between age and elevation is also affected by the nature of isostatically-driven exhumation. This effect is strongly dependent on the mechanical strength of the underlying lithosphere that determines whether the isostatic response to erosion-driven exhumation is spatially correlated or not. A strong lithosphere behaves like a thick elastic beam characterized by a large flexural wavelength; a weak lithosphere is charcaterized by a small flexural wavelength. Consequently, we demonstrate that age-elevation relationships also contain information about the mechanical strength of the underlying lithopshere and we provide means of extracting it. Finally, by coupling a surface processes model to the three-dimensional heat transport model, we demonstrate how thermochronological datasets can provide important constraints on the evolution with time of major geomorphic features such as the Great Escarpment of Southeastern Australia.

H52D-05 1440h INVITED

Coupled precipitation and long-term erosion rates across the Washington Cascades

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The central Cascades mountains of Washington state form a 150-200 km wide, north-south oriented topographic high with a mean summit elevation of ~1.5 km, and nonvolcanic peaks above 2.7 km. The largely post-late Miocene bedrock uplift that created this part of the range formed a barrier to Pacific-derived moisture, leading to a dramatic orographic rain shadow with mean annual precipitation rates >4 m/yr on the notoriously rainy west flanks and <0.2 m/yr on the sagebrush steppes to the east. To examine the timing and rate of rock exhumation across the range, as well as relationships between precipitation and erosional exhumation, we have measured over one hundred apatite (U-Th)/He ages in a transect across the range. Apatite He ages vary from 4 to 60 Ma in this part of the range, with youngest ages on the upper west flank, and the oldest ages near the summit, east flank, and far western side of the range. These ages can be inverted for model erosional exhumation rates, assuming constancy since closure of the He system, by accounting for the interdependence of cooling rate, closure temperature, and closure depth in a steady-state crustal thermal model, and correcting for mean local topography (10-km circle) on isotherm depths (method of Brandon et al., 1998). Using this model, erosion rates near the summit, east flank, and far west flank range from less than 0.05 mm/yr to about 0.10 mm/yr, while rates for the upper west flank are as high as 0.33 mm/yr. Patterns of fluivially based erosion potential indices (e.g., steepest descent slope and local channel discharge) show no correlation with the observed erosion rate variations across the range. Mean annual precipitation, however, is relatively well correlated with erosion rate across the Cascades, suggesting a strong coupling between the two processes. If the range is currently in topographic steady state, then not only erosion rates, but also rock uplift rates on the west flank are as much as an order of magnitude greater than elsewhere in the range, including at the summit. Alternatively, rock uplift rates may be constant across the range, in which case varying erosion rates reflect transient topographic development of the range.

H52D-06 1455h

Detrital Mineral Cooling-Age Signal Variability and Erosion Rates, Marsyandi Valley, Central Nepal

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Detrital mineral cooling ages from modern rivers have been used as a proxy for long-term erosion rates because they integrate bedrock cooling ages from the contributing basin. In theory, each age represents a particle's vertical travel time from the steady-state closure isotherm, such that, for a basin eroding at a constant, uniform rate that balances uplift, the shape of the predicted distribution of ages mimics the contributing area's hypsometry, and its width is defined by the erosion rate if uniform chronometer distribution and insignificant sediment transport/storage time requirements are satisfied. Based on our interpretation of new $^{40}Ar/^{39}Ar$ ages for >300 individual detrital muscovite grains from central Nepal, we suggest that results for this approach to estimating long-term erosion rates can vary significantly by grain size, sample size, site selection, and year-to-year sediment redistribution within a single tributary basin. Large samples (n>80) of fine muscovite (250-500 microns), coarse muscovite (>500 microns), and smaller samples dated by previous workers from the Marsyandi River and its tributaries were compared in order to quantify natural detrital cooling-age signal variability and to explore the degree to which model requirements are met. While the present study's trunk stream age distributions generally agree with the spread of previously dated grains, distinct populations were found in a single tributary basin for fine and coarse size fractions, samples collected in different years, and samples from nearby locations. This variability is equally consistent with significant sediment storage time due to landslide or flood, spatially or temporally variable erosion rates, unevenly distributed lithologies, and/or transient topography. In addition, no uniform steady-state vertical erosion rate can account for the entire signal in any sample from this study, highlighting the need to assess independently natural sampling variability and the likelihood of steady state at the catchment scale before this or any more complicated erosion model can be used to interpret detrital cooling ages in terms of erosion rates. It is unlikely that simple thermal/erosion models can be used to infer surface process rates from modern detrital cooling-age distributions in this setting. However, combined with structural mapping in the contributing basin, detailed bedrock thermochronology and characterization of older sedimentary deposits derived from the catchment, this type of dataset can be used to explore differential erosion, erosion-rate increase/decrease and the appropriate temporal and spatial scales for steady state.

H52D-07 1510h INVITED

Beyond Dates and Rates: The Next Step in Cosmogenic Isotope Analysis?

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The cosmogenic isotope concentrations (CICs) of detrital materials are used to estimate catchment erosion rates but have the potential to offer considerably more. This is because the detrital CIC of a grain leaving an erosional terrain reflects its particular history of erosion, transport and storage, meaning in effect that the CICs of a large number of grains provide an integrated signature of a catchment's history. This can readily be demonstrated in ideal cases, relying particularly on the co-variance of key variables (isotope production rate and perhaps erosion rate and storage time) with altitude. However, individual grains have a near-infinite range of possible histories so requiring (as yet) unfeasibly large numbers of samples. Thus, CICs cannot be used to decipher detailed catchment histories, but the approach may be used to differentiate competing hypotheses for the evolution of particular catchments. To assess the potential of this method we constructed a 1-Dimensional stochastic model of CIC acquisition incorporating more than 20 modifiable parameters; CICs are calculated for up to 1000 grains. Some of the model parameters can be fully constrained for given sites (such as geomagnetic latitude; altitude), whereas others can only be estimated with considerable uncertainty (soil creep rate; duration of fluvial storage). Using published data, estimates of the key parameters have been made for test sites, and the sensitivity of the model to different parameters established. Significant, systematic differences in CICs are obtained under different conditions (altitude, relief, erosion rate, storage), and the model is able to reproduce published CICs from different settings and from our own work in the Sierra Nevada, S Spain. These results indicate that detrital CICs do have the capability of differentiating tectonic settings / geomorphic histories. The range of CICs of sediments underlies the issue of inheritance' that causes difficulties when dating sedimentary deposits. There may be scope using the approach here for a priori estimates of inheritance that can then be accommodated in dating applications.

H52D-08 1525h

Conservation Relations for Cosmogenic Radionuclides: Application to Erosional Landscapes

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Cosmogenic radionuclides have proved to be a useful tracer allowing quantification of rates of erosion and transport of sediment and concomitant geomorphic change. In numerical models of morphodynamics, differential sediment transport is tracked using the Exner equation of conservation of sediment mass. Here a corresponding equation is developed to describe the conservation of a cosmogenic radionuclide. The combination of two equations of conservation, one for sediment mass and one for the radionuclide tracer, offers a powerful way to extend the amount of information that can be extracted from analysis of cosmogenic radionuclides. The general formulation is applied to the specific case of an eroding landscape with stochastic elevation fluctuations. In many applications to date the rate of erosion is directly tied to the concentration of cosmogenic radionuclides at the eroding surface, but the sediment sampled for radionuclides is often obtained from a river not far from the area of interest. Such river samples represent averages over an erosion rate that includes stochastic fluctuations of elevation. It is demonstrated that a failure to include these fluctuations can lead to an overestimate of the erosion rate by as much as a factor of two. A scheme is presented by which cosmogenic radionuclides can be used to estimate not only the mean erosion rate, but also the standard deviation of temporal fluctuations in bed elevation.

H52E MCC: 3022 Friday 1600h

Quantifying Rates of Geomorphic Processes III *(joint with T, V)*

Presiding: **A M Heimsath,** Dartmouth College**; T Ehlers,** University of Michigan**; L Reinhardt,** University of Glasgow

H52E-01 1600h

Topographic Evolution of Mountains: The Influence of Episodic Rejuvenation in Southern Spain.

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Uplift and denudation of the westernmost part of the Sierra Nevada, southern Spain has been assessed using a combination of optically stimulated luminescence (OSL) dating and ^{10}Be and ^{26}Al terrestrial cosmogenic nuclide (TCN) determinations, on both in-situ bedrock and detrital quartz from recent sediments, together with apatite fission track (AFT) ages from the metamorphic core. The Tertiary record of unroofing of this mountain area is shown to be episodic over all spatial and temporal scales. The presence of Tortonian marine sediments at altitudes up to 1830 m, indicate erosion rates < 0.03 mm.a $^{-1}$ over the past 7 Ma. However, adjacent AFT determinations of 4 Ma record at least ca. 3.5 km of unroofing at similar elevations to those marine sediments. Current rejuvenation of a small (21 km^2), high relief (2 km) catchment in the western Sierra Nevada has resulted in two distinct geomorphic zones: (1) a low angle, denudationally stable (unrejuvenated) headwater region with thin regolith cover and uniform erosion rates of 0.07 ± 0.02 mm.a $^{-1}$; and (2) a steep, actively rejuvenating lower catchment dominated by landsliding with erosion rates up to 7.9 ± 0.4 mm.a $^{-1}$. Rejuvenation of this catchment began ca. 17 ka following a rapid, tectonically generated ca. 50 m change in base level. An axial channel knickzone migrated upstream at ca. 0.5 m.a $^{-1}$, successively rejuvenating tributaries and propagating up

hillslopes at a mean rate of 0.05 m.a $^{-1}$. The mean rate of river incision into schistose bedrock and fluvial terrace deposits dated by optically stimulated luminescence at ca. 13000 a is approximately 5 mm.a $^{-1}$. The long lived contrast in geomorphic form, suggested by TCN and OSL measurement, has lead to the development of a general model for the medium-term denudation of small (< 50 km) rapidly uplifting catchments in which river incision, being slower than the uplift rate, is periodically subject to pulses of rejuvenation which lower base level. For example a ca. 50 m drop in base level every 85 000 to 185 000 a is sufficient to enable a small catchment to keep pace with uplift rates of 0.4 - 0.7 mm.a $^{-1}$over medium (10^4 - 2 x 10^6) to long (>2 Ma) timescales and develop high relief. In this model medium-term denudation equals uplift, but the area occupied by the high summit and ridges are unaffected by periodic rejuvenations and relief continues to increase until some other limiting factor, such as tectonic denudation is introduced. A significant component of the long-term denudation of the Sierra Nevada must be linked to a period of rapid but spatially variable tectonic denudation that occurred 4-5 Ma, driven by surface uplift of the Sierra Nevada.

H52E-02 1615h

Determining the Pace of Landscape Evolution in the Sierra Nevada, California, Using Cosmogenic Burial Dating of Cave Sediments

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We report cosmogenic nuclide burial ages of Sierra Nevada caves that constrain detailed river incision histories and help clarify models of late Cenozoic topographic evolution. Portions of many Sierra Nevada river canyons are cut into marble bedrock containing numerous caves. These caves represent former river levels etched into the bedrock. Using $^{26}Al/^{10}$Be ratios, we determined burial ages for granitic bedload sediments washed into caves once at river level and now perched high in canyon walls. In the South Fork Kings River canyon, where the record is most complete, rapid incision of $\sim$0.2 mm yr^{-1} from 2.7 to $\sim$1.5 Ma slowed markedly to $\sim$0.02 mm yr^{-1} thereafter. Other caves in nearby canyons indicate a similar history. Numerical modeling of river profile evolution indicates that the reduction in incision rate is likely due to a transient response to Pliocene rock uplift. Westward tilting sufficient to drive the proposed 1.5 - 2 km of crestal uplift initiates a pulse of accelerated erosion that begins at the edge of the Central Valley and propagates up the river profile, passing the caves between $\sim$5 and 2 Ma. Incision rates decline markedly after this time. Late Quaternary incision may have been further reduced by periodic mantling of riverbeds with glacially derived sediment. The caves demonstrate that while $\sim$400 m of incision has occurred in the last 2.7 Myr, canyons up to 1.6 km deep existed prior to that time. Much of this paleorelief may be relict from the late Cretaceous. In addition, ^{26}Al and ^{10}Be concentrations on granitic interfluve surfaces indicate that these surfaces are eroding at $\sim$0.012 mm yr^{-1} averaged over $\sim$70 kyr. This is more than an order of magnitude slower than late Pliocene and early Quaternary incision rates, and 2 to 3 times slower than late Quaternary incision rates. As slow interfluve erosion likely persisted throughout the Quaternary, local relief increased during the period of rapid incision. Our findings of substantial pre-Quaternary canyon relief and slow interfluve erosion serve to lessen the amount of flexural isostatic rock uplift expected due to late Cenozoic erosion, strengthening the case for geophysically-driven late Cenozoic uplift.

H52E-03 1630h INVITED

Low Rates of Weathering and Erosion in Wet, Steep, Tropical Highlands

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The Central Highlands of the island of Sri Lanka feature all the ingredients usually thought to promote high rates of weathering: crystalline rocks, warm climate, high rates of precipitation. Also the high relief (steep mountains of up to 2500m altitude) would potentially generate high rates of physical erosion, which in turn promotes weathering by providing fresh mineral surfaces. An analysis of the rates of total erosion, using cosmogenic nuclides, excluding the effects of anthropogenic perturbance [1], was performed on various parts of the landscape (bedrock, surface soil, river sediment). The results suggest that all parts of the Highlands erode at 5-15mm/ky only. Rates of chemical weathering, determined by analysing major cations in river water, further suggest that most of this denudation is chemical. These rates of erosion are amongst the lowest world-wide for any sloping area analysed to date with cosmogenic nuclides. No relationship between climate and erosion is apparent for these areas. For Sri Lanka, we suggest that rock weathering has been low for millions of years due to (a) development of a clay-rich surface layer protecting rocks from corrosive fluids; (b) thick vegetation inhibiting removal of this layer; and (c), most importantly, absence of recent tectonic activity that would rejuvenate the landscape and promote physical erosion. Therefore, climate does not appear to exert controls over rock weathering if active tectonic forcing is absent. 1 T. Hewawasam, F. von Blanckenburg, M. Schaller and W. Kubik, Increase of human over natural erosion rates in tropical highlands constrained by cosmogenic nuclides, Geology 31, 795-600, 2003.

H52E-04 1645h

Escarpment Erosion and Landscape Evolution in Southeastern Australia

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Passive margin escarpments are extensively studies around the world and understanding their evolution continues to present one of the more compelling interdisciplinary challenges tackled by Earth scientists today. Escarpments typically separate regions with different climatic and tectonic histories and the inferred rapid rates of escarpment retreat have been at odds with actual measurements of land surface exhumation and erosion. In this paper we present results from extensive cosmogenic 10Be and 26Al analyses across the escarpment of southeastern Australia to quantify the erosional processes evolving the highland, lowland, and scarp face landscapes. We document new relationships between soil production rates and soil thicknesses for the highland and lowland landscapes and compare these soil production functions with those published in two earlier studies from the highlands and at the base of the escarpment. Both new functions define exponential declines of soil production rates with increasing soil depths with inferred intercepts of 65 and 42 m/Ma for the highland and lowland sites, respectively, and slopes of -0.02. Exposed bedrock at both sites erodes more slowly than the maximum soil production rates, at 22 +/- 3 and 9 +/- 2 m/Ma, respectively, thus suggesting a "humped" soil production function. We suggest, instead, that lithologic variations set the emergence of bedrock, which evolves into tors, found extensively across the highlands. Compared to soil production rates from previous work using 10Be and 26Al measurements from two different sites, these results show remarkable agreement and specifically quantify a soil production function for the region with an intercept of 53 m/Ma and a slope of -0.02. Erosion rates determined from 10Be concentrations from outcropping tors, bedrock and saprolite from a main spur ridge perpendicular to the escarpment, and sediments from first and zero order catchments draining the main ridges, show a clear linear decline with elevation, from about 35 m/Ma near the escarpment base to about 3 m/Ma at the escarpment crest. This order of magnitude difference in erosion rates may be due to increases in stream incision with distance downslope on the escarpment, or to decreases in precipitation with elevation, neither of which we quantify here. The rates do agree, in general, with our soil production functions, suggesting that the biogenic processes actively eroding soil mantled landscapes are shaping the evolution of the escarpment despite our observations of block fall and debris flow processes across the steep regions near the scarp crest. Our results support recent results from studies using apatite fission track thermochronology, suggesting that the escarpment is relatively stable after having retreated rapidly immediately following rifting. Differences between our rates of surface erosion caused by processes active today and the scarp retreat rates needed to place the escarpment in its present position need to be explained by future work continuing to untangle the mysteries of escarpment evolution.

H52E-05 1700h

Spatial Patterns of Erosion in the Bolivian Andes Inferred From In Situ ^{10}Be

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The Eastern Cordillera of the Bolivian Andes comprises some of the world's most rugged topography and serves as the major sediment source for the Amazon Basin. The upper Beni River basin drains a large portion of the range north of the Bolivian orocline, including most of the highest peaks. Erosion rates have been measured or modeled in these mountains using a variety of approaches, but measurements reported to date are too sparse to document in much detail spatial patterns of erosion rate throughout the basin. Here, we present concentrations of ^{10}Be in quartz from alluvium at 48 sites sampling the montane tributaries of the upper Beni River. The ^{10}Be concentration in our samples, derived from drainage areas between 1 and 70,000 km^2, ranges from 20,000 to 150,000 atoms/gram. Variations in ^{10}Be concentration and thus model erosion rates are most pronounced among basins with drainage areas < 10^3 km^2. To interpret erosion rates from ^{10}Be concentrations, we account for the non-uniform distribution of quartz in polylithologic basins as well as for the effects of the rugged basin hypsometry on ^{10}Be production rates. The resulting erosion rates are on the order of 0.1 to 1 mm/yr, similar to those derived from apatite fission track analyses. The cosmogenic radionuclides average erosion rates over thousands of years, long enough to smooth decadal-scale variations in sediment output but short enough to reflect valley-scale variations in erosion rate due to location in the network, dominant geomorphic process, and lithology.

H52E-06 1715h

Application of Fallout Pb-210 Geochronology to River-Floodplain Systems

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Lowland floodplains store suspended sediment carried over bank during floods. Because floodplain sedimentation may account for the majority of the net sediment accumulation within sand-bedded river-floodplain systems, it is important to develop a means to quantify this process. Recent studies have demonstrated that the natural radionuclide Pb-210 can be used to determine floodplain accumulation rates over decadal-to-century timescales with a Constant Input Concentration and Constant Sedimentation rate model (CICCS). To investigate the application of the CICCS method to a large, dynamic, pristine river system with extensive forested floodplains, 265 vertical cores were collected throughout the floodplains along 2,000 km of the Beni and Mamore Rivers in northern Bolivia. Rather than measuring bulk-averaged down-core Pb-210 activity to estimate average accumulation rate according to the standard CICCS procedure, the cores were instead sectioned vertically to obtain a high-resolution record of Pb-210 activity and sediment accumulation. Over 95% of these profiles portray a history of episodic deposition with decadal recurrence intervals, and few profiles exhibit the steady-state accumulation assumed by the CICCS model. Because these discrete deposition events are large, few of the cores ever reach supported

background Pb-210 activity at depth, another requirement of CICCS. Furthermore, the input activity of Pb-210 is not constant, both at a site and down-channel. The Pb-210 content of sediment varies directly with fine sediment content (typically clay), which is highly variable with depth for many of the cores. Without a discretely sampled, clay-normalized Pb-210 activity profile, it is difficult to evaluate the suitability of CICCS for each core. To accommodate these complexities, a more labor intensive approach is proposed for dating sedimentation using discrete down-core, clay-normalized measurements of Pb-210 activity, coupled with a geomorphic model of Pb-210 input during large floods. Combined with a field determination of supported Pb-210 activity, collection of multiple terrace cores to determine the meteoric input of Pb-210, and a technique for independently dating the "meteoric cap" above discrete depositional events, this approach to Pb-210 geochronology provides a convenient and robust approach to dating floodplain sedimentation to a near-annual precision. In addition to the Bolivian pilot study, additional examples will be presented from recent floodplain sampling campaigns on the Sacramento River, California (80 cores), and the Strickland River, Papua New Guinea (190 cores).

H52E-07 1730h

A Synthesis of Denudation Rates in the Bolivian Andes: Tracking the Erosion Gradient in an Active Fold-Thrust Belt

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Dramatic along strike contrasts in the tectonics, topography, and climate of the Bolivian Andes (14-22 S) have been used to argue the importance of erosion in the evolution of the fold-thrust belt. Even though erosion has been invoked as a controlling factor for the along-strike variability in the kinematic evolution of the fold-thrust belt, current denudation rates are sparse. New and existing material-flux and denudation-rate estimates were synthesized in an attempt to more quantitatively describe the spatial and temporal variations in erosion across the Bolivian fold-thrust belt. The variety of sources used to calculate these estimates include structural cross-sections and their restorations, thermochronology, foreland basin sediment volumes, basin fill, erosion surfaces, mass balance and DEM analysis, landslide mapping, and sediment-flux data. Material-flux rates derived from structural cross-sections and their restorations of the entire thrust-belt range from 32.4-56.4 km2/Ma in the north to 31.6-58.9 km2/Ma in the south over the last 40 Ma. Apatite and zircon cooling ages in the northern Eastern Cordillera yield exhumation rates of 0.1-0.75 mm/yr. Approximated exhumation rates from reported apatite cooling ages in the southern central Eastern Cordillera range from 0.09-0.17 mm/yr over the last 45-25 Ma. Material-flux rates from the Subandean portion of the fold-thrust belt averaged over the last 10-20 Ma range from 21.3-41.8 km2/Ma in the north to 12.8-28.8 km2/Ma in the south. Approximated exhumation rates from apatite cooling ages in the southern Interandean zone are 0.19-0.42 mm/yr over the last 10-22 Ma. In the south, material-flux and denudation-rate estimates from erosion surfaces, DEM analysis, and Tertiary basin fill range from 11-82 km2/Ma and from 0.13-0.2 mm/yr over the last 2-10 Ma. Modeled fluvial incision in the northern Eastern Cordillera predicts variable local rates of up to 5.0 mm/yr over the last 7.5 Ma. Short-term (last 2-35 years) denudation-rate averages from sediment load data and landslide mapping range from 1.0-8.0 mm/yr in the north to 0.3-0.4 mm/yr in the south. The longest-term averaged rates are similar across both northern and southern regions. In general, the northern estimates begin to exceed their southern counterparts starting at rates averaged over 10-20 Ma. The southern region rates remain similar in magnitude over all timescales, whereas the northern rates appear to increase to the present. The disparity may be a reflection of the biases in the methods or the feedbacks associated with uplift, climate, and erosion. These rates and their contrasts constrain geomorphic process rates in an active fold-thrust belt over a wide range of timescales that may provide calibration for models that simulate uplift-climate-erosion feedbacks in mountain building.

H52E-08 1745h

Quantifying Sediment Storage Rates and History in the NW Argentinian Cordillera Using Luminescence Dating Techniques

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The quebradas of the Eastern Cordillera of NW Argentina contain Late Quaternary sedimentary sequences that reflect repeated alluvial fill and incision events that have created a series of inset terrace surfaces. Variation in climate is considered to be the principle trigger driving episodes of erosion and sediment deposition, even though ongoing tectonic uplift and deformation provides oversteepened slopes and can interrupt drainage patterns. The current chronological framework is based on tephrochronology and ^{14}C, but there are insufficient ash beds or organic remnants to produce a high resolution chronology of erosion and sediment storage. We are therefore producing a detailed chronological record of alluviation using optically stimulated luminescence (OSL) dating, combined with cosmogenic radionuclide dating to quantify erosion rates. Recent advances in single aliquot measurements of quartz have improved both precision and accuracy of the OSL dating method for sediments, where an age assessment is possible for each aliquot measured. Although initial OSL results are consistent with ^{14}C of shells and wood samples, the majority of alluvial samples studied have wide, multimodal age distributions. There are various possible explanations for these distributions, including inadequate bleaching of some quartz grains. However, we believe the age distributions are a result of variations in the interplay of sediment source and transport mechanisms, in concert with variability in grain-to-grain bleaching, and therefore contain an archive of the inherited grains from past sedimentation events. To improve our understanding of the age distributions we are investigating small aliquot (about 50-100 quartz grains) approaches in combination with a variety of distribution analysis techniques that identify not only the age since the last solar exposure, but also the age of inherited grains. In addition to providing rates of sediment accumulation and storage, such archives of basin sedimentation (and erosion) improve our understanding of the cycling of sediments within a basin through time and identify periods of alluvial storage and erosion.

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Pfister, R. G., and M. S. Nestler, Sharing community data, services and tools using the EOS clearinghouse (ECHO), *Eos Trans. AGU, 84*(46), Fall Meet. Suppl., Abstract U41B-0006, 2003.