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Cosmogenic Nuclides
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Cosmogenic Nuclide Dating of Earthquakes, Faults, and Toppled Blocks

Ridge and channel offsets along the trace of the Fuyun fault (China), site of the 11 August 1931 magnitude-8 strike-slip earthquake. Constraining the age of past displacements allows reconstructing fault slip histories.

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When the recurrence intervals of large earthquakes span several thousands of years, the dating of fault movements over long time intervals is essential for estimating the next event. Constraining the age of faulting, earthquake recurrence, or toppled rocks is especially important for determining if a fault is likely to break again soon. In recent years, cosmogenic nuclides have provided new insights into the dating of these ground movements. Approaches to gathering this information can be direct, such as dating fault surfaces with ^{36}Cl, or indirect, such as dating fault-offset alluvial fans with ^{10}Be or ^{26}Al. New results from these methods are certain to better define the tectonic and seismic hazards in areas with increasing population density.

Keywords: earthquakes, slip rate, geomorphology, cumulative fault scarp, ^{36}Cl and ^{10}Be cosmogenic nuclides

INTRODUCTION

When a strong earthquake occurs, the length and height of the earthquake rupture is proportional to the amount of released energy (Wells and Coppersmith 1994). The observation and accurate study of such ruptures allow an estimate of how much of the slip has propagated to surface and how this slip is distributed along the fault length. The incremental addition of the slip associated with each earthquake creates topographic relief that is eroded with time. The resulting displacement of Earth's surface along a fault can be horizontal or vertical and usually occurs at the limit between two tectonic plates colliding or sliding past each other.

Determining the age and size of past strong earthquakes provides important information for estimating the repeatability or periodicity of a past event. This is critical in determining the likelihood of future events. When averaged over many earthquake cycles, fault slip rates are generally considered steady. However, worldwide, there is evidence for clustering of earthquakes, suggesting that slip rates vary over several-thousand-year timescales (e.g. Friedrich et al. 2003). Numerous techniques encompassing different time spans provide chronological constraints on Quaternary fault slip rates and seismic histories. For example, geodesy provides slip rates over the most recent five to ten years, while geological slip rates commonly average over millions of years (Fig. 1). Until recently, information spanning millennial timescales was largely missing from these integrated records. Terrestrial cosmogenic nuclides allow estimates of the ages of morphological markers, such as river terraces, repeatedly offset by faults; seismically exhumed fault scarps; and even blocks that collapsed during earthquake events (Fig. 2). Terrestrial cosmogenic nuclides are commonly applied to vertical faults in limestone using ^{36}Cl and to horizontal faults in quartz-rich rocks using ^{10}Be and ^{26}Al. Because such features often integrate fault movement over several thousands to hundreds of thousands of years, the use of cosmogenic nuclides has revolutionized the quantification of fault movement by filling a critical gap between geodetically recorded slip rates and geological slip rates (e.g. Frankel et al. 2007).

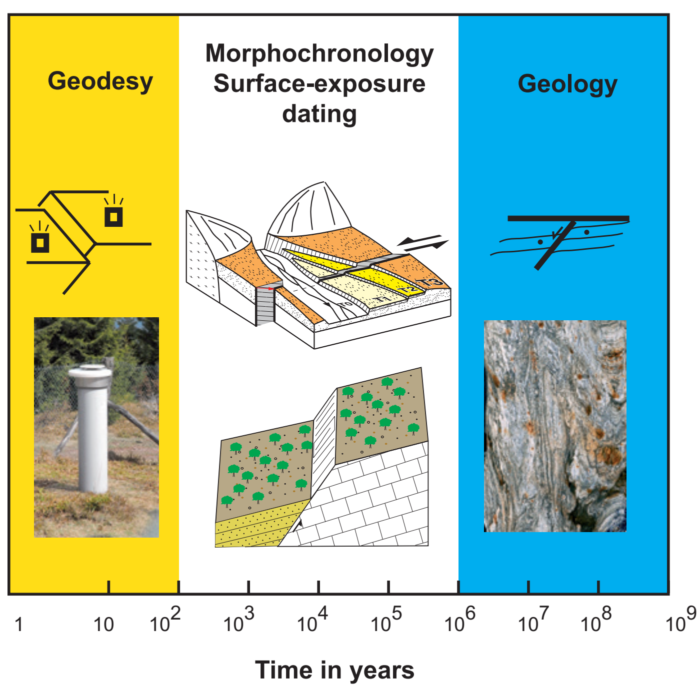

Figure 1 Methods available for measuring slip rates on active faults over different time windows. Geodetic measurements can generate decadal slip-rate determinations; morphochronology, based mainly on cosmogenic nuclide surface-exposure dating, can yield slip rates over tens of thousands of years; and geology reveals slip rates over millions of years. Geomorphic measurements integrate many earthquake cycles, while geodetic methods can be more sensitive to interseismic strain.

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COSMOGENIC NUCLIDES: POWERFUL PALEOSEISMOLOGICAL TOOLS

Dating Earthquake Fault Scarps Using Chlorine-36

The best-preserved fault scarps are generally found along normal faults, where plates move apart and one side of the fault drops downward relative to the other along a slanted fault plane. Typically, bedrock fault scarps mark the last 10 to 20 strong earthquake events that produced vertical displacement along the fault (Fig. 2a). If individual events can be identified, fault scarps can reveal the magnitude and frequency of recent earthquakes on a particular fault.

The simplest view of the process that creates fault scarps is that earthquakes repeat at regular intervals in the same place and have about the same amount of slip during each event. This concept of "characteristic earthquakes" forms the basis of recurrence-interval estimates and seismic risk assessment. However, the earthquake recurrence interval that is inferred from this information depends on the time span over which the seismic record is studied. Paleoseismological data and historical information worldwide suggest that over a period of ten thousand years, the frequency of major events varies substantially (e.g. Wallace 1987; Weldon et al. 2004; Sieh et al. 2008; Scholz 2010).

The traditional way to decipher the longer-term history of events on a fault is to dig trenches across the fault and to identify and date (generally using radiocarbon techniques) offset events. Such trench analysis is a time-consuming process that is limited by the size of the trenches, the availability of organic material for radiocarbon dating, and the time window provided by that dating technique. In practice, the time series derived from trench studies do not exceed 5000 years.

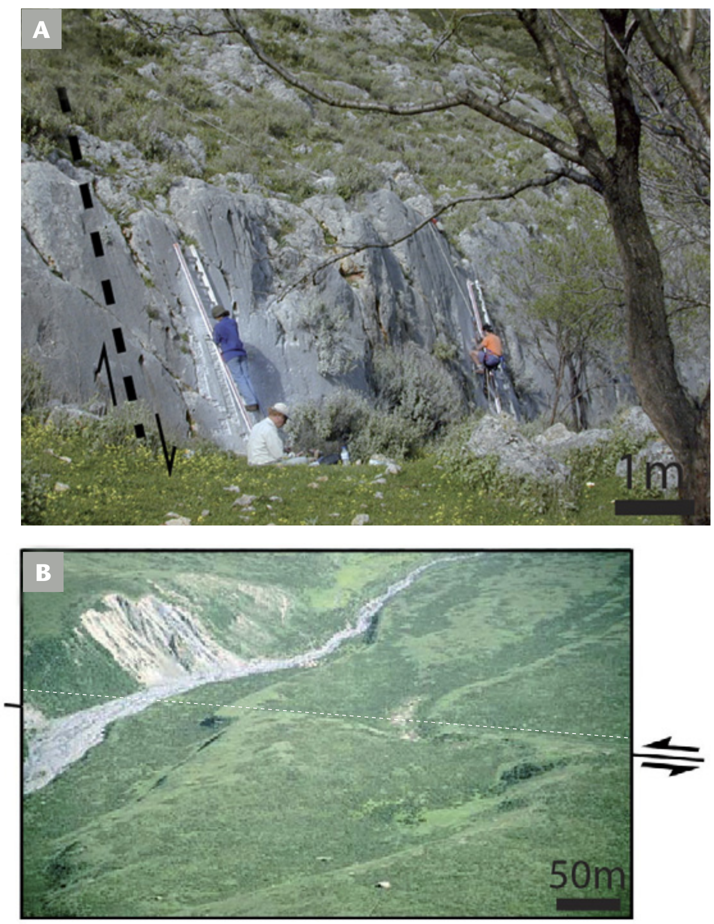

Figure 2 Examples of fault-motion markers datable with cosmogenic nuclides. (**A**) A normal fault scarp in Greece, vertically exhumed by the incremental addition of earthquake slip. (**B**) Laterally offset river terraces along the Haiyuan strike-slip fault in northeast Tibet (China). The older, upper terrace riser has accumulated more fault motion than the lower, younger one; offsets are 90 and 35 m, respectively.

Over the last ten years, a new technique has been developed to acquire paleoseismological records of seismically active normal faults that have occurred during the most recent ten to twenty thousand years (e.g. Benedetti et al. 2002; Schlagenhauf et al. 2010). The new method is based on the concentration of cosmogenic ^{36}Cl that has accumulated in the fault scarp as a result of the interactions between incoming cosmic rays and Earth-surface materials. These cosmogenic nuclides are produced when a sample is within about two meters of the surface, because beneath the surface, production rates decrease exponentially (see von Blanckenburg and Willenbring 2014 this issue). With each new earthquake, a new section of the fault scarp is exposed to incoming cosmic rays (Fig. 3a). As a result, the samples highest on the scarp are exposed longest and contain the highest concentration of cosmogenic nuclides.

A numerical model illustrates the expected ^{36}Cl concentration versus the height of a scarp that was produced by three earthquake events, each with two meters of slip (Fig. 3a). Beneath the surface, rocks along the fault plane accumulate nuclides, but at a rate that decreases exponentially with depth. When the buried portion of the fault plane is later exposed at the surface, ^{36}Cl begins to accumulate at a constant, higher rate. The profile of the ^{36}Cl concentration versus the height of the scarp thus has a series of cuspate shapes, with the three discontinuities marking individual seismic events (Fig. 3a, b). The earthquake ages are deduced from each cuspate ^{36}Cl concentration profile, which depends on various known parameters, including the chemical composition of each sample, the site geometry, and the density of the colluvium.

Limestone and marble contain ^{39}K, ^{40}Ca, and ^{35}Cl, which can serve as target elements for the in situ production of cosmogenic ^{36}Cl when they are exposed to cosmic rays. The production mechanism is fairly well known and quantitatively constrained (e.g. Schimmelpfennig et al. 2009; Schlagenhauf et al. 2010). In some cases, fault scarps in limestone and marble also present distinct, grooved abrasion surfaces associated with fault motion, which provide evidence that the scarp has not undergone significant erosion since the time it was formed. Preservation of the original surface is important when applying cosmogenic nuclide–exposure dating techniques, because erosion leads to loss of the accumulated nuclides and, hence, an underestimation of age.

In the Fucino area of central Italy, near the epicenter of the L'Aquila earthquakes (April 2009, magnitude 6.3; Pondrelli et al. 2009), the seismic history over the last 20 thousand years (ky) of seven normal faults that cut through limestone has been reconstructed using ^{36}Cl methodologies. These studies have established that strong earthquakes occur in great cycles of multiple events, consisting of a long quiescent phase (with 0–1 event during a period of 3–4 ky) alternating with intense seismic activity of three to five strong earthquakes on the same fault in relatively short periods of time (<1 ky) (Fig. 3c) (Benedetti et al. 2013).

By reconstructing the paleoseismicity on faults through cosmogenic nuclide methods, one can obtain a quantitative description of strong earthquakes (in terms of a displacement–time curve) over an unprecedented timescale. Such long records are particularly important for determining

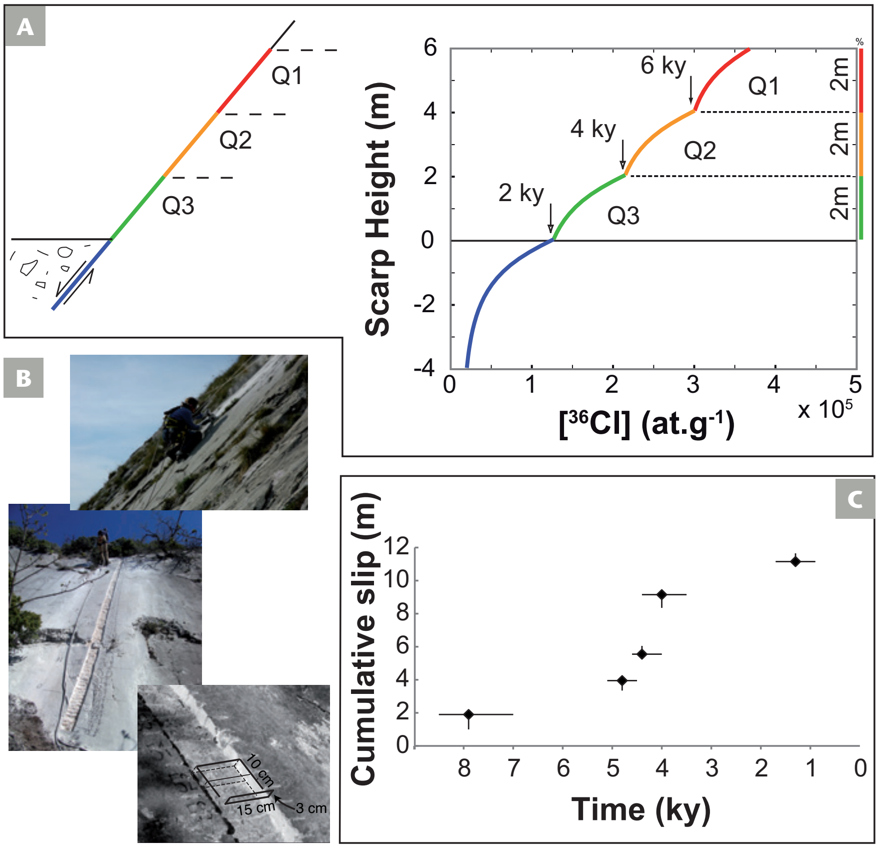

Figure 3 (**A**) Numerical modeling of ^{36}Cl accumulation on a fault scarp. (**B**) Samples are taken continuously on the best-preserved part of the fault scarp and ^{36}Cl measurements are made every 10 cm. Pictures are from fault sampling in the Apennines, Italy. (**C**) By comparing the measured ^{36}Cl concentrations of each sample with the theoretical ones modeled as in (A), the seismic history of the fault is retrieved (ky = thousand years). Dates are reproduced from Schlagenhauf et al. (2011) and are for the Magnola fault in the Apennines. At this site, the 11 m high fault scarp has been exhumed by five earthquake events over the last 8 thousand years. Each event produced a vertical slip of 2–3 m. Three events are clustered 4 to 5 ky ago. The two other events are separated by a long-time intervals of 3–4 thousand years with no earthquake events.

whether the fault is in a quiescent phase or a paroxysmal phase, which is critical for better anticipating the timing and size of future strong earthquakes in, for example, the Mediterranean region.

Dating the Effects of Strong Ground Motion

Another way to assess the age of past earthquakes is to date the effects of strong ground motion. Strong earthquakes can trigger major rockfalls (Bull 2007), such as the ones that occurred after the Christchurch earthquake in New Zealand in 2011 (Kaiser et al. 2012) and dislodged boulders the size of cars. In 1348, one of the most devastating earthquakes in northern Europe occurred at the Italy–Austria–Slovenia border, generating six simultaneous, large rockfalls (Merchel et al. 2014). Several million cubic meters of boulders collapsed at once. Similar rockfalls that occurred in the past can be dated using cosmogenic nuclides. Assuming that the fresh surfaces of the collapsed boulders experienced negligible exposure to cosmic rays prior to the rockfall, the accumulation of cosmogenic nuclides, such as ^{10}Be in quartz-rich boulders and ^{36}Cl in limestone boulders, can be used to date the rockfall event. In the Sierra Nevada, several rockfalls have been dated using this approach, and the exposure ages suggest that a strong earthquake may have triggered a large rockfall about 3600 years ago near Yosemite (Stock and Uhrhammer 2010).

Conversely, the presence of precariously balanced boulders in earthquake-prone areas suggests that no major ground motion has occurred since the boulders acquired their fragile positions. After a boulder falls, cosmogenic nuclides can reveal when the contact between the boulder and the support on which it rested was first exposed to cosmic rays. This moment corresponds to the time when the rock became vulnerable to earthquake ground motions (Balco et al. 2011). Together with other paleoseismological studies, this application of cosmogenic nuclides is useful for assessing if a region has been seismically quiet for an extended period of time.

DATING GEOMORPHIC MARKERS SUCH AS TERRACES, ALLUVIAL FANS, AND MORAINES

Determination of Fault Slip Rates

The use of surface offsets to determine fault slip rates requires sites where well-defined geomorphic features were first created, then preserved as displacement markers along the fault. The primary agents that create distinct landscape features through time are glacial and fluvial processes, both of which are modulated by climate. When several earthquakes occur on a fault, passive markers, such as abandoned terraces and moraines, become deformed and/or offset by the incremental fault motion. Typical examples occur when faults cut across alluvial fans along the piedmonts of rising mountain ranges (Van der Woerd et al. 2006) (Fig. 2b). Accurate measurements of such offsets give estimates of the cumulative deformation that has occurred after the markers became passive. Accurate dating of these markers can then yield a quantitative estimate of the fault slip rate over a specific time range.

The most promising locations for obtaining well-constrained slip rates are where fluvial processes have created multiple inset terraces and risers, allowing for slip-rate determinations over distinct time intervals at a single site along the fault. In principle, when a depositional landform is created (and begins to passively record fault slip), the boulders, pebbles, and sand that compose the landform's surface start accumulating cosmogenic nuclides. By measuring the concentration of nuclides in surface samples, it is possible to deduce when the landform was created.

Dating Depositional Landforms

Depositional surfaces are very different from bedrock fault scarps with respect to cosmogenic nuclide dating methods because these landforms result from the aggregation of mobile material into a single deposit. The depositional unit is thus a composite of debris particles with different predepositional exposure histories and different postdepositional behaviors. These pre- and postdepositional processes lead to what are commonly referred to as “nuclide inheritance” and “(postdeposition) erosion.” Inheritance is directly linked to exposures of the sampled rock before the particles were incorporated into the landform of interest. This prior exposure may occur at various places higher in the drainage basin from which a boulder originated, such as in the source area, or in transient depocenters, or during transport. After deposition in the landform to be dated, subsequent erosion can lead to the loss of nuclides from the boulder to be sampled and/or the surrounding matrix of the deposit, thus modifying the stability of the deposit over time. Accordingly, both inheritance and erosion must be constrained during the dating of alluvial terraces, fans, and moraines because both processes will affect the nuclide concentration of the sampled material and, hence, the final age determination.

Various methods for assessing inheritance in alluvial deposits have been proposed, including measurements of nuclide concentrations in geomorphic features such as young terraces and currently active channels (e.g. Bierman et al. 1995; Van der Woerd et al. 1998), and at great depths within a deposit where the material is effectively shielded from postdepositional nuclide accumulation (e.g. Anderson et al. 1996; Cording et al. 2014). Recent studies show that inheritance is rarely assessed by an independent age determination of the landforms (e.g. Le Dortz et al. 2012; Blisniuk et al. 2012).

A good example is seen in the Indio Hills in the area of the southern San Andreas fault, where a fan is right-laterally offset by about 500 to 800 m (Fig. 4). Using cosmogenic ^{10}Be, the age of the fan has been determined by surface-exposure dating of 20 cobbles and 11 boulder tops collected from the surface on both sides of the fault. Boulder-top ages, and particularly those of the largest boulders, are greater (ages of about 50 ka) than the average cobble ages (about 35 ka). Assuming negligible rock erosion, this relation may reflect progressive cobble exhumation due to erosion of the surrounding matrix of the deposit, and fan formation about 50 ky ago (Behr et al. 2010). However, large boulders (>1 m in diameter) may not be transported at the same rate as smaller cobbles (20–40 cm in diameter). The boulders’ older ages may reflect inheritance, which thus implies a fan age that is closer to 35 ka (Van der Woerd et al. 2006). In any case, the range of ages obtained at this site (35–50 ka) together with the offset (500–800 m) constrain the rate of movement along the southern San Andreas fault to between 14–22 mm/y (Fig. 4) (e.g. Van der Woerd et al. 2006; Behr et al. 2010). This rate is slower than geodetic estimates for this part of the San Andreas fault, implying that changes have occurred over time in slip rate or in faulting behavior.

CONCLUSIONS

Cosmogenic nuclide methods have enabled accurate dating of fault scarps that are gradually exhumed from beneath the surface as well as landforms that are deformed by fault slip over time. These dates have provided our first glimpses into fault behavior on timescales ranging from several thousands to several tens of thousands of years. Insights into seismic histories and slip rates of faults are critical to better understanding their seismic behavior and better anticipating future strong earthquakes on those faults. Using the methods presented here, it is possible to reconstruct past seismic history with unprecedented resolution both in time and in space, revealing seismic clustering at scales much larger than previously observed.

Of particular interest is the realization that cosmogenic nuclide methods provide information that fills an important temporal gap between short-term geodetic measurements and long-term geologic constraints on fault motion. This new window into fault behavior over intermediate timescales will improve our understanding of fault dynamics and allow fundamental advances in improving the accuracy of seismic risk assessment.

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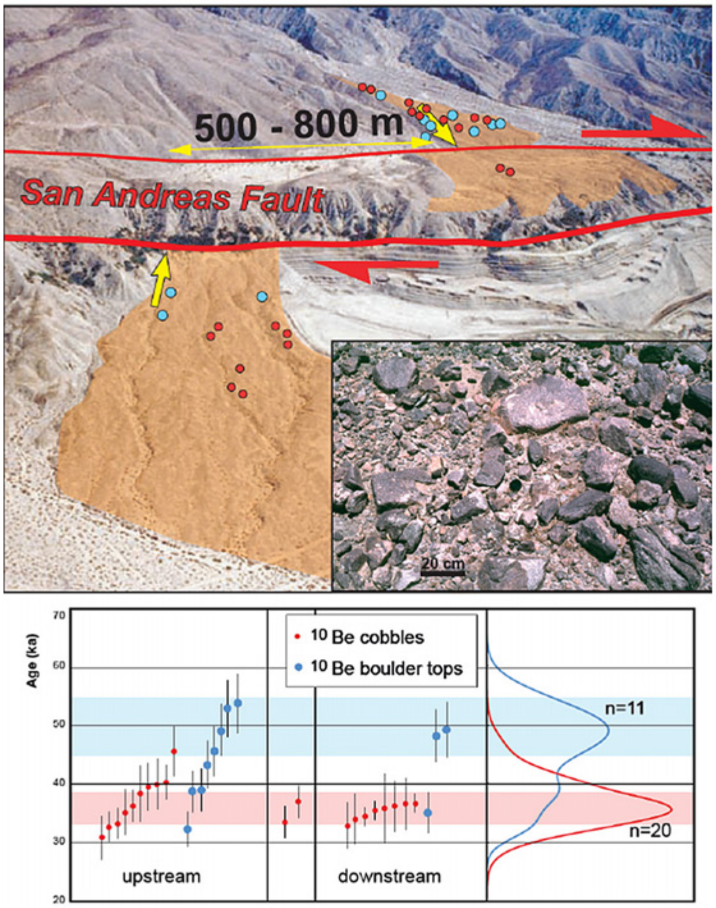

Figure 4 Offset alluvial fan along the southern San Andreas fault at Indio, California, USA. The age of the 500–800 m right-lateral offset is constrained by ^{10}Be cosmogenic dating of surface cobbles (red dots) and boulder tops (blue dots). The inset photo shows the type of material targeted for surface-exposure dating. In the lower panel, the ages of all samples are shown with the corresponding age distribution. Together with the offset, these ages suggest that the San Andreas slip rate over the last 35–50 ky was between 14 and 22 mm/y. Inset photo courtesy A. S. Meriaux

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