For submission to *California Geology*

February 13, 2002

Revisiting the age of the Blackhawk: Landslide dating using ^{10}Be and ^{26}Al

*Kyle K. Nichols
Paul R. Bierman
School of Natural Resources and Department of Geology
University of Vermont
Burlington, VT 05405

**Marc Caffee
Robert Finkel
CAMS
Lawrence Livermore National Laboratory
Livermore, CA 94550

*email: kknichol@zoo.uvm.edu
802 656 3398 (voice)
802 655 0045 (fax)

**now at: PRIME Lab, Purdue University, West Lafayette, IN, 47907

Abstract

Landslides have occurred in California throughout time. Some of these landslides, such as the Blackhawk landslide in the Mojave Desert, are prehistoric and are difficult to date. Previous attempts to date the Blackhawk landslide used radiocarbon dating of freshwater gastropod and pleceopod shells picked from calcareous mud beds. Such a carbon rich environment could deplete the shells of ^{14}C and produce an old age, (Stout, 1975; 17,400 ± 550 y.b.p.). Alternatively, the pond must have formed after the landslide occurred, thus the date would be younger than the landslide. A second attempt to date the Blackhawk landslide used cosmogenic ^{36}Cl to date the debris directly, but the results ranged from 10,000 to 55,000 y.b.p. (Stone and Fifield, 1995). The wide range of ages is due to not knowing the exposure and erosion histories of the samples. We use cosmogenic ^{10}Be and ^{26}Al to re-date the landslide. We chose our samples from levee crests that have simple exposure histories. Using exposure age and geomorphic modeling we date the Blackhawk landslide at approximately 30,000 to 35,000 y.b.p.

Introduction

Most Californians associate landslides with homes or sections of roads sliding down a hillside after prolonged or heavy rains. The more geologically aware Californians may also think of landslides induced by earthquakes that cause similar damage. There is, however, an older suite of prehistoric landslides that go mostly unnoticed by the general public, but are of interest to geologists. Many aspects of these prehistoric landslides such as initiation mechanisms, slide mechanics, and timing of failures are largely unknown.

The Blackhawk landslide, located in the western Mojave Desert, is a well-known example of a large prehistoric landslide (~ 2.8 km^3; Figure 1). The Blackhawk slide has received considerable attention and research primarily because its large volume and its long run-out distance (~ 9 km) compared to its vertical drop (~1.2 km). Some researchers have proposed mechanisms by which the Blackhawk debris could run out almost eight times the vertical drop; such as the debris riding on a cushion of air (Shreve, 1968) or various forms of acoustic fluidization, which suggests that large volume landslides can normally have horizontal runout distances up to ten times the vertical drop (e.g. Hsu, 1975, Campbell et al., 1995, Dade and Huppert, 1998). There is still debate on the behavior of large volume landslides.

The debated landslide mechanics, the well preserved debris zone, and the easy access by automobile make the Blackhawk Landslide a popular destination for field trips and field camps in the Mojave Desert. In addition to the landslide mechanics, geomorphologists are interested in determining the age of the debris zone so they can understand better the processes and rates that modify the debris zone.

Two previous studies attempted to date the Blackhawk Landslide. Stout (1975; 1977) radiocarbon dated freshwater gastropod and pleceopod shells to determine a limiting age of 17,400 ± 550 y.b.p. However, the dated shells were picked from calcareous mudstone beds. It is possible that the gastropods and plecepods incorporated "dead" carbon (depleted in ^{14}C) from calcareous rich rock and mud and thus, inflate the age. Alternatively, because the pond has to be younger than the slide debris, this technique only supplies an "older than" age for the Blackhawk slide. Stone and Fifield (1995) used cosmogenic ^{36}Cl to date the debris directly; they could only determine a range from 10,000 to 55,000 y.b.p. The wide range of landslide ages determined by Stone and Fifield (1995) results from not knowing the exposure and erosion history of the sampled debris. Given the uncertainties of these two studies, the age of the Blackhawk landslide is still poorly constrained. We use the cosmogenic isotopes ^{10}Be and ^{26}Al and geomorphic relationships to constrain better the age of the landslide.

Setting and Geology

The Blackhawk landslide (9 km long by an average of 2 km wide) is located on the northern flank of the tectonically active San Bernardino Mountains (Figure 1). There is a large climate variation from the landslide toe the to the summit of Blackhawk Mountain. The toe of the landslide (900 m) is in the Mojave Desert; the dominant vegetation is creosote. The proximal end of the debris (1200 m) is wetter as suggested by Joshua trees, while the top of Blackhawk mountain (6700 ft) has pinyon pines and the wettest climate.

Thrust faulting associated with the uplift of the San Bernardino Mountains is prevalent at Blackhawk Mountain. The top of Blackhawk Mountain is composed of Furnace Limestone thrust over gneiss, quartz monzonite, and sandstone (Shreve, 1968). Some researchers associate tectonic shaking as the initiation of the landslide (ref). Another initiation hypothesis is undercutting of more erodable sandstone from beneath the more resistant marble (Furnace Limestone) at the top of Blackhawk Mountain (Shreve, 1968).

The debris zone is dominated by marble breccia from the Furnace Limestone Formation. The center of the debris zone is dominated by small ridges (2 to 3 m high) perpendicular to the slide axis (Figure 2). These small ridges have imbricate thrust structure as a result of leading debris coming to rest and subsequent debris riding up the back of the stopped debris (Shreve, 1968). These small ridges form internal drainages, such as the one where Stout collected his samples for radiocarbon analysis (Stout, 1977).

The perimeter of the debris is defined by well-established levee (Figure 2). The levee crest is topographically higher than the debris it surrounds. The levee crests are rounded; some levees have well defined soil catenas suggesting at least some levee crest lowering (Figures 3A and 3B).

Cosmogenic nuclides

Geomorphologists are increasingly using cosmogenic nuclides to quantify ages and process rates of Earth's surface. Cosmogenic nuclides are produced when cosmic rays bombard Earth's surface and interact with quartz (^{10}Be and ^{26}Al) or with other minerals (^{3}He, ^{36}Cl, ^{21}Ne). These rare isotopes are produced at slow rates (10^0 to 10^2 atoms per year) depending on the altitude and latitude of the sampling location and on the strength of Earth's magnetic field (Lal, 1991). The inventories of these isotopes increase in a predictable manner (as a function of time) if the rock has a simple exposure history. By measuring the nuclide inventory and by correcting for the sample's altitude and latitude, the magnetic field strength, and the sample's depth or thickness we can model how long the samples has resided at or near Earth's surface.

Application of these rare isotopes to geologic problems was first suggested almost a half-century ago (Davis and Shaffer, 1955). However, at that time, the technology for counting small inventories of atoms was not feasible. Approximately 15 years ago, advances in accelerator mass spectrometry made counting small numbers of atoms feasible (ref). Today, geomorphologists are using cosmogenic nuclides to quantify the stability of Earth's surface by quantifing rock exposure ages (e.g. ref), burial ages (e.g. Granger, 2001), and terrace ages, (Anderson et al., 1996; Perg 2001). Geomorphologists are also quantifying the tempo of Earth surface processes by determining rock erosion rates (Lal ??), drainage basin erosion rates (e.g. Bierman and Steig; 1996; Granger et al., 1996; Clapp et al., 2000), soil production rates (e.g. Clapp et al., 2000; Heimsath et al., 1999), and sediment transport rates (Nichols et al., in press).

In order to use ^{10}Be and ^{26}Al to date rocks at Earth's surface, the sample has to yield about 40 g of pure quartz. Since quartz is a common mineral, one can use ^{10}Be and ^{26}Al to date many of Earth's surfaces. Although the Blackhawk landslide debris is dominantly limestone, there are clusters of quartz-rich sandstone and gneissic boulders scattered in the debris zone (Shreve, 1968). Thus, the Blackhawk landslide is a good candidate for exposure age dating using ^{10}Be and ^{26}Al.

Sampling and Field Methods

We used Shreve's (1968) geologic map to locate concentrations of gneissic, quartz monzonite, and sandstone boulders. We selected sites near the tops of levees because geomorphic interpretation suggests the simplest exposure history. Boulders resting on top of or near, levee crests were either initially exposed due to landsliding or they were initially buried and then exhumed after levee erosion. Since levee crests are local topographic highs, it is unlikely that the boulders would have experienced burial after they were exposed on the levee.

Several quartz-rich gniessic boulders are located on the left lateral levee (Figure 4). Here, we collected samples from three quartz-rich gniessic boulders (~ 1 m high) that were only about 1 meter below the elevation of the levee crest (Figure 5A). At the toe of the landslide, we collected a sample from a sandstone boulder located near the top of the levee crest (Figure 5B). We collected another sample from a 1.5 m high quartz-rich gniessic boulder located on the levee side slope facing the debris zone (Figure 5C). The side-slope lacks established drainages and evidence of deposition; thus, the slope is likely a surface of transport. There is however, the possibility that the boulder could roll down slope.

Sampling the boulders was simple. We used a hammer and chisel to collect the top most one to two centimeters of rock. All boulders exhibited varnish, suggesting that they were not eroding quickly. The gneissic boulders were weathering slightly by spallation of one-centimeter thick sheets. The sandstone boulder was competent with no evidence of erosion.

To estimate the maximum amount of ridge crest erosion and side slope deposition (soil catenas), we surveyed five topographic profiles across the left lateral levee. Three of the profiles cross the levee crest boulders, the other two profiles cross at and near the side slope boulder (Figure 6).

Laboratory analyses

Samples were prepared for AMS analysis at the University of Vermont Cosmogenic Isotope Extraction Laboratory (http://geology.uvm.edu/morphwww/cosmo/lab/cosmolab.html). We crushed, ground, and sieved rock samples to obtain the 250 to 850 micron fractions. Each sample was etched in a heated ultrasonic bath of 6N HCl for 7 hours, and etched in heated ultrasonic baths of 1% HF and HNO_3 up to four times to remove atmospheric ^{10}Be and isolate at least 40 g of pure quartz (Kohl and Nishiizumi, 1992). After the addition of 250 μg of ^{9}Be carrier, we digested the samples with HF. The native ^{27}Al was measured in duplicate aliquots, removed from HF solutions, by Inductively Coupled Argon Plasma Spectrometry – Optical Emission. The Be and Al were purified using chromatographic techniques. The Be and Al were packed into targets, and then taken to Lawrence Livermore National Laboratory to measure 10Be/^{9}Be and ^{26}Al/^{27}Al ratios using AMS. All measurements were corrected using similar-sized procedural blanks. Blanks were prepared with each batch of seven samples and analyzed at the same time as the other seven samples. We calculated ^{10}Be and ^{26}Al activity from ^{9}Be (added as carrier) and the measurements of native ^{27}Al.

Results and Discussion

The nuclide activities of our samples vary according to location. The three boulders near the levee crest have ^{10}Be nuclide activities ranging from 0.64 ± 0.05 to 0.93 ± 0.04 x 10^5 atoms g^{-1}. The side slope boulder has a much higher ^{10}Be nuclide activity of 3.46 ± 0.15 atoms g^{1} (Table 1). The ^{26}Al nuclide activities are approximately six times larger (Table 1). The ^{26}Al / ^{10}Be production rate ratio is approximately 6, which suggests no decay of nuclides and no long-term burial (Nishiizumi et al., 1989). We average the ^{26}Al and ^{10}Be exposure ages to best estimate the age of the landslide.

The interboulder discrepancies in nuclide activities are due to differences in boulder exposure or erosion histories. Such differences in exposure history could include: 1) exposure of boulders at or near the surface prior to landsliding (age overestimate), 2) erosion of boulders after landsliding (age underestimate), 3) burial of boulders under debris and subsequent erosion of overlying sediment after landsliding (age underestimate), or 4) rolling or tipping of boulders after deposition (age underestimate). We will discuss simple upper and lower age estimates and rigorously address each complexity to the boulder exposure histories to best constrain the age of the Blackhawk landslide.

Simple lower and upper limits of Blackhawk landslide age

We can obtain a simple lower limit of the Blackhawk landslide from the three boulders on the left levee crest. In order to understand the meaning of the exposure age we must clarify the assumptions that are used in the model. The exposure age model assumes 1) no erosion of rock since landslide deposition, 2) constant exposure of boulders at the surface, 3) no rolling or tipping of boulders, and 4) no inheritance of nuclides prior to landsliding. Using these assumptions, using the increasingly accepted production rates of ~ 5.17 atoms g^{-1} and 30.? atoms g^{-1} (Clark et al., 1995; Bierman et al., 1996; Gosse et al., 1999?) for ^{10}Be and ^{26}Al respectively, and using the exposure age equation:

$$t = \frac{-1}{\lambda}\ln\left(1 - \frac{N\lambda}{P_0}\right) \qquad (1)$$

where, t = time (years), λ = decay constant (years^{-1}), N = nuclide activity (atoms g^{-1}), and P_0 = production rate (atoms g^{-1} y^{-1}), the lower age limit of the Blackhawk Landslide is 7.6 ± 1.5 ka (Table 1). We assume that the oldest age of the three boulders is most representative of the real age because, the younger ages could be due to either, more erosion of the boulder or initial burial of the boulder by sediment.

Conversely, we can estimate a simple upper limiting age of the Blackhawk landslide from the side-slope boulder. For this model, the assumptions listed above must fit for the side slope boulder yielding an exposure age of 31.1 ± 6.2 ka (Table 1). The levee crest boulders however, must have either been initially buried under sediment or they have eroded significantly, providing an age underestimate.

There is a large discrepancy in our lower and upper age estimates of the Blackhawk landslide age. Therefore, we must analyze each of our assumptions to better constrain our age estimate of the Blackhawk landslide.

Note: this is where the text really starts to diverge!

Evaluation of assumptions

We can better estimate the age of the Blackhawk age by explicitly addressing each of the assumptions, and then developing a model that accounts for the modifications in the assumptions. The assumption of no erosion of boulders is difficult to verify. We observed that each boulder was spalling into ≤ 1 cm thick sheets. Such removal of mass by spalling or grain disintegration will give exposure ages that are too young (Bierman and Gillespie, 1991). Furthermore, if the boulders were buried under sediment, erosion rates of the boulders in the subsurface would be faster than erosion rates at the surface (Burke and Birkeland, 1979). Such erosion would further underestimate the age of the landslide. The dynamic nature of boulder erosion and sediment erosion becomes a greater problem as the landform increases with age (Hallet and Putkonen, 1994, Putkonen, 2000; 2001). Although such erosion and exposure history of the boulders are impossible to determine, we feel that the boulder erosion is not a significant factor in the dry Mojave Desert. Furthermore, the similarity in the nuclide activities of the boulders suggests that they have had similar exposure histories and it seems unlikely that the boulders were all buried at the same depth.

Constant exposure of boulders (no burial by sediment) is another assumption that is difficult to determine. If we look at the levee's geomorphic cousin, the glacial moraine, there are several studies that suggest moraine crests erode significantly (10^0 to 10^1 m) over the 10^3 to 10^4 year time scale (e.g. Hallet and Putkonen, 1994; Meierding, 1984; Hanks, 1984). Such initial burial of levee crest boulders would vastly underestimate the age of the Blackhawk landslide. Geomorphic evidence at the Blackhawk is consistent with an eroding levee. Presence of a valley on the non-debris-facing slope suggests erosion of the levee. Furthermore, topographic profiles across the levee boulders show a break in slope on the debris-facing slope (Figure 6). We infer the break in slope as a soil catena resulting from the erosion of the levee crest. The topographic profile at the side slope boulder location however, shows the break in slope below the sample location. Therefore, the slope where the boulder is located is geomorphically consistent a surface of transport (Figure 6). **Something about erodability of glacial moraine vs. granular landslide debris.**

The third assumption (no tipping or rolling of the boulders) is probably valid for the levee crest boulders. The location of the boulders only a few meters from the levee crest on a low slope make it likely that the boulders have not tipped or rolled since they were deposited. The side slope boulder could have rolled since landsliding, but given the steep slope we find it unlikely that the boulder would begin to roll and then come to rest at mid-slope. Therefore, we believe that the boulder is in its original position since the landslide deposited it.

Our assumption of whether the boulders have inheritance of nuclides from exposure prior to landsliding is not testable. We can infer that since the levee crest boulders all have similar nuclide activities it is unlikely that these boulders have nuclide inheritance. However, we cannot definitively determine if the side slope boulder or the boulder at the toe has nuclide inheritance.

Inheritance is a potential problem for large landslides. Shreve (1968) noticed that the Blackhawk debris had retained its gross stratigraphy and described the debris zone as a three-dimensional puzzle. Models of large-volume landslides also show the gross preservation of stratigraphy (Hsu, 1975, Campbell et al., 1995). Such observations and models suggest that some of the rocks at the debris surface were probably exposed prior to landsliding and rode along the surface during landsliding. These rocks, although impossible to identify in the field, would have nuclide inheritance and thus give old estimates of landslide age. Inheritance problems probably account for the higher age estimates measured by Stone and Fifield (1995). The model age would suggest that the side slope boulder does not have as much inheritance as Stone and Fifield's oldest samples, but does not rule out the possibility of inheritance.

Mixed model of burial and exposure

It is possible that the levee crest boulders were covered under sediment after the landslide. Subsequent erosion of the levee crest would eventually exhume the boulders. By developing a model of burial followed by exposure we can better constrain the age of the Blackhawk landslide.

Our first approximation of the initial height of the levee crest is to extrapolate the topographic profile (Figure 6A). We use the slope nearest the levee crest, as the slope lower on the levee may represent the deposited material eroded from the levee crest. Extrapolation of the profiles suggests a maximum of 9.5 m of erosion if the levee had a sharp crest. The boulders could have been located anywhere in those 9.5 m. If we take common erosion rates of glacial moraines from the eastern side of the Sierra (Hallet and Putkonen and reference therein) we can estimate the maximum age of the landslide. Using the burial followed by exposure model the age of the landslide can be upwards of 36,000 y.b.p., depending on chosen erosion rates.

Our best age estimate of Blackhawk Landslide

Given our data and the complexities in interpreting nuclide activities, we can only make a best guess of the Blackhawk's age. We feel that the two older boulders give the age closest to the age of the landsliding, between 30,000 and 35,000 y.b.p. Glacial geologists often use the practice of using the oldest boulder age when they date boulders to determine the age of glacial moraines (refs). By choosing the age of the oldest levee boulder, we conclude that the other three boulders were buried under sediment and thus the nuclide activity under represents the actual age of the landslide. Such young ages are due to a combination of both accelerated boulder weathering under a soil mantle and shielding of the boulder from cosmogenic isotope production. The side slope boulder has an age close to the actual age of the landslide, but may be young due to slight boulder erosion and/or burial.

Relation to previous age estimates

Our age for the Blackhawk Landslide is older than Stout's (1977; 1977) estimate of 17,400 ± 550 y.b.p. Such a large discrepancy is not troubling. The lake that contained the fresh water gastropod and pleceopod shells could have formed any number of years after the landslide. Stout's (1975;1977) radiocarbon age only provides a limiting age for the landslide.

Our age is at the middle of Stone and Fifield's age range from 10,000 to 55,000 years. We believe that Stone and Fifield's range represent ages that are both young and old. The young ages are representative of both burial and erosion, while the older ages represent inheritance from prior to landsliding. Our estimate seems to fit within the age range of Stone and Fifield's data.

Conclusion

I have to figure out what I conclude before I can write this section.

Acknowledgements

Funding for this project is from US ARO and DEPSCoR. We thank B. Copans, and J. Larson for laboratory assistance, L. Persico for field assistance, and R. Shreve and J. Stone for discussions about the Blackhawk landslide.

References

Anderson, R. S., Repka, J. L., and Dick, G. S., 1996, Explicit treatment of inheritance in dating depositional surfaces using in situ (super 10) Be and (super 26) Al. Geology v. 24, no. 1 p. 47-51.

Bierman, P., and Gillespie, A., 1991, Range fires; a significant factor in exposure-age determination and geomorphic surface evolution. Geology v. 19, no. 6 p. 641-644.

Bierman, P. R., Larsen, P., Clapp, E., and Clark, D. H., 1996, Refining estimates of (super 10) Be and (super 26) Al production rates. Radiocarbon v. 38, no. 1 p. 149.

Bierman, P. R., and Steig, E., 1996, Estimating rates of denudation using cosmogenic isotope abundances in sediment. Earth Surface Processes and Landforms, v. 21, n.2 p. 125-139.

Burke, R. M., and Birkeland, P. W., 1979, Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California. Quaternary Research, v. 11, no. 1 p. 21-51.

Campbell, C. S., Cleary, P. W.,and Hopkins, M., 1995, Large-scale landslide simulations; global deformation, velocities, and basal friction. Journal of Geophysical Research, B, Solid Earth and Planets, v. 100, no. 5 p. 8267-8283.

Clark, D. H., Bierman, P. R., and Larsen, P., 1995, Improving in situ cosmogenic chronometers. Quaternary Research, v. 44, no. 3 p. 367-377.

Clapp, E. M., Bierman, P. R., Schick, A. P., Lekach, J., Enzel, Y., and Caffee, M., 2000, Sediment yield exceeds sediment production in arid region drainage basins. Geology, v. 28, no. 11 p. 995-998.

Dade, W. B., and Huppert, H. E., 1998, Long-runout rockfalls. Geology, v. 26, no. 9 p. 803-806.

Davis and Shaffer 1995

Gosse et al, 1999

Granger, D. E., Kirchner, J. W., and Finkel, R.., 1996, Spatially averaged long-term erosion rates measured from in situ-produced cosmogenic nuclides in alluvial sediments. Journal of Geology, v. 104, no. 3 p. 249-257.

Granger, D. E., Muzikar, P. F., 2001, Dating sediment burial with in situ-produced cosmogenic nuclides; theory, techniques, and limitations. Earth and Planetary Science Letters, v. 188, no. 1-2 p. 269-281.

Hanks, T. C., Bucknam, R. C., Lajoie, K. R., and Wallace, R. E., 1984, Modification of wave-cut and faulting-controlled landforms. Journal of Geophysical Research, v. 89, no. B7 p. 5771-5790.

Hallet, B., and Putkonen, J., 1994, Surface dating of dynamic landforms; young boulders on aging moraines. Science v. 265, no. 5174 p. 937-940.

Heimsath, A. M., Dietrich, W. E., Nishiizumi, K., and Finkel, R. C., 1999, Cosmogenic nuclides, topography, and the spatial variation of soil depth. Geomorphology, v. 27, no. 1-2 p. 151-172.

Hsu, K. J., 1975, Catastrophic debris streams (sturzstroms) generated by rockfalls. Geological Society of America Bulletin, v. 86, no. 1 p. 129-140.

Kohl, C. P., Nishiizumi, K., 1992, Chemical isolation of quartz for measurement of in-situ-produced cosmogenic nuclides. Geochimica et Cosmochimica Acta 56, no. 9 p. 3583-3587.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion models. Earth and Planetary Science Letters, v. 104, no. 2-4 p. 424-439.

Meierding, T. C., 1984, Correlation of Rocky Mountain Pleistocene deposits by relative dating methods; a perspective. In: Correlation of Quaternary chronologies, Mahaney, W. C. Ed., p. 455-477.

Nichols in press

Nishiizumi, K., Winterer, E. L., Kohl, C. P., Klein, J. ; Middleton, R., Lal, D., and Arnold, J. R., 1989, Cosmic ray production rates of (super 10) Be and (super 26) Al in quartz from glacially polished rocks. Journal of Geophysical Research, B, Solid Earth and Planets, v. 94, no. 12 p. 17,907-17,915.

Perg, L. A., Anderson, R. S., and Finkel, R. C., 2001, Use of a new (super 10) Be and (super 26) Al inventory method to date marine terraces, Santa Cruz, California, USA. Geology (Boulder) v. 29, no. 10 p. 879-882

Putkonen 2000

Putkonen 2000

Shreve, R.L., 1968, The Blackhawk landslide. Geological Society of America Special Paper 108, Boulder, CO, 47p.

Stone and Fifield 1995

Stout, M. L., 1975, Age of the Blackhawk landslide, southern California. Abstracts with Programs , v. 7, no. 3 p. 378-379.

Stout, M. L., 1977, Radiocarbon dating of landslides in southern California. California Geology, v. 30, no. 5 p. 99-105.

Figure Captions

Figure 1. Do not have yet…I am going to have a nice color phtograph

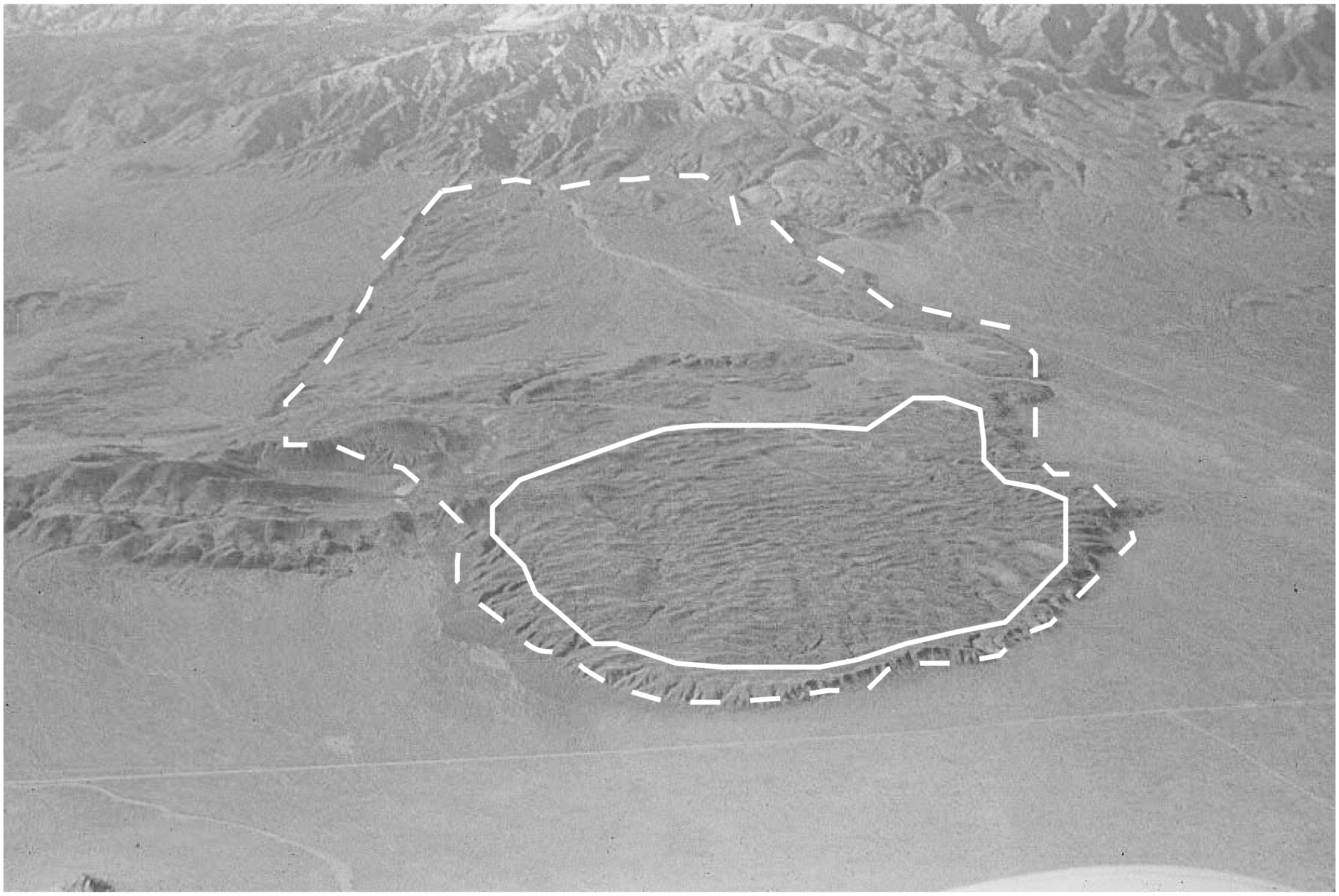
Figure 2. A) Oblique aerial photograph of the Blackhawk debris zone circled in white dashed line. White solid line encircles small transverse ridges are in the center of the slide mass. Small internal drainages dominate this area of the debris. B) The levee that surrounds the slide mass is higher than the debris.

Figure 3. Some levees have soil catenas. A) White arrow points to soil catenas at toe of the landslide. B) View of left lateral levee. Soil catenas are outlined with white line. Some soil catena extend more than halfway up the levee.

Figure 4. Map of sample locations. Three granitic boulders are located near top of levee crest on left lateral levee (Figure 5A). One sandstone boulder at levee crest at toe of the landslide (Figure 5B). One granitic boulder located on a sideslope of left lateral levee (Figure 5C). Base map is Shreve's (1968) geological map.

Figure 5. Photographs of boulder samples. A) Three granitic boulders located just below the levee crest (BH-4, BH-5, and BH-6). B) Sandstone boulder located at toe of landslide (BH-7). C) Granitic boulder located on slide slope (BH-3). Notice no significant deposition around boulder.

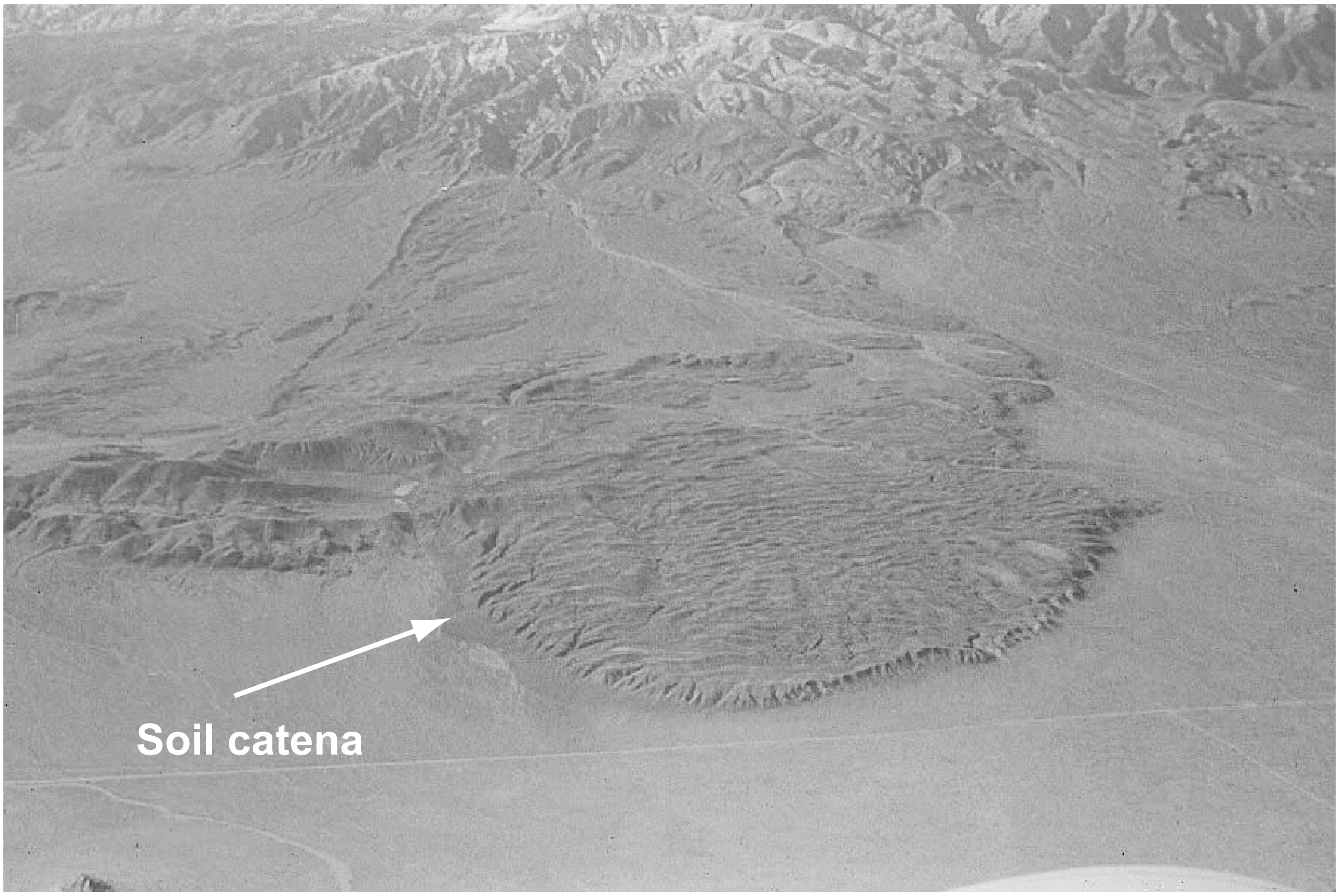
Figure 6. Topographic profiles of left lateral levee. A) Topographic profile across the levee at site of samples BH-4, BH-5, and BH-6. Assuming a sharp crest immediately after landslide deposition suggests maximum crest erosion of 9.5 m. B) Topographic profile of slope at BH-3. Soil catena is developed below the break in slope. Notice soil catena is below BH-3.



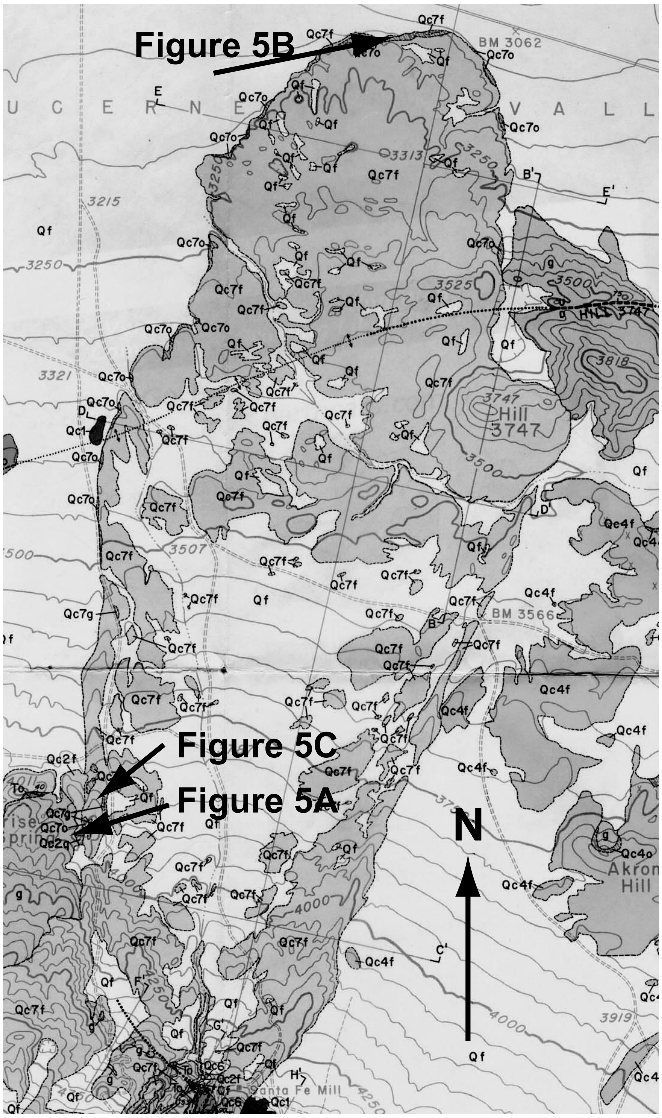
Nichols et al., Figure 2A

Nichols et al., Figure 2B

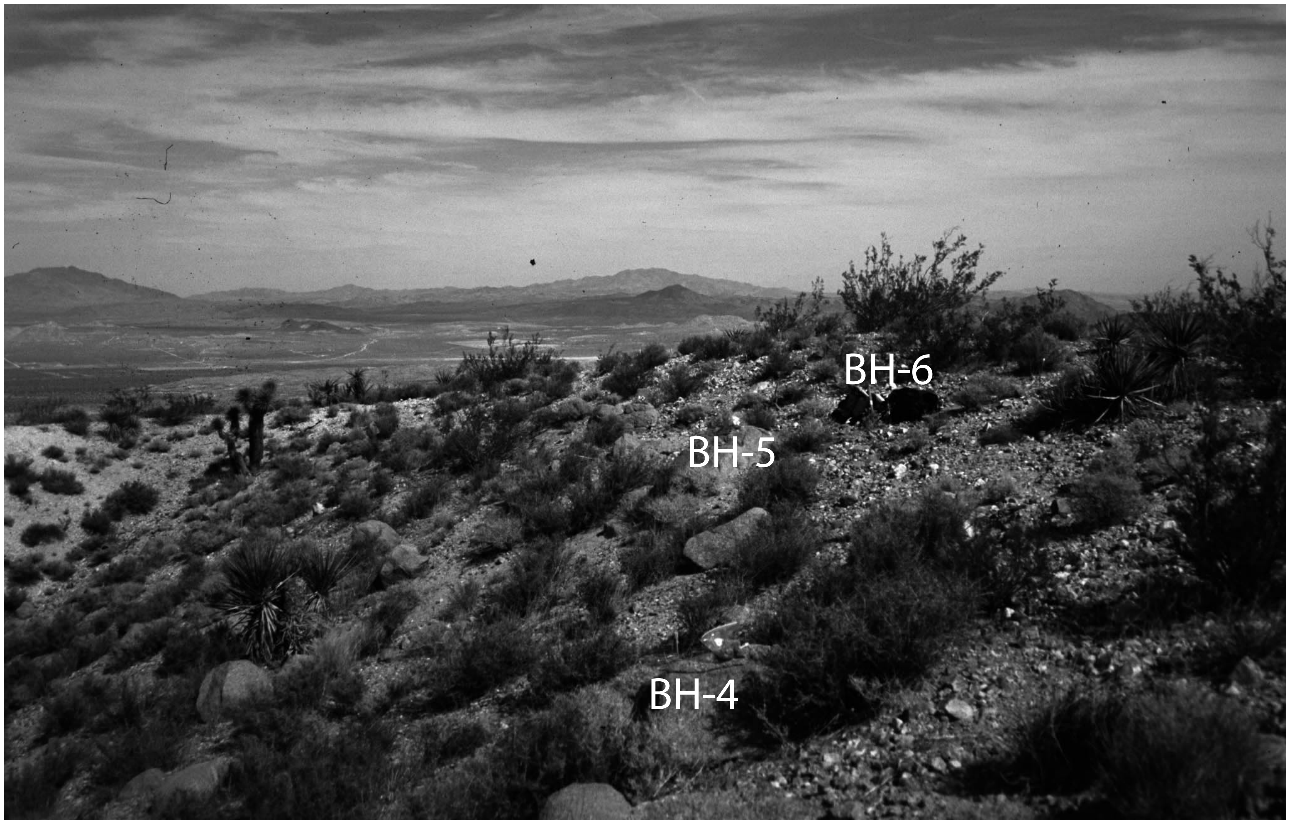
Nichols et al., Figure 3A



Nichols et al., Figure 3A



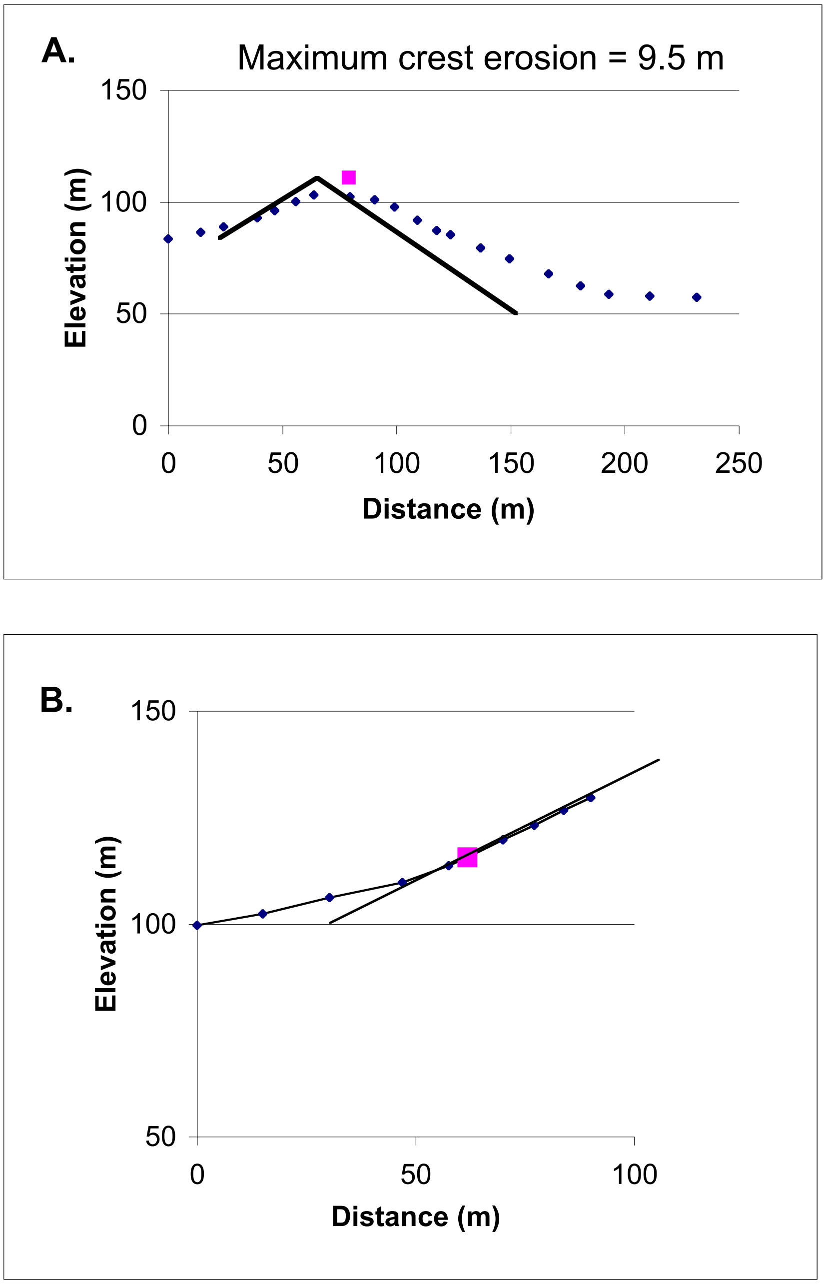
Nichols et al., Figure 4



Nichols et al., Figure 5A

Nichols et al., Figure 5B

Nichols et al., Figure 5C



Nichols et al., Figure 6

Table 1. ^{10}Be and ^{26}Al data

Sample	UTM coordinates[a]		^{10}Be activity[b]	^{26}Al activity[b]	^{26}Al/^{10}Be	^{10}Be exposure age[c]	^{26}Al exposure age[c]	Average age[d]
	Northing	Easting	(x 10^5 atoms g-1)	(x 10^6 atoms g-1)		(years)	(years)	(years)
BH-3	518049	3803844	3.48 +/- 0.15	1.96 +/- 0.14	5.6 +/-	29100 +/- 5800	30100 +/- 6000	29600 +/- **5900**
BH-4	517970	3803584	0.64 +/- 0.05	0.41 +/- 0.03	6.4 +/-	5300 +/- 1100	6200 +/- 1200	5800 +/- **1200**
BH-5	517970	3803584	0.88 +/- 0.05	0.45 +/- 0.03	5.1 +/-	7300 +/- 1500	6800 +/- 1400	7100 +/- **1500**
BH-6	517970	3803584	0.93 +/- 0.04	0.50 +/- 0.04	5.4 +/-	7700 +/- 1500	7500 +/- 1500	7600 +/- **1500**
BH-7	520097	3808848				35000		

[a] Coordinates are based on hand-held Garmin 12 GPS using NAD 27 grid zone 11S.

[b] Error is AMS counting statistic error

[c] Exposure age using production rates of Bierman et al., 1996, and altitude and latitude corrections of Lal, 1991. Error is 20% based on production rates.

[d] Based on average of ^{10}Be and ^{26}Al data.

Table 1. Model ages of exposure followed by burial for oldest levee boulder

	Burial depth (m)									
Erosion rate (cm/ka)	**9.5**	**9**	**8**	**7**	**6**	**5**	**4**	**3**	**2**	**1**
30	36000	34300	31000	27600	24300	21000	17700	14500	11500	8900
40	28900	27700	25200	22700	20200	17700	15200	12800	10500	8600
50	24700	23700	21700	19700	17700	15700	13700	11800	10000	8500