# Method details

## High-resolution topography and fault displacements

We used a combination of Terrestrial LiDAR Scanning (TLS), UAV-based Structure-from-Motion photogrammetry (Bunds and Stahl, 2019), and manual surveys (RTK and handheld GPS) to survey fault displacements and assist with detailed mapping. All TLS data were collected with a Riegl VZ-1000 scanner operated with the assistance of a UNAVCO field engineer. Scans were tied together using fixed-point reflectors and georeferenced by occupying the scan station and reflectors with GPS in the field. All individual point clouds at sites were merged, aligned, and georeferenced. We used lastools Blast2DEM toolbox to process TLS point clouds to 1 m digital surface models (DSMs). Vegetation was not removed due to the low vegetation cover present at field sites and negligible effect on DSM-based measurements.

For UAV-based photogrammetry, Bunds et al. (2019) used a DJI Phantom 2 mounted with a Sony A5100 camera with 24.3 megapixel APS-C sensor and 16 mm pancake lens. Ground Control Points (GCPs) and checkpoints were measured using an RTK GPS system consisting of a Trimble R8 rover and Trimble 5700/Zephyr Geodetic antenna reference station. The position of the reference station was determined using the National Geodetic Survey’s Online Positioning User Service and occupations of over eight hours. Structure-from-Motion (SfM) processing was conducted with Agisoft Photoscan running on three to eight workstations. A selection of photographs was initially aligned on low setting to estimate coverage and photographs were added to areas that lacked overlap. The revised selection of photographs was aligned on the ‘high’ setting to generate a final sparse point cloud of the survey area. GCPs were hand-positioned in each photograph, and camera models were re-optimized (‘bundle adjustment’) with GCP locations incorporated. A dense point cloud was then generated using the ‘high’ setting in Photoscan followed by creation of a 6 cm pixel-resolution DSM.

Topographic profiles of selected faults were obtained with either a handheld Garmin GPS with barometric altimeter or with a Trimble R8 RTK GPS. While the accuracy of these datasets to actual ground elevations is variable, the internal precision of the point positions is acceptable for measuring fault scarp profiles and to supplement the UAV and TLS DSMs.

## Geochronology

Multiple dating techniques were employed to improve the chronology of volcanism and faulting in the Sevier Desert. Below, we provide an overview of each of the techniques and their applications. Further details about sampling, sample preparation, and age modelling are included in the supplementary information.

### 3He exposure age dating

Samples of Tabernacle basalt were processed and analyzed for cosmogenic 3He content in olivine. Approximately 5 cm-thick samples were crushed, passed through a disc mill and sieved. Olivine phenocrysts in the Tabernacle flow were abundant in the 250-750 μm fractions. Phenocrysts within these fractions were separated using standard magnetic and heavy liquid separation techniques then sonicated in 5% HF:HNO3 to remove surface alteration. We manually picked out contaminant phases, phenocrysts with adhering ground mass, and polymineralic grains under a binocular microscope. Olivine was then crushed using stainless steel pistons in a vacuum to release potential non-cosmogenic 3He. The olivine powder was melted in crucibles within an ultra-high vacuum furnace to measure remaining 3He and 4He abundances on a magnetic sector mass spectrometer at Woods Hole Oceanographic Institute (e.g., Kurz, 1986; Goehring et al., 2010).

There are three sources of 3He in olivine: cosmogenic, mantle-derived or magmatic, and nucleogenic. The equations of Kurz (1986) and Goehring et al (2010) were used to isolate the cosmogenic 3He:

 3Heinherited = (3He/4He)crush x 4Hetotal (Eqn. 1)

 3Hecosmogenic = 3Hetotal – 3Heinherited (Eqn. 2)

Exposure ages were then calculated using the CRONUS-Earth 3He exposure-age calculator using “LSDn” scaling (Lifton et al., 2014).

Table S1: 3He Samples and analytical results.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Mass olivine (g) | 3He (106 atoms/g) | ±1σ | 4He (1010 atoms/g) | ±1σ | R/RAcrush | R/RA melt1 |
| TH100 | 0.18338 | 1.373 | 0.0501 | 1.338 | 0.030 | 5.06 | 79.22 |
| TH101 | 0.19806 | 2.429 | 0.0758 | 1.359 | 0.028 | 6.07 | 135.19 |
| TH200 | 0.18494 | 2.324 | 0.0689 | 5.252 | 0.039 | 5.61 | 37.58 |
| TH201 | 0.14824 | 3.275 | 0.0916 | 3.598 | 0.040 | 4.63 | 70.39 |

1Ratio of (3He/4He)magmatic to the ratio in air (1.6 x 10-6)

Table S2: 3He exposure-age results.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Lat./Long.(Decimal Degrees) | Elevation (m) | Topographic Shielding factor1 | 3He (106 atoms/g) | 3He Production Rate (atoms/g/yr)2 | Age (ka)3 | ±1σ |
| TH100 | 38.932385,-112.524813 | 1450 | 0.344 | 1.373 | 112 | 12251 | 1421 |
| TH101 | 38.932385,-112.524813 | 1450 | 0.499 | 2.429 | 161 | 15077 | 1726 |
| TH200 | 38.932385,-112.524813 | 1450 | 0.440 | 2.324 | 143 | 16280 | 1857 |
| TH201 | 38.932385,112.524813 | 1450 | 0.613 | 3.275 | 199 | 16445 | 1868 |
| 1Calculated using online topographic and CRONUS-Earth Geometric Shielding Calculator 1.1 (Balco, 2006) without incorporating particle leakage effects.2Using scaling of Lifton et al. (2014) “LSDn” on CRONUS-Earth Online v. 3 (e.g. Balco et al., 2008).3Age errors include measurement and production rate uncertainty.  |

### 40Ar/39Ar

We collected one sample from each of the Deseret, Pavant I, and Pavant II lava flows for 40Ar/39Ar analysis to constrain long-term extension rates across fault zones that transect these flows. Groundmass concentrates were prepared via crushing and hand-picking, then irradiated for 20 minutes at the USGS TRIGA reactor in Denver, CO with Fish Canyon tuff sanidine as a neutron flux monitor. The samples were incrementally heated in 11 steps using a defocused diode laser and gas was measured on a Helix MC-Plus Mass Spectrometer at the New Mexico Bureau of Geology and Mineral Resources. Plateau ages were calculated using inverse-variance-weighted mean of the steps (Taylor, 1982); isochron ages and errors were calculated after York (1969).

Table S3: 40Ar/39Ar Sample locations and step heating results.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Sample | Lat./Long.(Decimal Degrees) | Heating steps | n steps1 | Plateau age (ka BP ± 1σ)2 | Isochron Age (ka BP ± 1σ)3 | MSWD4 |
| DesAR01 | 39.207406, -112.76661 | 11 | 10 | -- | **668 ± 9** | 9.0 |
| DKF1 | 39.05612, -112.50954 | 11 | 8 | **758±21** | 746±67 | 1.7 |
| ARAR5 | 39.029925, -112.497154 | 11 | 6 | **66±13** | 73±21 | 10.6 |
| 1Number of steps used in plateau or isochron age determination2Plateau ages include *n steps* of the 11 steps for each sample. Error is calculated using method of Taylor (1982) then multiplied by MSWD1/2 after Roddick (1978). 3Isochron age and error after York (1969) then multiplied by MSWD1/2 after Roddick (1978)4Mean sum weighted deviates  |

### 10Be exposure age dating

We used 10Be exposure-age dating to constrain the ages of post-Provo highstand alluvial fans in the House Range. Full overviews of the technique, different sampling strategies, pitfalls, and applications to alluvial fans in arid to semi-arid regions are given in several studies (Frankel et al, 2007, Owen et al., 2011). Here, we provide a brief overview of our sampling strategy and methods.

The tops of >1 m-diameter boulders were sampled with an angle grinder down to ~3 cm depths to constrain alluvial fan depositional ages. Whole-clast samples less than 5 cm thick and approximately the same volume as boulder samples were recovered from an adjacent dry wash in an attempt to correct for cosmogenic inheritance. Quartz extraction and purification was undertaken at the University of Michigan using standard mineral separation techniques. Chemical preparation of 10Be for AMS was conducted at the Purdue Rare Isotope Measurement Laboratory (PRIME Lab) at Purdue University. Purified quartz was dissolved in HF:HNO3 acid after adding 0.27 mg of ~1 x 10-15 10Be/9Be ratio carrier. The volume of samples were reduced by adding H2SO4 and evaporating on a hot plate for ~12 hours. The samples were then fumed to remove fluoro-silica compounds and Fe and Ti were precipitated out of solution. Beryllium was then precipitated as Be(OH)2 and dissolved in oxalic acid in preparation for cation exchange. Eluted, purified Be(OH)2 was dried and ignited to oxidize to BeO. Niobium binding powder was mixed with BeO and loaded into stainless-steel holders for AMS analysis at PRIME. Surface exposure-ages were calculated using blank-corrected measurements of 10Be atoms/g (Table 4) and the CRONUS-Earth online exposure age calculator v. 2.3 (e.g., Balco et al., 2008). In the age models, we assume no erosion rate and use the time-dependent production rate of Lal (1991) and Stone (2000).

Table S4: 10Be Sample locations and analytical results.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Sample | Lat./Long. | Elev. (m) | Unit | Thickness (cm) | Boulder Height (m) | Shielding Correction1 | 10Be (106 atoms/g)2 | ±1σ | Exposure age (ka)3 | ±1σ |
| HR01 | 39.388966, -113.394105 | 1434 | Qla2 | 3 | 0.6 | 0.9751 | 1.574 | 0.0226 | 127.379 | 12.343 |
| HR02 | 39.389276, -113.394892 | 1430 | Qla2 | 3 | 0.2 | 0.9751 | 1.215 | 0.0204 | 98.974 | 9.562 |
| HR03 | 39.394376, -113.389462 | 1462 | Qaf1 | 3 | 0.5 | 0.9751 | 0.7618 | 0.0136 | 61.973 | 5.943 |
| HR04 | 39.394095, -113.389513 | 1461 | Qaf1 | 3 | 0.3 | 0.9751 | 0.4720 | 0.0089 | 38.216 | 3.651 |
| HR05 | 39.371072, -113.405076 | 1431 | Qaf1 | 3 | 0.6 | 0.9751 | 0.3345 | 0.0063 | 27.628 | 2.632 |
| HR06 | 39.371269, -113.405725 | 1428 | Qaf1 | 3 | 0.5 | 0.9751 | 0.3394 | 0.0078 | 28.011 | 2.696 |
| HRC1 | 39.389887, -113.394795 | 1429 | Qaf1 | Whole cobble<5 cm thick  | -- | 0.9751 | 0.9182 | 0.0133 | 74.664 | 7.141 |
| HRC2 | 39.389887, -113.394795 | 1429 | Qaf1 | Whole cobble <5 cm thick  | -- | 0.9751 | 1.052 | 0.0178 | 85.842 | 8.268 |
| HRC3 | 39.389887, -113.394795 | 1429 | Qaf1 | Whole cobble <5 cm thick  | -- | 0.9751 | 0.5374 | 0.0108 | 43.120 | 4.136 |
| HRC4 | 39.389887, -113.394795 | 1429 | Qaf1 | Whole cobble <5 cm thick  | -- | 0.9751 | 0.6532 | 0.0126 | 52.663 | 5.055 |

1Ratio of the production rate at the shielded site to a flat surface using CRONUS-Earth Geometric Shielding Calculator 1.1.

2Calculated using 07KNSTD standard with a reported 10Be/9Be ratio of 2.85x10-12 (Nishiizumi et al., 2007). 10Be concentrations were corrected for those found in a blank of 74.140 ± 32.325 x 103 atoms per mg of 9Be carrier.

3Model exposure ages using zero erosion rate, sample densities 2.7 g cm-3 using the time-dependent production rate and scaling scheme for spallation of Lal (1991) and Stone (2000). Modelled using CRONUS-Earth exposure-age calculator v. 2.3. Uncertainty is the “external” uncertainty incorporating both measurement and production rate uncertainty.

### 5.1.4 10Be exposure-ages to constrain age of MRE

We adopted an alternative to the minimum age approach in which we fit a generalized Pareto distribution (GPD) to the observed ages, after an approach proposed by Prush and Oskin (2019), to the overall distribution of clast ages. Clast ages for fluvial terraces are expected to follow a GPD in catchments where material is sourced from competition between landsliding and steady background erosion; empirical analysis of published surface clast datasets indicates, in general, agreement with the GPD model (Prush and Oskin, 2019). The cumulative distribution function (CDF) of the GPD is defined as

$f\left(κ,σ,θ\right)\left(x\right)=1-(1+\frac{κ\left(x-θ\right)}{σ})^{(-\frac{1}{κ})}$ Eqn. 4

for κ≠0, and where κ is a shape parameter, σ is a scale parameter, and θ is a threshold parameter related to the minimum (true) age of the fan surface. Best-fitting GPD parameters were estimated using a range of acceptable threshold values (θ) as boundary conditions given the minimum observed exposure ages, likelihood of under-sampling the minimum fan surface age, and geological estimates (10 ka – 30 ka). Once a threshold value was selected on this interval, we used a maximum likelihood method to find the values of κ and σ for that value of θ, and calculated the normalized root mean square error (NRSME) between the resulting model and the empirical CDF. The resulting NRMSEs were ranked from 0 to 1, with 1 being the set of best-fitting model parameters.

This method yields a best-fitting model with θ=22.5 ka, which would represent the age of the post-Provo fan surface (Fig. S1). However, we consider that the utility of this model is limited by (i) potential undersampling of the youngest fan ages and (ii) by the analytical uncertainty of the youngest surface exposure age measured (HR06). We investigated another model where we limited threshold values to being less than the maximum calibrated calendar age for the Bonneville flood (c. 18.5 ka) (Oviatt, 2015). This model yielded threshold ages in models with acceptable overall fits for the fan surface of between 13.6 and the imposed upper limit of 18.5 ka, which is consistent with geologic interpretations, yields reasonable NRSMEs and varies only slightly from the best statistical fits (Fig. S1).

While we cannot tightly constrain the age of the Qaf surface, our exposure-age modelling indicates that the resurfacing of Qla, and deposition of Qla2 and Qaf, likely occurred soon after final regression from the Provo level. This is consistent with a purely geomorphic interpretation that lake-level drop in the Tule Valley took place rapidly following regression from Provo shoreline and isolation of Lake Tule from other sub-basins of Bonneville.



**Figure S1:** 10Be exposure age modelling results for samples from Qla2 / Qaf surfaces (Figure 8). (A) Cumulative distribution function (CDF) of ages (red) and first model run with minimum age constraints of between 15-30 ka BP. This model yields a ‘best-fit’ age of c. 22 ka BP for the timing on fan formation, which is geologically untenable. (B) Second model run with minimum age constraint of <18.5 ka BP added and a normalized residual mean square error (NRMSE) constraint of 0.85 or greater (with 1 being the best model fit). This model yields acceptable model fits between 13.6 and 18.5 ka BP, with the best fitting models all skewed towards the upper age constraint. (C) Conceptual model for selecting appropriate ages from the two models, using real outputs of theta from (A) and (B). Acceptable model fits and feasible geologic ages align in the green region. (D) Probability density function (PDF) of sample ages (red) and the two model fits (black solid and dashed) with the best-fitting ages reported for each model.

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