sediment over the shortest time intervals ($10^{4\text{-}2}$ yrs). A seismic survey completed in August 2018 reveals multiple depocenters in Jackson Lake and 'perched' basins on the edge of major fault-bounded grabens. Processing of all seismic lines continues and should be completed in Spring 2019. Additonally, all AHe samples have been collected and are currently being processed for thermochronologic analysis. Similar to the seismic data processing and interpretation, we expect the AHe analysis to be completed in Spring 2019.

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