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Determination of Teton Fault slip rates using surface exposure dating of fault-offset glacial landforms in Grand Teton National Park

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Abstract The central goal of this project is to establish direct constraints on time-integrated slip rates along the trace of the Teton fault in Grand Teton National Park. The key research strategy is to develop cosmogenic ^{10}Be surface exposure ages of glacial deposits bisected by the fault – in particular lateral moraines along the eastern Teton Range front – and to combine these landform ages with precise geomorphic measurements of postglacial fault scarp offsets on these features as determined from field surveys and analyses of newly available LiDAR data. Time-integrated slip rates on the Teton fault will then be derived from the amount of tectonic displacement on the dated lateral moraines. Improved constraints on the rate of tectonic activity along the Teton fault resulting from this project are anticipated to lead to better-informed geologic hazard assessment in the park and adjacent regions. Furthermore, the moraine chronologies developed in this work will advance our understanding of the late Pleistocene glacial and paleoclimatic history in Grand Teton National Park and more broadly in the northern Rocky Mountains.

Justification and Scope

Prior work on Teton fault slip rates

The Teton fault is a prominent and striking feature that cuts across the length of Grand Teton National Park (Figure 1). The fault has played a central role in the past and ongoing geologic development of the Teton Range and its spectacular landscapes (Love et al., 1992). Clear evidence of Holocene tectonic activity along the fault attests to potentially significant geologic hazards in a heavily visited national park and adjacent populated regions. And yet, surprisingly few previous studies have attempted to derive quantitative estimates of long-term offset rates and recent tectonic activity along the Teton fault. Moreover, slip rates estimated in these prior studies have been limited by the paucity and/or lack of direct age control on measured fault displacement events.

The late Cenozoic history of the fault can be inferred from the age and attitude of originally horizontal volcanic and sedimentary rocks found at Signal Mountain, where the Kilgore Tuff (4.45 ± 0.05 Ma) and older units dip about 22° into the fault whereas the Huckleberry Ridge Tuff (2.053 ± 0.006 Ma) is tilted 11° into the fault (Morgan et al., 2008; Pierce et al., in press). Various published estimates for total stratigraphic displacement along the fault imply long-term vertical slip rates ranging from 0.5 to 1.2 m/kyr (Love, 1977; Smith et al., 1993; Byrd et al., 1994). Vertical surface offsets measured from scarps in glacial landforms range from 30 m near the central part of the fault to 15 m or less toward the north and south. In the absence of direct landform dating, previous authors have assumed an age of 15 ka for these scarps to define postglacial vertical displacement rates of up to ~2 m/ka. More recent paleoseismic events were examined by trenching across the southern Teton fault

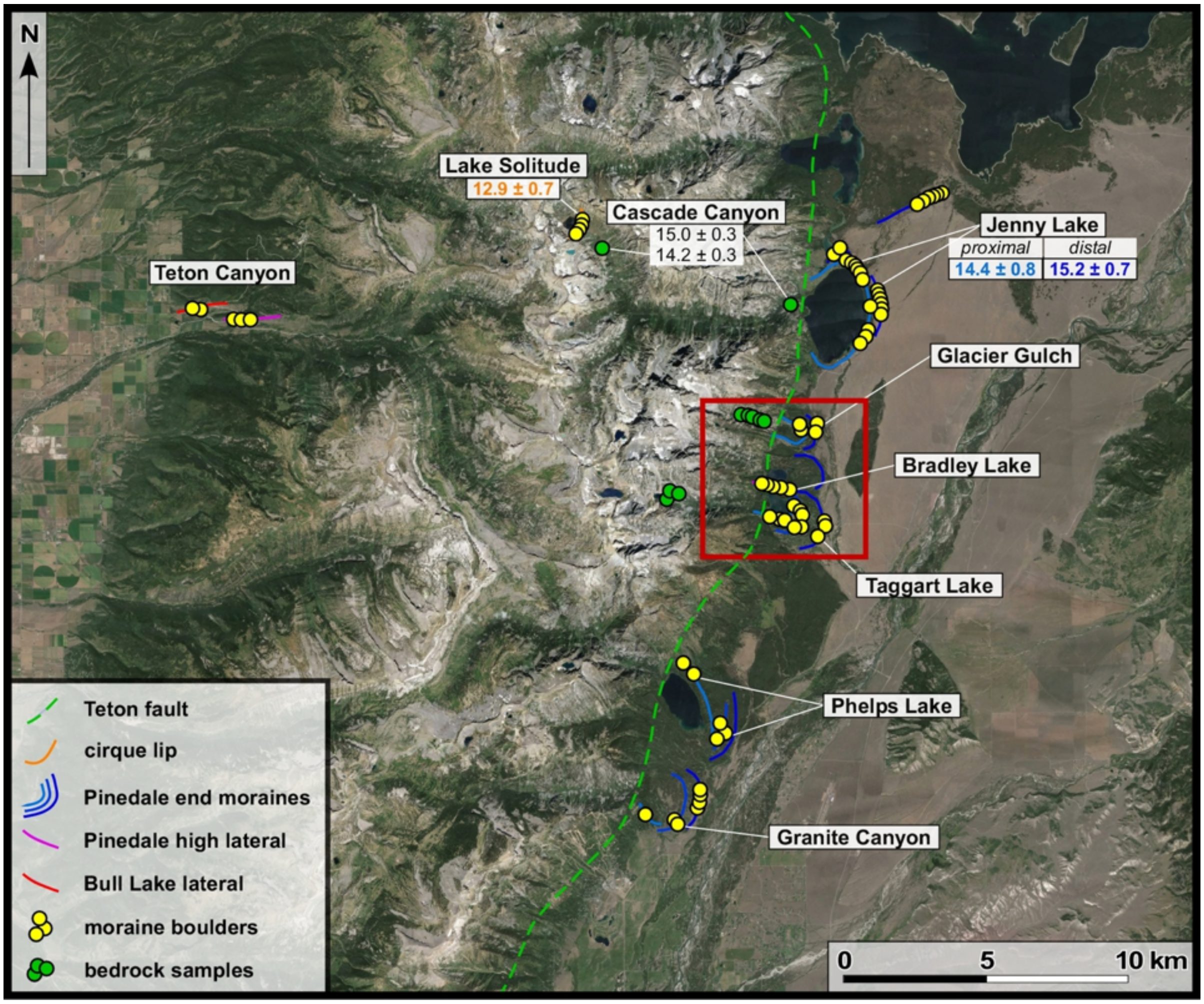

Figure 1. Compilation map of moraines and study sites in the Teton Range. Mean ^{10}Be exposure ages (expressed in ka) of Jenny Lake, Cascade Canyon, and Lake Solitude sites are recalculated from Licciardi and Pierce (2008). Enlargement of area in red box shown in Figure 2. Base map from Google Maps.

at Granite Creek, which revealed 2.8 m of vertical offset in sediments dated at 8 ka and 1.3 m of vertical offset in units dated at 5 ka (Smith et al., 1993; Byrd et al., 1994). Vertical surface offsets in glacial landforms near the trenching site are 15 m. Collectively, these observations suggest vertical displacement rates of 1.5 m/kyr from 15–8 ka, 0.51 m/kyr since 8 ka, and 0.26 m/kyr since 5 ka. Additional insights on possible trends in Teton fault behavior during the late Pleistocene and Holocene come from modeling work by Hampel et al. (2007), who performed numerical simulations that predict generally slower slip during glacial loading and faster slip during deglacial intervals.

The approach followed in this research to define offset rates along the Teton fault (described in detail in the Methods section) has several advantages over previous attempts:

- We will directly date glacial landforms offset by the fault using geochronologic techniques capable of yielding centennial-scale age resolution.
- We will take advantage of the opportunity to directly date multiple features cut by the fault along its trace from north to south with a range of displacement amounts, which will enable identification of spatial patterns in slip rates along the fault.
- Examination of scarps in landforms likely to span

a range of distinctly different ages will allow us to define temporal variations in slip rates, although our estimates will necessarily be time-integrated over the age of the offset landforms.

- Results from this project will provide an integral component in a planned synthesis of evidence from land-based geophysical surveys (Thackray and Staley, 2017), detailed fault trace mapping (Zellman et al., 2016), and lake sediment core proxy records of glacial and seismic activity (Larsen et al., 2016) to more comprehensively characterize Teton fault behavior and potential future hazards.

Relationships with late Pleistocene glacial history

At its Pleistocene maximum, the greater Yellowstone glacial system consisted of an ice cap on the Yellowstone Plateau joined by glaciers from adjacent high mountains, including the Teton Range (Pierce, 1979; Licciardi and Pierce, 2008). Although the Tetons harbored a relatively small portion of the greater Yellowstone ice complex, valley glaciers in this range left behind some of the region's best-preserved moraine sequences and scoured bedrock (Figure 1). Ongoing investigations are focused on developing moraine chronologies in several drainages on the eastern and western Teton Range fronts, and obtaining exposure ages along scoured bedrock transects in glacial troughs upvalley from the dated moraines to define rates of ice recession (Licciardi, 2014; Licciardi et al., 2015; Pierce et al., in press).

Glacial landforms and deposits in the Tetons are interwoven with the tectonic history, as they preserve clear geomorphic imprints of fault activity during glacial and postglacial times. The trace of the Teton fault fortuitously cuts across numerous high lateral moraines along the eastern range front, creating numerous opportunities for examination of glacial features offset by the Teton fault (Figures 1 & 2). The rare opportunity to directly date those lateral moraines and precisely measure vertical surface offsets of the fault scarps that displace them is, in essence, the crux of our approach for constraining slip rates on the Teton fault.

Earlier work on moraine and bedrock exposure dating

In our earlier work on the glacial history of the Teton Range, we developed cosmogenic ^{10}Be exposure ages for moraines deposited by the valley glacier that once occupied Cascade Canyon (Licciardi and Pierce, 2008). At the mouth of Cascade Canyon, the outer (distal) and inner (proximal) moraine belts that enclose Jenny Lake are dated to 15.2 $\pm$ 0.7 ka and 14.4 $\pm$ 0.8 ka, respectively (Figure 1). Following deposition of the inner Jenny Lake moraines, upvalley recession was quite rapid, as indicated by glacial boulders on the bedrock threshold of Lake Solitude $>$90% of the upvalley distance that date to 12.9 $\pm$ 0.7 ka. Two exposure ages of glacially scoured bedrock in Cascade Canyon are consistent with rapid ice retreat at $\sim$15 ka, which we interpret as our current best estimate for the timing of deglaciation in the Tetons.

Our new investigations have expanded to focus on glacial deposits and scoured bedrock surfaces at Glacier Gulch, Bradley Lake, Taggart Lake, Phelps Lake, Granite Canyon, and adjacent areas. These deposits and surfaces were mapped previously by co-investigator K.L. Pierce (Pierce and Good, 1992), but samples were not collected at that time. Initial cosmogenic ^{10}Be ages (Licciardi, 2014; Licciardi et al., 2015) show the surprising result that massive high-elevation lateral moraines in selected drainages along the Teton range front date to ca. 21–18 ka, and are thus several thousands of years older than adjacent low-elevation lateral and end moraines that date to ca. 16–15 ka. This implies that the high laterals were constructed during an earlier phase of the Pinedale glaciation and then acted to topographically confine subsequent ice advances that deposited the end moraines we had previously dated.

The location of samples collected from moraine boulders for ^{10}Be dating and the measured vertical fault offsets shown in Figure 3 illustrate our strategy for determining slip rates along the Teton fault. Previous studies have successfully followed a similar strategy for constraining fault slip rates at other study sites (e.g., Brown et al., 2002; Matmon et al., 2006), but ours is the first application of this approach in the

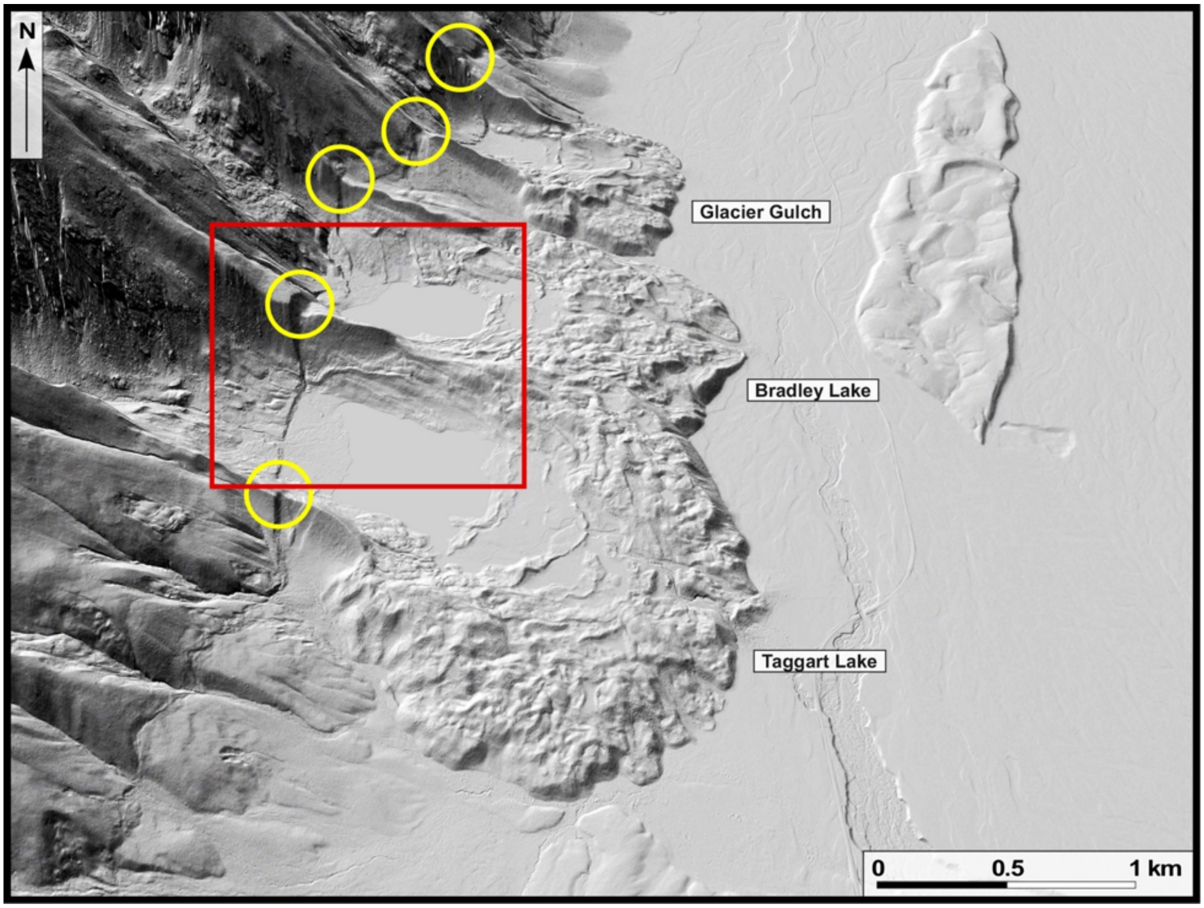

Figure 2. View of moraine complexes at Glacier Gulch, Bradley Lake, and Taggart Lake. Yellow circles indicate sites where Teton fault offsets high lateral moraines. Enlargement of area in red box shown in Figure 3. Oblique hillshade image created from LiDAR data obtained courtesy of Kathy Mellander at Grand Teton National Park.

Teton Range. Exposure ages obtained from several sampled boulders just above and below the fault scarp will be used to develop a representative age of the high lateral moraine segment cut by the fault. We will determine a deglaciation age for the valley floor from boulder ages on the lower reaches of the lateral moraine as well as terminal moraines enclosing Taggart Lake. These new ages are expected to refine the presently estimated ∼15 ka deglaciation age based on published boulder ages of the inner end moraine at nearby Jenny Lake (Licciardi and Pierce, 2008). The vertical offsets in the high lateral moraine and valley floor outwash were measured by colleague Dr. Glenn Thackray (see Thackray and Staley, 2017). Taken together, these data indicate cumulative offsets of 15.0 m from the time since the high lateral moraine was abandoned to 15 ka, and 11.8 m since 15 ka, corresponding to a vertical displacement rate of 0.8 m/kyr since 15 ka. An initial set of exposure age data from boulders on the high lateral moraine ridge shown in Figure 3 and other fault-offset moraine segments in adjacent drainages is being developed with support from a 2016 UW-NPS research grant. Obtaining a precise age of the high lateral moraine will allow us to compare glacial-age slip rates with the estimated 0.8 m/kyr postglacial rate since 15 ka, and thus enable us to explore dynamic links between glacial loading-unloading and fault slip rates (Hampel et al., 2007). Results from this pilot project are anticipated to provide the impetus for additional future research, which will build on preliminary findings and develop a denser network of ^{10}Be exposure ages and measured vertical offsets on additional high lateral moraines to further define temporal and spatial trends in Teton fault slip rates. Improved knowledge of past tectonic activity along the Teton fault will enable more informed assessment of potential future geologic hazards in Grand Teton National Park, the town of Jackson, and adjacent populated regions.

Methods

Moraine ages will be developed from cosmogenic ^{10}Be surface exposure dating methods, a technique which has enabled us to assemble a rich and detailed chronology for moraine sequences and other glacial features in the greater Yellowstone region in our past research (e.g., Licciardi et al., 2001; Licciardi and Pierce, 2008; Pierce et al., in press). Unlike conventional radiometric dating, which determines the crystallization age of rocks, surface exposure dating with cosmogenic isotopes is a technique for determining how long a geologic surface has been exposed to radiation from cosmic sources. Cosmogenic nuclides (e.g., ^{10}Be) are produced in surface materials when target atoms are struck by high-energy cosmic rays, inducing reactions that shatter atomic nucleii (Gosse and Phillips, 2001). The concentration of cosmogenic nuclides accumulated within surface rocks is directly related to the duration of exposure to cosmic rays. The *exposure age* is a function of the concentration of the cosmogenic nuclide divided by the effective nuclide production rate at the sample locality. In the case of glacial moraines, exposure ages of erratic boulders on the moraine correspond to the timing of boulder release from glacial ice. Because boulders atop the moraine are the last to be deposited, their exposure ages reflect the final stage of moraine construction, and hence indicate the timing of glacial culminations. Recent advances in knowledge of isotope production rates and increased analytical precision of AMS measurements have led to dramatic improvements in the attainable accuracy of ^{10}Be exposure ages, which now routinely reach centennial-scale resolution on late Pleistocene surfaces (Balco, 2011).

In this work, we follow the strategy of sampling multiple boulders (>5) from each targeted moraine position to enable calculation of a mean and standard deviation of boulder exposure age populations, while also allowing identification of young or old outliers. We will collect samples from several high lateral moraines that are offset by the Teton fault (see Figures 2 & 3), taking care to select boulders above and below the scarp to ensure a representative age of the offset moraine segment.

Rock sampling and field protocols follow those described in previous investigations (e.g., Licciardi et al., 2001). Field work involves collection of small rock samples (~0.5 kg) with a hammer and chisel from near the center of boulder top surfaces on stable parts of moraine crests. The tallest stable boulders (>1 m where possible) with glacial polish, smoothing, and/or negligible surface pitting are targeted to minimize issues with erosion and to reduce the potential for soil and snow cover. Geographic coordinates and altitudes at each site are obtained using a handheld GPS unit and topographic shielding will be measured with a clinometer.

Laboratory work is conducted in rock preparation and clean lab facilities at the University of New Hampshire. Rock samples are crushed and subjected to a series of acid leaching baths to isolate the quartz fraction. Beryllium is extracted from purified quartz using ion-exchange chromatography and selective precipitation, following well-established methods developed in prior research. ^{10}Be concentrations will be measured at the Center for Accelerator Mass Spectrometry at the Lawrence Livermore National Laboratory (CAMS-LLNL), and resulting isotopic ages will be determined with an online ^{10}Be exposure age calculator program (Balco et al., 2008). All ^{10}Be ages will be calculated using recently published calibrations and scaling of ^{10}Be production rates (Lifton et al., 2014; Borchers et al., 2016).

Preliminary Work

Field work in support of this project was conducted in September 2016. Samples were collected for ^{10}Be exposure dating from a total of 19 boulders resting on several high lateral moraines that are offset by the Teton fault (Figures 1, 2, 3). An effort was made to obtain samples from boulders on moraine segments located above and below measurable offsets in the

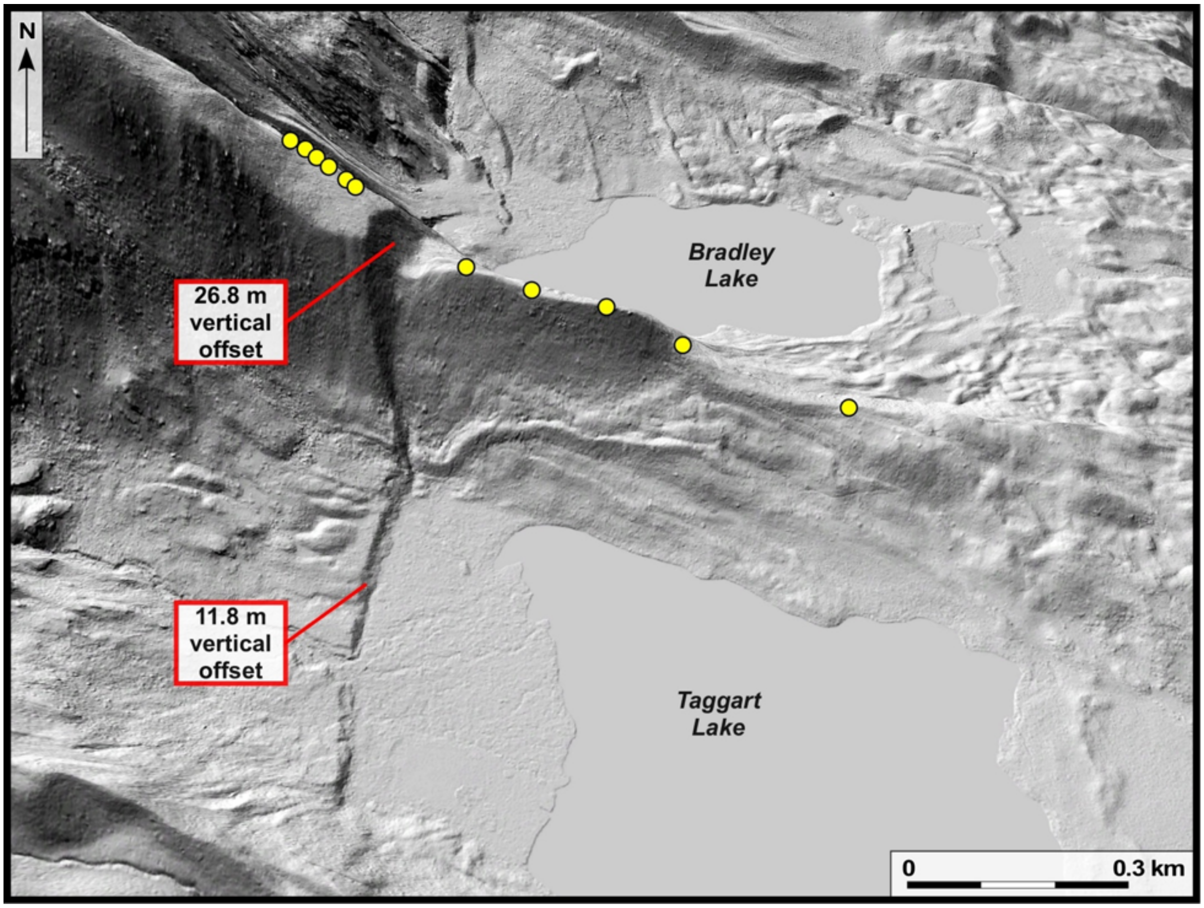

Figure 3. Samples collected for cosmogenic ^{10}Be surface exposure ages of moraine boulders (yellow dots) and vertical fault offsets on lateral moraine and valley bottom near Taggart Lake. LiDAR data provided courtesy of Kathy Mellander at Grand Teton National Park.

ridge crests. Targeted field sites include high lateral moraines associated with the Glacier Gulch, Bradley Lake, Taggart Lake, and Granite Creek drainages.

At the time of this writing, physical processing of all rock samples has been completed and chemical processing is underway. Once the beryllium is extracted from purified quartz and BeO target material is fully prepared, ^{10}Be concentrations will be measured at CAMS-LLNL and exposure ages will be calculated. From these data, representative ages of the sampled fault-offset high lateral moraines will be determined. Results are anticipated to provide direct constraints on time-integrated slip rates at five separate sites along the trace of the Teton fault in Grand Teton National Park.

Acknowledgements

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