U-Series Dating Results
USGS Denver Radiogenic Isotope Lab

^{230}Th/U ages Supporting Hanford Site-Wide Probabilistic Seismic Hazard Analysis

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Purpose

Pacific Northwest National Laboratory (PNNL) is responsible for conducting a site-wide probabilistic seismic hazard assessment analysis at the Department of Energy's Hanford Site near Richland, WA. This assessment requires estimates of the ages of Quaternary alluvial deposits and geomorphic surfaces in order to evaluate deformation rates in the Yakima Fold and Thrust Belt.

To support this effort, the U.S. Geological Survey was contracted by the Department of Energy to obtain U-series age estimates for several soil horizons associated with the study area. USGS geochronologist James B. Paces accompanied members of the Quaternary Geologic Studies Team, geologists Kathryn Hanson and Christopher Slack, both of AMEC Environmental and Infrastructure, on a site visit in June of 2013 to examine available materials and select samples from several exposures in the Richland, Pasco, and Kennewick area that were deemed representative of geomorphic surfaces in the area by the Quaternary Geologic Studies Team. The purpose of this report is to document those materials, describe the analytical results, and provide uranium (U)-series age estimates of the dated pedogenic components contained within those soils.

Samples

Sites consisted of alluvial or colluvial sand and gravel deposits with varying degrees of pedogenic cementation. Samples collected from the five sites listed in Table 1 were used for geochronological analyses. Samples consisted of rock clasts with poorly to well-developed pedogenic rinds ranging from less than 1 mm to greater than 10 mm in thickness. In some cases, rinds that had become separated from their associated clasts were also collected. In all cases, multiple clasts from the same soil horizon were collected in order to evaluate the consistency of their isotopic compositions and calculated ages.

Rinds consist of mixtures of calcite and silica typically formed on the undersides of gravel clasts. Rind textures range from single layers of uniform material, to finely laminated or more complex, irregularly mottled layers. Rind-growth occurs by progressive accumulation of secondary cements precipitated from water films that preferentially accumulate on the undersides of clasts. Therefore, layers adjacent to the clast/rind interface are likely to yield the oldest dates, which represent ages of pedogenic cements that are closest to the age of alluvial deposition. These layers were targeted for dating in this study. Photographs of individual rinds in cross sections of polished slabs are included in appendix 1.

In addition to clast rinds, a block of carbonate-rich fault gouge exposed at Finley quarry also was sampled. The block was cut into slabs, polished, and subsampled from several different layers to evaluate the age of carbonate development potentially associated with paleoseismic events.

Table 1. Site locations and sampling comments

Site Name	Location	Latitude	Longitude	Comments
Steptoe quarry	Richland, WA	46.23564°	-119.24877°	Clasts sampled from K-horizon high up on west wall about 150 cm below upper surface
Yakima Bluff	Richland, WA	46.2652°	-119.31339°	Clasts and pedogenic rinds sampled from natural exposure at two different depths; 0-70 cm and 70-170 cm below surface
South Bombing Range Road quarry	West Richland, WA	46.27829°	-119.34403°	Clasts with well-developed rinds sampled from small scour channel exposed in upper soil near the center of the north wall
Finley quarry	Kennewick, WA	46.12017°	-119.04328°	Exposure of fault juxtaposing Umatilla basalt forming the footwall against cataclysmic flood deposits forming the hanging wall. Two samples: (1) basalt clasts from sediment on the north end of the exposure, and (2) a 30–50 cm wide calcite-cemented fault breccia
MCBONES quarry	Kennewick, WA	46.15964°	-119.26653°	Clasts and pedogenic rinds sampled from alluvial fan deposits exposed in lowermost layer of the quarry underlying 3–4 m of loess

All locations given relative to NAD83 datum

Aliquots prepared for U-series dating

Thin layers (typically ~1-mm or less in thickness) of mixed calcite and silica cement were sampled by prying or milling material present adjacent to the clast/rind interface. Targets focused on layers that were relatively free of obvious detrital material (sand and silt). This practice tends to minimize contributions of detrital components that contain rock-derived thorium (Th) not related to the ingrowth of ^{230}Th from the decay of ^{234}U present in authigenic cement. These layers typically have the greatest hardness and density and tend to be darker in color than less well-formed cements. In order to gain confidence that ages derived from these materials have geological significance, samples of rinds from multiple clasts within the same horizon were obtained. Ideally, dates obtained for inner rind layers within a given soil horizon should be concordant if they formed as a result of the same pedogenic episode.

Sample names follow the convention used by the Quaternary Geologic Studies Team members, where the first 2 digits represent the year (13 = 2013) and the next three digits represent the Julian Day Number within the year (166 = June 15). The next two digits designate the Project leads (SH = Slack, Hanson), and the final digits represent the consecutive site visited during that day. Alphanumeric characters following the dash designate from which clast the sample came and an indication of whether more than one subsample was analyzed.

Chemical Processing and Mass Spectrometry

Activities performed as part of this study followed standard operating procedure *USGS-DRIL-01, R0 Uranium-Thorium Disequilibrium Studies* (unpublished document available on request) for sampling, chemical preparation, and isotope analysis. This procedure addresses sample labeling and control, analysis of samples, maintenance of records and reporting of results. These procedures are summarized below.

Aliquots of rind fragments or powders were weighed, and then spiked with known amounts of a high purity mixed-isotope tracer (^{236}U-^{233}U-^{229}Th). Samples were digested using nitric and hydrochloric acid in PFA-Teflon vials at atmospheric pressures and temperatures of 105° to 125°C. The carbonate component was completely dissolved in this step; however, residue was common representing authigenic opal or detrital silicates including silt and clay. Residue was separated from the supernatant, digested using hydrofluoric acid, and recombined with the original solute resulting in analyses that represent total digestions. U and Th were separated from the acid digestate and purified using standard ion chromatographic separations with Biorad™ AG1×8 (200-400 mesh) resin. Resulting U salts were loaded on the evaporation side of Re double-filament assemblies. Th salts were loaded onto single Re-filament assemblies as a sandwich between layers of graphite suspension. Isotope ratios were obtained on a Thermo Finnigan Triton™ thermal ionization mass spectrometer equipped with an RPQ (retarding potential quadrapole) electrostatic filter. Ratios were determined in peak-jumping mode using a single ETP secondary electron multiplier.

Quality control was established by analyzing several standards processed and run along with unknown samples. These standards include a National Institute of Standards and Testing (NIST) uranium-isotope primary standard, and several in-house materials of known age and isotopic composition. U isotopic compositions of NIST 4321 U-isotope standard determined over the same time period yielded an average ^{234}U/^{235}U value of 0.0072923 ±0.15% (2×standard deviation [SD] for 65 analyses analyzed between 2/11/2013 and 2/14/2014), which is within analytical uncertainty of the certified value of 0.0072939. Results for solutions of uranium ore from the Schwartzwalder mine yielded an average ^{234}U/^{238}U activity ratio (AR) of 0.9999 ±0.47% and an average ^{230}Th/^{238}U AR of 0.9990 ±0.38% (±2×SD for 12 analyses determined between 6/26/2013 and 12/29/2013), both of which are within analytical uncertainty of the secular equilibrium values of 1.000 expected for the 69.3 Ma ore (Ludwig et al., 1985). Results for a USGS in-house U-series dating standard (late Pleistocene Acropora coral with an age of 119.6 ±1.9 ka; Watanabe and Nakai, 2006) yield an average age of 118.4 ±3.5 ka (±2×SD, N=32) and an average initial ^{234}U/^{238}U AR value of 1.152 ±0.004 (±2×SD, N=32), which is within uncertainty of accepted values for seawater (1.150 ±0.006; Delanghe et al., 2002).

All uncertainties presented in this report are given at the 95% confidence level (2-sigma) and include errors arising from within-run analytical uncertainties based on counting statistics, external errors based on reproducibility of standards, and errors propagated from uncertainties assigned to the assumed detrital component and the amount of detrital material present in a given sample.

Analytical Results

Thirty-six analyses of clast rinds from six sites plus four analyses from a cross section of fault gouge were analyzed for U and Th isotopes (Table 2). All samples had U and Th concentrations that were amenable to U-series dating with U concentrations ranging from 2.4 to 28.6 µg/g and Th concentrations ranging from 0.03 to 3.64 µg/g. Resulting ^{232}Th/^{238}U AR are relatively low reflecting high U/Th ratios. As a consequence, corrections for non-authigenic ^{230}Th present at the time the cements formed are relatively small for most samples.

Calculation of ^{230}Th/U Ages

Dating by the ^{230}Th/U method is based on the in-growth of ^{230}Th derived from in-situ decay of ^{234}U that is present both as excess ^{234}U incorporated at the time of mineral formation and as the product of in-situ decay of ^{238}U . Any ^{230}Th that was present initially must be identified and excluded from age calculations. Because of the very low solubility of Th in most near-surface water, purely authigenic cements commonly form with no initial ^{230}Th, and measured ^{230}Th/^{238}U AR can be used to calculate ages. However, any silicate detritus present in the samples, including fine clay particles, will contain ^{232}Th as well as small amounts of ^{230}Th that must be subtracted from the measured ^{230}Th in order to obtain only the ^{230}Th that was contributed from in-situ decay of U. Fortunately, measured ^{230}Th/^{238}U and ^{234}U/^{238}U AR values can be corrected for the presence of a non-authigenic component (i.e., silicate sediment) using measured ^{232}Th/^{238}U AR values and the assumptions that this material is uniform, has a U/Th composition similar to average crustal material, and is in radioactive secular equilibrium (that is, a composition of ^{232}Th/^{238}U AR = 1.276 ±0.64; ^{230}Th/^{238}U AR = 1.0 ±0.25; ^{234}U/^{238}U AR = 1.0 ±0.1). Correction methods are described in Ludwig and Titterington (1994) and Ludwig and Paces (2002). Uncertainties are propagated through this calculation in such a way that errors for the detritus-corrected ratios are only slightly larger than analytical uncertainties if the measured ^{232}Th/^{238}U AR is very small (say <<0.1), but may be very large if substantial amounts of ^{232}Th are present (i.e., ^{232}Th/^{238}U AR >0.2). Ages and initial ratios were calculated using routines described elsewhere (Ludwig, 2003).

Detritus-corrected AR for ^{230}Th/^{238}U and ^{234}U/^{238}U in the analyzed samples are given in Table 2 and shown on U-series isotope evolution plots (figures 1 & 2). Finite ages can be calculated using the first-derivative solution to the ^{230}Th/U age equation for most, but not all analyses. This calculation uses the values given for the detritus-corrected AR, which yield valid solutions as long as the isotopic compositions fall to the left of the infinite-age line shown on isotope evolution plots. In these cases, analytical errors are used to directly estimate uncertainties for ^{230}Th/U ages and initial ^{234}U/^{238}U AR. In several cases, values for present-day ^{230}Th/^{238}U AR and ^{234}U/^{238}U AR result in points that plot to the right of the infinite-age line, which is impossible in a closed isotopic system where the only change in composition is caused by radioactive decay and ingrowth. Points plotting to the right of the infinite-age line indicate some degree of open system behavior involving removal of soluble U relative to insoluble Th resulting in anomalously high ^{230}Th/^{238}U AR values. Some of the analyses in Table 2 have present-day isotope compositions that plot within analytical uncertainty of the infinite age line (i.e., the 2σ error ellipses intersect the infinite age line), suggesting that only a slight amount of chemical disturbance has occurred. In these cases, ages can be calculated using a Monte-Carlo approach, where the stated analytical uncertainties are used to randomly propagate a number of compositions distributed within the error ellipse. Those compositions that allow calculation of positive finite ages are tallied until 1000 age results are obtained. The average from this data set is then reported as the estimated age using a Monte-Carlo solution. The two calculations yield similar, but not exactly matching results due to the random factor used in Monte-Carlo simulations. This allows additional age information to be extracted that is especially useful for old materials that are very close to the limits of the dating system (typically between 400 and 600 ka).

Open-System Geochemical Behavior

The post-depositional mobility of soluble uranium (open-system behavior) can cause erroneous ages. This is because U can readily be added or removed relative to insoluble Th, resulting in compositions that typically show large ^{230}Th/^{238}U AR variations but only small ^{234}U/^{238}U AR variations (points move along sub-horizontal trajectories in figures 1 and 2). Open-system behavior as a consequence of U removal is apparent in a small number of samples shown in figure 1: four samples exhibit substantial U loss that does not allow calculation of ^{230}Th/U ages and four samples exhibit minor U loss that still allows calculation of ^{230}Th/U ages by the Monte-Carlo method described above. The remaining samples have compositions that are consistent with closed-system behavior. The tendency for data to plot close the infinite age line for ancient samples represents strong evidence that rind cements have not experienced substantial chemical disruption.

Initial ^{234}U/^{238}U Activity Ratios

Once an age is determined for a given sample, it can be used to calculate the isotopic composition of the water from which the cement was precipitated using the present-day measured ^{234}U/^{238}U AR and the known decay constant for ^{234}U. Because soil waters typically have ^{234}U/^{238}U AR >1, initial ratios are equal to or larger than the measured ratio, following the curved isotope-evolution paths in figure 1 to the point where they reach the Y-intercept (dark blue curves). This is a very valuable check on ages because samples precipitated from a given water source at various times should yield the same initial ^{234}U/^{238}U AR values (i.e., follow the same closed-system evolution curve in fig. 1). Samples that are affected by open-system conditions will usually have anomalously large ^{230}Th/^{238}U AR values resulting in erroneously old ages and anomalously large initial ^{234}U/^{238}U AR values.

Samples of soil rinds analyzed in this study have a remarkably limited range of initial ^{234}U/^{238}U AR values (Table 2 and figure 1). The youngest samples from Steptoe quarry and Finley quarry with ages between 18.3 and 14.8 ka have initial ^{234}U/^{238}U AR values that range from 1.04 to 1.14. Older samples that do not show evidence for open-system behavior have values that largely fall in this same range. The consistency of initial ^{234}U/^{238}U AR values is viewed as evidence that, despite their antiquity, soil rinds retain isotopic compositions that preserve fundamental age information.

Ages for Individual Sites

Steptoe Quarry

Four of the six analyses determined on inner rinds from clasts at the Steptoe quarry site yielded ages that were close to the limits of the ^{230}Th/U method. ^{230}Th/U ages calculated using both methods described above range from 509±86 to 736±831 ka. The large uncertainties are a consequence of isochrons becoming tightly compressed as the dating limit is approached (typically considered to be five times the half-life of ^{230}Th, or about 380 ka), even though analytical uncertainties remain small (small red error ellipses shown clustering near the infinite age line in figure 2). However, the actual limit depends on how precisely the isotopes of interest can be measured. Results determined by high-precision mass spectrometry allow reliable dates of 500 ka or greater to be obtained, albeit with larger uncertainties due to the exponential loss of resolution as the infinite age line is approached. Age calculations also depend on the decay of ^{234}U, which has a longer half-life of 245,000 years. Therefore, at least semi-quantitative age information may be preserved in materials as old as 1.2- to 1.4-million years before secular equilibrium conditions are reached.

One sample had an elevated ^{230}Th/^{238}U AR value indicative of open-system behavior; however, the fact that the rest of the analyses yielded reasonably consistent finite ages this close to the method's age limit indicates that this range of ages is reliable within the stated analytical uncertainties. One thin inner rind on a quartzite clast (13166SH01-D1) had a much younger age of 17.3±1.0 ka indicating that pedogenic cement was added in the late Pleistocene. Importantly, the initial ^{234}U/^{238}U AR of 1.038 for this young rind is consistent with those obtained for the older rinds.

Therefore, ages from the older rinds suggest that alluvium within the upper several meters of the surface at Steptoe quarry was deposited shortly before about 500 ka, and most likely after about 700 ka.

Yakima Bluffs

Inner rinds developed on clasts from outcrops at Yakima Bluffs showed the greatest degrees of open system behavior (figures 1 and 2). Five of the seven samples from the upper 70 cm of the deposit had excess ^{230}Th to varying degrees. Two of those only had minor U loss allowing calculation of Monte-Carlo age estimates of $630^{+300}/_{-180}$ ka and $775^{+300}/_{-210}$ ka (asymmetric errors are caused by the non-linear effects of radioactive decay). Sample 13166SH02-E1 yielded a robust ^{230}Th/U age of 408±34 ka, which is within error overlap of the 370±44 ka ^{230}Th/U age obtained from rind 13166SH02A-I1 collected from slightly deeper alluvium between 70 and 170 cm below the surface. Several other clasts from the lower unit had much younger ages (27.5±0.2 ka and 52.5±0.4 ka) indicating that pedogenic cement was added or mobilized in the late Pleistocene; however, their initial ^{234}U/^{238}U AR values are within the error of the value obtained from the older sample from the same unit (~1.07 versus 1.08). One sample from the upper unit with an intermediate age of 272±45 ka had an initial ^{234}U/^{238}U AR value less than 1 (0.978±0.028) indicating that water/rock interaction preferentially removed ^{234}U relative to ^{238}U at some time in the past. This is the only sample that shows substantial ^{234}U depletion (albeit within analytical uncertainty of a secular equilibrium value of 1.0) and, as such, is viewed with suspicion. In addition, the oldest Monte-Carlo age estimate determined for sample 13166SH02-F1 also has an anomalously high initial ^{234}U/^{238}U AR of 1.7, which also suggests substantial U mobility.

The greater degree of open-system behavior apparent for inner rinds of Yakima Bluffs clasts makes it difficult to estimate a reliable age of alluvial deposition. The two most robust ^{230}Th/U ages suggest that soils may have started forming around 400 ka. However, at least one analysis hints at the possibility that deposition could be somewhat older.

South Bombing Range Road Quarry

Four inner rinds from clasts near the surface at South Bombing Range Road quarry yield ages ranging from 308±12 ka to $564^{+310}/_{-180}$ ka. The two younger ages (308±12 ka and 346±14 ka) have low age uncertainties and are not within error overlap (figure 2). The two older ages have substantially larger uncertainties, allowing the possibility of ages in the range of ~400 ka or less. Available data indicate that alluvium was deposited prior to about 350 ka.

Finley Quarry

Samples of rinds on clasts from calcified cataclysmic flood deposits at Finley quarry are thinner and less well developed than those from other sites consisting of little more than selvedges of non-laminated carbonate cement less than 0.5 mm. Uranium concentrations are similar to other samples, but Th concentrations are somewhat higher. Consequently, measured ^{230}Th/^{232}Th AR values are lower than values from other samples (table 2) requiring larger corrections for a detrital component. ^{230}Th/U ages for 8 analyses cluster between 14.8±8.4 ka and 18.3±5.7 ka (table 2 and figure 1). The larger uncertainties associated with these dates do not allow resolution of any differences between these ages. Therefore, it can be assumed that all analyses represent a single population that is normally distributed about a weighted mean age of 17.0±1.8 ka (weighting based on the 2σ errors for individual analyses; figure 3). Values of initial ^{234}U/^{238}U AR for these same samples range from 1.060±0.009 to 1.137±0.018 and do not agree within analytical error.

Therefore, it is likely that this spread represents small, but real variability in the $^{234}U/^{238}U$ AR values of soil water from which the cements formed.

Carbonate-rich gouge present along the fault exposed at Finley quarry shows complex layering and cementation paralleling the attitude of the fault. Textures range from coarsely crystalline spar to fine-grained micrite. Four distinct 1- to 2-mm-thick layers were sampled over a ~3-cm-thick section for dating (see photo 13167SH02B in appendix). In general, U concentrations and U/Th ratios are amenable to U-series dating, and resulting ages range from 700+270/-160 ka to 224±36 ka (table 2 and figure 2). Ages do not vary monotonically with distance across the slabbed section, implying complex spatial patterns of fracturing and cementation associated with near-surface fault ruptures. All initial $^{234}U/^{238}U$ AR values are identical within analytical error (weighted mean value of 1.053±0.010), providing confidence that the range of calculated ages is real rather than the consequence of secondary U mobility. These ages are consistent with repeated faulting over a several hundred thousand year time frame in the middle Pleistocene. If younger fracturing and cementation events are present (for instance, the event that formed the colluvial fault wedge dated at 17 ka), they were not sampled in this block of gouge.

MCBONES Quarry

Analyses of seven clast rinds from alluvial fan deposits exposed at the base of the MCBONES (Mid-Columbia Basin Old Natural Education Sciences) quarry yielded a range in ages from 145±20 ka to 268±7 ka, as well as initial $^{234}U/^{238}U$ AR values (1.075±0.005 to 1.233±0.033). One rind had an isotopic composition indicating substantial U losses that did not allow calculation of a viable $^{230}Th/U$ age (magenta point to the right of the infinite age line in figure 1). Ages from this deposit do not appear to have the same antiquity as those observed at Steptoe quarry, Yakima Bluffs, and South Bombing Range Road quarry. The fact that the oldest rind had an initial $^{234}U/^{238}U$ AR that follows the same 1.15 evolution curve as two other rinds in figure 1 suggests that the closest minimum age to the depositional event may be 268±7 ka. Certainly the two well-dated rinds with ages of 205±6 ka and 196±6 ka indicate that alluvium was present at about 200 ka. If the oldest age best reflects the age of alluvial deposition, the younger rinds suggest an extended period of pedogenesis within this horizon.

Conclusions

Ages of innermost rinds on a number of samples from five sites in eastern Washington are consistent with a range of minimum depositional ages from 17 ka for cataclysmic flood deposits to greater than 500 ka for alluvium at several sites. Isotope data suggest that the Steptoe quarry site represents the oldest alluvial deposit. Data indicate that alluvium at Yakima Bluff and South Bombing Range Road may be nearly as old; however, estimating more precise minimum-depositional ages from the present data set is not possible. Minimum depositional ages for alluvium at the MCBONES quarry site are most certainly younger; data suggest the deposit was present at about 200 ka, and possibly is as old as 268 ka. Data from Yakima Bluff and Steptoe quarry sites indicate that pedogenic cements continued to be added during the late Pleistocene. This is likely the case for other sites; however, sampling was not designed to address the history of pedogenesis or climate change at any of these sites. A cataclysmic flood deposit at Finley quarry yielded a well-constrained minimum age of 17.0±1.8 ka using a number of clast rinds from the same horizon. Ages ranging from ~200 to 700 ka obtained from several samples within fault gouge at Finley quarry suggest repeated fracturing and subsequent carbonate cementation during middle Pleistocene time.

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References

Delanghe, D., Bard, D., Hamelin, B., 2002, New TIMS constraints on the uranium-238 and uranium-234 in seawaters from the main ocean basins and Mediterranean Sea. Marine Chemistry, v. 80, p. 79-93.

Ludwig, K.R., 2003. User's Manual for Isoplot 3.00 a geochronological toolkit for Microsoft Excel. Berkeley Geochronology Center Special Publication, No. 4, 73 p.

Ludwig, K.R., and Paces, J.B., 2002, Uranium-series dating of pedogenic silica and carbonate, Crater Flat, Nevada: Geochimica et Cosmochimica Acta, v. 66, p. 487–506.

Ludwig, K.R., and Titterington, D.M. 1994, Calculation of 230Th/U isochrones, ages, and errors. Geochim. Cosmochim. Acta, 58, 5031-5042.

Ludwig, K.R., Wallace, A.R., and Simmons, K.R., 1985, The Schwartzwalder uranium deposit, II: Age of uranium mineralization and Pb-isotope constraints on genesis. Econ. Geol. 80, 1858-1871.

Watanabe, Yumiko, and Nakai, Shun'ichi, 2006, U-Th radioactive disequilibrium analyses for JCp-1, coral reference distributed by the Geological Survey of Japan. Geochemical Journal, vol. 40, p. 537-541.

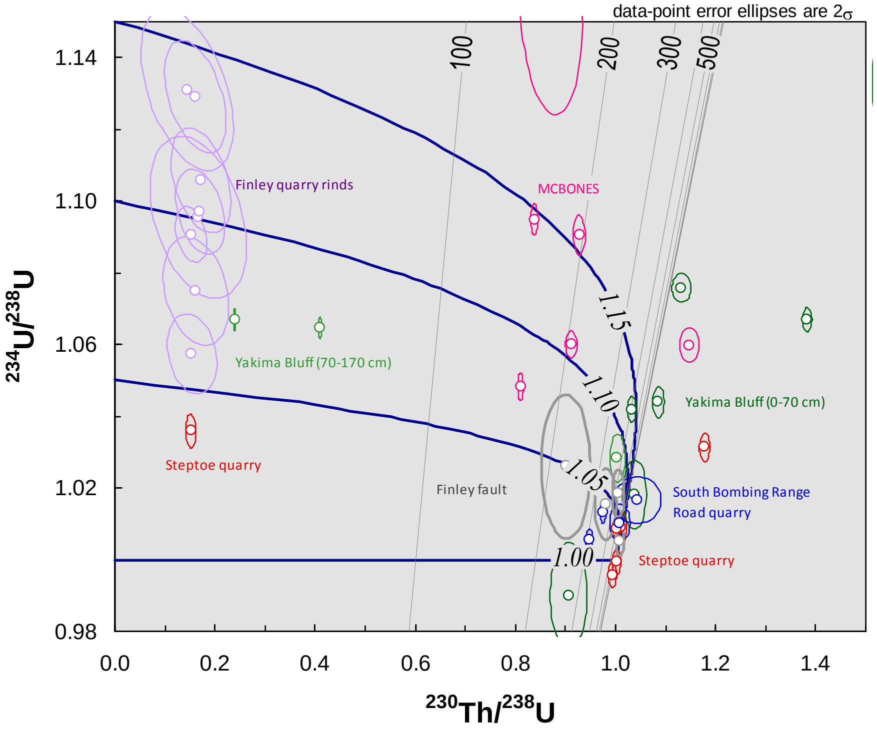


Figure 1. U-series isotope evolution plot showing U-Th isotopic compositions (circles) and 2-sigma uncertainties (error ellipses) for samples of calcite-silica rinds from the eastern Washington sites listed in table 1. Data are from table 2. Thick blue curves represent compositional evolution paths of $^{234}U/^{238}U$ and $^{230}Th/^{238}U$ activity ratios under closed conditions (no loss or gain of mass since the time of formation) for material with initial $^{234}U/^{238}U$ AR of 1.0, 1.05, 1.10, and 1.15. Straight sloping lines are isochrons given at 100-ka intervals. Isochrons older than about 500 ka become highly condensed, and define an infinite age line representing the upper dating limit based on ^{230}Th decay. Samples plotting to the right of the infinite age line indicate open-system behavior, which is typically manifested as recent U loss that leaves insoluble Th behind (including ^{230}Th generated in situ).

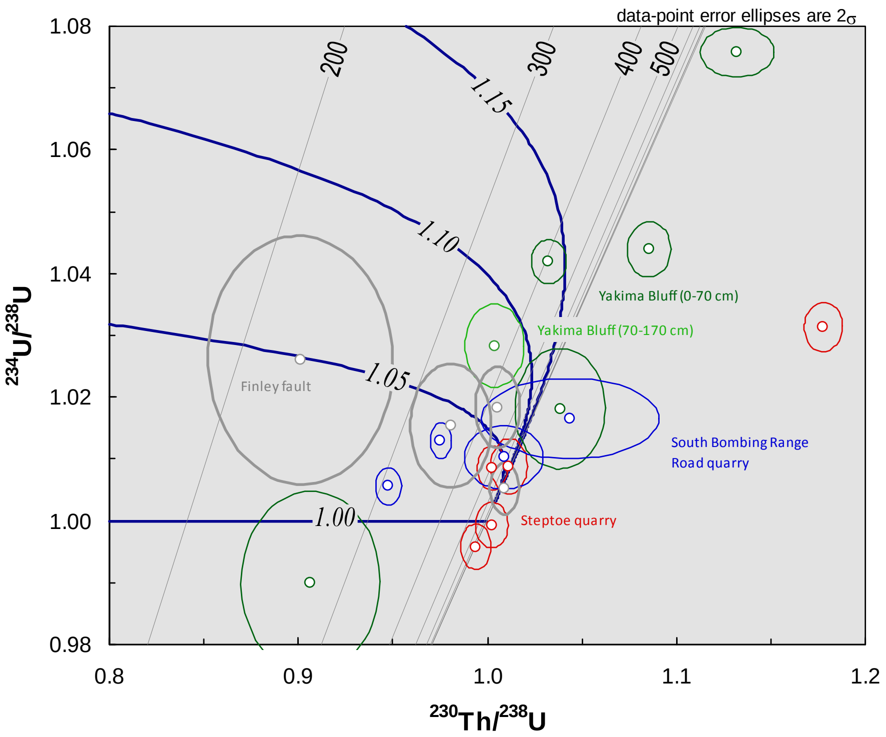


Figure 2. U-series isotope evolution plot showing the same data as in figure 1 , but at an expanded scale to better illustrate compositions of older materials.

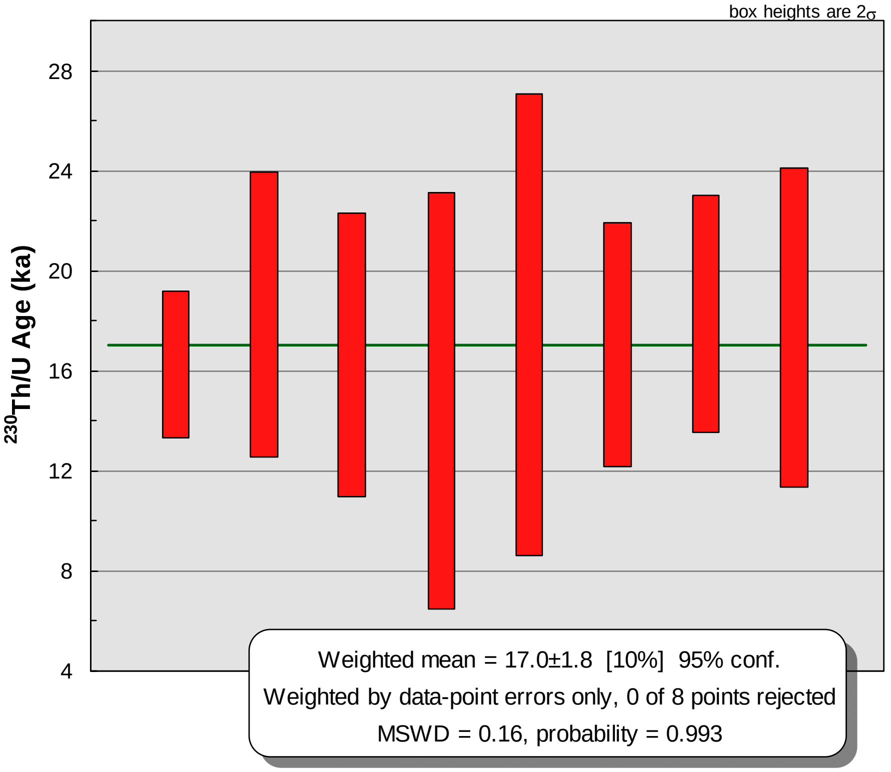


Figure 3. Graphical representation of ^{230}Th/U ages for 8 samples of rinds from clasts collected from cataclysmic flood deposits exposed at Finley quarry. Weighted mean is calculated using analytical uncertainties for individual dates as weighting factors. MSWD = Mean Square of Weighted Deviates and represents a measure of the ratio of the observed scatter of the points to the scatter expected from assigned errors (Ludwig, 2003).

Table 2: U-Th concentrations, isotope compositions, calculated ages, and initial ^{234}U/^{238}U activity ratios (AR) for soils in the vicinity of Richland, WA, determined at the USGS Denver Radiogenic Isotope Lab.

Sample Name	Sample weight, g	[U], in µg/g	[Th], in µg/g	Measured ^{230}Th/^{232}Th AR[a]	Detritus-corrected activity ratios					First-derivative solution to age equation					Monte Carlo solution, constrained to positive finite ages						
					^{230}Th/^{238}U AR[a,b]	±2s	^{234}U/^{238}U AR[a,b]	±2s	$\rho_{48\text{-}08}$	^{230}Th/U Age (ka)	±2s	Initial ^{234}U/^{238}U AR	±2s	$\rho_{age\text{-}go}$	^{230}Th/U Age (ka)	+2σ	-2σ	Initial ^{234}U/^{238}U AR	+2σ	-2σ	$\rho_{age\text{-}go}$
Steptoe quarry, upper soil: 46.23564° N, -119.24877°																					
13166SH01-A1	0.0112	16.70	0.864	58.8	1.002	0.007	0.999	0.003	0.00000	Near secular Equilibrium compositions					705	300	170	1.002	0.020	0.022	-0.150
13166SH01-A2	0.0422	20.09	1.497	40.5	0.994	0.007	0.996	0.003	0.00012	Near secular Equilibrium compositions					663	290	150	0.975	0.020	0.042	-0.768
13166SH01-B1	0.0446	8.10	0.720	34.6	1.012	0.008	1.009	0.004	0.00049	736	831	1.071	0.154	0.987	644	290	150	1.062	0.063	0.025	0.852
13166SH01-C1	0.0409	7.67	0.627	43.6	1.178	0.008	1.031	0.003	0.02414	Excess 230Th — substantial U loss					Not Calculable						
13166SH01-D1	0.0313	6.32	0.403	7.9	0.152	0.008	1.036	0.004	-0.06620	17.3	1.0	1.038	0.004	-0.108	17.2	1.0	1.0	1.038	0.004	0.004	-0.080
13166SH01-F1	0.0306	23.78	1.247	58.0	1.003	0.006	1.009	0.003	0.00006	509	86	1.036	0.011	0.219	520	130	72	1.037	0.014	0.011	0.470
Yakima Bluff (0-70 cm): 46.2652° N, -119.31339°																					
13166SH02B-A1	0.0444	6.31	0.244	108	1.383	0.008	1.067	0.003	0.03010	Excess 230Th — substantial U loss					Not Calculable						
13166SH02B-A2	0.0413	2.66	0.167	73.3	1.526	0.011	1.133	0.010	0.04249	Excess 230Th — substantial U loss					Not Calculable						
13166SH02B-B1	0.0380	9.20	2.458	11.8	1.038	0.019	1.018	0.008	0.00617	Excess 230Th — minor U loss					630	300	180	1.140	0.180	0.066	0.879
13166SH02B-C1	0.0583	5.65	2.266	6.9	0.906	0.030	0.990	0.012	0.00859	*272*	*45*	*0.978*	*0.028*	*-0.508*	*275*	*55*	*39*	*0.978*	*0.025*	*0.031*	*-0.524*
13166SH02-E1	0.0431	5.04	0.219	72.2	1.033	0.007	1.042	0.003	0.00199	408	34	1.133	0.012	0.716	409	38	31	1.134	0.014	0.012	0.754
13166SH02-F1	0.0553	3.48	0.062	193	1.132	0.016	1.076	0.003	0.00103	Excess 230Th — minor U loss					775	300	210	1.70	0.84	0.34	0.974
13166SH02-H1	0.0313	4.86	0.488	32.8	1.086	0.010	1.044	0.004	0.01918	Excess 230Th — substantial U loss					Not Calculable						
Yakima Bluff (70–170 cm): 46.2652° N, -119.31339°																					
13166SH02A-C1	0.0377	28.63	0.123	169	0.239	0.002	1.067	0.002	-0.00428	27.5	0.2	1.072	0.003	-0.344	Not calculated						
13166SH02A-F1	0.0320	24.22	0.159	190	0.410	0.002	1.065	0.002	-0.00518	52.5	0.4	1.075	0.003	-0.399	Not calculated						
13166SH02A-I1	0.0339	8.09	1.385	17.8	1.004	0.013	1.028	0.005	0.00082	370	44	1.081	0.014	0.178	Not calculated						
South Bombing Range Road quarry, upper soil: 46.27829° N, -119.34403																					
13168SH01-A1	0.0447	7.09	0.122	167	0.948	0.006	1.006	0.003	-0.00010	308	12	1.013	0.006	-0.428	308	12	11	1.013	0.006	0.006	-0.430
13168SH01-D1	0.0319	7.44	0.049	468	1.009	0.017	1.010	0.004	0.00000	562	325	1.050	0.044	0.899	542	270	130	1.050	0.061	0.023	0.803
13168SH01-G1	0.0410	9.75	1.702	18.1	1.044	0.038	1.017	0.005	0.00201	Excess 230Th — minor U loss					564	310	180	1.090	0.110	0.046	0.890
13168SH01-G2	0.0372	21.21	0.028	2304	0.975	0.004	1.013	0.002	0.00000	346	14	1.035	0.006	-0.397	347	14	12	1.035	0.006	0.006	-0.370

Sample Name	Sample weight, g	[U], in µg/g	[Th], in µg/g	Measured $^{230}\text{Th}/^{232}\text{Th}$ AR^{a}	Detritus-corrected activity ratios					First-derivative solution to age equation					Monte Carlo solution, constrained to positive finite ages						
					$^{230}\text{Th}/^{238}\text{U}$ AR^{a,b}	±2s	$^{234}\text{U}/^{238}\text{U}$ AR^{a,b}	±2s	$\rho_{48\text{-}08}$	$^{230}\text{Th/U}$ Age (ka)	±2s	Initial $^{234}\text{U}/^{238}\text{U}$ AR	±2s	$\rho_{age\text{-}go}$	$^{230}\text{Th/U}$ Age (ka)	+2σ	-2σ	Initial $^{234}\text{U}/^{238}\text{U}$ AR	+2σ	-2σ	$\rho_{age\text{-}go}$
Finley quarry, hanging wall colluvial wedge: 46.12017° N, -119.04328°																					
13167SH02A-A1	0.0313	8.23	1.558	3.1	0.152	0.025	1.091	0.006	-0.31758	16.3	3.0	1.095	0.006	-0.237				Not calculated			
13167SH02A-B1	0.0340	4.20	1.485	2.1	0.172	0.049	1.106	0.012	-0.38013	18.3	5.7	1.111	0.012	-0.284				Not calculated			
13167SH02A-C1	0.0302	6.49	2.342	2.0	0.161	0.050	1.129	0.013	-0.44598	16.7	5.7	1.135	0.012	-0.334				Not calculated			
13167SH02A-D1	0.0283	7.13	3.642	1.5	0.144	0.075	1.131	0.018	-0.46656	14.8	8.4	1.137	0.018	-0.346				Not calculated			
13167SH02A-E1	0.0260	4.25	2.290	1.6	0.166	0.079	1.095	0.018	-0.35851	17.9	9.3	1.100	0.019	-0.265				Not calculated			
13167SH02A-F1	0.0333	5.65	1.667	2.2	0.154	0.041	1.057	0.009	-0.22161	17.1	4.9	1.060	0.009	-0.169				Not calculated			
13167SH02A-G1	0.0202	5.80	1.713	2.4	0.170	0.040	1.097	0.010	-0.35137	18.3	4.7	1.102	0.010	-0.262				Not calculated			
13167SH02A-G2	0.0242	4.58	1.747	1.9	0.162	0.053	1.075	0.012	-0.28252	17.8	6.4	1.079	0.013	-0.211				Not calculated			
									Weighted Average	***17.0***	***1.8***	***MSWD = 0.16***									
Finley quarry, fault gouge: 46.12017° N, -119.04328°																					
13167SH02B-1	0.0296	3.24	0.036	275	1.009	0.006	1.005	0.003	0.00000	Near secular Equilibrium compositions					700	270	160	1.047	0.053	0.024	0.753
13167SH02B-2	0.0317	2.42	0.573	12.6	0.981	0.017	1.015	0.008	-0.00221	352	54	1.042	0.020	-0.261	356	67	48	1.042	0.019	0.020	-0.240
13167SH02B-3	0.0323	2.59	0.224	35.2	1.005	0.009	1.018	0.005	0.00026	429	63	1.062	0.014	0.004	434	82	54	1.063	0.014	0.014	0.140
13167SH02B-4	0.0320	2.72	1.410	5.4	0.901	0.040	1.026	0.016	-0.02334	224	36	1.049	0.029	-0.284	226	41	32	1.049	0.028	0.030	0.330
MCBONES quarry on Clodfelter Road, lower unit: 46.15964° N, -119.26653°																					
13167SH03-A1	0.0475	4.66	0.064	185	0.838	0.006	1.095	0.004	-0.00233	152	3	1.146	0.005	-0.357				Not calculated			
13167SH03-B1	0.0447	6.68	0.840	22.5	0.928	0.010	1.091	0.005	-0.04149	196	6	1.158	0.007	-0.127				Not calculated			
13167SH03-C1	0.0316	3.09	1.952	4.3	0.871	0.051	1.155	0.025	-0.14889	145	20	1.233	0.033	-0.182				Not calculated			
13167SH03-D1	0.0376	8.15	0.031	807	0.997	0.005	1.070	0.003	0.00000	268	7	1.148	0.005	-0.125				Not calculated			
13167SH03-E1	0.0289	5.21	0.243	74.5	1.148	0.016	1.060	0.004	0.00527	Excess 230Th — substantial U loss								Not calculated			
13167SH03-F1	0.0322	5.74	0.085	187	0.912	0.009	1.060	0.003	-0.00066	205	6	1.107	0.005	0.016				Not calculated			
13167SH03-H1	0.0259	9.95	0.092	267	0.811	0.004	1.048	0.003	-0.00091	158	2	1.075	0.005	-0.478				Not calculated			

[a] Measured isotope ratios corrected for mass fractionation, spike contributions, procedural blank and normalized relative to a standard value for NIST SRM 4321b $^{234}\text{U}/^{238}\text{U}=0.0000529$.

[b] Assumed Th-bearing detrital component has an atomic Th/U of 4 with the following activity ratios and 2s errors: $^{232}\text{Th}/^{238}\text{U}=1.276\pm0.64$; $^{234}\text{U}/^{238}\text{U}=1.0\pm0.1$; and $^{230}\text{Th}/^{238}\text{U}=1.0\pm0.25$.

[c] ^{230}Th/U age, initial $^{234}\text{U}/^{238}\text{U}$ ratio and associated errors calculated using detritus-corrected activity ratios

MSWD = Mean Square of Weighted Deviates

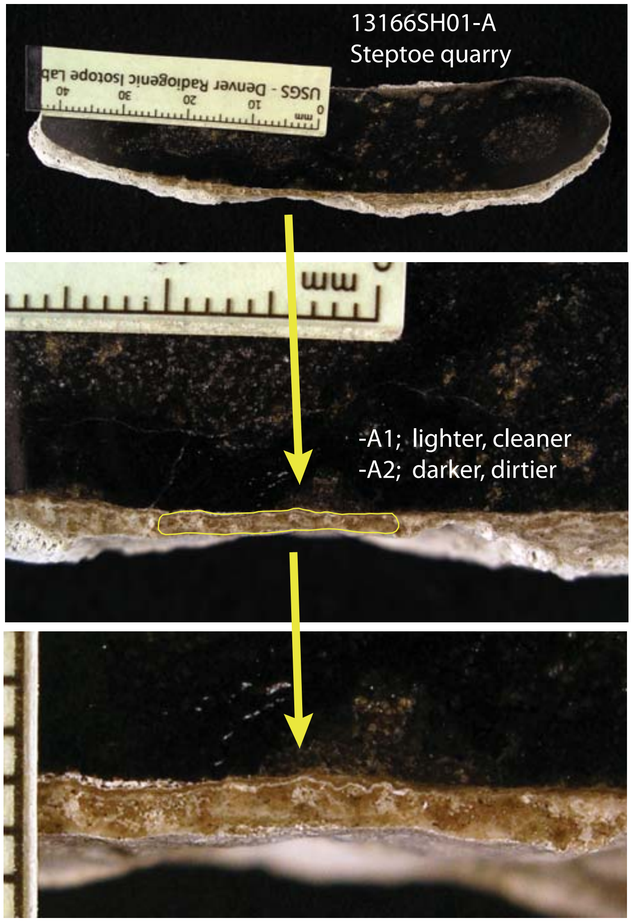
^{230}Th/U ages Supporting Hanford Site-Wide Probabilistic Seismic Hazard Analysis

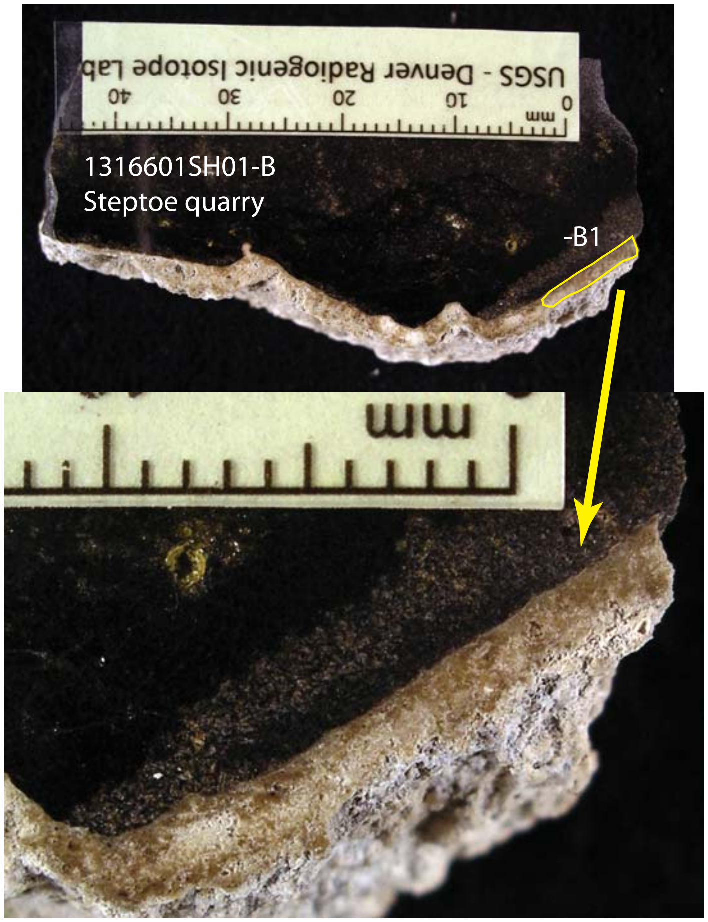
James B. Paces (303-236-0533; jbpaces@usgs.gov)

March 13, 2014

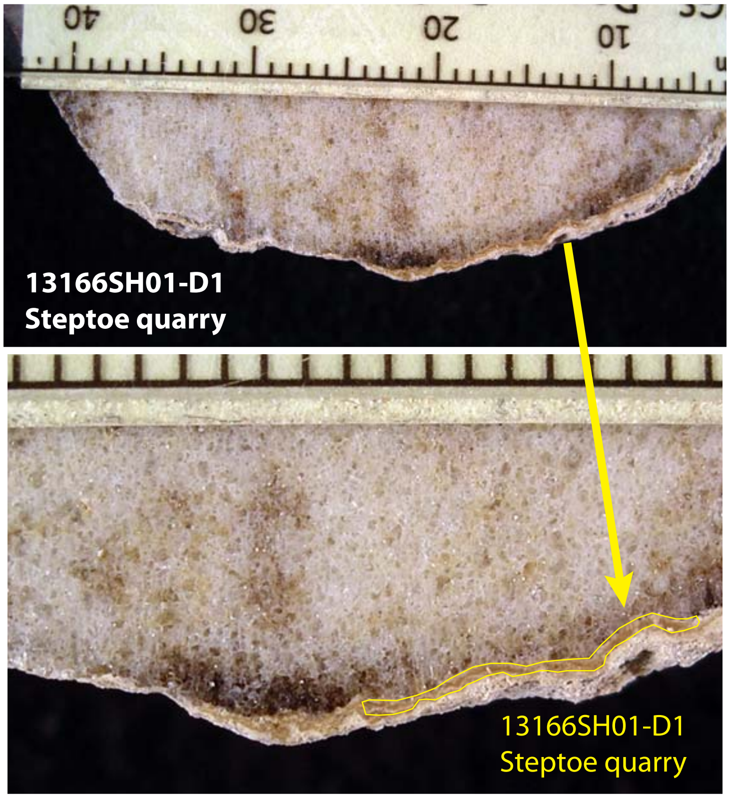
Appendix

Photographs of inner rinds on alluvial clasts and fault gouge sampled and analyzed for U-Th isotope analysis. Site names and locations are given Table 1 of the main report. Individual sample names and results, including ^{230}Th/U ages, are given in Table 2 of the main report.


13166SH01-A
Steptoe quarry
USGS - Denver Radiogenic Isotope Lab
-A1; lighter, cleaner
-A2; darker, dirtier

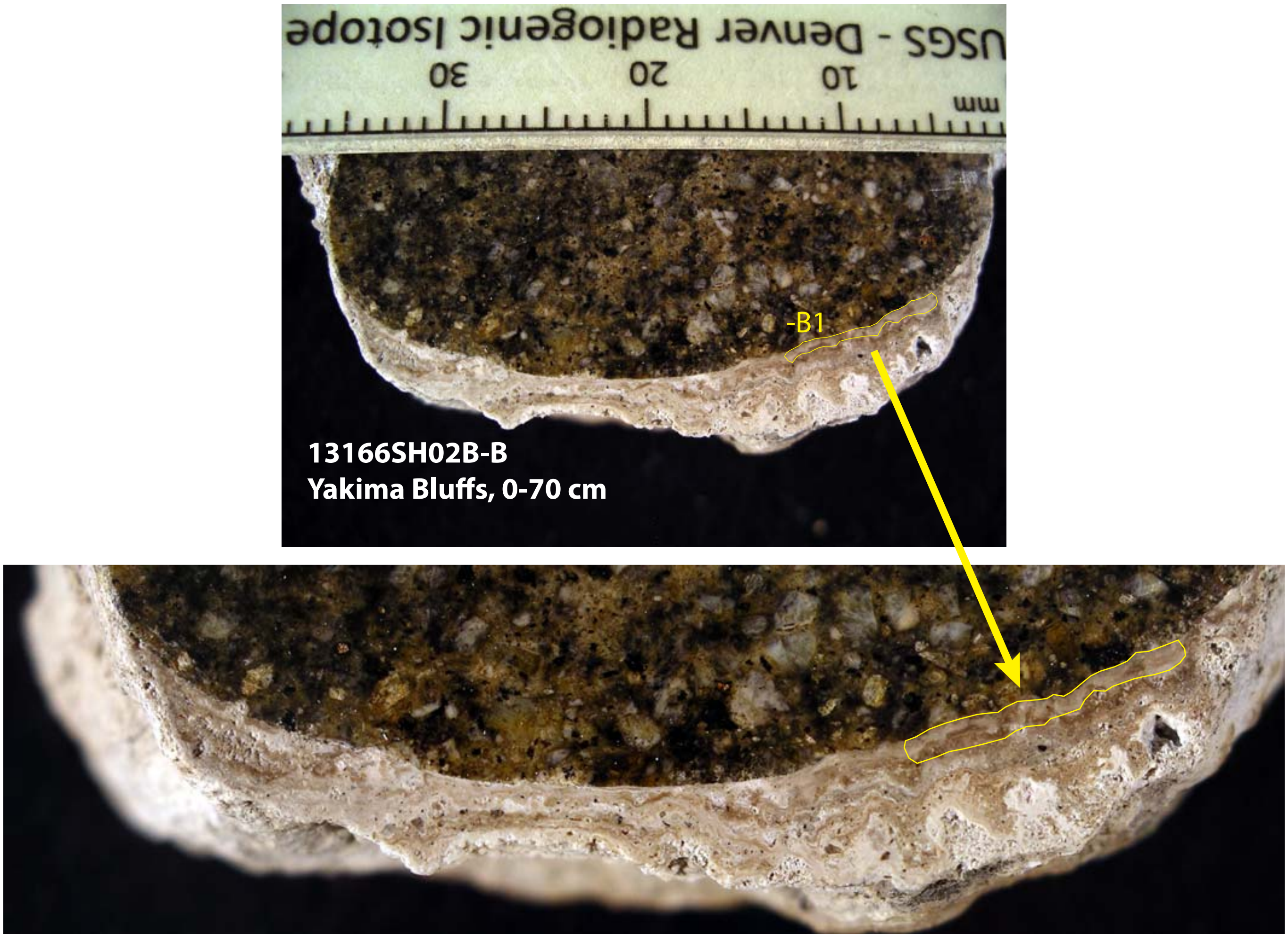

USGS - Denver Radiogenic Isotope Lab
1316601SH01-B
Steptoe quarry
-B1


WA soils (PNNL-AMEC)
USGS - Denver Radiogenic Is
13166SH01-C1
Steptoe quarry


40
30
20
10
13166SH01-D1
Steptoe quarry
13166SH01-D1
Steptoe quarry


13166SH01-F
Steptoe. quarry
6/15/2013
WA soils (PNNL-AMEC)
USGS - Denver Radiogenic Isotope Lab
0
mm
10
20
30
40
13166SH01-F1
Steptoe quarry


13166SH02B-A
Yakima Bluffs, 0-70 cm
-A1
-A2


USGS - Denver Radiogenic Isotope
mm
10
20
30
-B1
13166SH02B-B
Yakima Bluffs, 0-70 cm

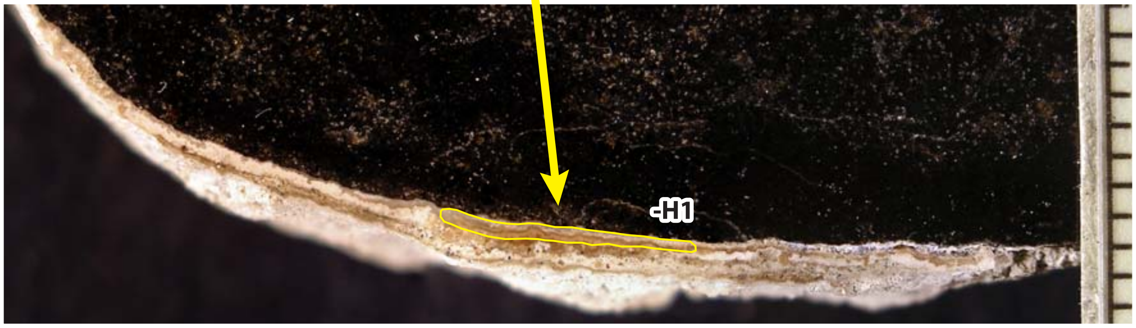

- Denver Radiogenic Isotope Lab
10
20
30
40
13166SH02B-C
Yakima Bluffs, 0-70 cm
-C1


- Denver Radiogenic Isotope L
10
20
30
40
13166SH02B-E
Yakima Bluff 0–70 cm
6/15/2013
WA soils (PNNL-AMEC)
13166SH02B-E
Yakima Bluffs, 0-70 cm
-E1


13166SH02B-F
Yakima Bluff 0–70 cm
6/15/2013
WA soils (PNNL-AMEC)
0 mm 10 20 30
USGS - Denver Radiogenic Isot


same horizon, other side of slab
-F1
13166SH02B-F
Yakima Bluffs, 0-70 cm

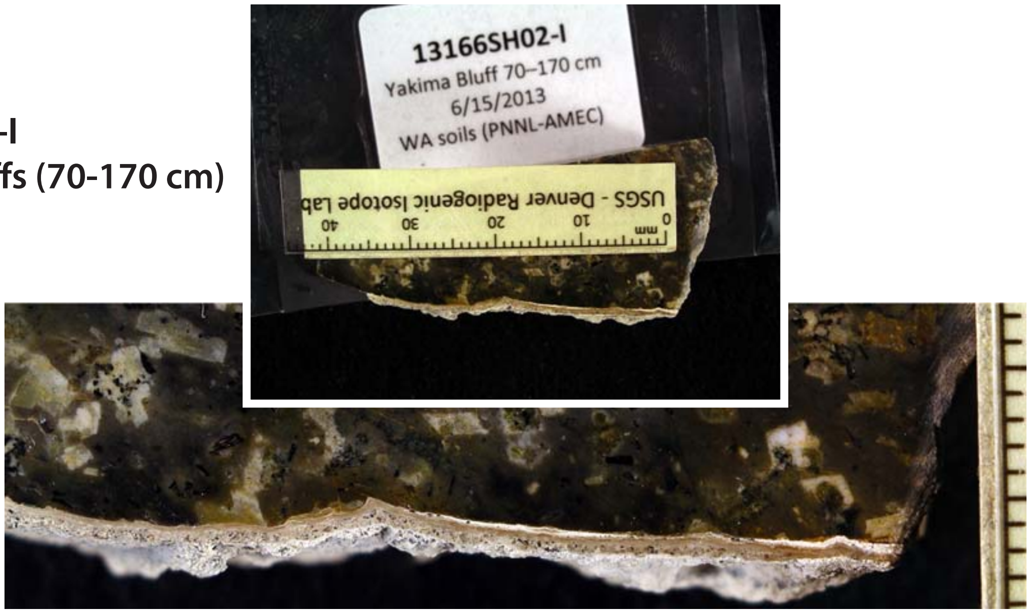

13166SH02B-H
Yakima Bluff 0–70 cm
6/15/2013
WA soils (PNNL-AMEC)
0 mm 10
USGS - Denve
13166SH02B-H
Yakima Bluffs, 0-70 cm

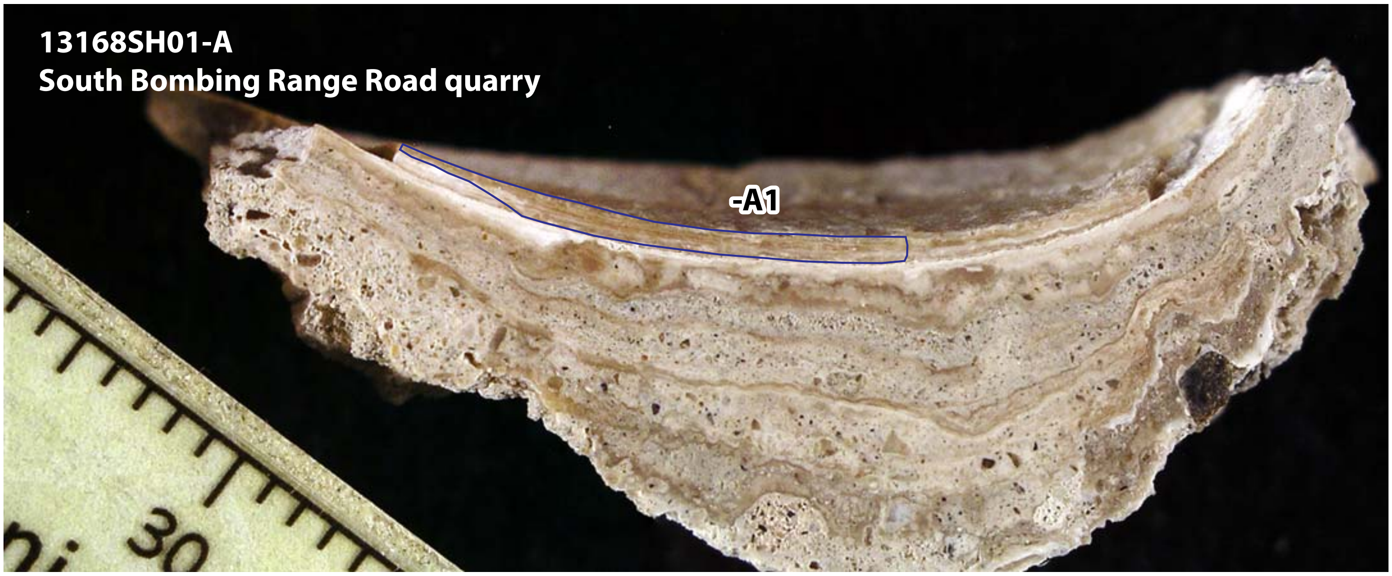

-H1

13166SH02-C
Yakima Bluffs (70-170 cm)

13166SH02-F
Yakima Bluffs (70-170 cm)

13166SH02-I
Yakima Bluffs (70-170 cm)

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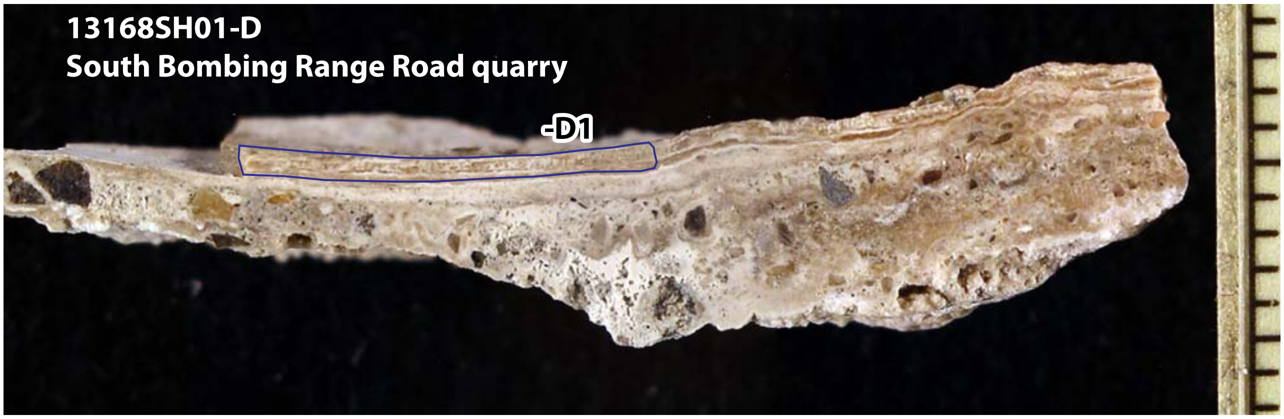
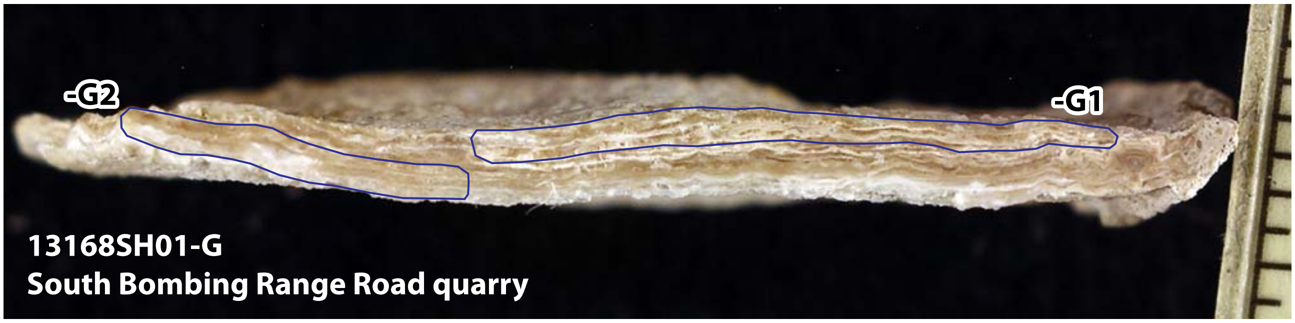
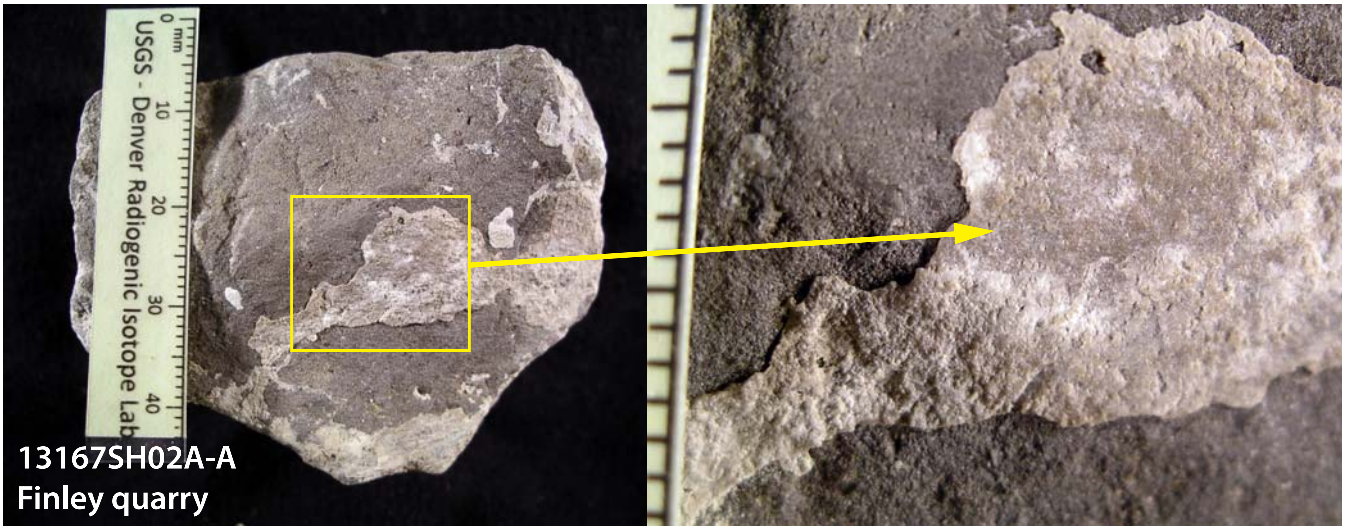
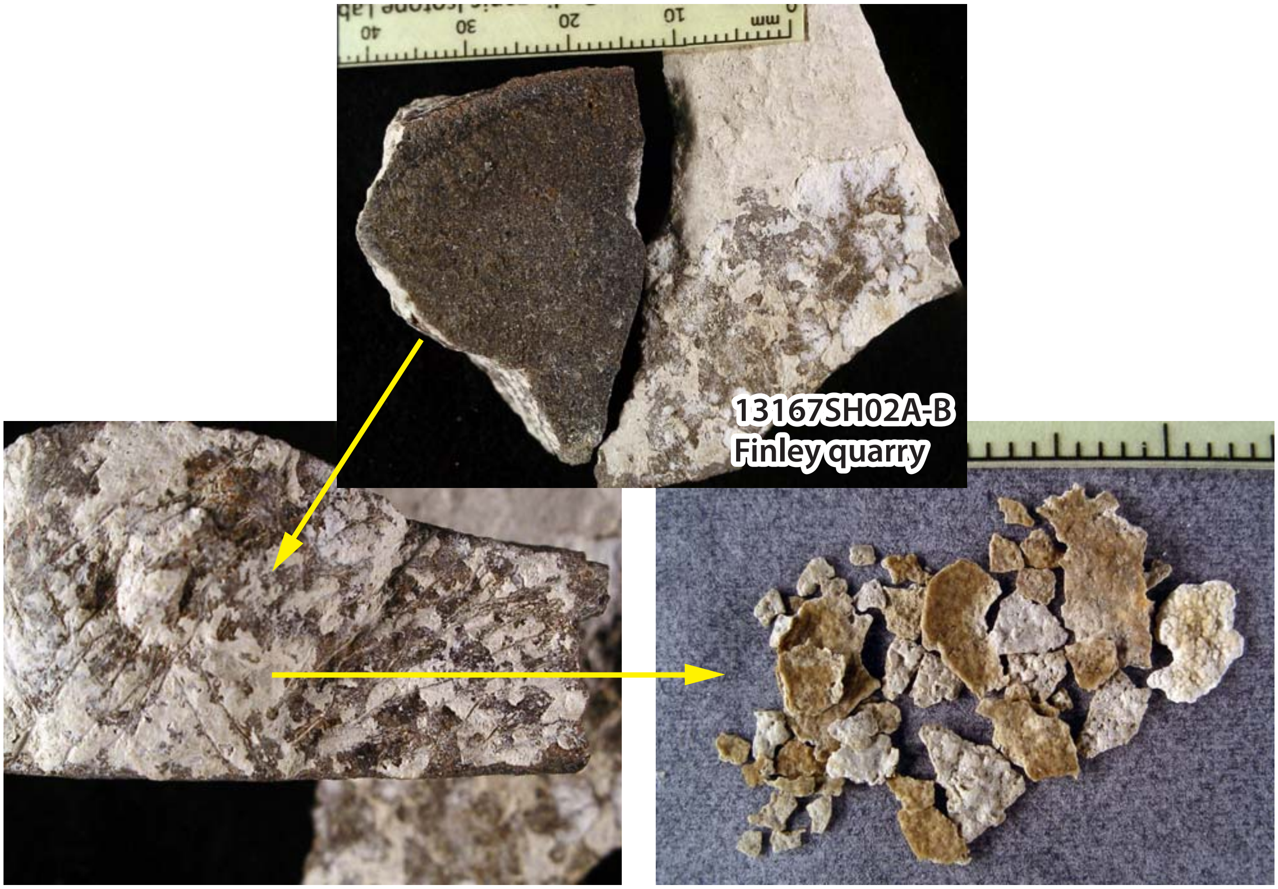
South Bombing Range Road quarry


13168SH01-D
South Bombing Range Road quarry


13168SH01-G
South Bombing Range Road quarry


0 mm 10 20 30 40
USGS - Denver Radiogenic Isotope Lab
13167SH02A-A
Finley quarry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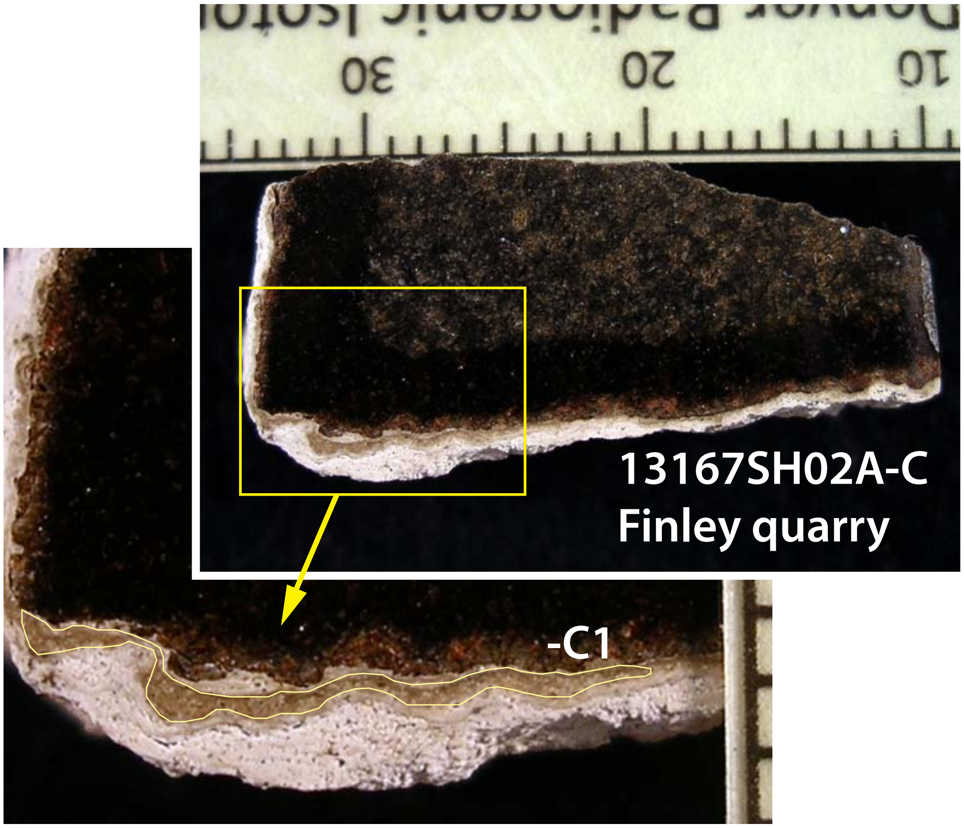
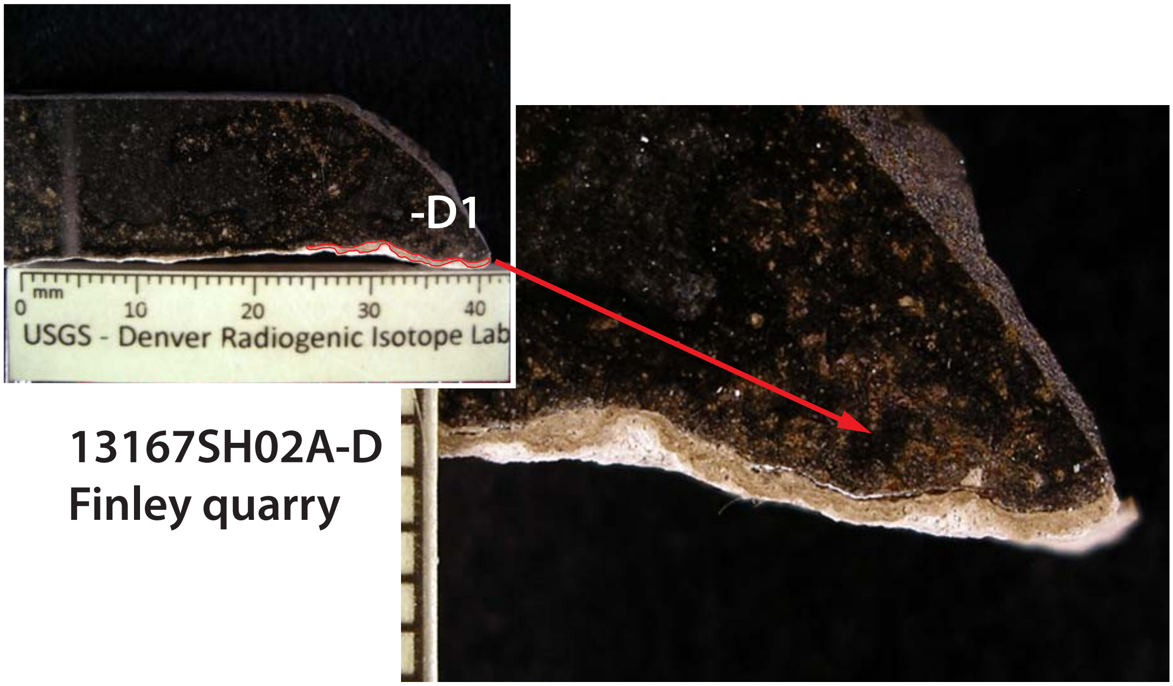
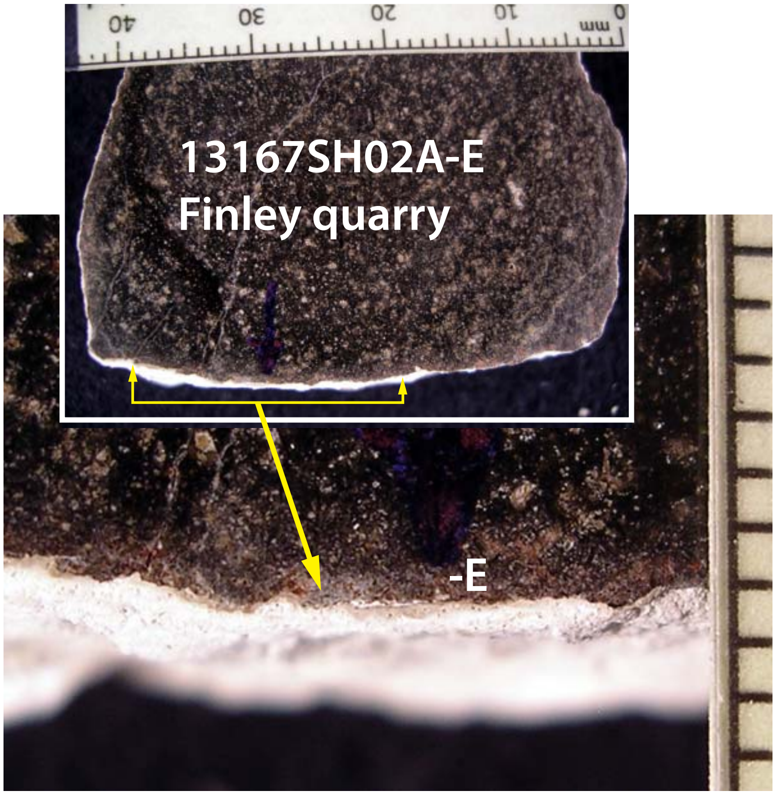
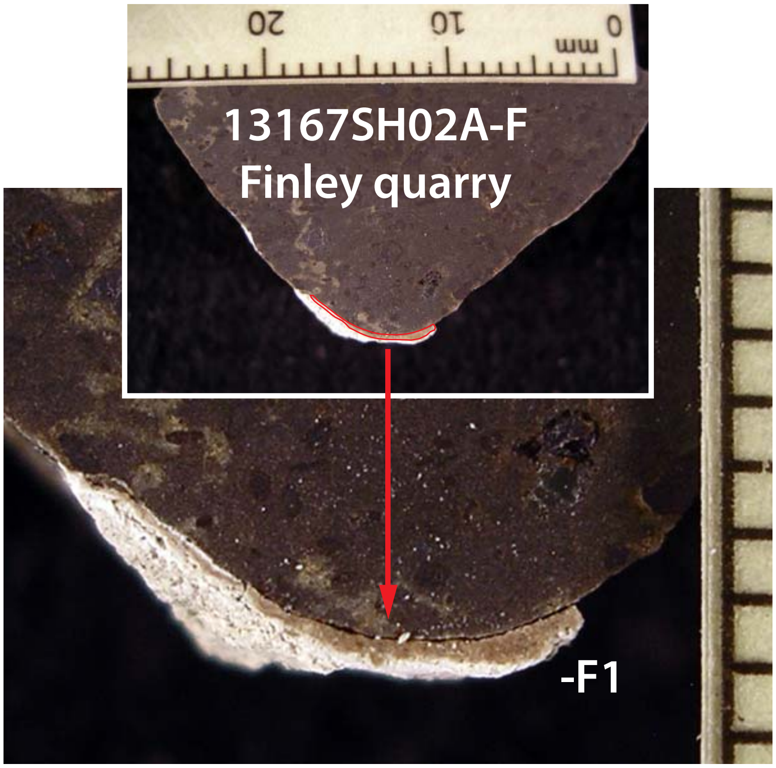
13167SH02A-B
Finley quarry

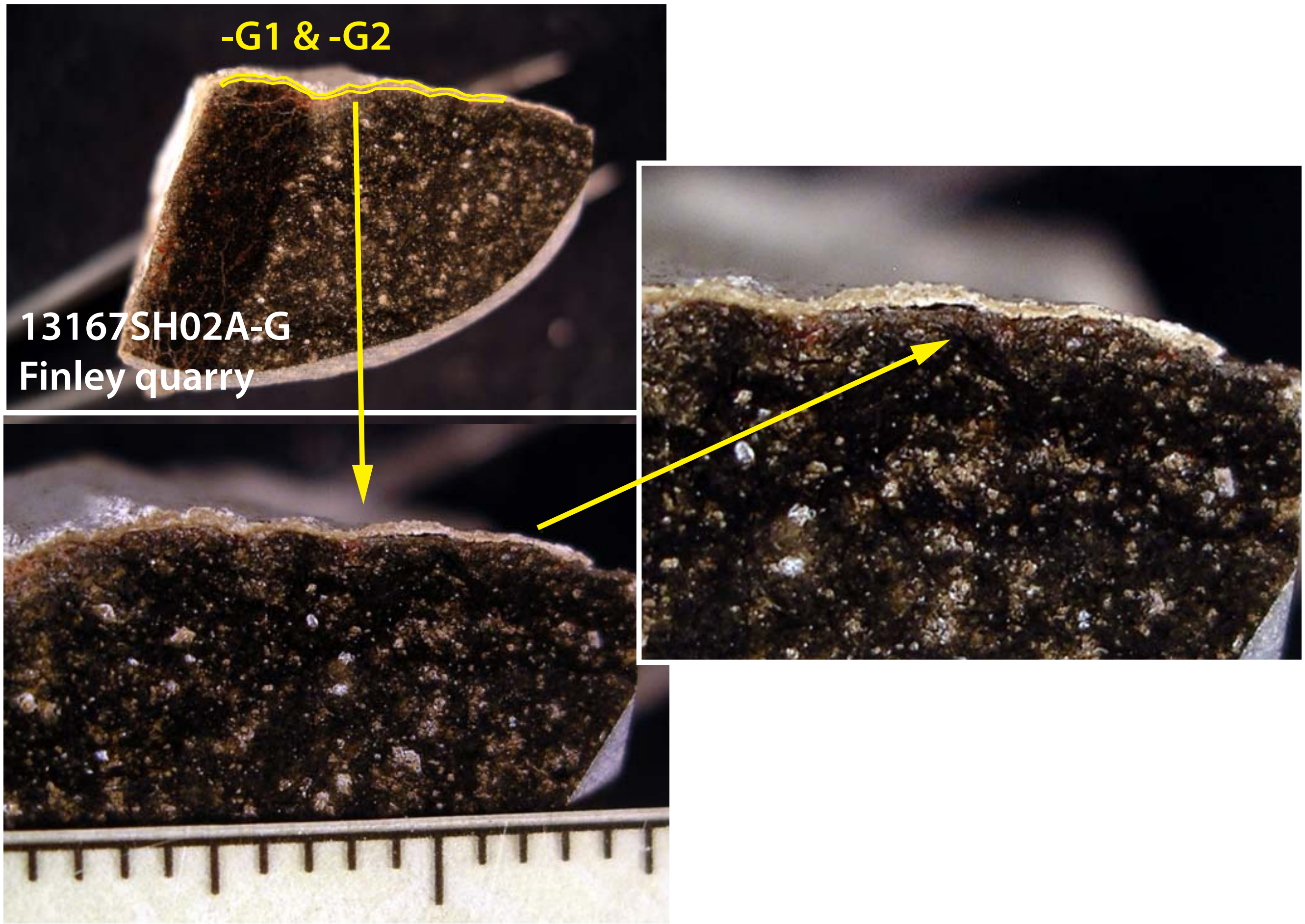


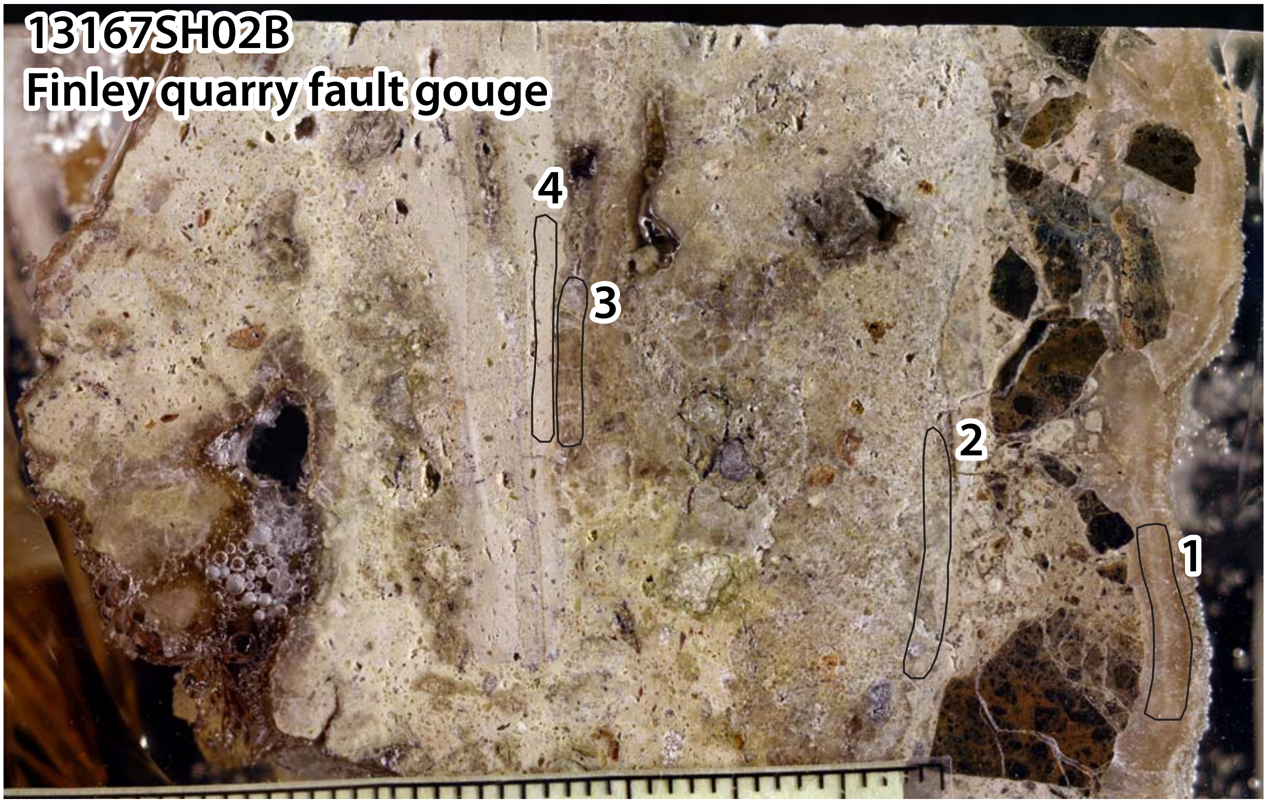


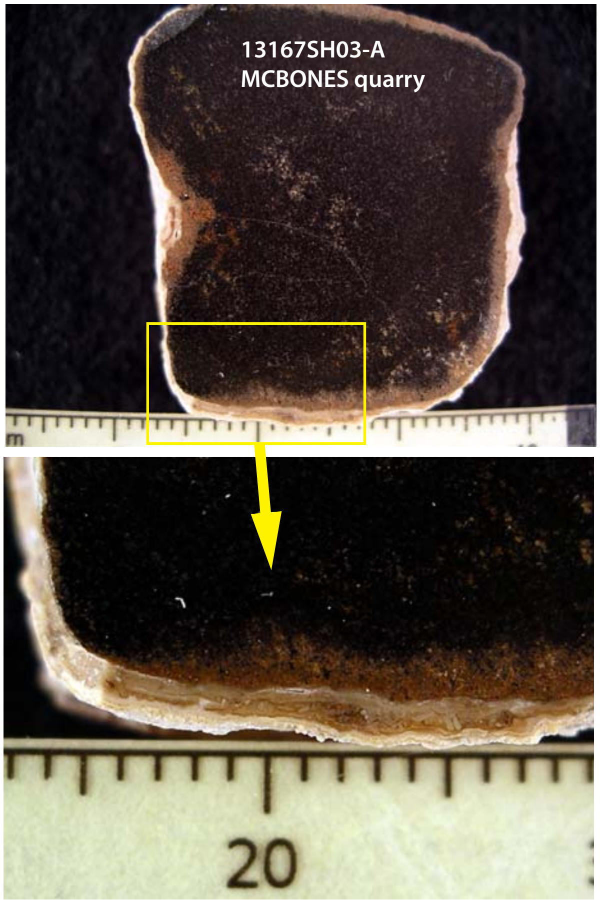
13167SH02A-D
Finley quarry

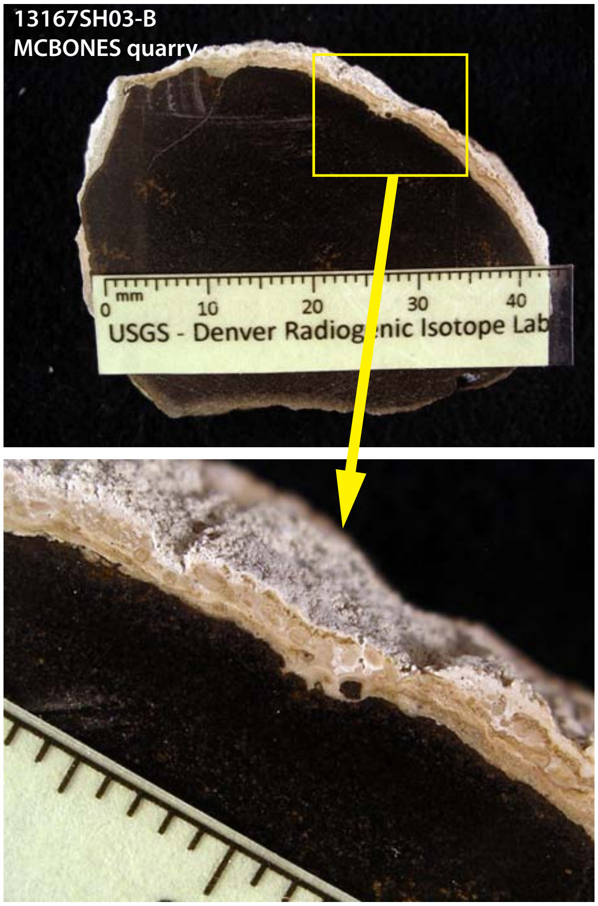

13167SH02A-E
Finley quarry
-E
0 mm
10
20
30
40

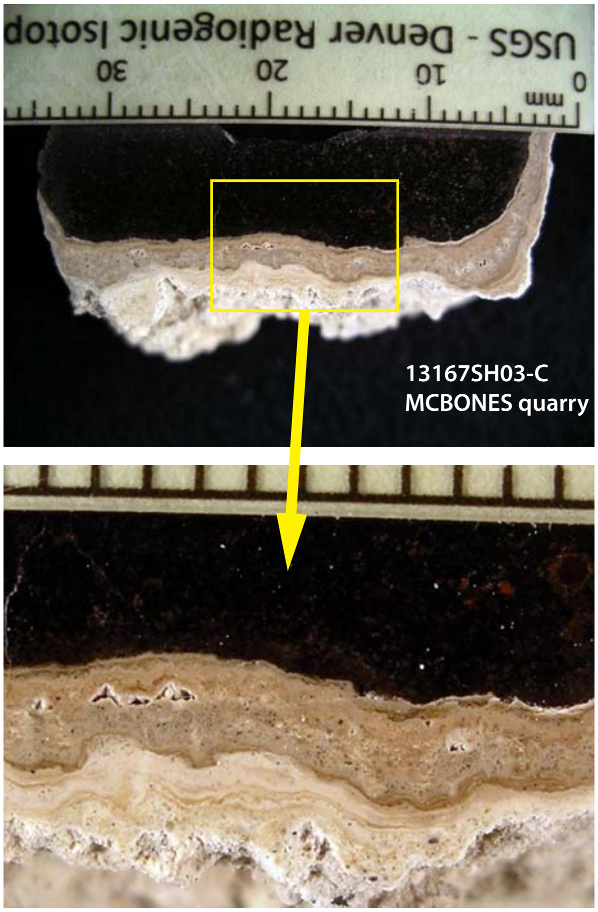

13167SH02A-F
Finley quarry
-F1
0 mm
10
20

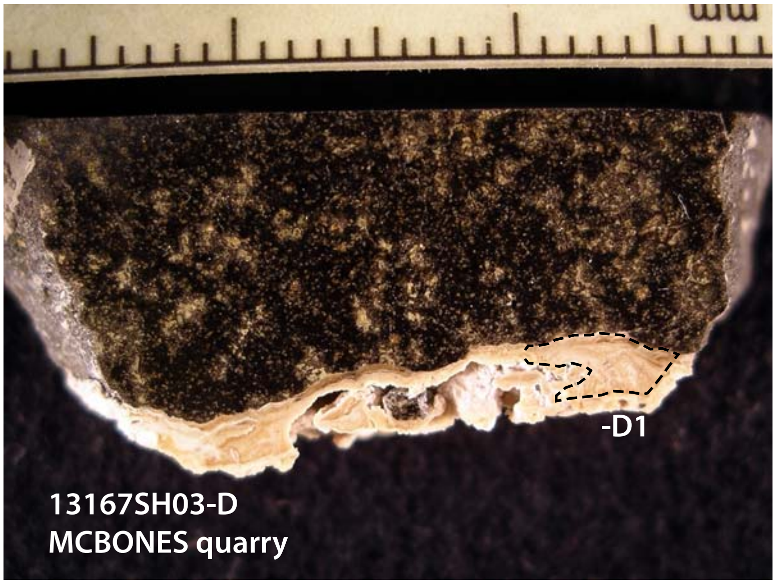

-G1 & -G2
13167SH02A-G
Finley quarry


13167SH02B
Finley quarry fault gouge
4
3
2
1


13167SH03-A
MCBONES quarry
20

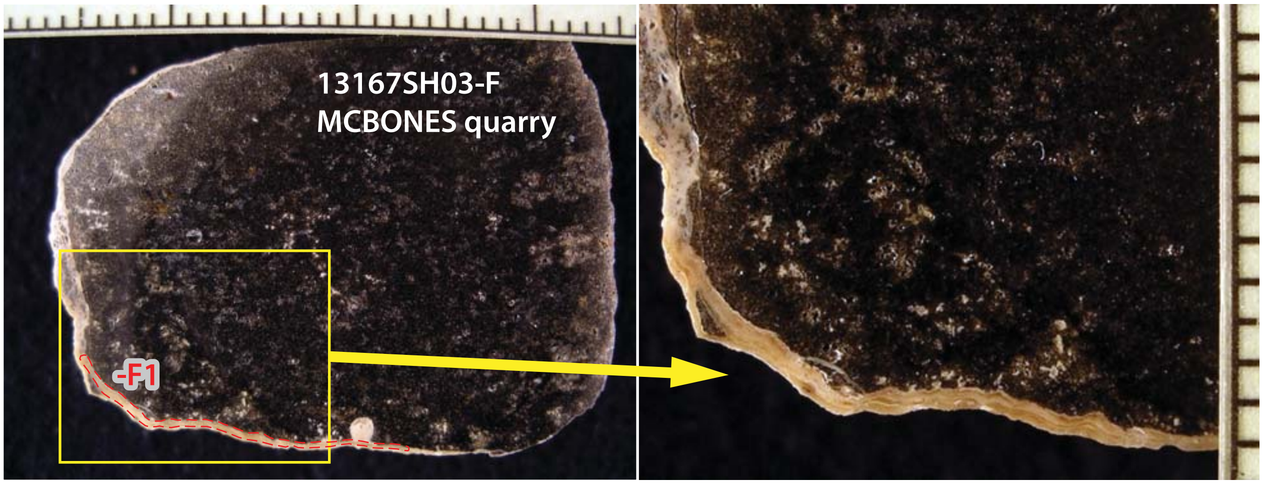

13167SH03-B
MCBONES quarry
0
mm
10
20
30
40
USGS - Denver Radiog
nic Isotope Lab


USGS - Denver Radiogenic Isotop
0
mm
10
20
30
13167SH03-C
MCBONES quarry


mm
-D1
13167SH03-D
MCBONES quarry


-E1
13167SH03-E
MCBONES quarry


13167SH03-H
MCBONES quarry
-H1


13167SH03-F
MCBONES quarry
-F1