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Determining the impact of faulting on the rate of erosion in a low-relief landscape: A case study using *in situ* produced ^{21}Ne on active normal faults in the Bishop Tuff, California

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Abstract

Normal faults exposed in the Volcanic Tableland in the south-eastern part of the Bishop Tuff provide a unique opportunity to investigate whether tectonic faulting and associated fracturing control the rate of erosion in the vicinity of actively growing faults. If fracturing increases with fault displacement, erosion close to the faults should be more rapid for faults with higher displacement. Here we use *in situ* produced cosmogenic ^{21}Ne to quantify the

erosion rate in the flat footwall blocks of three normal faults that have maximum vertical displacements between ~12 and ~160 meters. ^{21}Ne concentrations in surface samples from volcanic bedrock and desert pavements along the three faults are nearly uniform and demonstrate that erosion is spatially invariant, both along individual faults and between faults with different tectonic offsets. Hence, faulting and fracturing of rocks adjacent to the active normal faults in the Bishop Tuff do not have a significant impact on the rate of erosion in the sub-horizontal footwall blocks next to the faults. This is further supported by samples from sites which are unaffected by faulting but record a similar erosion rate as samples located near faults. Using the density of the Bishop Tuff and a published $^{40}\text{Ar}/^{39}\text{Ar}$ eruption age for the tuff (760 ± 2 ka), the absolute amount of erosion since eruption has been quantified. At most sample sites the time-integrated amount of erosion ranges between ~0.9 and ~1.9 m, which is equivalent to average erosion rates between ~1.2 and ~2.5 m/Ma. Samples of bedrock-derived clasts from desert pavements have slightly higher ^{21}Ne concentrations than adjacent bedrock outcrops and thus yield higher *apparent* exposure ages (calculated assuming no erosion). Thus, desert pavements are more suitable for determining the minimum eruption ages of yet-undated welded tuffs than bedrock exposures. Desert pavements from the Bishop Tuff yield exposure ages that are ~60% of the tuff's $^{40}\text{Ar}/^{39}\text{Ar}$ eruption age.

Keywords: cosmogenic ^{21}Ne , active faulting, erosion rate, desert pavement

1. Introduction

The rate at which material is removed from the Earth's surface by erosion is one of the prime factors that control the geomorphic evolution of landscapes. Factors that influence the rate of erosion include local relief and hillslope gradient (e.g. Ahnert, 1970; Montgomery

and Brandon, 2002) as well as climatic factors like precipitation and temperature (e.g. Reiners et al., 2003). Another parameter that may exert an important control on denudation is the level of tectonic activity (e.g. Riebe et al., 2001; Densmore et al., 2004; von Blanckenburg et al., 2004). For example, small catchments in the vicinity of active faults in the Sierra Nevada, California, have been reported to erode faster than catchments without active faults (Riebe et al., 2001). The importance of active tectonics and seismicity for the rate of erosion has also been emphasized by Dadson et al. (2003), who showed that decadal erosion rates in Taiwan are linked to the level of historic seismicity; mainly because earthquakes act as trigger for landslides.

One may hypothesize that the observed correlation between faulting and rapid erosion results from continued tectonic activity, which increases the local relief and steepens fluvial channels, thereby enhancing the capacity of rivers to downcut into bedrock (e.g. Whipple and Tucker, 1999). Fluvial incision in turn leads to steeper hillslopes that are increasingly affected by fast mechanisms of mass transport such as landsliding. In tectonically inactive areas, high relief and steep hillslopes do not necessarily cause fast erosion – even when coupled with high amounts of precipitation. This is evident from the rugged landscape in central Sri Lanka, which erodes at very low rates of 2–11 m/Ma, probably because the island is not tectonically active (von Blanckenburg et al., 2004).

Alternatively to the indirect link between faulting and erosion via the generation of relief and fluvial incision, a more direct coupling could be expected, because in the vicinity of active faults intact bedrock is being fractured as faults grow and accumulate displacement (e.g. Vermilye and Scholz, 1998). Fracturing should promote the disintegration of bedrock and may ultimately lead to enhanced weathering, which is the first step in the erosion process preceding the transport of material (e.g. Gilbert, 1877; Molnar et al., 2007).

In order to investigate whether tectonic faulting – in the absence of fluvial incision and steep hillslopes – leads to enhanced erosion, a setting is required where active faults are present but have not yet generated significant relief. The Volcanic Tableland in eastern California, where young active normal faults deform the low-relief surface of the Bishop Tuff, provides such a setting. Here, normal fault scarps ranging in height from less than a meter to more than a hundred meters have not yet undergone fluvial incision. The local erosion of the flat, uplifted footwall blocks of these faults is interpreted to be controlled by bedrock weathering. We determined the concentrations of cosmogenic ^{21}Ne in samples from flat bedrock surfaces and desert pavements taken (i) along-strike of three normal faults with different amounts of displacement and (ii) at two sites not affected by faulting, thereby evaluating the impact of faulting on erosion.

2. Geological setting and normal faulting of the Bishop Tuff

The Bishop Tuff is situated at the western margin of the actively extending Basin-and-Range Province in the northern Owens valley, eastern California (e.g., Pinter et al., 1994) (Fig. 1). The Bishop Tuff is an ignimbrite that erupted during the formation of the Long Valley Caldera 760 ± 2 ka ago, as constrained by $^{40}\text{Ar}/^{39}\text{Ar}$ dating of sanidine phenocrysts and matrix glass (van den Bogaard and Schirnick, 1995). An identical $^{40}\text{Ar}/^{39}\text{Ar}$ age, within uncertainty, of 758.9 ± 1.8 ka was also obtained by Sarna-Wojcicki et al. (2000). The volcanic rocks of the caldera eruption are classified into two groups: fall deposits and voluminous partly welded ignimbrite (Wilson and Hildreth, 1997). The southeastern part of the Bishop Tuff has an average thickness of 120-150 m (Gilbert, 1938) and forms a plateau-like landscape known as the Volcanic Tableland (Hildreth, 1979). In the southern part of the Volcanic Tableland, the uppermost section of the Bishop Tuff consists of a 40 to 80 m-thick ignimbrite unit referred to as Ig2Eb by Wilson and Hildreth (1997). This ignimbrite unit is

increasingly welded towards the top and forms a conspicuous flat surface north of the Owens River. The Ig2Eb ignimbrite contains abundant pumice and rhyolite lithics with ortho- and clinopyroxene phenocrysts, sanidine, magnetite (Wilson and Hildreth, 1997), and quartz phenocrysts up to 3 mm in size.

Since eruption and cooling of the ignimbrite units, the flat and smooth surface of the Volcanic Tableland has been deformed by numerous north-south striking normal faults, which indicate active E-W extension in this part of the Basin-and-Range Province. The traces of the N-S-trending normal faults, which offset the low-relief surface, are clearly visible on a shaded relief image derived from digital elevation SRTM (Shuttle Radar Topography Mission) data with a spatial resolution of 10 m (Fig. 2a). In general, the normal faults dip steeply at $\sim 70^\circ$ as observed along the northern side of the Owens River valley (Fig. 2a). With the exception of the normal fault scarps and the valley walls of Owens River slopes in the Volcanic Tableland are sub-horizontal, dipping at angles of only a few degrees (Fig. 2b). The absence of significant footwall erosion and hanging wall deposition (Bateman, 1965) allowed Dawers et al. (1993) to measure the displacement of the ignimbrite's erosion-resistant upper cooling surface along-strike of these faults (Fig. 3a). They found that the normal faults, varying in length over three orders of magnitude from ~ 20 m to ~ 12 km, share two main characteristics. First, their maximum throw is located near the center of the faults and decreases gradually to zero toward the fault tips (Fig. 3a). Second, the maximum displacement scales linearly with fault length over three orders of magnitude (Dawers et al., 1993), i.e. the ratio of displacement to fault length is scale-invariant. Hence, after nucleation these faults have grown by lateral propagation and have progressively increased their displacement (Dawers et al., 1993). The maximum displacement for the smallest discernible faults is about 0.5 m, while the largest normal fault – the Fish Slough fault (Fig. 2a) – has a maximum displacement of $\sim 145 \pm 20$ m (Dawers et

al., 1993).

The flat surface of the Volcanic Tableland receives a mean annual precipitation of ~130 mm (averaged over the last 60 years) and is sparsely vegetated with bushes and shrubs. In the uplifted footwalls of the normal faults bedrock is commonly exposed, whereas the down-faulted hanging walls are largely covered by a thin veneer of soil (Fig. 3b). The bedrock exposed in the footwall blocks adjacent to the faults is characterized by fractures that are presumably related to faulting (Fig. 3b). These fractures may enhance the disintegration of the bedrock by weathering and may thus increase the local rate of erosion, if the weathered material is constantly removed. As the intensity of fracturing presumably increases with fault displacement, erosion may be faster near faults with higher displacement.

3. Sampling sites

A total of twenty samples were collected from ignimbrite unit Ig2Eb for measurement of cosmogenic ^{21}Ne in quartz. Thirteen samples were taken along the flat footwalls of three normal faults of different lengths and vertical displacements (Table 1; Fig. 2a). The distance of the samples to the steep fault scarp ranges from one meter to several tens of meters (cf. Fig. 2a). Five samples were collected from two sites unaffected by faulting and two samples came from ephemeral stream channels at the southern edge of the Volcanic Tableland near the Owens River. In general, samples were collected from bedrock surfaces with well-developed dark desert varnish or from flat desert pavements with closely interlocking clasts coated with dark varnish, suggesting that these surfaces are relatively stable (Fig. 4a-d). Samples from both bedrock and desert pavements had a maximum thickness of 4 cm; the average thickness of the pavement clasts is about 1 cm less than that of the bedrock samples. Bedrock samples commonly show a weathering rind up to 4 cm in thickness. Weathering of

the bedrock proceeds by episodic spalling of slabs up to a few centimeters in thickness, disintegration along grain boundaries, and dissolution by meteoric water trapped in small bedrock cavities. From the pavements only clasts with dark desert varnish on their upper side have been sampled. Beneath desert pavements there is commonly a homogeneous vesicular A horizon (further referred to as Av horizon) of fine-grained, gray material varying from 2 to 9 cm in thickness, which locally contains ~0.5 millimeter-sized vesicles. Similar stone pavements in the southwestern US have formed by the inflation of eolian dust, which has accumulated beneath gravel layers at the surface (Wells et al., 1985; McFadden et al., 1987).

The smallest fault (in this study informally named 'small' fault) from which we collected samples is ~1 km long and has a maximum displacement of 12 m near its midpoint (Fig. 2a). Along strike of this fault we took samples at four locations in clusters of one to three samples. Sample sites in the flat footwall portion are located 3-15 m away from the fault scarp. The sample cluster 05BT4, 5, and 6 was taken from the upper part of a bedrock high, from ~40 cm lower lying bedrock and from a desert pavement with a 2 to 4 cm-thick Av horizon (Fig. 4a). In this study a bedrock high refers to a portion of bedrock that sticks out of the flat surrounding bedrock. Just south of this location, bedrock samples 05BT7 and 8 were taken from a similar site with a bedrock high ~60 cm above the adjacent bedrock. Samples 05BT9 and 10 were collected between the midpoint and the tapering northern end of the fault scarp. 05BT9 is from a flat bedrock outcrop, which stands ~10 cm above the surrounding desert pavement, whereas 05BT10 consists of an amalgamation of angular pavement clasts collected over an area of ~1 m², with an Av horizon that is 6 to 9 cm thick. At the northern tip of the 'small' fault, sample 05BT11 was taken from a desert pavement with an Av horizon underneath that is 4 to 5 cm thick.

The second fault is a ~7 km-long segmented normal fault with a maximum throw of 90-

100 m that was described in detail by Dawers and Anders (1995). We took three bedrock samples along-strike of the southern fault segment: one in the central part of the segment where the vertical offset is maximal, and two others towards the southern end (Fig. 2a). All sample sites are flat bedrock surfaces covered with dark desert varnish. The last and largest fault that we investigated is the Fish Slough fault. Two bedrock samples about 800 m apart were collected on the upthrown footwall in the southern part of this fault, where the vertical fault offsets are ~160 and ~140 m, respectively (Fig. 2a). Both samples were taken from flat bedrock exposures at a distance of 2-3 m from the steep scarp.

For comparison with samples from faults, we took five samples from two sites that are not affected by faulting (Table 1, Fig. 4c, d). Otherwise these sites look similar to the ones described above as they have flat bedrock surfaces, local bedrock highs, and desert pavement. Two samples are from locations higher than the surrounding bedrock by 50 and 115 cm, respectively, and at one of these sites we sampled adjacent desert pavement above a 2 cm-thick Av horizon. Two bedrock samples (05BT16, 17) were taken from bedrock channels at the southern rim of the Volcanic Tableland near the cliff overlooking the Owens River (Fig. 2a). The boundaries of these 5 to 10 m-wide ephemeral channels are poorly defined; thus, the amount of incision into the Bishop Tuff surface is difficult to quantify in the field but has been estimated at about 1-2 m.

4. Sample preparation, neon analysis and data reduction

All samples were crushed, washed and sieved. The 315-710 μm and 710-1000 μm size fractions were split into a magnetic and a non-magnetic fraction using a Frantz magnetic separator. The quartz in the non-magnetic fraction was treated and purified according to procedures described by Kohl and Nishiizumi (1992). This treatment involved a first leach in 6M HCl at a temperature of ~80°C, followed by several leaching steps in dilute HF/HNO₃

(see Hetzel et al., 2002 for details).

Noble gas analysis of the purified quartz samples was carried out in the noble gas laboratory of the GFZ Potsdam. In general the 315-710 μm grain size fraction was used for analysis. In addition, the 315-1000 μm grain size fraction was analyzed in two aliquots of sample 05BT11 and for sample 05BT17, whereas the 250-710 μm fraction was used for 05BT13. The four samples measured first (05BT4, 8, 17, 21) were ground in an agate mortar before analysis with the aim of reducing the contribution of non-cosmogenic Ne from fluid inclusions. However, the results from a coarse-grained (315-1000 μm) aliquot of 05BT17 (Table 2) showed that trapped Ne concentrations are very low and that the total excess of cosmogenic ^{21}Ne is equal in the coarse and fine fractions. Therefore the remaining samples were not pulverized with a mortar.

Gas extraction was accomplished by stepwise heating of 0.5-0.7 g of quartz. Samples were degassed in three or four temperature steps at 400, 600, 800 and 1200°C and neon was analyzed in a VG5400 noble gas mass spectrometer; results are shown in Table 2. Isotopic abundances of He, Ar and Xe were monitored for a few samples only. They showed low He and Ar concentrations with only small radiogenic contributions and entirely atmospheric Xe isotope ratios, suggesting no significant contribution of nucleogenic ^{21}Ne in Bishop Tuff quartz. The latter component may be produced by nuclear reactions of alpha particles from the U and Th decay chains with O and F (e.g. Niedermann, 2002). In addition, the isotopic composition of neon contained in fluid inclusions was checked by analyzing the gas released by crushing of ~ 1.0 g aliquots of three samples *in vacuo* (05BT9, 05BT17, and 05BT20; Table 2).

All data have been corrected for analytical blanks, isobaric interferences, and mass discrimination effects. Error limits correspond to the 95% confidence level; they include statistical uncertainties of the measurement, uncertainties of sensitivity and mass

discrimination determination, and blank and interference corrections. Further details about the standard analytical procedures and data reduction methods can be found in Niedermann et al. (1997). The procedure that was used for the evaluation of Ne isotopic compositions substantially different from air is outlined in detail in the appendix.

5. Results

Results of the Ne analyses of the samples obtained by stepwise heating are shown in Table 2. Cosmic-ray-produced Ne in quartz is characterized by a unique $^{22}\text{Ne}/^{21}\text{Ne}$ ratio and therefore mixtures of cosmogenic Ne and another Ne component must plot on a ‘spallation line’ in a three-isotope diagram (Niedermann et al., 1993). Often, the non-cosmogenic Ne component is assumed to be atmospheric in composition and the amount of cosmogenic ^{21}Ne is then quantified, for each heating step, as:

$$^{21}\text{Ne}_{\text{cosmogenic}} = [(^{21}\text{Ne}/^{20}\text{Ne})_{\text{sample}} - (^{21}\text{Ne}/^{20}\text{Ne})_{\text{atmospheric}}] * ^{20}\text{Ne}_{\text{sample}} \quad (1)$$

Trapped Ne components in quartz may, however, have a $^{21}\text{Ne}/^{20}\text{Ne}$ ratio that significantly exceeds the $^{21}\text{Ne}/^{20}\text{Ne}$ value of air (0.00296), which, if not considered, leads to overestimations of the cosmogenic Ne component when using the above formula (Hetzel et al., 2002). The fact that the neon isotopic composition of three samples analyzed by crushing *in vacuo* is indistinguishable from air indicates that trapped Ne in Bishop Tuff quartz is indeed atmospheric in composition. Moreover, the Ne three-isotope diagrams (Fig. 5) provide no indication for the presence of additional Ne components such as nucleogenic Ne, since all data points plot along the spallation line for quartz (Niedermann, 2002). Thus, the amount of cosmogenic ^{21}Ne in each heating step has been calculated according to formula (1).

It has been shown that cosmogenic ^{21}Ne is generally released from quartz below 800°C (Niedermann, 2002). However, the quartz samples studied for release characteristics were

typically smaller than ~250 μm in grain size, while we used considerably larger grains for most samples of this study. Assuming that the diffusion length is similar to the grain size, it is possible that the temperature required for complete release of cosmogenic Ne depends on the grain size. Indeed, the $^{21}\text{Ne}/^{20}\text{Ne}$ ratios in the 1200°C steps are consistently higher than atmospheric although trapped Ne is atmospheric (as shown by the crushing extractions; see Table 2). Therefore, we have included the 1200°C data for the calculation of total cosmogenic ^{21}Ne concentrations except for the four samples that were ground before analysis. The relative contributions of the 1200°C steps are small in either case: typically ~1% and at most $2.5 \pm 2.1\%$ (05BT11) in the coarse-grained samples but only ~0.1% in the fine-grained ones (cf. Table 2).

In general, the concentration C of a stable cosmogenic nuclide such as ^{21}Ne in a steadily eroding rock surface depends on the exposure time t and the erosion rate ε and is given by:

$$C = \frac{P \Lambda}{\rho \varepsilon} (1 - e^{-\rho \varepsilon t / \Lambda}) \quad (2)$$

Thus, for a rock surface of known age t , the erosion rate ε can be quantified if the local production rate P , the rock density ρ , and the attenuation length Λ are known. As the age of the Bishop Tuff is well constrained at 760 ± 2 ka (van den Bogaard and Schirnack, 1995), the erosion rate at the different sampling sites can be calculated iteratively by solving equation (2) for ε . The density of the Bishop Tuff has been determined at 1.65 g/cm^3 from the quantified volume of water that was displaced by putting a fresh 900 g rock sample in a water basin. The local ^{21}Ne production rates have been derived by scaling the sea level and high latitude production rate of 19.0 at/g/a (Niedermann, 2000) to the sample sites with the algorithm of Dunai (2000), using a mean annual sea level temperature of 15°C and a mean annual sea level pressure of 1013.25 mbar . The fraction of ^{21}Ne produced by muons was assumed to be zero. Topographic shielding by mountains is negligible at all sample sites and

no correction for temporary shielding by snow or ice has been applied. The resulting production rates are listed in Table 3. After calculating the erosion rate from equation (2) with an attenuation length Λ of 160 g/cm² (Gosse and Phillips, 2001), the total amount of material that has been removed by erosion was determined by multiplying the erosion rate with the age of the Bishop Tuff (Table 3). For samples from desert pavements, which consist of amalgamations of 20-40 clasts each with dark varnish, the erosion has not been quantified because the irradiation history of each clast is presumably different. As equation (2) cannot be solved analytically for ϵ , it is not possible to use ordinary error propagation to calculate erosion uncertainties. Therefore we have estimated these uncertainties by inserting both the upper and lower error limits of cosmogenic ²¹Ne concentrations in equation (2), computing the corresponding erosion values and converting the results back to an uncertainty range.

For most sample sites the total amount of erosion ranges between ~0.9 and 1.9 m over the past 760 ka; calculated with the assumption of a temporally constant erosion rate. As expected, a larger amount of erosion occurred in the two ephemeral streams (samples 05BT16, 17), where about 3 m of material has been removed. Sample 05BT13 from a local bedrock high indicates ~2.5 m of erosion, however, sample 05BT15 from the nearby bedrock surface 50 cm below the bedrock high yields only ~1.8 m of erosion (Table 3). This raises doubts about the higher amount of erosion recorded by sample 05BT13, even though it was reproduced by a duplicate analysis (Table 2). The bedrock high is expected to have eroded more slowly than the surrounding bedrock, which is contrary to what we observe. The reason for the apparently high amount of erosion inferred for sample 05BT13 might be several depressions as deep as 8 cm in the bedrock high from which the sample was collected. We speculate that these depressions might have reduced the local production rate, probably owing to the disturbance of the neutron flux across the irregular air-rock interface and the dispersion of neutrons back into the air (cf. Masarik and Reedy, 1995).

Removal of material from the geomorphic surface of the Bishop Tuff affects the calculated exposure ages. To illustrate this, we also report *apparent* exposure ages calculated with the invalid assumption of no erosion. These *apparent* exposure ages range from ~224 to ~520 ka (Table 3) and underestimate the known age of the Bishop Tuff of 760 ka by 32-70%.

6. Discussion

The cosmogenic ^{21}Ne concentrations in samples from the Volcanic Tableland combined with the known eruption age of the Bishop Tuff provide the unique opportunity to quantify the absolute amount of erosion along the footwalls of actively growing normal faults (Fig. 2) using equation (2). Along the southern part of the segmented normal fault three bedrock samples (05BT1, 2, 3) record similar amounts of erosion (147 ± 13 , 127 ± 13 , and 130 ± 13 cm, respectively) and yield similar apparent exposure ages of about 400 ka (Table 3; Figs. 6, 7). Bedrock erosion along the 'small' fault is more variable (0.9 - 1.7 m), but the amount of erosion is unrelated to the spatial position of the five bedrock samples along the fault (Figs. 6, 7). Thus, we find no systematic trend in the amount of total erosion along strike of these two normal faults. The two samples from the Fish Slough fault again indicate an amount of erosion similar to the other faults (125 ± 16 and 188 ± 16 cm), despite the fact that the Fish Slough fault has accumulated a vertical offset that is more than ten times larger than that of the 'small' fault, i.e. ~150 m versus 12 m. This means that on the spatial scale of the investigated faults erosion is also independent of the absolute amount of tectonic displacement, which varies by an order of magnitude between the three studied faults (Fig. 6).

The amount of erosion inferred from the two sites where no faulting occurs is 1.3-1.8 m (Table 3; as outlined in section 5 the ~2.5 m of erosion inferred from 05BT13 is considered

an overestimate). This amount of erosion is similar to those found along the three faults and underlines the conclusion that faulting and associated fracturing does not result in an enhanced rate of erosion in the vicinity of the active faults on the Bishop Tuff. The only two samples that record a larger amount of erosion (~2.8 and ~3.2 m) are those collected from the ephemeral drainages at the southern edge of the Volcanic Tableland (Fig. 7). The shaded relief image and the slope map show that other ephemeral streams have incised the cliff edge to even greater depth (Fig. 2), and have thus caused even more fluvial erosion on the Volcanic Tableland. Headward retreat of these steep bedrock channels into the southern edge of the Volcanic Tableland is limited however, presumably because their drainage area is relatively small (Fig. 2b). Apart from these short channels near the Owens River and small channels in the hanging walls of some faults, erosion of the Volcanic Tableland is spatially rather uniform.

Factors that are likely to control the erosion of the Volcanic Tableland include the bedrock weathering rate as well as the rate of sediment removal. In the uplifted footwall blocks of normal faults, where bedrock exposures are widespread and soil cover is minimal, the bedrock weathering rate is considered the rate-limiting factor. In contrast, for the down-faulted hanging walls, which are largely covered by thin soil, the removal of sediment is the limiting factor controlling erosion. The total denudation of the Bishop Tuff's surface since its deposition varies between ~0.9 and ~1.9 m, as determined for the investigated sites except the two bedrock channels. This corresponds to an average erosion rate of ~1.2 to ~2.5 m/Ma.

Based on cosmogenic ^{21}Ne alone, it is not possible to test whether the assumption of steady-state erosion inherent in equation (2) is indeed valid. However, we have also determined the ^{10}Be concentrations. These data will be reported in a forthcoming paper, where we will focus on the $^{10}\text{Be}/^{21}\text{Ne}$ production-rate ratio. When plotted in a two-nuclide

353 diagram ($^{21}\text{Ne}/^{10}\text{Be}$ vs. ^{10}Be concentration; not shown), all data are consistent with steady-
354 state erosion within uncertainties. Although we can neither exclude minor variations of the
355 erosion rate nor short periods during which the rock may have been covered to some extent,
356 the combination of ^{21}Ne and ^{10}Be clearly shows that steady-state erosion is a safe
357 approximation for the Bishop Tuff samples.

358 The apparent ^{21}Ne ages of various Bishop Tuff samples allow us to evaluate what
359 sample type is most appropriate for constraining eruption ages of young, yet-undated
360 ignimbrites with cosmogenic nuclides. Sample types include local bedrock highs, flat
361 bedrock surfaces, or desert pavements. One might think that local bedrock highs are less
362 eroded than surrounding flat bedrock and that they should yield the oldest apparent exposure
363 ages, which are closest to the true eruption age. This is indeed the case for sample 05BT7
364 from a bedrock high that stands 60 cm above the surrounding bedrock, which yields a
365 significantly older apparent age of 506 ± 25 ka compared to that of sample 05BT8 from the
366 adjacent flat bedrock with an age of 353 ± 16 ka (Table 3; Fig. 7). The ^{21}Ne concentrations
367 of samples 05BT7 and 8 record 85 ± 12 cm and 174 ± 13 cm of erosion, respectively, and
368 suggest that this bedrock high formed by differential erosion of an originally almost plain
369 surface. In contrast, two other sample pairs of bedrock highs and adjacent flat bedrock
370 (05BT4, 6 and 05BT18, 19) yield the same amounts of erosion for each pair and apparent
371 ages that are identical within error limits (Table 3; Fig. 7). Therefore, these two bedrock
372 highs were apparently an integral part of the ignimbrite's irregular original surface and
373 during slow denudation of the ignimbrite these local irregularities have been preserved. At
374 least for the sample pair 05BT18 and 19 this is quite surprising because the bedrock high
375 stands 115 cm above the surrounding bedrock (Fig. 4d). In summary, it should not be
376 assumed that bedrock highs on the surface of welded volcanic ignimbrites are generally less
377 eroded (and have older apparent ages) than adjacent flat bedrock surfaces.

Physical model simulations suggest that cosmogenic nuclide production rates on boulder surfaces are lower than those beneath a flat surface at the same location (Masarik and Wieler, 2003). For the two bedrock highs that have been preserved since eruption of the Bishop Tuff we have estimated the lowering of local production rates at ~4% based on the plots given in Masarik and Wieler (2003). For the two samples from these bedrock highs (05BT4, 18), the amount of erosion and the apparent age that result from a 4% lower production rate are not significantly different from those determined by neglecting the shape of the bedrock highs (see Table 3) and thus our conclusions remain the same.

All desert pavement samples, which consist of amalgamations of at least 20 ignimbrite clasts, yield higher apparent ages than the nearby bedrock (Table 3; Fig. 7). The pavement sample 05BT14 has an apparent age of 412 ± 21 ka, whereas the adjacent bedrock sample 05BT15 yields an age of only 341 ± 19 ka (Fig. 7). The same is true for sample 05BT5, which has an apparent age of 443 ± 24 ka, whereas the two bedrock samples 05BT4 and 6 yield ages of 373 ± 22 ka (or 389 ± 23 ka, considering the 4% lower production rate owing to the shape of the bedrock high) and 393 ± 24 ka. Sample pair 05BT9 and 10 have apparent ages that are identical within error, yet the nominal apparent age of the pavement sample is higher than that of the adjacent bedrock (Fig. 7). The isolated pavement sample 05BT11 near the end of the 'small' fault yields an age of 453 ± 18 ka. Owing to the higher apparent ^{21}Ne ages of the pavement samples, as compared to the bedrock samples, we conclude that amalgamated clasts from desert pavements are the most appropriate sample type for estimating the age of yet-undated ignimbrites. However, as a result of erosion and the disintegration of clasts, exposure dating yields only minimum ages. In case of the Bishop Tuff, the mean age of the four desert pavement samples is ~450 ka, i.e. 40% younger than the known eruption age of 760 ka.

The higher apparent ages of the pavement samples, as compared to the bedrock samples, suggest that the clasts residing in the pavements were derived from adjacent bedrock outcrops and have remained at the surface ever since. The ages of the pavements are correlated with the thickness of the Av horizon; i.e. the thicker the Av horizon, the higher are the apparent ages. These observations support the model of McFadden et al. (1987), who studied stone pavements developed on basaltic lava flows and inferred that (i) pavements form at the surface and (ii) pavement clasts are never deeply buried but stay at the surface. A subsequent study on these pavements showed that basaltic pavement clasts have the same ³He exposure ages as the adjacent basaltic bedrock (Wells et al., 1995). The two main differences between our study and the one of Wells et al. (1995) are that the basaltic bedrock and the pavements are much younger (≤ 100 ka) than the Bishop Tuff, and that Wells et al. (1995) dated individual pavement clasts whereas we combined many clasts into one sample. Fenton et al. (2002) dated a basaltic lava flow (~180 ka) using cosmogenic ³He concentrations in both intact bedrock surfaces (i.e. primary flow surfaces) and in amalgamations of basalt clasts from the surface of the basalt flow. Like Wells et al. (1995), Fenton et al. (2002) found that the desert pavements produced comparable ages to those of the bedrock surfaces, and in many cases even older ages because of bedrock erosion.

Conclusions

By determining the concentration of *in situ* produced cosmogenic ²¹Ne in quartz we have quantified the amount and rate of erosion in the Volcanic Tableland of the Bishop Tuff, California, since ~760 ka. Overall, the amount of denudation inferred for bedrock exposures on the sub-horizontal ignimbrite surface is nearly uniform and is 1-2 meters. There is no correlation between erosion rate and the spatial position of bedrock samples taken in the flat footwalls of active faults with different lengths and displacements. Hence, faulting does not

affect erosion rates in a recognizable way in the low-relief landscape of the Volcanic Tableland. Sites where denudation exceeds two meters are largely restricted to bedrock channels that are incising the southern edge of the Volcanic Tableland but these channels experienced only a limited headward retreat. This suggests that tectonic activity enhances erosion only when it is associated with the production of relief and steepening of hillslopes by river incision.

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Appendix: Evaluation of Ne isotopic compositions

Very low amounts of ^{20}Ne released by the Bishop Tuff quartz in certain heating steps, along with isotopic ratios considerably different from the atmospheric ratios (Table 2), lead to a fast change of the gas composition during the mass spectrometric analysis. This so-called “memory effect” is a consequence of sample gas ions being lost by implantation into the mass spectrometer walls, and gas atoms implanted during earlier measurements being released again. Since the calibration gas used in our laboratory, as well as the gas from most other samples analyzed here, has an atmospheric or close-to-atmospheric Ne isotope composition, all isotope ratios will tend towards atmospheric during the measurement. For Bishop Tuff quartz the change from the original sample gas composition is often non-linear,

in particular for the $^{21}\text{Ne}/^{20}\text{Ne}$ ratio (Fig. A1a). Fortunately, the reciprocal ratio $^{20}\text{Ne}/^{21}\text{Ne}$ evolves in a rather linear way (Fig. A1b), therefore we have used the linear extrapolation of $^{20}\text{Ne}/^{21}\text{Ne}$ to determine the sample gas $^{21}\text{Ne}/^{20}\text{Ne}$ ratios shown in Table 2. For $^{22}\text{Ne}/^{20}\text{Ne}$, the curvature is less evident in the raw data of the measurement (Fig. A1c). However, since $^{22}\text{Ne}/^{20}\text{Ne}$ in the sample gas is elevated above the atmospheric ratio of 0.1020 by less than a factor of 2 in most heating steps, while this factor may be more than 20 for $^{21}\text{Ne}/^{20}\text{Ne}$, $^{22}\text{Ne}/^{20}\text{Ne}$ approaches the atmospheric value more quickly and, thus, must evolve in a non-linear manner because otherwise the ratio would soon become less than that of the atmosphere (Fig. A1c). As the same behavior holds for the reciprocal ratio $^{20}\text{Ne}/^{22}\text{Ne}$, a linear extrapolation to the time of gas admission may considerably underestimate the true sample gas $^{22}\text{Ne}/^{20}\text{Ne}$ ratio. As a consequence, data points in the three-isotope diagram (cf. Fig. 5) would be shifted to an apparent position below the ‘spallation line’, i.e., the mixing line between atmospheric and cosmogenic Ne (see section 5).

It is possible to establish a mathematical function describing the non-linear evolution of $^{21}\text{Ne}/^{20}\text{Ne}$ and $^{22}\text{Ne}/^{20}\text{Ne}$ with time based on certain assumptions (Fig. A1a, c). However, it is difficult to assess how well these assumptions, e.g. a constant increase of the ^{20}Ne signal with time, are fulfilled, and in addition the uncertainties of an extrapolation according to that function are very high. Therefore we have adopted another method: Instead of extrapolating to the time of gas admission, we have used a linear extrapolation (or interpolation) of Ne isotope ratio measurements to a later time during the measurement. This avoids the problem of relatively long extrapolations along a curve with a poorly known shape, and indeed the difference between the curve fit and the linear fit becomes small about five minutes after gas admission (Fig. A1c; the whole Ne analysis takes about 27 minutes). Of course, to determine the ^{20}Ne concentration and the isotope ratios in the sample as shown in Table 2, the “memory” Ne gas accumulated during these first five minutes has to be corrected for, which

works in a way analogous to the blank correction. For the ^{21}Ne excess, however, it is irrelevant whether an extrapolation to the time of gas admission or a later time during the measurement is used, because all non-cosmogenic components, i.e. trapped Ne, blank Ne and “memory” Ne, have the same atmospheric isotopic composition. Therefore, and because the $^{20}\text{Ne}/^{21}\text{Ne}$ trend is indeed linear to a high level of accuracy, the choice of the extrapolation method only affects the $^{22}\text{Ne}/^{20}\text{Ne}$ ratio (and thus the position of data points in the three-isotope diagram), but not the ^{21}Ne excess.

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Figure Captions

Fig. 1: Map showing the location of the Bishop Tuff, eastern California, which erupted during formation of the Long Valley Caldera (modified from Sarna-Wojcicki et al., 2000). Black rectangle shows location of figure 2.

Fig. 2: (a) Shaded relief image of the study area in the Volcanic Tableland, southeastern Bishop Tuff, showing the positions of all sample sites (x indicates sample 05BTx). For location see figure 1. The digital elevation model has a spatial resolution of 10 m, therefore the ‘small fault’, with a maximum offset of ~12 m, tapers out beyond sample 11 in northern direction in reality. The two stars indicate the locations from where two photographs shown in figure 3 were taken. Topographic profiles perpendicular to three fault scarps are shown below the shaded relief image (their location in the image is marked by black lines). Vertical arrows in these profiles illustrate the position of samples taken in the footwall blocks of the three faults. Vertical exaggeration of the profiles is two. **(b)** Slope map of the area shown in (a). Normal fault scarps are characterized by steep slopes. The catchments of five ephemeral channels that drain the Volcanic Tableland are outlined by black lines. Fluvial incision of these channels into the southern rim of the Tableland increases with catchment size. Black circles indicate sample locations.

Fig. 3: (a) Overview of the Volcanic Tableland looking southwest from the uplifted footwall of the Fish Slough fault. In the center of the image a 1.7 km-long normal fault offsets the flat surface of the Bishop Tuff. The maximum vertical offset of ~20 m occurs in the center of the fault. Toward the fault tips the offset decreases gradually to zero. Mountains in the background belong to the Sierra Nevada. For location of photograph see figure 2a. **(b)**

Southeastward view along the segmented normal fault scarp with fractured bedrock in the foreground. For location of photograph see figure 2a.

Fig. 4: (a) Flat bedrock surface (sample 05BT6) in the footwall of the 'small' fault with local bedrock high, 40 cm above the surrounding ground (05BT4). Sample 05BT5 has been taken from the desert pavement visible to the left of the people. View is to the south. **(b)** Planar desert pavement with interlocking clasts at sampling site of sample 05BT5. Width of photograph is ~3 m in the center. **(c)** Flat bedrock surface (05BT15) with bedrock high, up to 50 cm above surrounding surface (05BT13). View is to the south. **(d)** Bedrock high (05BT18) about 115 cm above the surrounding bedrock (05BT19). View is to the northwest.

Fig. 5: Ne three-isotope diagrams for samples 05BT5, 9, 13, and 20. Circles represent the neon isotopic compositions of gas released at 400, 800, and 1200°C, whereas the triangle represents the neon composition of air. Gas extracted from two samples (05BT9, 20) by crushing has a neon isotopic composition (open diamonds) that is indistinguishable from air. Solid lines represent the mixing lines between atmospheric and cosmogenic Ne ("spallation line") for quartz (Niedermann et al., 1993). The array in the vicinity of atmospheric Ne is shown enlarged in the insets.

Fig. 6: (a) Sketch showing the vertical fault offset along the three investigated normal faults and the spatial position of the samples. Note that the vertical and horizontal scales are different for the three faults. The locations of the faults are shown in figure 2a. **(b)** Apparent ²¹Ne exposure ages (y-axis on left) and amount of erosion (y-axis on right) derived from the samples shown in (a). Note that the scale indicating the amount of erosion is non-linear. The lower an apparent age, the higher is the amount of erosion (Table 3). Although the apparent

ages and the amounts of erosion are slightly variable among individual faults, they are similar for the different faults, despite the fact that the tectonic offsets vary by one order of magnitude.

Fig. 7: Shaded relief image of the Volcanic Tableland showing all sample sites and for each sample the total amount of erosion and the apparent ^{21}Ne exposure age as summarized in Table 3. For samples from desert pavements, which consist of many amalgamated clasts, only apparent exposure ages are reported (in italics).

Figure in the appendix

Fig. A1: Measured isotope ratios $^{21}\text{Ne}/^{20}\text{Ne}$ (a), $^{20}\text{Ne}/^{21}\text{Ne}$ (b), and $^{22}\text{Ne}/^{20}\text{Ne}$ (c) in the 400°C step of 05BT1, plotted versus time t since admission of sample gas to the mass spectrometer. While all ratios evolve towards atmospheric values with time proceeding, $^{21}\text{Ne}/^{20}\text{Ne}$ and $^{22}\text{Ne}/^{20}\text{Ne}$ show clearly curved trends but $^{20}\text{Ne}/^{21}\text{Ne}$ is linear. The curved functions in (a) and (c) can be described by equations of the form $y = (y_0 + y_1 * a * t) / (1 + a * t)$, where y_0 is the initial isotope ratio at $t = 0$, y_1 is the atmospheric ratio, and a is the relative increase of ^{20}Ne (normalized to ^{20}Ne at $t = 0$) per unit time. Since this function is only valid under certain assumptions and the uncertainty of the extrapolation is large, we prefer a linear interpolation to a time when the difference between linear and curved fits is small, e.g. 300 s (c).

648 **Table 1:** Location and description of samples from the Volcanic Tableland (Bishop Tuff,
649 California).

650

651 **Table 2:** Results of neon concentrations and isotope ratios for samples from the Volcanic
652 Tableland (Bishop Tuff, California). $^{21}\text{Ne}_c$ is the cosmogenic ^{21}Ne concentration. Error limits
653 are 2σ .

654

655 **Table 3:** Cosmogenic ^{21}Ne concentrations, production rates at sampling sites, amounts of
656 total erosion, and apparent ^{21}Ne ages for samples from the Volcanic Tableland (Bishop Tuff,
657 California). Error limits are 2σ .

658

Sample site

- Fault footwall
- Unaffected by faulting
- ▲ Bedrock channel

- 127±13 cm Total amount of erosion assuming a temporally constant erosion rate
- 359±24 ka Apparent age calculated assuming no erosion

Table 1: Location and description of samples from the Volcanic Tableland (Bishop Tuff, California).

Sample ID	Sample type	Latitude (°N)	Longitude (°W)	elevation (m)
'Small' fault				
05BT4	bedrock high ^{\$}	37.4236	118.4262	1365
05BT5	desert pavement	37.4236	118.4262	1365
05BT6	bedrock	37.4236	118.4262	1365
05BT7	bedrock high ^{\$}	37.4233	118.4264	1369
05BT8	bedrock	37.4233	118.4264	1369
05BT9	bedrock	37.4264	118.4253	1366
05BT10	desert pavement	37.4264	118.4253	1366
05BT11	desert pavement	37.4296	118.4239	1361
Segmented fault				
05BT1	bedrock	37.4566	118.4877	1507
05BT2	bedrock	37.4499	118.4884	1502
05BT3	bedrock	37.4435	118.4909	1496
Fish Slough fault				
05BT20	bedrock	37.4466	118.3998	1411
05BT21	bedrock	37.4393	118.4002	1406
Samples from 2 sites not affected by faulting				
05BT13	bedrock high ^{\$}	37.4142	118.4555	1387
05BT14	desert pavement	37.4142	118.4555	1387
05BT15	bedrock	37.4142	118.4555	1387
05BT18	bedrock high ^{\$}	37.4162	118.4566	1395
05BT19	bedrock	37.4162	118.4566	1394
Samples from ephemeral streams				
05BT16	bedrock	37.4126	118.4696	1368
05BT17	bedrock	37.4130	118.4645	1376

^{\$} Bedrock is here referred to as a part of the bedrock that stands out above the surrounding bedrock

Table 2: Results of neon concentrations and isotope ratios for samples from the Volcanic Tableland (Bishop Tuff, California). $^{21}\text{Ne}_c$ is the cosmogenic ^{21}Ne concentration. Error limits are 2σ .

Sample	Temp. (°C)	^{20}Ne ($10^{-12} \text{ cm}^3 \text{ STP/g}$)	$^{22}\text{Ne}/^{20}\text{Ne}$	$^{21}\text{Ne}/^{20}\text{Ne}$	$^{21}\text{Ne}_c$ (10^6 at/g)
'Small' fault					
05BT4	400	47.6 ± 2.8	0.1214 ± 0.0017	0.01718 ± 0.00057	18.2 ± 1.1
	600	4.6 ± 1.4	0.1039 ± 0.0026	0.00347 ± 0.00029	0.063 ± 0.032
	800	1.4 ± 1.6	0.107 ± 0.016	0.0031 ± 0.0011	0.005 ± 0.044
	1200	3.8 ± 1.3	0.1042 ± 0.0074	0.00316 ± 0.00047	0.020 ± 0.047*
	Total	57.4 ± 3.8	0.1185 ± 0.0017	0.0148 ± 0.0011	18.3 ± 1.1
05BT5	400	11.5 ± 1.0	0.1462 ± 0.0034	0.0418 ± 0.0021	12.01 ± 0.86
	800	24.0 ± 2.2	0.1170 ± 0.0047	0.01764 ± 0.00088	9.46 ± 0.81
	1200	21.2 ± 1.6	0.1034 ± 0.0021	0.00335 ± 0.00028	0.22 ± 0.16
	Total	56.7 ± 2.9	0.1178 ± 0.0023	0.01721 ± 0.00082	21.7 ± 1.2
05BT6	400	12.8 ± 1.4	0.1289 ± 0.0032	0.0288 ± 0.0024	8.88 ± 0.90
	800	16.4 ± 1.8	0.1257 ± 0.0033	0.0260 ± 0.0016	10.19 ± 0.75
	1200	10.8 ± 1.0	0.1024 ± 0.0021	0.00357 ± 0.00048	0.18 ± 0.14
	Total	40.0 ± 2.5	0.1205 ± 0.0019	0.0209 ± 0.0012	19.3 ± 1.2
05BT7	400	9.8 ± 1.1	0.1558 ± 0.0082	0.0515 ± 0.0031	12.83 ± 0.94
	800	25.5 ± 2.1	0.1228 ± 0.0028	0.02012 ± 0.00071	11.77 ± 0.79
	1200	32.5 ± 2.2	0.1024 ± 0.0011	0.00322 ± 0.00025	0.22 ± 0.22
	Total	67.9 ± 3.2	0.1178 ± 0.0018	0.01658 ± 0.00088	24.8 ± 1.3
05BT8	400	48.3 ± 2.9	0.1165 ± 0.0011	0.01623 ± 0.00066	17.2 ± 1.1
	800	5.2 ± 1.4	0.1042 ± 0.0023	0.00306 ± 0.00032	0.014 ± 0.045
	1200	3.0 ± 1.3	0.1059 ± 0.0029	0.00318 ± 0.00063	0.018 ± 0.051*
	Total	56.5 ± 3.5	0.1148 ± 0.0010	0.01431 ± 0.00069	17.2 ± 1.2
05BT8^{&}	400	2.06 ± 0.36	0.213 ± 0.024	0.117 ± 0.018	6.29 ± 0.76
	800	37.4 ± 2.3	0.1144 ± 0.0019	0.01387 ± 0.00046	10.95 ± 0.74
	1200	40.6 ± 2.2	0.1026 ± 0.0017	0.00314 ± 0.00023	0.20 ± 0.25
	Total	80.1 ± 3.1	0.1109 ± 0.0015	0.01107 ± 0.00073	17.4 ± 1.1
05BT9	crusher	89.9 ± 7.0	0.10215 ± 0.00082	0.00299 ± 0.00013	—
05BT9	400	6.37 ± 0.83	0.1529 ± 0.0067	0.0515 ± 0.0045	8.31 ± 0.68
	800	41.1 ± 3.0	0.1164 ± 0.0018	0.01567 ± 0.00057	14.0 ± 1.0
	1200	51.6 ± 3.3	0.1028 ± 0.0016	0.00333 ± 0.00023	0.52 ± 0.32
	Total	99.1 ± 4.5	0.1116 ± 0.0013	0.01155 ± 0.00060	22.9 ± 1.3
05BT10	400	69.6 ± 4.5	0.1109 ± 0.0014	0.01000 ± 0.00035	13.2 ± 1.0
	800	36.7 ± 2.7	0.1124 ± 0.0018	0.01350 ± 0.00046	10.40 ± 0.76
	1200	28.5 ± 1.9	0.1024 ± 0.0018	0.00325 ± 0.00026	0.22 ± 0.20
	Total	134.9 ± 5.6	0.1095 ± 0.0010	0.00952 ± 0.00026	23.8 ± 1.3
05BT11	400	19.0 ± 1.1	0.1203 ± 0.0022	0.0210 ± 0.0011	9.20 ± 0.73
	800	51.6 ± 2.9	0.11062 ± 0.00094	0.01164 ± 0.00043	12.02 ± 0.85
	1200	49.8 ± 2.7	0.1021 ± 0.0010	0.00337 ± 0.00035	0.55 ± 0.46
	Total	120.4 ± 4.1	0.10862 ± 0.00070	0.00969 ± 0.00034	21.8 ± 1.2
05BT11^{&}	400	2.58 ± 0.42	0.204 ± 0.018	0.091 ± 0.014	6.06 ± 0.59
	800	13.1 ± 1.3	0.1602 ± 0.0051	0.0474 ± 0.0032	15.7 ± 1.1
	1200	4.87 ± 0.80	0.1053 ± 0.0058	0.00573 ± 0.00093	0.36 ± 0.11
	Total	20.6 ± 1.6	0.1526 ± 0.0047	0.0429 ± 0.0032	22.1 ± 1.3
Segmented fault					
05BT1	400	2.88 ± 0.54	0.281 ± 0.034	0.166 ± 0.022	12.62 ± 0.72
	800	12.7 ± 1.0	0.1288 ± 0.0052	0.0280 ± 0.0021	8.53 ± 0.78
	1200	12.79 ± 0.83	0.1005 ± 0.0029	0.00370 ± 0.00064	0.25 ± 0.22
	Total	28.3 ± 1.4	0.1315 ± 0.0053	0.0311 ± 0.0036	21.4 ± 1.1
05BT2	400	18.4 ± 1.7	0.1256 ± 0.0045	0.0275 ± 0.0011	12.10 ± 0.86
	800	26.7 ± 2.1	0.1172 ± 0.0021	0.01786 ± 0.00074	10.69 ± 0.80
	1200	25.7 ± 1.9	0.1020 ± 0.0012	0.00335 ± 0.00015	0.27 ± 0.10
	Total	70.8 ± 3.2	0.1139 ± 0.0015	0.01508 ± 0.00060	23.1 ± 1.2
05BT3	400	30.5 ± 2.2	0.1144 ± 0.0020	0.01339 ± 0.00037	8.55 ± 0.60
	800	66.3 ± 4.4	0.1110 ± 0.0011	0.01070 ± 0.00022	13.77 ± 0.93
	1200	39.3 ± 2.6	0.1017 ± 0.0010	0.00330 ± 0.00025	0.36 ± 0.26
	Total	136.1 ± 5.6	0.1091 ± 0.0008	0.00916 ± 0.00021	22.7 ± 1.1

Fish Slough fault

05BT20	crusher	23.0 ± 1.7	0.1017 ± 0.0018	0.00301 ± 0.00017	—
05BT20	400	11.7 ± 1.1	0.1321 ± 0.0046	0.0298 ± 0.0022	8.42 ± 0.83
	800	8.3 ± 1.2	0.1610 ± 0.0090	0.0614 ± 0.0070	13.0 ± 1.1
	1200	5.78 ± 0.62	0.1017 ± 0.0022	0.00462 ± 0.00063	0.258 ± 0.097
	Total	25.7 ± 1.7	0.1346 ± 0.0039	0.0343 ± 0.0029	21.7 ± 1.4
05BT21	400	44.5 ± 2.7	0.1184 ± 0.0018	0.01711 ± 0.00048	16.94 ± 0.93
	800	1.9 ± 1.7	0.1057 ± 0.0048	0.00333 ± 0.00069	0.019 ± 0.031
	1200	4.7 ± 1.1	0.1050 ± 0.0037	0.00294 ± 0.00034	-0.002 ± 0.040*
	Total	51.1 ± 3.4	0.1167 ± 0.0017	0.01530 ± 0.00064	16.95 ± 0.93

Samples from 2 sites not affected by faulting

05BT13	400	3.70 ± 0.68	0.176 ± 0.015	0.0708 ± 0.0099	6.75 ± 0.53
	800	11.0 ± 1.3	0.1246 ± 0.0032	0.0248 ± 0.0021	6.46 ± 0.55
	1200	13.9 ± 1.1	0.1025 ± 0.0016	0.00327 ± 0.00040	0.12 ± 0.15
	Total	28.5 ± 1.8	0.1205 ± 0.0029	0.0203 ± 0.0020	13.32 ± 0.77
05BT13^{&}	400	2.93 ± 0.80	0.186 ± 0.024	0.084 ± 0.019	6.35 ± 0.56
	800	9.7 ± 1.1	0.1320 ± 0.0056	0.0330 ± 0.0025	7.87 ± 0.61
	1200	9.70 ± 0.71	0.1023 ± 0.0024	0.00310 ± 0.00052	0.038 ± 0.038
	Total	22.4 ± 1.5	0.1262 ± 0.0047	0.0267 ± 0.0035	14.26 ± 0.83
05BT14	400	11.5 ± 1.0	0.1337 ± 0.0040	0.0317 ± 0.0015	8.85 ± 0.66
	800	16.8 ± 1.7	0.1277 ± 0.0031	0.0283 ± 0.0016	11.44 ± 0.80
	1200	19.8 ± 3.0	0.1014 ± 0.0013	0.00342 ± 0.00027	0.25 ± 0.15
	Total	48.0 ± 3.6	0.1183 ± 0.0019	0.0189 ± 0.0012	20.5 ± 1.1
05BT15	400	6.93 ± 0.86	0.152 ± 0.011	0.0529 ± 0.0042	9.30 ± 0.72
	800	11.5 ± 1.3	0.1299 ± 0.0037	0.0272 ± 0.0021	7.51 ± 0.57
	1200	19.0 ± 1.4	0.1023 ± 0.0014	0.00331 ± 0.00016	0.177 ± 0.080
	Total	37.5 ± 2.1	0.1200 ± 0.0027	0.0198 ± 0.0014	16.99 ± 0.93
05BT18	400	6.13 ± 0.86	0.1650 ± 0.0099	0.0646 ± 0.0059	10.16 ± 0.77
	800	11.5 ± 1.4	0.1290 ± 0.0029	0.0263 ± 0.0019	7.21 ± 0.54
	1200	14.4 ± 1.1	0.1015 ± 0.0037	0.00336 ± 0.00031	0.15 ± 0.12
	Total	32.1 ± 2.0	0.1235 ± 0.0031	0.0233 ± 0.0019	17.52 ± 0.95
05BT19	400	0.93 ± 0.44	0.47 ± 0.16	0.36 ± 0.15	8.84 ± 0.98
	800	7.32 ± 0.81	0.1510 ± 0.0041	0.0485 ± 0.0041	8.95 ± 0.69
	1200	9.92 ± 0.72	0.1020 ± 0.0024	0.00357 ± 0.00021	0.163 ± 0.056
	Total	18.2 ± 1.2	0.140 ± 0.012	0.040 ± 0.011	18.0 ± 1.2

Samples from ephemeral streams

05BT16	400	12.7 ± 1.3	0.1116 ± 0.0043	0.0147 ± 0.0010	3.99 ± 0.39
	800	17.8 ± 1.7	0.1190 ± 0.0031	0.0201 ± 0.0014	8.19 ± 0.73
	1200	17.4 ± 1.4	0.1004 ± 0.0015	0.00318 ± 0.00032	0.10 ± 0.15
	Total	47.9 ± 2.6	0.1103 ± 0.0018	0.01250 ± 0.00071	12.28 ± 0.84
05BT17	crusher	7.31 ± 0.66	0.1011 ± 0.0026	0.00310 ± 0.00030	—
05BT17	400	43.4 ± 2.7	0.1123 ± 0.0014	0.01175 ± 0.00061	10.25 ± 0.84
	800	4.4 ± 1.7	0.1066 ± 0.0028	0.00367 ± 0.00046	0.095 ± 0.042
	1200	2.6 ± 1.2	0.1059 ± 0.0041	0.00315 ± 0.00086	0.013 ± 0.059*
	Total	50.4 ± 3.6	0.1115 ± 0.0022	0.01062 ± 0.00060	10.35 ± 0.84
05BT17^{&}	400	8.1 ± 3.3	0.146 ± 0.020	0.045 ± 0.017	9.1 ± 1.2
	600	5.8 ± 3.1	0.1103 ± 0.0070	0.0097 ± 0.0037	1.05 ± 0.16
	800	7.2 ± 4.2	0.1042 ± 0.0047	0.00329 ± 0.00086	0.06 ± 0.16
	1200	3.5 ± 3.1	0.138 ± 0.035	0.0034 ± 0.0013	0.04 ± 0.11
	Total	24.6 ± 6.9	0.124 ± 0.010	0.0185 ± 0.0075	10.3 ± 1.2
05BT17^{&}	400	13.2 ± 1.2	0.1091 ± 0.0027	0.0109 ± 0.0011	2.82 ± 0.40
	800	20.7 ± 1.4	0.1199 ± 0.0012	0.01887 ± 0.00066	8.83 ± 0.55
	1200	19.3 ± 1.1	0.1039 ± 0.0025	0.00325 ± 0.00030	0.15 ± 0.15
	Total	53.2 ± 2.2	0.1114 ± 0.0013	0.01121 ± 0.00047	11.80 ± 0.70

* 1200°C degassing step was not included for calculation of total Ne_c.

& Duplicate or triplicate analysis.

Table 3: Cosmogenic ^{21}Ne concentrations, production rates at sampling sites, amounts of total erosion, and apparent ^{21}Ne ages for samples from the Volcanic Tableland (Bishop Tuff, California). Error limits are 2σ .

Sample ID and description	^{21}Ne (10^6 at/g)	Prod. rate of ^{21}Ne (at/g/a)	Total erosion (cm)*	Apparent age (ka)**
'Small' fault				
05BT4, bedrock high (40 cm)	18.2 ± 1.1	48.9	159 ± 16	373 ± 22
" "	18.2 ± 1.1	46.9#	149 ± 15	389 ± 23
05BT5, desert pavement	21.7 ± 1.2	48.9	—	443 ± 24
05BT6, bedrock	19.3 ± 1.2	48.9	146 ± 16	393 ± 24
05BT7, bedrock high (60 cm)	24.8 ± 1.3	49.1	85 ± 12	506 ± 25
05BT8 ^{&} , bedrock	17.34 ± 0.79	49.1	174 ± 13	353 ± 16
05BT9, bedrock	22.9 ± 1.3	49.0	104 ± 13	467 ± 26
05BT10, desert pavement	23.8 ± 1.3	49.0	—	486 ± 27
05BT11 ^{&} , desert pavement	21.9 ± 0.9	48.8	—	453 ± 18
Segmented fault				
05BT1, bedrock	21.4 ± 1.1	54.8	147 ± 13	391 ± 20
05BT2, bedrock	23.1 ± 1.2	54.5	127 ± 13	423 ± 22
05BT3, bedrock	22.7 ± 1.1	54.3	130 ± 13	418 ± 21
Fish Slough fault				
05BT20, bedrock	21.7 ± 1.4	50.8	125 ± 16	426 ± 28
05BT21, bedrock	16.95 ± 0.93	50.6	188 ± 16	335 ± 18
Samples from 2 sites not affected by faulting				
05BT13 ^{&} , bedrock high (50 cm)	13.75 ± 0.56	49.8	246 ± 13	276 ± 11
05BT14, desert pavement	20.5 ± 1.1	49.8	—	412 ± 21
05BT15, bedrock	16.99 ± 0.93	49.8	183 ± 15	341 ± 19
05BT18, bedrock high (115 cm)	17.52 ± 0.95	50.1	177 ± 15	350 ± 19
" "	17.52 ± 0.95	48.1#	166 ± 15	364 ± 20
05BT19, bedrock	18.0 ± 1.2	50.1	170 ± 18	359 ± 24
Samples from ephemeral streams				
05BT16, bedrock	12.28 ± 0.84	49.0	277 ± 23	250 ± 17
05BT17 ^{&} , bedrock	11.05 ± 0.49	49.3	316 ± 16	224 ± 10

[&] Weighted mean of 2 or 3 analyses.

* Calculated assuming a temporally constant erosion rate.

** Calculated assuming no erosion.

Production rate decreased by 4% to correct for the shape of the bedrock high (cf. Masarik and Wieler, 2003).