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Combined uranium series and ^{10}Be cosmogenic exposure dating of surface abandonment: a case study from the Ölgiy strike-slip fault in western Mongolia

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Abstract Time-averaged fault slip-rates can be established by reliably dating the abandonment of an alluvial deposit that has been displaced by Quaternary movement along a cross-cutting fault. Unfortunately, many Quaternary dating techniques are hindered by uncertainties inherent to individual geochronometers. Such uncertainties can be minimised by combining multiple independent techniques. In this study, we combine ^{10}Be exposure dating of boulder tops and U-series dating of layered pedogenic carbonate cements accumulated on the underside of clasts from two separate alluvial surfaces. These surfaces are both displaced by the active Ölgiy strike-slip fault in the Mongolian Altay Mountains. We date individual layers of pedogenic carbonate, and for the first time apply a Bayesian statistical analysis to the results to develop a history of carbonate accumulation. Our approach to the U-series dating provides an age of initiation of carbonate cement formation and avoids the problem of averaging contributions from younger layers within the carbonate.

The U-series ages make it possible to distinguish ^{10}Be samples that have anomalously young exposure ages and have hence been subject to the effects of post-depositional erosion or exhumation. The combination of ^{10}Be and U-series dating methods provides better constrained age estimates than using either method in isolation and allows us to bracket the abandonment ages of the two surfaces as 18.0–28.1 kyr and 38.4–76.4 kyr. Our ages, combined with measurements of the displacement of the surfaces, yield a right-lateral slip-rate for the Ölgiy fault of 0.3–1.3mm yr^{-1}, showing that it is a relatively important structure within the active tectonics of Mongolia and that it constitutes a substantial hazard to local populations.

Keywords: Quaternary dating, uranium series, cosmogenic isotopes, Altay, active faulting

Highlights

- Complementary ^{10}Be and U-series results reliably date surface abandonment.
- Novel modeling of U-series data isolates contamination from younger carbonate.
- The Ölgiy fault in western Mongolia has an average slip-rate of 0.3-1.3 mm yr^{-1}.

1. Introduction

Establishing the age of abandonment for Quaternary landforms is important in studies of neotectonics, geomorphology, and paleoclimate. Accurate dating is necessary for the determination of averaged fault slip-rates, and slip-rate studies are in turn important for assessing earthquake hazard along active faults and understanding the kinematics of active continental deformation in a variety of tectonic settings (e.g. Brown et al., 2002; Densmore et al., 2007; Frankel et al., 2007). Placing firm constraints on the timing of surface abandonment is often hindered by uncertainties, both analytical and geological, which are specific to the individual Quaternary dating techniques. These limitations may be overcome by combining complementary dating methods (e.g. DeLong and Arnold, 2007;

Kock et al., 2009; Behr et al., 2010; Fletcher et al., 2010; Blisniuk et al., 2012).

Late Quaternary dating techniques can be particularly difficult to apply in arid to semi-arid mountainous environments, where organic material suitable for radiocarbon (^{14}C) dating and the fine-grained sediments necessary for optically stimulated luminescence (OSL) are often not available (Faure, 1986; Wintle and Huntley, 1982; Richards, 2000). Terrestrial cosmogenic nuclide (TCN) dating is often used to constrain the abandonment of landforms in mountainous settings, and the method has been successfully applied in several studies in western Mongolia (Ritz et al., 1995; Nissen et al., 2009a; Frankel et al., 2010).

TCN age calculations are reliant on quantifying the pre- and post- depositional processes affecting the sampled material, which are often difficult to establish, particularly in the case of ^{10}Be cosmogenic boulder dating (Gosse and Phillips, 2001; Putnam et al., 2010). Erosion of the boulders and of the surrounding alluvium leads to an underestimation of the true surface exposure age, and inherited ^{10}Be accumulated prior to deposition leads to an overestimation of the age. It is often unclear which age is the `true' exposure age when there is a spread in data from individual samples (e.g. Fenton and Pelletier, 2013).

^{238}U-^{234}U-^{230}Th dating (U-series) of pedogenic carbonate that has accumulated in-situ on pebbles in soils is a valuable complementary dating technique to TCN dating (Ku et al., 1979; Blisniuk and Sharp, 2003; Sharp et al., 2003; Fletcher et al., 2011). The U-series method utilises short-lived intermediate isotopes from the uranium decay chain to constrain the timing of carbonate growth, which in turn establishes the timing of abandonment of an alluvial deposit. The method has high analytical precision (requiring only small sample sizes), is based on well-defined decay constants, and can be used on samples aged up to 500 kyr (> 1 Myr for model $^{234}U/^{238}U$ ages). U-series dating is possible because uranium is incorporated into carbonate during growth, whereas thorium is initially excluded, such that (ideally) all ^{230}Th measured in the sample is the daughter product of the initial uranium. However the potential for incorporation of initial ^{230}Th may lead to problems in calculating U-series ages. There may be some lag between sediment deposition and carbonate pedogenesis. Therefore U-series results constrain the minimum age of surface deposition, and are complementary to TCN exposure dating. By combining U-series dating with ^{10}Be TCN dating, it is possible to gain insight into the spread of TCN ages that can occur due to post-depositional processes, placing firmer constraints on the geochronology of a displaced landform.

In this paper, we use ^{10}Be cosmogenic nuclide and U-series dating to establish the timing of abandonment of a pair of alluvial deposits in the Altay Mountains of western Mongolia that have been displaced by active faulting. There are only three published quantitative slip-rate studies published for this region, and none of the fault zones in Western Mongolia have slip-rates measured in more than one locality. Several of the faults have no quantitative estimate of slip-rate. Our slip-rate study is the first in the Altay to compare rates with another location on the same fault, based on data from Frankel et al. (2010).

We first describe the geomorphological setting of the study site, followed by a detailed description of both ^{10}Be cosmogenic nuclide and U-series methodologies. We then show that the two chronological methods produce results that are in agreement across two separate deposits. The U-series results are further explored through Bayesian statistical analysis, which we apply to a sequence of sub-samples in stratigraphic order within the pedogenic carbonate coatings. This approach is typical when analysing radiocarbon data, but has not previously been applied to a U-series dataset from pedogenic carbonate and adds confidence to our results. The age constraints are used to estimate the average slip-rate of the Ölgiy strike-slip fault in the Central Altay Mountains, followed by a discussion of the tectonic, geomorphological, and geochronological implications of our work.

2. Tectonic and environmental setting

Our study site is located on the Ölgiy fault, a right-lateral strike-slip fault in the centre of the Altay Mountains, western Mongolia (Figure 1). The Altay are a transpressional mountain range, with sinuous and anastomosing NNW-SSE oriented right-lateral strike-slip faults that likely accommodate NE–SW directed shortening from the India-Eurasia continental collision by anticlockwise rotation about a vertical axis (e.g. Baljinnyam et al., 1993; Cunningham, 2005; Bayasgalan et al., 2005). Where faults strike ~350° they accommodate nearly pure strike-slip motion (e.g. Walker et al., 2006; Nissen et al., 2009a), and oblique reverse slip occurs on faults that strike more westerly. The few existing slip-rate estimates for individual faults in the Altay range between 0.5 and 2.5 mm yr^{-1} (Vassallo, 2006; Nissen et al., 2009a,b; Frankel et al., 2010; Figure 1). There is one existing constraint of 0.9 +0.2/-0.1 mm yr^{-1} on the rate of slip of the Ölgiy fault at a site 100 km south of our present study site (Frankel et al., 2010).

The Altay has a semi-arid, mountainous continental climate with large seasonal temperature variations, from -30°C in the winter to more than 25°C in the summer. The western (Russian and Chinese) Altay receive significantly more precipitation (1500 mm yr^{-1}) than the eastern (Mongolian) Altay (as low as 150 mm yr^{-1}), which are located in the rain shadow of the northwest part of the mountain range (Morinaga et al., 2003; Lehmkuhl et al., 2007). Precipitation in Mongolia is concentrated in the summer months, and less than 10% of the mean annual precipitation falls in the winter, mostly as snow (Morinaga et al., 2003). Mountains at elevations > 3500 m are capped by glaciers, which are currently retreating and have been since the Little Ice Age (Grunert et al., 2000; Dundon and Ganbold, 2009). The Altay experienced two to three Pleistocene glacial advances, correlated with MIS 2 and 4 (or between approximately 35–15 ka and 70–55 ka, respectively; Lehmkuhl, 1998; Lehmkuhl and Owen, 2005).

3. Site description

Our study site is located on the central part of the Ölgiy fault where it strikes ~340–350° (Figure 2a). The site is 20 km south of Ölgiy city, one of the major towns in western Mongolia (Figure 1). At the sampling locality, the fault runs along the eastern side of a north-south bedrock ridge outcropping in the foreland of the Hungui Mountains and composed of large quartz bodies and copper ore (Figure 2b). Several east-west oriented alluvial deposits are emplaced at gaps in the ridge (Figure 2c). These abandoned landforms are incised by streams that are displaced right-laterally at the fault (Figure 3). At the sample site, there is also an east-facing scarp along the fault that varies in height from 3–6 m.

Although the Ölgiy fault is situated close to the western escarpment of the Hungui Mountains, the vertical component in the late Quaternary appears to be negligible and the east-facing scarp at the site is at least partially due to right-lateral displacement of the sloping alluvial surface (as described further below). A mostly strike-slip motion of the fault at our site is supported by the 340–350° fault trend, which is typical for pure strike-slip faulting in the Altay (Walker et al., 2006; Nissen et al. 2009a). Near the site, there is an exposed bedrock fault plane dipping NE (S, D = 343°, 74°) with obliquely dipping slickensides oriented north-south (P, T = 64°, 008°; location shown on Figure 3). The vertical scarp observed at the study site is not continuous along strike, and only occurs where the fault strikes oblique to the hillslope. Approximately 2.5 km north of the site, the fault, still trending 340–350°, crosses a wide valley bottom without producing any vertical scarp (Figure 2b). North of this valley, the fault strikes 320–330° and there is a continuous west-facing scarp along this section (Figure 2a, b).

Our sample site is one of the few locations along the Ölgiy fault that preserves obvious cumulative fault displacements. It includes two alluvial deposits that were emplaced in a direction that is nearly perpendicular to the strike of the fault. The surfaces have slopes that dip between 10° and 20° and are now abandoned and incised by streams (Figure 3). The two main streams at the site are more deeply incised on the western, uplifted, side of the fault (down slope, Figure 4). Although the two surfaces are superficially similar in appearance, and indeed our initial field interpretation was of a single surface covering the entire site, our dating results confirm that there are two distinct deposits.

We label the older deposit `F1' and a younger deposit `F2'. Their approximate extents are shown in Figure 3. There is a third deposit on the northern boundary of the site, but it was not sampled and is labeled ‘unknown’ on Figure 3. Both of the dated deposits have abundant clasts on their surfaces that are angular and range in size from small pebbles to 2 m boulders. Low grass is present on the surfaces, and there is no desert pavement or Av soil developed on both F1 and F2. The surfaces are mildly used by local herders for grazing livestock, which combined with cold temperatures, frequent summer storms, and winter snowfall may impair vesicular soil and desert pavement development in the region. The clasts imbedded in the surfaces are composed of metasedimentary rock with prominent quartz veins, and some are composed of pure veins of quartz. Some clasts and boulders have a faint desert varnish. Based on observations of the catchment morphology in satellite imagery, the material is likely derived from a small steep catchment in the western margin of the Hungui Mountains and the maximum transport distance from the source of the rock is less than 1 km (Figure 2c).

At the surface, the deposits are poorly sorted with no organised morphology visible, which suggests there has been no repeated fluvial resurfacing. It was not possible to dig into the surface due to the presence of large boulders throughout, and as a result, a detailed sub-surface stratigraphy of the deposits was not determined. We refrain from defining a specific transport mechanism for the two deposits, though the coarse and poorly sorted sediment containing very large angular boulders, and the short steep catchment from which they were derived, argue for rapid transport and deposition in a high-energy environment, possibly in a single event. The western side of the fault is particularly protected from active alluvial modification as a result of the east-facing scarp. Samples for both dating methods were only collected from this western, more protected side of the fault (Figure 3).

Two streams that are incised into the abandoned surfaces show right-lateral displacement as they cross the fault (Figures 3 and 5). The active stream channels are 3–4 m wide, and on the western, uplifted, side of the fault they are more than 2 m deep (Figure 4). Several topographic profiles measured on both sides of the fault are displayed in Figure 4c (extracted from the DEM, along profile lines displayed in white on Figure 4b). Figure 4d shows the map view trace of the streams based on the DEM. We project the best fit line of each stream to the fault, and the displacement of these lines represents the time-averaged fault displacement of the deposit, similar to the method used by Frankel et al., 2010. The stream channels are approximately perpendicular to the trace of the fault, and the projected lines are the best fit through 20-30 m of the mapped stream trace. The width of the streams (measured from the DEM) is used to assign an uncertainty to the displacement measurement (e.g. Frankel et al., 2010). The southern stream is displaced by 17.8 ± 7.2 m, and the northern stream by 14.3 ± 6.2 m, with an average displacement of 16.0 ± 6.6 m. The uncertainty of the stream displacements is the root sum square of average measurements of the stream widths and the magnitude of bends in the stream paths (see Table A1 in the supplementary material for the measurements that were included in uncertainty calculations). The two displaced streams are incised into the margins of the younger surface F2, likely due to the slight convexity in the F2 surface that has caused post-depositional drainage channels to flow along its edges. As such, and because the deposition of F2 is also likely to have overprinted any preexisting stream channels, the displacement of the streams represents the displacement of the F2 deposit, and not any prior fault offset.

As the motion on the fault at our study site is likely to be almost pure strike-slip, we can also use the scarp height to estimate the maximum lateral displacement of F1, because there are no linear, offset features available on this deposit. In Figure 6 we show our method for estimating the maximum horizontal displacement based on the height of the vertical scarp, assuming that the fault motion at the site is pure strike-slip and that the scarp is formed by oblique displacement of a sloping surface. This method yields an estimate of 29.1 ± 5.6 m. The mean displacement is calculated based on four profiles across the deposit, and the uncertainty is the standard deviation of all calculated horizontal displacements (see Figure A1 and Table A2 in the supplementary material for plots and measurements of all four profiles). This displacement can be considered as a maximum due to the potential for reverse faulting, up on the west side of the fault, at our site.

4. Quaternary dating techniques: methods and results

4.1. U-series dating of pedogenic carbonate rinds

^{238}U-^{234}U-^{230}Th dating takes advantage of the intermediate nuclides produced in the ^{238}U decay chain to produce ages with high analytical precision for samples up to ~500 kyr. Pedogenic carbonate accumulates particularly well in gravelly soils, and is typically found between about 0.5 and 1 m depth, but can be found from the surface down to 2 m (Birkland, 1984). The depth of carbonate pedogenesis can vary due to many factors, which include temperature, local precipitation, and soil texture. The effect of climate change on pedogenic carbonate precipitation has been noted particularly in arid regions of western North America, where there is a bimodal distribution of carbonate ages that are Pleistocene at depth and late Holocene in shallow soils (<75 cm), attributed to LGM (Last Glacial Maximum) related climate change (McDonald et al., 1996). Carbonate pedogenesis may begin at any time after surface deposition, which implies that U-series ages are a minimum bound on abandonment.

Uranium is relatively soluble in ground water and is incorporated into the carbonate in similar concentrations as in the water (relative to Ca^{-2}), whereas ^{230}Th is insoluble in water, allowing for the fractionation of uranium from thorium at the time of carbonate formation (see van Calsteren and Thomas, 2006, for an overview). The radiogenic decay of uranium to ^{230}Th allows for the timing of carbonate growth to be determined. The carbonate coatings on clasts generally show a progressively outward growth, with the oldest layers closest to the pebble, and younging outwards in stratigraphic succession. When the technique was first applied, large sample sizes were necessary to obtain high enough ion concentrations (Ku et al., 1979). However with modern day MC-ICP-MS (multi-collector inductively coupled plasma mass spectrometry) techniques, it is possible to measure small samples of carbonate (~6 x 10^{-4} g), and the method is becoming more widely applied in Quaternary science and active tectonics (e.g. Blisniuk and Sharp, 2003; Sharp et al., 2003; Kock et al., 2009; Fletcher et al. 2010; Behr et al., 2010; Blisniuk et al., 2012).

4.1.1. U-series sample preparation and analytical methods

In the summer of 2009, large (30-50 cm in diameter), stable, and in-situ clasts partially exposed at the surface were collected from F1 and F2. Each of these clasts had a rind of pedogenic carbonate coating only present on the base of the clast, which grew at depths equivalent to the thickness of the clast (30—50 cm), and was later subsampled in the lab. In order to ensure that the carbonate grew *in situ*, we only sampled clasts with a diameter of 30-50 cm that were firmly rooted within the surrounding sediment. We also took care to select samples from regions where the surface appeared stable and undisturbed, and far from the margins of the alluvial surfaces or stream channels. Several samples were collected from the two surfaces, but based on the carbonate having a thickness of at least 1 cm and the quality of the pedogenic carbonate, material from two separate samples were measured from F2 (MN09-OG12 and MN09-OG13), and one sample from F1 (MN09-OG7).

Standard and accepted sampling procedures for U-series dating of soils involves sampling carbonate-coated clasts from depths greater than ~50 cm and detailed description of the soil and sediment profile at depth (e.g. Ku et al., 1979; Blisniuk and Sharp, 2003; Sharp et al., 2003; Fletcher et al., 2011). At the Ölgiy site, it was not possible to sample pedogenic soils from depth due to the large boulders present in the deposit and the remote locality. We caution the reader that our method is not the accepted practice. However, our results are still useful for establishing a minimum age of the Ölgiy deposits because the surface cannot be younger than the age of the pedogenic carbonate, and this is discussed further below.

Pedogenic carbonate rinds were cross-sectioned with a diamond rock saw, rinsed with 18MΩcm (Milli-Q) water and dried, before sub-samples were taken with a New Wave Research Micro Mill (Figure 7). Where possible, sub-samples were taken from depressions cut parallel to visible stratigraphic layering within the rind. Depressions were milled with a tungsten carbide drill bit, and were typically 200 μm wide. For each sub sample approximately 0.6–3.0 mg of powder was collected with a scalpel, and weighed in a micro centrifuge tube on a ±0.00001 g balance.

Sub-sample powders were transferred to Teflon vials with 1 mL 18MΩcm water, and were spiked with a mixed ^{229}Th:^{236}U tracer solution. Total digestion of samples was undertaken with approximately 15M HNO_3 and concentrated HF (the exact concentration of HF is unknown as it is distilled by sub-boiling at the University of Oxford, and titration adds unnecessary hazard). Equilibration of sample and spike isotopes was ensured by twice drying and re-dissolving the sample in concentrated HNO_3. Uranium and thorium were separated from each other and the sample matrix using the protocol of Negre et al. (2009).

Measurement of Th and U isotope ratios was performed on a Nu Instruments MC-ICP-MS with a DSN-100 desolvating nebuliser sample introduction system, following the protocols of Negre et al. (2009) with modifications to optimize the measurements of small ion beams. Uranium was measured statically with all isotopes measured simultaneously. Each sample measurement was bracketed with two measurements of CRM-145 uranium standards: one at a similar ^{234}U intensity to the samples, to assess the reproducibility of the $^{234}U/^{238}U$ and the $^{238}U/^{236}U$ (using the $^{238}U/^{235}U$ as a proxy for the reproducibility of the $^{238}U/^{236}U$); and one more concentrated so that higher precision corrections for mass bias and ion counter efficiency could be made. Thorium isotopes were measured dynamically, with both ^{230}Th and ^{229}Th measured in the same ion counter in two steps and ^{232}Th in a Faraday collector. A separate measurement of a CRM-145 standard was made between sample analyses to characterize the mass bias and ion counter detector efficiency. A uranium standard is chosen here rather than a thorium standard, which may produce more accurate corrections, because of the need to limit the amount of thorium entering the sample introduction system and hence keep background contamination low. Prior to all measurements, assessments of the memory and detector noise were made on a 2 wt% HNO_3 solution and by blocking the ion beam entirely. The contribution from tailing of the ^{238}U and/or ^{232}Th beam, to all other isotopes, was corrected for by measuring at half masses on standard and sample solutions.

Isotope abundances were calculated accounting for the minor natural components of the ^{229}Th:^{236}U tracer solution, and the procedural blanks. The total procedural blanks and their uncertainties are ^{238}U: 65 ± 117 pg, ^{232}Th: 9 ± 17 pg, and ^{230}Th: 0.7 ± 1.1 fg (2σ based on 14 measurements of the total procedural blank processed alongside samples similar to those measured here). The final uncertainties in isotope abundances, which are dominated by the uncertainty in the blank correction, are up to 70%, but for the majority of samples (where the blank is a more minor component) total uncertainties are less than 10%.

4.1.2. ^{238}U-^{234}U-^{230}Th results

Uranium concentrations, U-series isotope ratios, and calculated ages are listed in Table 1. Ages are calculated from the measured (^{230}Th/^{238}U) and (^{234}U/^{238}U), using the age equation of Broecker (1963) employed in the isoplot software (Ludwig, 2003). Calculated ages show some agreement within each sub-sample but in some cases the order of the ages violates the stratigraphic order of outward growth from the pebble. This stratigraphic discrepancy can be accounted for by considering the initial isotopic composition of the subsamples. Contamination from detrital particulates within the authigenic carbonate will have incorporated ^{230}Th and uranium with a potentially different (^{234}U/^{238}U), which will typically bias the ages to older values (van Calsteren and Thomas, 2006). Relatively low $^{230/232}$Th activity ratios (<5) are also suggestive of detrital contamination because 'common' ^{232}Th is stable on Quaternary timescales. However with relatively young samples, lower $^{230/232}$Th is expected, due to lesser amounts of radiogenic ^{230}Th that will have had time to form in the sample. To correct for detrital contamination, the measured (^{232}Th/^{238}U) is used as a proxy for the amount of contamination and the isotopic compositions of the contaminant phase is assumed to be of approximately crustal composition (Table 1). As the correction for detrital contamination places samples in stratigraphic order, we have more confidence in the accuracy of the corrected ages.

The crustal composition and associated uncertainties are estimated from the means and 2σ uncertainties of U-series data archived in the EarthChem database (http://www.earthchem.org). While this is largely a dataset consisting of measurements of volcanic rocks, which are typically selected to avoid weathering products, it does provide a reasonable estimate of the isotopic composition of the likely contaminant. Ages calculated from corrected ($^{230}Th/^{238}U$) and ($^{234}U/^{238}U$) are within error of stratigraphic order in all cases, and ages are not corrected to be less than zero (within error), giving some confidence to the initial ^{230}Th and ^{234}U correction used (Table 1, Figure 8). The detrital corrected ages for individual subsamples of the pedogenic carbonate from F1 are between 42 ± 6 kyr and 19.6 ± 1.7 kyr.

Ages from the two samples of the F2 surface are between 21 ± 4 kyr to 9 ± 5 kyr (2σ uncertainties). These ranges neglect the outermost stratigraphic samples, which have large detrital contributions resulting in detrital corrected ages that range beyond the date they were sampled (Table 1).

4.1.3. Bayesian statistical analysis of U-series results

Considered separately, the individual ages from each carbonate rind do not necessarily place constraint on the exact time of deposition. Instead, the sequence of U-series results represents the growth of pedogenic carbonate rinds through time. Because each individual age may have some contamination from the carbonate formed above and below the specific layer that was sampled, it is necessary to incorporate the full suite of results in calculating the initiation of pedogenesis. This is accomplished by undertaking a Bayesian statistical analysis procedure, utilizing the OxCal program (Bronk Ramsey, 2009). The basic premise of the analysis is that for each carbonate rind sample an age model is constructed that places each sub-sample in stratigraphic order within a sequence that is bounded by the initiation and end date of rind growth, with the assumption that the ages represent a random sampling of a uniform distribution between the boundaries of the model. Even the sub-sample that was collected closest to the pebble surface may have some averaged contamination from younger laminae within the sub-sample, thus the statistical treatment of the suite of results better predicts the probability of initiation of carbonate formation, because it is based on the full set of results instead of a single measurement.

Additional information based on what is known about the samples and the U-series system can be added to the Bayesian analysis in OxCal, which was originally constructed for radiocarbon dating. In cases where the ages, when corrected for initial ^{230}Th and ^{234}U, have uncertainties that overlap with the date the samples were collected from the field (AD 2009), the additional constraint that the samples existed at the time of sampling is applied. This constraint is applied by adding an event to the young end of the age model with an age of -0.059 kyr (which is the year the samples were collected relative to time 0 in OxCal, Bronk Ramsey, 2009). Carbonate growth may continue up until the time of sampling. The OxCal statistical analysis stipulates that even the oldest samples may have contamination from a younger layer of carbonate, and produces a carbonate growth sequence that is bounded by a statistically probable start and end date.

The results of the statistical analyses are given as mean, median, and start and end values, and these are detailed in Tables 2 and A3. The model also produces probability distribution functions (PDF) for the age of each stratigraphic layer in the carbonate rind, shown in Figures 9 and A2. The effects of this approach are to reduce the uncertainties on the ages of the individual sub-samples while forcing the ages to be in stratigraphic order, as would be expected if the carbonate grows outward through time.

Because there are two samples from the F2 alluvial surface (MN09-OG12 and MN09-OG13), an additional model was run with the constraint that both carbonate rinds initiated growth at the same time, based on the assumption that carbonate growth on F2 started simultaneously for both samples. This is a reasonable assumption because, considered separately, the two samples have similar initiation ages. The result of modeling the two samples together provides an estimate of when carbonate began to accumulate on the two samples from the F2 surface, which is based on a larger dataset because it takes into account the results from each sub-sample of carbonate from both rinds. The results of modeling the samples together are presented in Figure 9 and Table 2, with 1σ uncertainties (instead of 2σ) for comparison with the ^{10}Be cosmogenic nuclide dating results. Sample MN09-OG07 is also presented in Table 2, with 1σ uncertainties listed.

The PDFs for carbonate growth do not have a normal distribution, because there tends to be a long `tail' of old ages that are possible for the given inputs, but the older ages have a much lower probability (Figure 9). The long tail of the distribution of ages biases the mean to older values, but the median still represents the value for which there is a 50% likelihood that the true value is less than. We therefore use the median when quoting ages. For calculating fault slip-rates, the age of initiation of carbonate growth is an approximation for the timing of stabilisation of a landscape, because carbonate pedogenesis does not occur in a high-energy environment. It should however be noted that there is a potential for a lag between the deposition and stabilization of the landscape and carbonate pedogensis, due to climatic conditions being unfavorable for pedogenic carbonate formation at the time of surface abandonment. Therefore the most useful aspect of the U-series results is the minimum age for growth initiation. In order to calculate the slip-rate of the Ölgiy fault, the minimum ages of stabilisation/deposition of the two surfaces is constrained by simply using the minimum constraint from the range of boundary initiate results from the OxCal model (in columns `from' and `to' in Table 2). For F1, the lower boundary initiate is 38.4 kyr from the one sample measured (MN09-OG7, based on a range of 57.0 kyr to 38.4 kyr). The results from the two separate pebbles measured from F2 are combined in a single OxCal model (samples MN09-OG12 and MN09-OG13, Figure 9), with the assumption that the initiation of carbonate growth on both pebbles occurred at the same time on the deposit. The results of the combined OxCal model place the estimate of deposition of F2 before 18.0 kyr (from a range of 22.3 kyr to 18.0 kyr). The carbonate results are complementary to ^{10}Be results presented below, because the ages for initiation of carbonate growth provide a statistically probable cutoff date for the existence of the deposit, a constraint that is important for interpreting the cosmogenic dates.

4.2. ^{10}Be terrestrial cosmogenic nuclide dating

^{10}Be is a long-lived isotope that is produced in-situ in quartz, mainly as a result of high-energy spallation reactions (with O and Si) due to cosmic rays (Nishiizumi et al., 1989). The ^{10}Be concentration in a sample is used to estimate the duration of exposure to cosmic rays, based mainly on empirically determined production rates (see Gosse and Phillips, 2001, for a thorough review). The concentration of cosmogenic nuclides in a sample reflects the duration of time that the sample has been exposed to cosmic rays. The concentration of a cosmogenic nuclide N (in atom g^{-1}) at depth x from the surface can be generally represented as a function of time (t) by:

$$N(t) = \frac{Pe^{-xL^{-1}}}{(\epsilon L^{-1} + \lambda)}\left[1 - e^{(\epsilon L^{-1}+\lambda)}\right] + N(0)e^{-\lambda t}$$

where ε is the mass erosion rate (g cm^{-2} yr^{-1}), P is the production rate (atom g^{-1} yr^{-1}, dependent on several factors discussed further below), L is the effective attenuation length of cosmic rays, which is ~ 150-200 cm in sediments (Lal, 1991; Brown et al., 1992). λ is the radioactive decay constant (per year), and N(0) is the cosmogenic nuclide concentration already present at the initiation of surface exposure. If the production rate is known, the function has three unknowns: ε, t, and N(0). Thus the erosion rate (ε) and nuclide concentrations inherited from prior exposure N(0) must be assessed in order to determine accurate exposure ages.

4.2.1. ^{10}Be TCN sample preparation and analytical methods

Samples from boulders comprising schistose metasediment (mostly conglomeratic) and vein quartz were collected from the F1 and F2 deposits in the summers of 2008 and 2009. Eleven samples were collected from surface F1 (nine were measured) and six samples from surface F2 (three were measured). Most of the boulders that were sampled were 50 to 100 cm across their b-axis, and all samples stood over 50 cm high above the surface (Figure 10). Care was taken to collect samples from boulders with uniform cover of lichen or desert varnish, and with no evidence of recent weathering or erosion, in order to minimise the potential for complications in exposure history. Where possible, we avoided boulders situated near the edges of the deposits or near stream channels. In order to have sufficient quartz for ^{10}Be analyses, thick quartz veins present in the metasediment boulders were preferentially collected.

Unfortunately, it was not possible to dig a pit for sampling of a TCN depth profile because the deposits are composed of coarse sediment with abundant large boulders throughout.

At least 2 kg of material was collected for each sample. The top 2–6 cm of each boulder sample was crushed using a jaw crusher and disc mill, and sieved to a fraction of 250–700 µm. The approximate maximum thicknesses of samples were estimated during processing and the correction for sample thickness (self-shielding) is included in exposure age calculations. Further sample preparation was carried out at the NERC Cosmogenic Isotope Analysis Facility (CIAF) at the Scottish Universities Environmental Research Center (SUERC) in East Kilbride, Scotland.

Detailed processing followed the description in Wilson et al. (2008), as modified in Glasser et al. (2009), but is described briefly here. Magnetic grains were separated using a Frantz separator. The resulting fraction was purified by several stages of etching in HF and heavy liquid separation, and checked for purity under optical microscope. After the pure quartz was completely dissolved, ^{9}Be was added as carrier. Once Be was isolated in samples through cation-exchange column chemistry, $^{10}Be/^{9}Be$ ratios were measured on the accelerator mass spectrometer (AMS) at SUERC (Freeman et al., 2004; Xu et al., 2010). Total procedural blanks were prepared alongside samples using approximately the same ^{9}Be carrier mass as the samples. SUERC AMS measurements of $^{10}Be/^{9}Be$ ratios are normalised to the reference standard NIST SRM4325 (using a $^{10}Be/^{9}Be$ ratio of 3.06×10^{-11}). This ratio was later re-normalised to 2.79×10^{-11} by Nishiizumi et al. (2007). The measured blank $^{10}Be/^{9}Be$ ratios are on the order of 10^{-15} (Table A4 in supplementary material), and these values were subtracted from the sample $^{10}Be/^{9}Be$ ratios, with the uncertainty of this correction included in the 1σ concentration uncertainties. The total reported 1σ uncertainties for ^{10}Be concentrations include a standard conservative 2.5% preparation uncertainty (mainly from the uncertainty in the Be carrier solution, Wilson et al., 2008), along with AMS measurement uncertainties for sample measurement, for measurement of the primary standard, and for blank corrections.

4.2.2. Exposure age calculation

The online calculator CRONUS-Earth, Version 2.2.1 was used to calculate exposure ages (Balco et al., 2008, at URL: http://hess.ess.washington.edu). This version includes the updated ^{10}Be half-life of 1.387 ± 0.012 x 10^6 yr (Chmeleff et al., 2010; Korschinek et al., 2010). Uncertainty in ^{10}Be half-life estimates has very little effect on age calculations for samples that are relatively young (10^4 yrs), and because a standard calculator is used, the ages are easily recalculated using adjusted constants. ^{10}Be data are reported in Table 3, with all data necessary for recalculating exposure ages (e.g. Balco et al., 2008; Dunai and Stuart, 2009). Sample elevations measured in the field with a hand-held GPS are converted into atmospheric depth in the CRONUS calculator (Balco et al., 2008).

The calibrated production rates for ^{10}Be must be scaled to the elevation and latitude of the site (e.g. Stone, 2000; Dunai, 2000; Staiger et al., 2007). In the CRONUS calculator, production due to muon flux is only varied by elevation, not by latitude or time (i.e. ignoring magnetic effects); however muon production is only a few percent of the total surface ^{10}Be production. High-energy spallation is the most significant component of production, and there are five different schemes generally used for scaling ^{10}Be production rates from spallation.

The simplest scaling scheme is from Lal (1991), improved by Stone (2000), which works on the variation of production rate by latitude and elevation (or atmospheric pressure). We use this time-varying spallation production-rate scaling scheme, with the modification of Nishiizumi et al. (1989) for correcting for the changing magnetic field over time from palaeomagnetic data (the `Lm' scheme in CRONUS; Balco et al., 2008). This scheme does not take into account higher spherical harmonic fields, thus the scaling is based on a geocentric axial dipole (i.e. there is only magnetic variation according to latitude).

Azimuthal elevations of the horizon were measured at the sample locality, and these are used to calculate the shielding of cosmogenic rays by topography with the program described in Balco et al. (2008). The effect of topographic shielding is generally quite small because the majority of incoming cosmogenic radiation is focused about the vertical (Gosse and Phillips, 2001). Shielding is small at the site (0.972), but is included in the age calculations. Estimates of sample thicknesses and densities are also included to correct for the attenuation of cosmogenic flux through rock (listed in Table 3). The uncertainty typically associated with the thickness correction is small (1–2% Gosse and Phillips, 2001).

Corrections for erosion of the boulder surface have not been applied for exposure age calculations in this study. Whilst there was no field evidence for in-situ rock-spallation or freeze-thaw weathering on the boulders that were sampled, this cannot be ruled out. Surface lowering may lead to anomalously low ^{10}Be concentrations from late exposure, but an independent method for calculating the denudation of the surface surrounding the boulders is not available for the Ölgiy site. The only surface erosion rate that has been measured in the Altay comes from an alluvial fan near Har Us Lake, on the eastern side of the Altay, where Nissen et al., (2009b) calculated a very low surface erosion rate of 2.5 m Myr^{-1} from a ^{10}Be depth profile. A denudation rate of this order of magnitude would not have a significant effect on samples of Late Quaternary age (Gosse and Phillips, 2001), and care was taken to sample boulders at a height of at least 50 cm to minimise the effects of surface erosion on exposure ages. The effect of either surface lowering or boulder surface erosion can in some ways be dealt with by integrating the oldest exposure age for calculating fault slip-rates, but in some cases even boulders with the greatest cosmogenic nuclide concentrations may have experienced some post-depositional effects (Hallet and Putkonen, 1994). Surface coverage (from snow) is also an important consideration. If significant snow cover has occurred, for example about 1 m of cover for four months of the year, this could lead to up to a 5% difference in calculated ages from the actual exposure age (Gosse and Phillips, 2001). However, measures of snow cover in the region of the site are poorly constrained, and cover corrections are not included in age calculations.

4.2.3. ^{10}Be TCN results

Our age calculation results incorporate corrections for shielding, elevation, sample thickness, and density (Table 3). From the ^{10}Be exposure ages, there are two groups of exposure ages representing two distinct events, with all samples from F1 substantially older than samples from F2 (Figure 11). There is a large spread in the data from F1, with the calculated boulder exposure ages ranging from 40.8 ± 3.8 to 102.9 ± 9.6 kyr. With the exception of the oldest and youngest boulders, all are within one standard deviation (17.2 kyr) of the mean (65.3 kyr) of all samples (Figure 11). Ages from F2 are more tightly grouped than F1, with a moderate spread of data, though this could be an artifact of the small number of samples (N=3). Ages for the three samples measured range between 10.6 ± 0.9 to 25.9 ± 2.2 kyr, and two of three boulder ages are within 1σ uncertainty (25.9 ± 2.2 and 21.3 ± 1.8 kyr).

5. Discussion

Our age data are important in showing the advantages of combining multiple dating techniques in reducing the uncertainties inherent in any individual method. Our results also allow us to estimate the slip-rate of a major active fault within the Altay Mountains of western Mongolia. In the discussion, we first describe the interpretation of our age data and the benefits in combining U-series and ^{10}Be dating for reducing the uncertainty in surface exposure age estimates. We then describe the implications of our chronologic data in determining the slip-rate of the Ölgiy strike-slip fault.

5.1. Age constraint on the timing of surface abandonment from combined ^{10}Be cosmogenic and U-series dating.

Samples for U-series dating are typically collected from depths of up to 1 m in the soil (Ku et al., 1979; Blisniuk and Sharp, 2003; Sharp et al., 2003; Fletcher et al., 2011). Whilst our U-series samples were collected from depths no greater than 30-50 cm, the results are still useful for establishing the minimum age of deposition at the Ölgiy site, because the deposits must have existed before carbonate pedogenesis began. Inheritance of carbonate that has been re-deposited after growing elsewhere can be a problem, but this is unlikely due to the high-energy deposition at the Ölgiy site and the rinds only being present at the base of cobbles collected, suggesting they grew *in-situ*. We therefore assume that inheritance does not affect the calculated ages, though this assumption could be tested by analysing more samples. Age data from individual layers are continuous from oldest to youngest, in order from the cobble surface to the edge of the rind, which implies that pedogenesis has been continuous since the statistically predicted initiation of growth. The predicted ages for initiation of carbaonte growth provide useful minimum bounds on the age of the Ölgiy deposits, and help to assess the scatter in the cosmogenic nuclide results.

Several factors may influence the ^{10}Be concentrations in samples (e.g. Brown et al., 1998; Zreda and Phillips, 2000; Vassallo et al., 2011). Post-depositional processes may lead to underestimation of the abandonment age of a surface, through erosion of either the boulder surfaces themselves, or denudation of the surrounding alluvial surface. Conversely, the abandonment age may be overestimated if the sampled boulders have been subjected to pre-depositional accumulation of cosmogenic nuclides during transport or from exposure as bedrock upstream, producing an `inherited' signal in the ^{10}Be concentrations. Interpreted alone, the TCN data only constrain the age of abandonment of the surface to any time within the spread of the boulder ages, which for the F1 deposit has a range of at least from 40 to 100 kyr.

When considering the fidelity of exposure ages it is important to consider appropriate uncertainties. If a suite of samples at a locality are free from the effects of erosion and inheritance, they should have ^{10}Be concentrations that are within the measurement uncertainties. Therefore when using the consistency of exposure ages to argue for the absence of erosion or inheritance, exposure ages should agree according to their internal errors (Balco et al., 2008). Uncertainties arising from the calibration of the ages, due to scaling schemes and production rate uncertainties, which contribute to the total uncertainty, will all be correlated between samples and should therefore be discounted when comparing between samples of the same locality. Figure 11 shows the standard deviation of the F1 samples based on the internal uncertainties.

Schematic diagrams of the age constraints from both ^{10}Be and U-series dating, for each surface, are shown in Figure 12. Typically, when interpreting nuclide concentrations measured in surface boulders, especially from glacial moraines, the calculated ages are assumed to underestimate surface exposure due to post-depositional processes such as surface lowering (Hallet and Putkonen, 1994; Behr et al., 2010; Pallàs et al., 2010; Vassallo et al., 2011). In this case, the oldest TCN ages are used to establish the timing of exposure, with the stipulation that the estimated exposure age is a minimum. Erosion of the boulder surfaces themselves can also be problematic (Hallet and Putkonen, 1994; Matmon et al., 2005). Whilst the lack of correlation between the measured ^{10}Be concentrations with boulder composition in our results may imply that boulder surface erosion is minimal, it is possible that some spallation or boulder surface erosion has occurred based on the large spread in data from the older F1 surface (compositions listed in Table A3 in supplementary material).

Comparison of the cosmogenic and U-series dates for F2 shows that some post-depositional processes must have affected the boulder ages (Figure 12a). Boulder sample MN09-OG4 is significantly younger (10.6 ± 0.9 kyr) than suggested by U-series dates (20.4 ± 2.3 kyr), implying that the exposure of boulder MN09-OG4 post-dates abandonment of the surface, presumably due to surface lowering. MN09-OG4 is located on the crest of F2, close to the trace of the fault, and hence in a site potentially prone to enhanced erosion (Figure 3). The two older boulders were collected further downslope, in the centre of the deposit and away from the two streams.

Surface lowering may have affected other samples, both on F2 and F1. The large range in ^{10}Be concentrations from F1 also implies that the F1 surface has been subjected to some post-depositional processes because, in general, the effect of erosion becomes more pronounced with increasing age (Brown et al., 1998, Figure 12b). Comparison of ^{10}Be results with the U-series constraint for surface F1 suggests that samples B08-01 and B08-06 may be biased to a younger age by post depositional processes. Although these two samples are not younger than the uncertainty allows for the U-series age, they are younger than the cluster of exposure ages for this surface that agree within internal error and that are towards the older limit of the carbonate age.

Estimates for surface erosion rates from western Mongolia vary from 10 m Ma^{-1} in the Göbi Altay to as low as 2.5 m Ma^{-1} in the eastern Mongolian Altay (Vassallo et al., 2007; Nissen et al., 2009b, respectively). Also working in Western Mongolia, Vassallo et al. (2011) suggest that even at these low erosion rates, boulders that are initially at different depths in the deposit can be exhumed at different rates based on the size of the boulders and their position relative to bars and swales in the surface of the alluvium (e.g. Figure 9 in Vassallo et al., 2011). Over time, the bar-and-swale topography of the fan surface is reduced, exposing boulders that were buried at the time of deposition, as well as causing smaller boulders to migrate from their original position as the surrounding surface is eroded away. This process is also observed on alluvial fans of granitic composition in southern California, in potentially similar climatic conditions to those in Mongolia (Matmon et al., 2006; Behr et al., 2010). The result is an increase in the spread of ^{10}Be concentrations in the boulder population with increasing durations of surface exposure (e.g. Figure 12b).

We also consider the possibility that inherited ^{10}Be nuclides accumulated prior to the deposition of the boulders. The effect of inheritance is likely to be stochastic (unless there is a particular store of similar clasts up stream), and may result in a small number of outliers in a TCN dataset that appear much older than the actual abandonment of the surface (Figure 12b). In the Göbi-Altay of western Mongolia, Vassallo et al. (2011) found that whilst many boulder sample sites were affected by surface lowering, there was a small fraction of boulders with 100% greater levels of TCN concentrations than other samples from the same deposit. These outliers might be a result of the episodic nature of mass-wasting deposits in the arid Mongolian climate, which mix boulders that have had a long prior residence time on hill slopes, and have hence accumulated a large inherited ^{10}Be concentration, with boulders that have little pre-depositional exposure. This emplacement mechanism results in a few randomly distributed samples with high levels of inheritance at the surface. The amount of inherited nuclides in a boulder sample is not possible to quantify directly from the spread of exposure ages, as it is dependent on the length of time the sample was previously exposed in the catchment and the characteristics of prior exposure (e.g. elevation and depth, if buried; Vassallo et al., 2011).

The simplest interpretation of the data from the Ölgiy fault is thus to use the oldest boulder dated from each of the two deposits as an approximation for the maximum age (102.9 ± 9.6 kyr and 25.9 ± 2.2 kyr for F1 and F2, respectively), with the stipulation that these ages may underestimate surface abandonment if all of the boulders have experienced some form of post-depositional erosion (e.g. Figure 12). This interpretation appears particularly reasonable for surface F2, because the sample that has anomalously low nuclide concentrations is located close to the active trace of the fault.

The ^{10}Be data from surface F1 show a spread in age from 40.8 ± 3.8 kyr to 102.9 ± 9.6 kyr. However, sample B08-4 (102.9 ± 9.6 kyr) lies well outside of one standard deviation of the mean of all boulder ages (Figure 11) and, if B08-4 is excluded from the mean of all boulders, it is also outside of two standard deviations of the mean. If inheritance is not the cause of the anomalous ^{10}Be concentrations in sample B08-4, then surface lowering must have had a significant effect on all of the other boulders sampled (Figure 12b). This seems unlikely, however, because the effect of surface lowering should be similar in small areas of the fan, and erosion should have similar effects on the ^{10}Be concentration in boulders with the same composition and similar heights above the surface. Boulders in close proximity to B08-4 have significantly younger exposure ages, of 48.2 ± 4.4 kyr and 60.0 ± 5.5 kyr, and it is unlikely that post-depositional processes would affect a small area of the deposit at the same level in such a random manner (see sample localities labeled on Figure 3). We therefore exclude sample B08-4 from the estimate of the abandonment of the F1 surface, and suggest that it is likely to have had significant exposure prior to deposition in the F1 surface. A similar approach to the variability in TCN concentrations within a catchment was taken by van der Woerd et al. (1998) and Brown et al. (2003). For the maximum abandonment of F1, we use the oldest boulder age within the remaining population of results (70.0 ± 6.4 kyr), with the assumption that there has been some surface lowering that has led to the spread in ages in the samples (Table 3).

5.2. Slip-rate of the Ölgiy fault

We present a range of slip-rates for the Ölgiy fault, calculated from our estimates of surface displacement and the geochronological results from both F1 and F2. All age constraints in this section are quoted at the 1σ level for comparison between U-series and cosmogenic results (see Tables 2 and 3). The maximum horizontal displacement of the F1 deposit is 29.1 ± 5.6 m (Section 3) and its age is bracketed by a minimum of 38.4 kyr from the Bayesian modeling of carbonate growth, and a maximum of 76.4 kyr from the oldest bound on the ^{10}Be cosmogenic boulder ages that lie within one standard deviation of the mean of all F1 boulder ages (Figure 11, Section 5.8). These displacement and age ranges yield an average Quaternary slip-rate in the range 0.3–0.9 mm yr^{-1}.

F2 is displaced by 16.0 ± 6.6 based on two offset channels (Section 3). The timing of abandonment of F2 is bracketed between a minimum from the U-series dates, and a maximum from the ^{10}Be TCN boulder ages, to be within the range 18.0–28.1 kyr. The displacement and age estimates yield an average slip-rate of 0.3–1.3 mm yr^{-1}.

In summary, our use of complementary ^{10}Be and U-series techniques places independent maximum and minimum estimates on surface abandonment, adding a higher degree of confidence to the estimates of abandonment age. The slip-rates estimated from the two different deposits, 0.3–0.9 and 0.3–1.3 mm yr^{-1}, are in agreement with each other. These rates are very similar to the rate determined by Frankel et al. (2010) of 0.9 +0.2/-0.1 mm yr^{-1} based on displaced alluvial fans at two sites of a similar Late Pleistocene age (44.8 ± 6.8 kyr and 18.8 ± 2.6 kyr). Their site is ~100 km south of our study site, suggesting that the rate of slip of the Ölgiy fault zone is continuous over at least a major section of this >400 km long fault. We agree with the suggestion made by Frankel et al. (2010) that the Ölgiy fault must take up a significant portion of the deformation measured on the short term in sparse geodetic data across the whole of the Altay (~4-7 mm yr^{-1}; Calais et al., 2003).

There are very few estimates of the slip-rate of the major strike-slip faults of western Mongolia, despite several of them having a proven record large recent, historic, and prehistoric earthquakes (e.g. Baljinnyam et al., 1993; Nissen et al., 2007; Klinger et al., 2011), and constituting potential hazards to local populations. No large earthquakes (ancient or modern) are known from the Ölgiy fault and yet our study and that of Frankel et al. (2010) confirms that the Ölgiy fault is slipping at substantial rates in the late Quaternary.

Conclusions

Our study demonstrates the potential for U-series dating of pedogenic carbonates as a useful method in surface dating, particularly when working in regions where the application of other techniques may be problematic, or as a means of aiding interpretation of other, independent, dating results. We overcome the problem of averaging contributions from older and younger growth strata within each carbonate rind by sub-sampling of layers within carbonate rinds, and treating the data as a statistical sequence of events with Bayesian probability distributions. This is the first study to apply Bayesian statistics to U-series data from pedogenic carbonate, and we demonstrate that this is a powerful approach. Dating of carbonate rinds provides only a minimum age on surface abandonment, and so used alone the U-series technique cannot bracket the full range of possible surface ages. The U-series data are, however, able to confirm that the ^{10}Be concentrations in boulder samples have been affected by post-depositional erosion, and hence they aid discrimination of the scattered ages. Finally, although not a focus of the present paper, the U-series dating provides a potential insight into the climatic history of a region. For example, our results suggest continual carbonate growth from ~40 kyr through to the present day, implying that climate conditions have been favorable for carbonate pedogenesis since at least that time.

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Table titles

Table 1: Uranium concentrations, and measured U-series isotope activity ratios for sub samples of pedogenic carbonate rinds.

Table 2: Inputs to, and results from, Bayesian analysis of age data with the two samples from F2 combined, all shown with 1σ uncertainties.

Table 3: Summary of ^{10}Be data from the Ölgiy alluvial surfaces.

Figure captions

Figure 1: SRTM shaded-relief topographic maps of the Altay. GPS velocities are shown relative to stable Eurasia and suggest ~7 mm yr^{-1} of northeast directed shortening across the Altay (Calais et al., 2003). Earthquake focal mechanisms in black are from Sloan et al. (2011), those in dark grey are from Nissen et al. (2007), and light grey mechanisms are solutions either modeled or compiled by Bayasgalan et al. (2005). Active faults are plotted in black. Existing slip-rate measurements from the Altay are indicated, including the Ölgiy site (within black box labeled 'Fig. 2'). Red dots indicate strike-slip rates, from Nissen et al. (2009b;

2.4 ± 0.4), and Vassallo (2006; 0.5 and >1.2). Orange dots indicate shortening rates, fraom Nissen et al. (2009a; 0.2-0.6 and 0.1-0.4). The measurement site of Frankel et al. (2010) is indicated by a red dot located on the Ölgiy fault to the south of our site and corresponding to a slip-rate of 0.9 +0.2/-0.1 mm yr^{-1}.

Figure 2: (a) ASTER satellite image (15-m resolution) showing the Hungui Mountain range and the reverse fault scarps at its base. At the latitude of our study site, the fault has a strike of 340–350°. (b) Kompsat-2 satellite image (1 m resolution) showing the western ridge of the Hungui Mountains to the east of the fault, with the active trace of the fault indicated by white arrows. Where the active fault trace crosses a wide valley in the north of the image it produces no vertical scarps, implying almost pure strike-slip motion. The trace of the fault bends to strike 320-330° at the top of the image, and a vertical component, up on the NW side, was observed along this section. (c) Kompsat-2 image of the study site. The active fault trace is located between the Hungui Mountains and a series of ridges. The alluvial deposits that we sampled originate from a small catchment within the Hungui mountains and pass through a narrow gap in the bedrock ridge. Outline in (c) is area covered by Figure 3.

Figure 3: Quickbird imagery (0.6 m resolution) of the study site. The lower panel is an annotated version of the upper image. Streams are traced in blue, and the two surfaces are coloured in green (F1) and brown (F2). The fault is marked by a bold dashed line. Buff-coloured surfaces (in the interpretation) were not sampled and may be an older deposit (labeled ‘unknown’). Black hashing indicates steep stream risers. The site slopes down to the west. Sample localities are indicated by white (U-series) and orange (TCN) circles with respective sample numbers, and slickensides were measured at a location represented by a yellow star.

Figure 4: (a) Digital elevation model (DEM) made from a kinematic GPS survey. The 3D view highlights the scarp along the fault that is likely to be caused by right-lateral displacement of topography. (b) 2D view of the DEM. Black line indicates the fault. White lines parallel to the fault show the position of the

topographic profiles shown in 'c'. White lines perpendicular to the fault are the scarp profile lines that are drawn in Figure 6. (c) Topographic profiles from the east and west sides of the fault. The two streams that cross the fault are visible as low points in the profiles, traced in grey. (d) Plane view of the trace of the two streams, in NUTM45 coordinates. Black lines show the best fit through each stream trace, projected to the fault (dashed line). Uncertainties listed are the root sum square of average stream width and 'wiggle'.

Figure 5: Field photographs looking west at the northern and southern stream displacements. The stream beds are traced by white dotted lines. The scarp of the Ölgiy fault runs across the centre of the photographs and black arrows mark its base. The large angular boulders that are embedded throughout the surfaces are visible. Person (circled) for scale.

Figure 6: Diagram showing the method for calculating the lateral displacement '**x**' necessary for creating vertical scarp of a measured height '**h**' on a sloping surface. The plunge of the sloping surface and fault plane intersection line was calculated using a stereonet from strike and dip measurements of the alluvial surface, assuming a vertical fault. Lower panel shows all profiles across the surface of F1, showing the vertical offset due to right-lateral displacement of topography along the Ölgiy fault. Individual profiles are displayed in Figure A1 in the supplementary materials.

Figure 7: Photos of the carbonate rind from sample MN09-OG12, with sample sites indicated in (a). Insets show the layers that were milled to extract subsamples. The milky buff-coloured carbonate is ideal for dating, as the opaque white carbonate will have detrital contamination.

Figure 8: U-Th ages of sub-samples from pedogenic carbonate samples MN09-OG12 and 13. Open symbols are uncorrected ages for each sub-sample, and filled symbols are corrected for detrital contamination. The sub-samples are ordered stratigraphically with the oldest, nearest to the pebble, at the top of the figures. The correction for detrital contamination results in younger ages, an increase in

the uncertainty (shown at 2σ), and ages which are more consistently in stratigraphic order.

Figure 9: Results of the Bayesian analysis of the ages within each of the three sampled carbonate rinds. The top panel shows the analysis based on the two samples from F2 modelled together, with the stipulation that the start and end date of both samples must occur at the same time. Figure A2 shows the independent analyses from the two F2 samples. The lower panel shows the analysis from the F1 sample. For each analysis, the sub-samples are ordered stratigraphically, with the oldest uppermost. The distributions of the input ages (corrected for detrital contamination) are shown in light grey, while those resulting from the additional constraints of the age models are in dark grey. Summary statistics of the modeled distributions that are shown below each distribution include: mean (open circle) and 1σ, median (cross), and 95% interval of the age distribution (horizontal bar).

Figure 10: (a) Example of a boulder sampled from the F1 surface (b) Example of a boulder sampled from the F2 surface. (c) Panoramic photograph of the site, looking west, with both alluvial surfaces (F1 and F2) and the two main streams labelled. The Ölgiy fault trace is marked by a white line.

Figure 11: ^{10}Be age results from the CRONUS calculator for F1 (black) and F2 (grey). All uncertainties are displayed at the 1σ level, the thicker bar representing the internal uncertainty and the thinner bar the external. Samples from the two fans do not overlap in age, and the 1 and 2 standard deviation envelopes are indicated for the population of results from F1. The 1 and 2 standard deviation bands for a subset of the F1 data are also shown where stared samples are excluded (solid lines).

Figure 12 (a) Summary of age constraints for the F2 surface abandonment. The dashed line indicates the oldest exposure age from cosmogenic dating, but if samples are affected by erosion, the actual age of abandonment may be older than shown. If the samples have an inherited signal, then the actual abandonment will be younger than the individual boulder ages. The dotted line indicates the minimum age of F2 abandonment from U-series dating. (b) As for 'A', summary of age constraints for the F1 surface abandonment. The outlier boulder (sample B08-04) is beyond 1 standard deviation of the mean of the boulder ages, and we have excluded it from our estimates of surface abandonment age. A small adjustment (+0.059kyr) has been made to the U-series data so that it is comparable to the exposure ages.

Supplementary Material

Tables

Table A1**:** F2 uncertainties

Table A2: Measurements of profile heights perpendicular to the Ölgiy fault across F1.

Table A3: Inputs to, and results from, Bayesian analysis of age data.

Table A4: Be blank ratios and cosmogenic sample compositions.

Figures

Figure A1: Vertical profiles from west to east across F1. Vertical 'displacement' is calculated from the difference in elevation between lines fit to the surface above and below the fault. The lines are not always parallel, so the displacement is calculated at the approximate location of the fault (distance downslope 'D' in Table A1). The average height offset for all profiles was used to calculate fault displacement. Profile locations are are shown in Figure 4, and are in numeric order from north to south.

Figure A2: Results of the Bayesian analysis of the ages within each of the three sampled carbonate rinds. The lower panel shows the analysis from the F1 sample. For each analysis, the sub-samples are ordered stratigraphically, with the oldest uppermost. The distributions of the input ages (corrected for detrital contamination) are shown in light grey, while those resulting from the additional constraints of the age models are in dark grey. Summary statistics of the modeled distributions that are shown below each distribution include: mean (open circle) and 1σ, median (cross), and 95% interval of the age distribution (horizontal bar).