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A large landslide on the urban fringe of metropolitan Phoenix, Arizona

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Abstract

A granitic rock avalanche, one of the largest Quaternary landslides in Arizona outside the Grand Canyon with a volume of approximately 5.25 M m^3 and a width a little under 0.5 km, ran ~1 km from the eastern McDowell Mountains. With lateral levees and pressure ridges, the rock avalanche deposit displays many features found on classic sturzstroms. Failure occurred along a major joint plane paralleling the slope with a dip of 44°, when a major base level lowering event in the Salt River system would have undermined the base of the failed slope, and probably during a period of more moisture than normally available in the present-day arid climate. Failure at the subsurface weathering front highlights the importance of the dramatic permeability change between grussified regolith and relatively fresh bedrock. Rock varnish microlaminations (VMLs) dating, in concert with other geomorphic evidence, suggests that the rock avalanche deposit is slightly older than ~500 ka. The rock vanish results also have important implications for sampling strategies designed to use cosmogenic nuclide to date Quaternary landslide deposits. Discovery of a large landslide in close proximity to the extending urban fringe of metropolitan Phoenix argues for a more careful analysis of landslide hazards in the region, especially where rapid development excavates bedrock at the base of steep mountain slopes and where the subsurface weathering front is near the surface.

Keywords: Central Arizona; Cosmogenic nuclide; Dating; Geomorphology; Natural hazard; Urban growth

1. Introduction

Urban growth in arid regions often faces natural hazards very different from those in wetter climates (Schick et al., 1999; Arrowsmith, 2001; Gupta et al., 2002). Commonly addressed hazards include flooding along larger streams (Greenbaum et al., 1998; Graf, 2000), flash flooding on smaller drainages (Holle and Bennett, 1997), and ground subsidence (Hoffmann et al., 1998). Mapping efforts help define those locales likely to experience future growth under such natural hazards (Christenson et al., 1978–1979; Schick et al., 1999).

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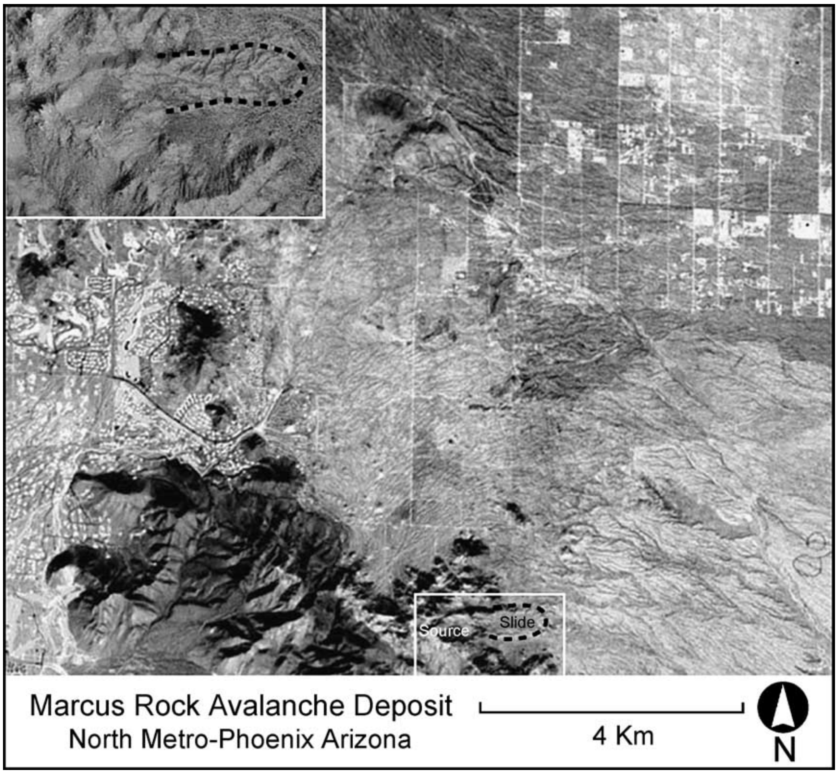

Fig. 1. Location of the Marcus rock avalanche deposit with respect to growth in Scottsdale, AZ. Note how the development is starting to emerge next to very steep slopes on the eastern side of the McDowell Mountains, even though the landslide itself rests in a land preserve.

Staggering urban expansion in metropolitan Phoenix takes place both gradually and by leapfrogging—jumping tens of kilometers from the former outer edge—often to create communities in aesthetic settings in and among steep mountainous terrain. Building at the foot of mountainous areas offers better vistas with commensurately higher property values (Alexander, 1989). Mountains and landsliding, however, go hand-in-hand—even in arid regions (Selby, 1993; Yarnold, 1993). As surprising as it sounds, large landslides do sometimes host suburbanization (Smith, 2001), with people living in locales known to have large-volume landslides with long runouts (Kilburn and Pasuto, 2003). Landsliding, however, remains a largely underappreciated hazard in metropolitan Arizona, despite explicit notations to historic rockfall events (Péwé, 1989) and efforts to understand landsliding at a regional level in Arizona (Welsch and Péwé, 1979; Realmuto, 1985; Welty et al., 1988; Arrowsmith, 2003).

The McDowell Mountains in central Arizona, immediately NE of the city of Phoenix, offer scenic vistas and development potential. The 1970s brought scrutiny to assess potential environmental hazards for future development on the western flank, and numerous small landslides were identified (Christenson et al., 1978–1979). A quarter century later, Scottsdale continues development on the granite piedmont with thin soils on the north end of the McDowell Mountains (Stefanov, 2000)—with the latest growth snaking southward on the eastern flank (Fig. 1). Fountain Hills continues slow growth northwards on the eastern side from the south. Between these extending cities rests a previously unrecognized rock avalanche deposit (Fig. 2) in a land preserve, large enough to be classified a small sturzstrom (Hsü, 1975).

This paper presents one of the largest Quaternary landslides reported in Arizona outside of the Grand Canyon (Savage et al., 2002), a deposit we informally named the Marcus rock avalanche in honor of former

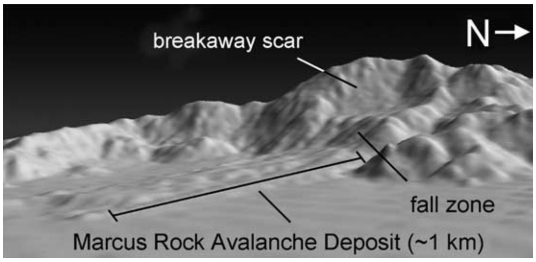

Fig. 2. A west-looking view of the Marcus rock avalanche deposit without vertical exaggeration and from a height of 200 m, constructed from a 10-m resolution digital elevation model in MicroDEM™. Ripples in the foreground represent DEM artifacts.

Arizona State University professor Melvin Marcus. After detailing rock avalanche characteristics, we present its age, its significance in future mapping of landslide hazards in granitic landscapes of the Sonoran Desert, and examine whether this large rock avalanche deposit could take place under present-day conditions. Although we conclude that failure likely took place under a wetter climate during the Pleistocene, we cannot rule out future landslides in the metropolitan area given the right conditions.

2. Description

The Marcus rock avalanche deposit (Fig. 2) failed in a steep portion (Fig. 3) of the McDowell Mountains onto an incised bedrock granite pediment. Geomorphic context often makes identification of Pleistocene and older landslides a difficult endeavor (Mather et al., 2003)—as in this case where prior investigations did not report or map it (McDonald and Padgett, 1946; Christenson et al., 1978–1979; Péwé et al., 1983; Skotnicki, 1996; Stefanov, 2000). Rough topographic similarities between landslide and spheroidally weathered granite on the adjacent granite pediment and the extraordinary size of the rock avalanche deposit perhaps made it difficult to

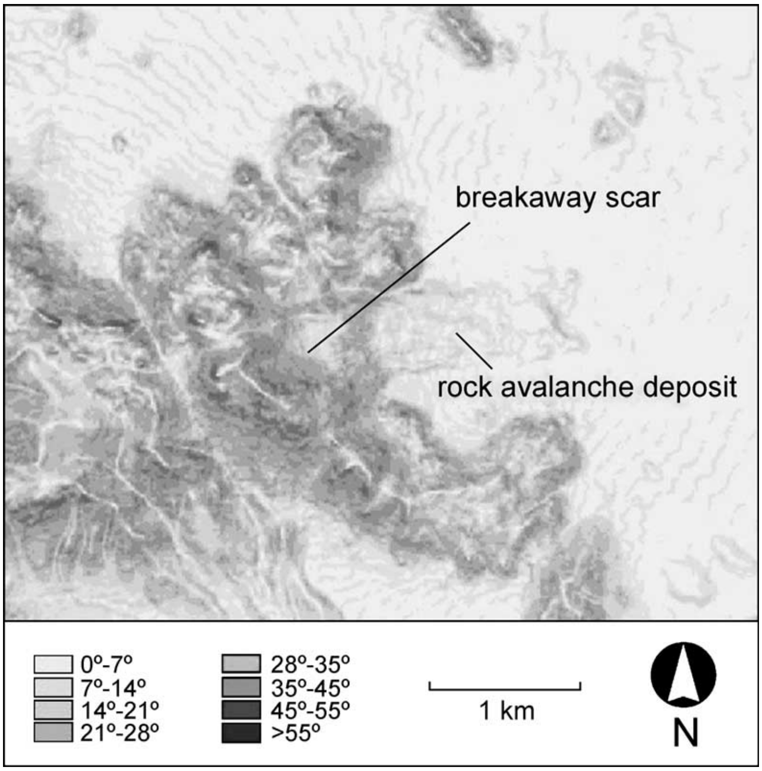

Fig. 3. A slope map in degrees generated in ArcView with a 10-m DEM of the northern McDowell Mountains. Note that the most prominent values for the mountain flanks fall between 28° and 45°.

see while field mapping (cf. Stout, 1991), or perhaps the 1995 Rio wildfire scarred the landscape enough to change the appearance. The rock avalanche deposit is most visibly noticeable from a summit ridge by a difficult climb (Fig. 4A).

The source area consists of fairly uniform Precambrian granite. This medium to coarse-grained, leucocratic, K-feldspar porphrytic granite ranges to quartz monzonite with little evidence of foliation (Skotnicki, 1996). Although metamorphic units occur in the McDowell Mountains around the landslide, we found only isolated inclusions along the rock avalanche's failure plane.

The rock avalanche initially released along an azimuth N46°E for 325 m and altered to an azimuth of N82°E, a shift of 36°. The rock avalanche then broke away and fell the remaining distance at N82°E perpendicular to the mountain front oriented roughly N10°W. A key element in its failure was the prominent and steep bedrock joint plane nearly parallel to N46°E and likely parallel to the original slope (Fig. 4C).

A chair shaped morphology (Jiao and Nandy, 2001) best describes the source area. Hsü (1975) termed this type of headwall profile a jumping platform or breakaway scar. The source area naturally divides into an upper headwall and a lower pocket (Fig. 5). The upper headwall slope averages 34° and hosts few prominent topographic features, with the exception of a depression traversing the length of the headwall. The upper headwall contains bedrock exposures, tens of meters across, that lack grussified granite. Such freshness (Fig. 4C), extraordinarily rare in the Sonoran Desert, perhaps played a key role since granitic hillslopes can develop highly permeable regolith overlying nearly impermeable bedrock (Lerner et al., 1986).

The lower pocket portion of the breakaway scar hosts a much reduced slope of 14°. Interfluve ridges on the eastern boundary of the pocket likely formed as a result of post-rock avalanche deposit headward erosion of gullies. These intergully ridges developed after the rock avalanche event and extend from the pocket to a lower steeper section of the mountain front termed the fall zone. The rock avalanche event spilled over and across the fall zone, with an average slope of 26°, to the mountain piedmont and settled as the rock avalanche deposit (Fig. 5).

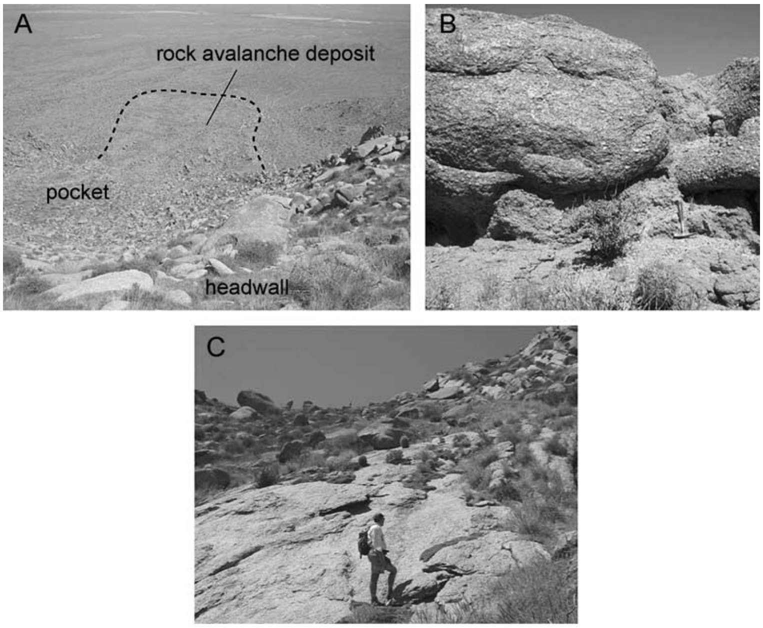

Fig. 4. Photographs of the Marcus landslide. (A) View looking down from atop the headwall towards the rock avalanche deposit. (B) Rubified grus cements boulders in the rock avalanche deposit (rock hammer for scale). (C) Exposure of ungrussified granite in the source area with a slope of about 34°.

The rock avalanche deposit extends about a kilometer from the mountain front. It maintains a fairly uniform width of about 0.45 km, but narrows slightly near the mountain front and at the toe. The deposit exhibits forms, generalized in the geomorphic map (Fig. 5), found on sturzstroms. Three notable pressure ridges bulge just west of the relatively flat north toe, extending in a northeasterly direction and range between 200 and 300 m in length. We hypothesize that as the toe came to a halt about a kilometer from the mountain front, velocity dropped sharply and formed topographic wrinkles—smaller in size, but similar to those described for the Blackhawk landslide (Shreve, 1968). Also similar to the Blackhawk (Shreve, 1968), two prominent lateral ridges or levees (cf. Shreve, 1968) extend about 0.4 km from the mountain front on the north (left lateral) and south (right lateral) sides.

We note that ongoing soil erosion, including formation of gullies, explains the dominance of AC soil profiles, as well as the lack of argillic or even stage-1 pedogenic carbon B soil horizons. Ongoing soil erosion also explains the visual distinctness of pressure ridges and lateral levees, as seen from the top of the failure (Fig. 4A). These distinct lineations of boulders, with some boulders in excess of 4 m in diameter, are due in part to erosion of the adjacent fines.

3. Rock avalanche volume

Our overall strategy estimates landslide volume by measuring both source area and rock avalanche deposit morphologies. Field mapping of source and runout areas first ascertained rock avalanche deposit boundaries. We used the 10-m McDowell Peak 1:24,000 USGS digital elevation model (DEM) and MicroDEM™ version 6.02 to then generate topographic profiles or transects.

We simplified the problem of source area volume calculation by using a series of five transects perpendicular to rock avalanche flow direction. Transect 1 rests 55 m from the top of the source area and extends roughly perpendicular to the long axis of the landslide (Fig. 6). The remaining four transects are spaced 110 m apart in a downhill direction. Transects 2 and 3 orient nearly parallel with transect 1. Transects 4 and 5 are situated perpendicular to the lower long axis portion of the source area and offset from transects 1–3 about 36°. Transect even spacing divides the source area into five sections with a transect at the midpoint of each section. As a result of the changed orientation in the landslide failure direction, we assume that the unavoidable overlapping between transects 3 and 4 approximates unmeasured portions of the source area where spacing between transects 3 and 4 widens (Fig. 6).

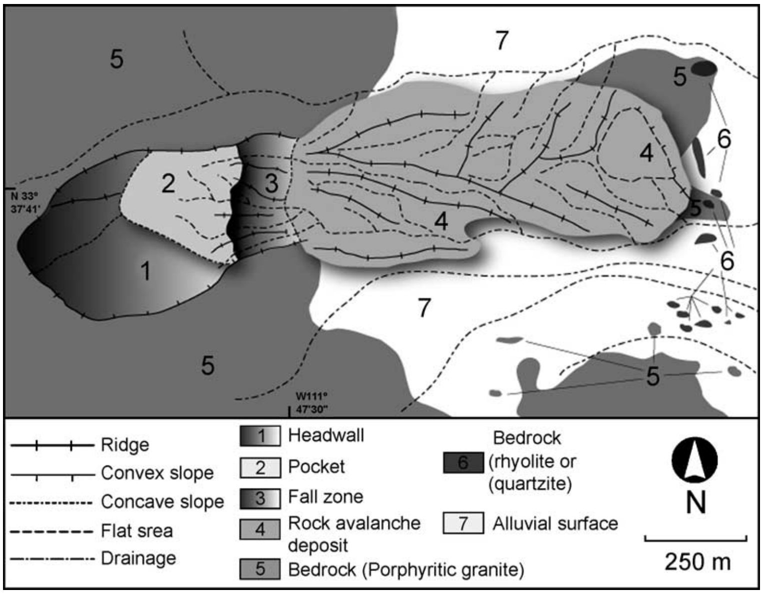

Fig. 5. Geomorphic map of the Marcus landslide.

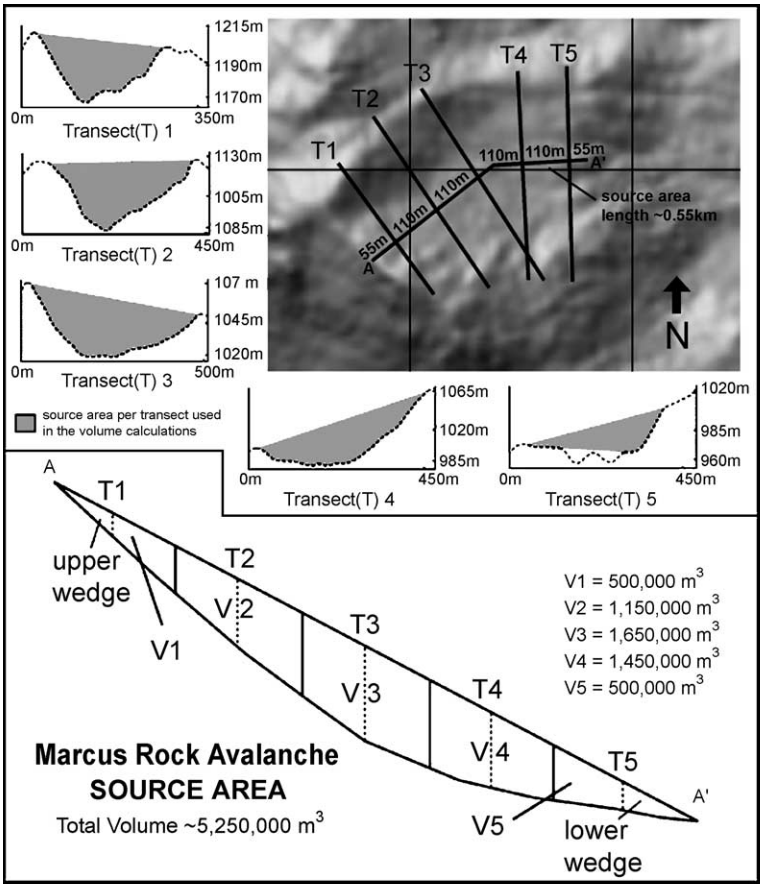

Fig. 6. Five transects derived from the McDowell Peak 1:24,000 USGS DEM permit ready visualization of volume for the source area of the Marcus rock avalanche.

In order to check the calculations by hand, each transect was subdivided into right triangles and rectangles and added together per transect to arrive at an area in square meters. Checking by hand facilitates small adjustments for field realities. For example, transect 5 exhibits noticeable gullies at the base of the source area that obviously postdate the landslide event and should not be included in area calculations using simple subtractions from a hypothetical original DEM.

Transect areas 2–4 are translated into volume estimates when each section is multiplied by the segment length of 110 m. To account for the wedge shape of the ends, transects 1 and 5 were multiplied by 55 m and then by 27.5 m. Addition of volume sections generates a volume estimate for the entire source area totaling 5.25 M m^3. We note, again, that this volume estimate assumes an original planar surface from the northern to the southern ridge (Fig. 6), and the entire purpose of this exercise rests in a broad estimation of eroded volume.

Rock avalanche deposit volume calculations also use five transects perpendicular to the long axis. Transect 1 starts 100 m from the contact between rock avalanche deposit and mountain front. The remaining transects are spaced 200 m from each other, thus evenly accounting for the 1-km-long rock avalanche deposit (Fig. 7). Similar hand-checking mirrors source volume calculation procedures, allowing for adjustment of major post-depositional modifications.

The rock avalanche deposit experienced substantive post-depositional erosion, as evidenced by the presence of weathering flutes along the side of granitic boulders,

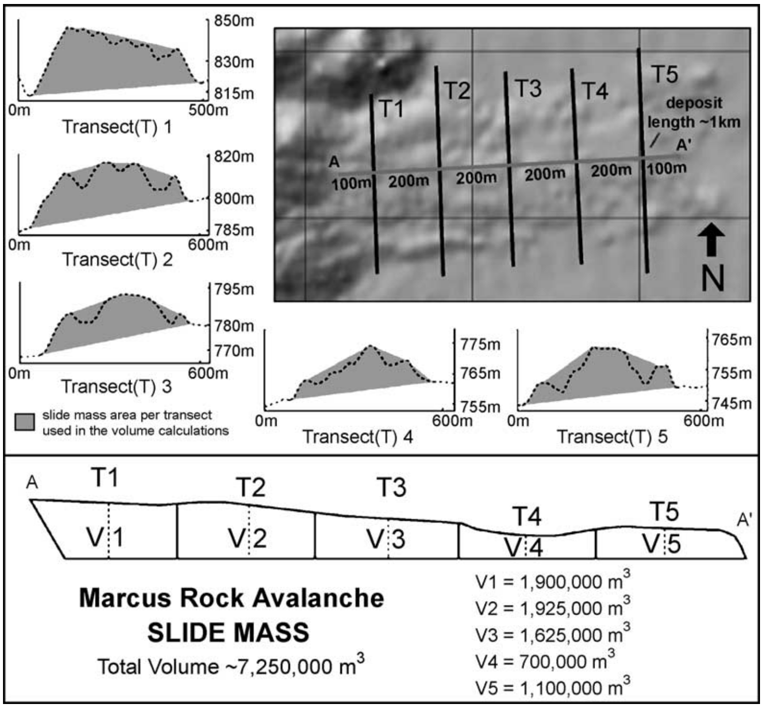

Fig. 7. Five transects derived from the McDowell Peak 1:24,000 USGS DEM permit ready visualization of volume for the rock avalanche deposit portion of the rock avalanche.

pedestal rocks, only AC profiles of residual eroding soils, and gullies. Even though hand-checking permits “filling in” of obvious topographic gullies, our calculation is only a minimum estimate of original rock avalanche deposit volume.

We had difficulty establishing the base of the rock avalanche deposit because of two uncertainties. First, the southern margin of the rock avalanche deposit experienced substantial post-rock avalanche deposit aggradation, burying the pre-existing incised pediment and likely a portion of the rock avalanche deposit itself. Second, we hypothesize that the rock avalanche flowed into a topographic valley or swale, based on topographic trends in adjacent McDowell Mountain front topography. To maintain our conservative minimum volume estimate, we simply assumed a planar surface from present-day topographic edges of the rock avalanche, realizing that this process produces a minimum estimate for the rock avalanche deposit volume of ~7.25 M m^3 (Fig. 7).

In summary, our best estimates place the source area of the rock avalanche at ~5.25 M m^3 with the minimum rock avalanche volume at ~7.25 M m^3. A range of 5–7 M m^3 places the Marcus rock avalanche deposit at the lower end of sturzstroms (Hsü, 1975).

4. Age

The presence of mature saguaro cacti (*Cereus giganteus*) indicates that the rock avalanche deposit is at least a century old, since it takes 50–100 years before saguaro will start to grow arms, let alone grow extensive multiple arms (Nobel, 2002). However, this minimum age is not very informative. Therefore, we add to the list of landslide dating methods (Lang et al., 1999) by turning to rock varnish (Dorn, 1998) microlaminations (Liu and Dorn, 1996; Liu, 2003), a correlative dating method that was recently supported by a blind test:

> This issue contains two articles that together constitute a blind test of the utility of rock varnish microstratigraphy as an indicator of the age of a Quaternary

basalt flow in the Mohave Desert. This test should be of special interest to those who have followed the debate over whether varnish microstratigraphy provides a reliable dating tool, a debate that has reached disturbing levels of acrimony in the literature. . .Results of the blind test provide convincing evidence that varnish microstratigraphy is a valid dating tool to estimate surface exposure ages (Marston, 2003, p. 197).

Varnish microlamination (VML) sequences require calibration to provide anything other than a relative sequence. Unfortunately, the calibration for the Great Basin (Liu, 2003) does not extend to central Arizona. Thus, we used local calibration surfaces of the ~500 ka ^{36}Cl-dated Mesa terrace of the Salt River (Campbell, 1999), the rough 50 ka estimate for the Blue Point terrace of the Salt River (Arrowsmith, 2001), and early Holocene-age petroglyphs at Hedgepeth Hills at the Deer Valley Rock Art Center. Although limited in number, these calibration sites permit us to place informative age thresholds.

Surfaces of granitic boulders on the rock avalanche deposit and bedrock surfaces in the source area experience millimeter- to centimeter-scale exfoliation (cf. Blackwelder, 1925). Because all varnish microstratigraphies formed on top of these eroding surfaces, the most complex stratigraphy only provides a minimum age for the rock avalanche.

We sampled 35 individual boulders on the rock avalanche deposit, as well as eight bedrock granite joint surfaces in the breakaway scar. We followed methods used to develop Liu's (2003) calibration, in terms of broad sampling parameters for a boulder and in terms of the types of millimeter-sized microbasins that are the focus of making ultra-thin sections.

Only 2 of the 35 boulders and 8 bedrock surfaces revealed a VML age more complex than ~500 ka Mesa river terrace (Fig. 8). Replicate sections reveal that these boulders experienced nine major wet periods, indicated by the black layers in varnish (Liu, 2003). In contrast, the Mesa river terrace calibration contains only eight major wet periods.

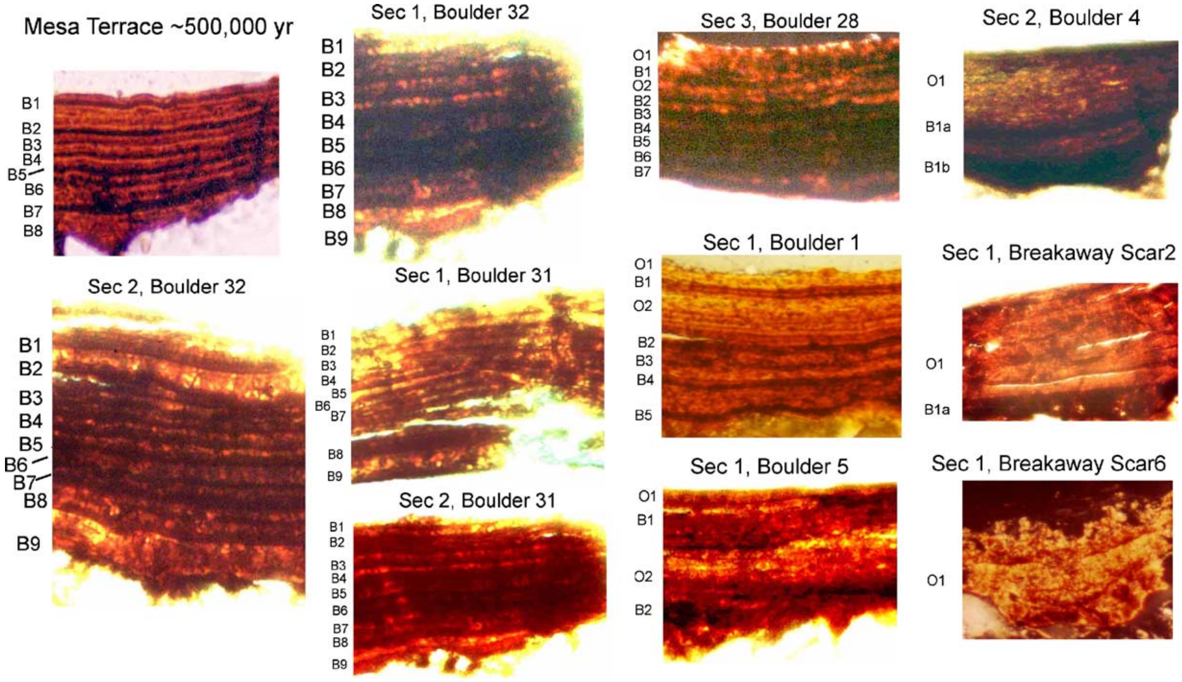

Fig. 8. Varnish microstratigraphy from the two most stable boulders and a few examples of younger microlamination sequences on less stable surfaces. Nomenclature on the margins presents the microstratigraphic units B (black in thin section representing major wet intervals), alternating with O (orange in thin section). The oldest varnishes on the most stable boulders have microstratigraphies similar to the ~500 ka ^{36}Cl calibration site of the Mesa river terrace (Campbell, 1999). (For interpretation of the references to colour in this legend, the reader is referred to the web version of this article).

A minimum age slightly greater than the 500 ka age of the Mesa river terrace receives support from three semi-quantitative lines of reasoning. First, flutes occur on the sides of large granite boulders, and the tallest of flutes reach about a meter. If the top of these flutes are interpreted as a former soil surface (cf. Twidale, 1982), and if we use rates of erosion for granite bedrock pediments in the Phoenix area of 2.2 mm/ka (Campbell, 1999), such flutes would take on the order of 450,000 years to emerge into the elevated positions seen today.

Another semi-quantitative line of support derives from alluvial sediment aggraded behind the south side of the rock avalanche deposit. Modern gullying reveals that the south-side piedmont surface once contained meter-deep channels incised into former pediment surfaces. Since that time, more than 750,200 m^3 of fill accumulated behind the south margin of the rock avalanche. Because the area behind the south part of the rock avalanche deposit is no longer a closed basin, an unknown amount of sediment has been transported over the sill between the rock avalanche deposit and McDowell Mountain bedrock (Fig. 5). A minimum amount of 1.33 m of erosion of the mountain drainage area would be required to supply this fill. Very few erosion rates exist for desert mountain masses of granite lithology. However, if we use the rate of summit lowering of about 5.1 mm/ka for granitic mountains in Namibia (Cockburn et al., 1999), in the same order of magnitude as pediment lowering rates for the Phoenix area of 2.2 mm/ka (Campbell, 1999), we obtain a time frame between about 250 and 600 ka needed to accumulate the sediment behind the rock avalanche deposit.

A third line of support for an age slightly greater than ~500 ka could be drawn from base level changes prior to the formation of the Mesa river terrace. Piedmont channels seen in Fig. 1 on the east side of the McDowell Mountains, draining eastward into the Verde River, must have maintained an adjustment to stream terraces equivalent to those on the nearby Salt River, since the Salt River confluence is located 15 km downstream. The Mesa river terrace is inset into the higher Sawik river terrace (Arrowsmith, 2001). At the position of the Marcus rock avalanche deposit, the elevation drop from the Sawik terrace to the floodplain represented by the Mesa terrace would have been ~36 m. The piedmont channels that reach the Marcus rock avalanche area would have only been 7 km away from this dramatic incision. Thus, this large base level adjustment must have propagated up into the McDowell Mountains, undermining the base of the slope. The timing of this base level drop would have been sometime before the 500,000 year age of the Mesa river terrace—consistent with the VML age of slightly older than the Mesa terrace itself.

The above evidence, taken collectively, provides reasonable support for an age slightly greater than 500 ka. Our age estimate could be tested against future optically stimulated luminescence ages on the rock avalanche or the south-side fill (e.g., Lang et al., 1999) or cosmogenic nuclide ages for boulders 31 and 32.

Our VML results have implications for future efforts to date landslides with cosmogenic nuclides. More than 90% of sampled boulders and bedrock surfaces yielded VML ages far younger than the Mesa river terrace and boulders 31 and 32. Seven boulders had VML ages scattered between the ~500 and ~50 ka calibrations. Fifteen boulders yielded VML ages between the ~50 ka and early Holocene Blue Point and Deer Valley petroglyph calibrations. Eleven boulders and all eight bedrock samples from the breakaway scar showed only a Holocene VML signal, younger than the Deer Valley petroglyph calibration. The tremendous decline in time of stable surfaces occurs on granite boulders on glacial moraines (Gordon and Dorn, in press) and should not be surprising given the ubiquitous nature of weathering processes.

These boulders were not sampled in a random fashion. We targeted surfaces that appeared to be the most stable, based on years of calibrating the second author's eye in collecting samples from boulders for both cosmogenic nuclides (e.g., Nishiizumi et al., 1993; Phillips et al., 1991) and rock coating (Liu and Dorn, 1996) analyses. Even with this informed training, more than 90% of our samples yielded ages far younger than the oldest exposed boulders. Unless the individuals who sample landslides for cosmogenic nuclide dating are somehow intuitively apt at sampling only the most stable surfaces, the mode VML ages for boulders in our study suggest that any three boulders typically sampled for cosmogenic dating could have a high level of statistical precision, but likely a low accuracy.

The ^{36}Cl calibration age of the Mesa river terrace was based on sampling dozens of very resistant quartzite clasts. Current approaches in the cosmogenic dating of landslide deposits, however, usually involve collection of individual samples from large boulders. Our VML results suggest three implications for the use or interpretation of cosmogenic nuclide ages on landslides. (i) Prior to spending a few thousand US dollars on an individual cosmogenic nuclide measurement, cosmogenic nuclide projects could consider an inexpensive pre-sorting strategy such as VML or weathering-rind dating to pre-select surfaces of greatest stability. (ii) Without such a sorting step, readers may wish to consider the potential that precision in groups of cosmogenic ages on landslide deposit boulders might not equate to accuracy. (iii) Projects using cosmogenic nuclide dating will require greatly expanded budgets to be sure that the most stable surface is included in the sampling.

5. Enhanced wetness as a key failure condition

Five conditions likely led to the failure of the Marcus rock avalanche. The site of the rock avalanche hosted steep slopes in excess of 40° (Fig. 3), as well as steeply dipping prominent bedrock joint planes between 40° and 45° and nearly parallel to the N46°E hillslope. In addition, the subsurface weathering front was close to the surface; in other words, weathered granite regolith rested on top of relatively unweathered granite (Fig. 4C), creating a permeability change (cf. Lerner et al., 1986). There was also a drop in base level of the Verde River by ~36 m prior to the rock avalanche. As the 7-km-long piedmont channels incised in response, undermining the base of the McDowell Mountains. The fifth key failure condition, the need for enhanced wetness, is the focus of this section.

Abundant field evidence indicates the presence of rubified grus between boulders in the rock avalanche deposit (Fig. 4B). Excavations reveal that the rubification is not from pedogenesis and likely reflects strong regolith chemical weathering in the pre-failure landscape. Strong weathering could have occurred during the wetter Pliocene prior to the rock avalanche event (cf. Smith et al., 1993) or during glacial maxima when mountains in the region hosted dwarf conifer woodlands (McAuliffe and Van Devender, 1998).

Robust numerical models (e.g., Gritzner et al., 2001; Martino et al., 2004) would normally be used to reconstruct failure conditions, and in particular moisture conditions needed to generate the rock avalanche. Certainly, future work conducted on assessing contemporary stability will utilize numerical modeling tools, because we are able to obtain physical measurements on input parameters. However, uncertainties involved in estimating conditions of failure ~500 ka exceed error values generated by using numerical methods. In other words, state-of-the-art models typically provide far more accurate results than our ability to estimate the input values of conditions on the slope prior to the rock avalanche.

In order to obtain some degree of understanding of moisture conditions needed for failure, we turned to a strategy where our input data quality would not invalidate basic assumptions. Dividing the sum of the resisting forces by the sum of the driving forces generates the factor of safety (FS) value (F). F values >1 indicate a stable slope, whereas F values <1 indicate a slope that could potentially fail. This equilibrium based method in slope stability studies (Bishop, 1955; Spencer, 1967; Duncan, 1996) remains in use today in various forms (e.g., Chen, 2004; Qian and Koerner, 2004).

A FS strategy based on method of slices (Bishop, 1955; Spencer, 1967) is flexible enough to permit a general sensitivity analysis to establish a first order approximation of the moisture conditions that led to failure of the Marcus rock avalanche. We utilize an analysis calculation reliant on estimates of Mohr–Coulomb's shear strength parameters, c' and ϕ, to approximate the conditions of unity responsible for failure (Tang et al., 1999). Our approach assumes an infinite slope and does not account for the effects of lateral pressure. The effects from the infinite slope assumption are negligible because the Marcus rock avalanche is 10 times longer than it is thick with fairly uniform soil conditions. The presence of the nearly uniform coarse to medium granite, coupled with the fairly even thickness of regolith that failed in the source area, supports the uniform soil conditions necessary in the infinite slope assumption. Our FS calculations do not, however, account for lateral pressures. Nevertheless, equilibrium-based equations, satisfying all conditions of equilibrium, can yield results with errors ±6% of the actual value, compared with finite equation analyses (Duncan, 1996). Thus, our heuristic use of FS analysis is sufficiently sensitive to distinguish the broader moisture condition leading to failure of the Marcus rock avalanche.

The general FS equation can be restated as

$$FS = \frac{c' + hg\cos(\phi)d'\,(p_{\mathrm{r}} - p_{\mathrm{w}}m)\tan(\phi)}{p_{\mathrm{r}}hg\sin(\phi)\cos(\phi)}$$

where p_{r} is the rock avalanche deposit density with a range of 2.5–2 g/cm^3; p_{w} is the density of water at 1 g/cm^3; and g is the acceleration of gravity at 9.81 m/m.

The following variables are difficult to estimate for a Pleistocene event: c', the effective cohesion; d', the dip angle; h, the thickness of the rock avalanche; m, the portion of saturated thickness of the rock avalanche, where m=1 is fully saturated and m=0 is completely dry; and ϕ is the angle of internal friction. We use a range of reasonable internal angles of friction from 30° and 45° based on the hillslopes surrounding the Marcus Landslide (Fig. 3). Selby's (1993) effective cohesion values for granite hillslopes provide a rough possible range between 35,000 and 55,000 kPa. Values for h and d' are estimated directly off the landslide at five equidistant segments; approximating changes in depth and slope values from the headwall to the pocket sections of the breakaway scar (Fig. 9). For this heuristic analysis, we use the moisture extreme conditions of M=1 for a fully saturated state and M=0 for a completely dry state.

This sensitivity analysis of extreme values permits a comparison of very dry and very wet conditions (Fig. 10). Higher c' and ϕ values, representing greater stability (between 40°–45,000 kPa and 45°–55,000 kPa), would have led to a fairly stable slope. Only the lower range of c' and ϕ values between 30°–25,000 kPa and 35°–35,000 kPa drops the FS below the critical value of 1, but only with an M value approaching 1, close to saturation. This sensitivity analysis fits generalizations that prolonged periods of rainfall are needed to activate deep-seated landslides (Baum et al., 1993).

The FS analysis suggests that the Marcus rock avalanche deposit probably did not fail under present-day arid conditions. The regolith seems to have been nearly saturated before failure could occur. The weathered condition of matrix regolith similarly argues for failure during a much wetter period than found today—perhaps in a condition found during a glacial maxima.

Simply because the McDowell Mountains rock avalanche deposit requires much wetter conditions than at present does not necessarily negate present-day hazard potential. A number of factors could enable contemporary large landslides, including: (i) slopes steeper than 30° are common in the eastern side of the

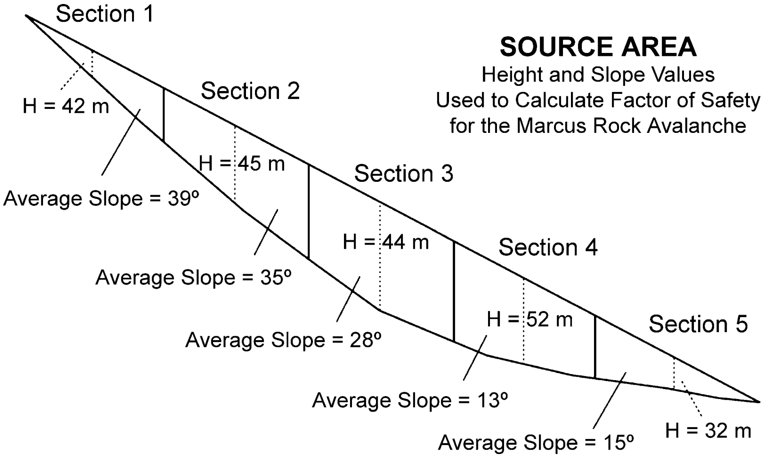

Fig. 9. A subdivision of the breakaway scar into slices (cf. Selby, 1993, p. 272) permits rough estimates of pre-failure thickness and dip angle. This diagram is not to scale.

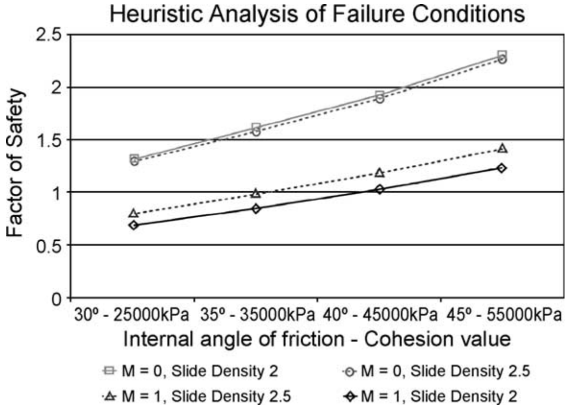

Fig. 10. FS values plotted verses extreme values for internal angle of friction and effective cohesion. This heuristic exercise suggests that landslide failure (F<1) could have taken place when regolith was near saturation and the rock avalanche deposit must have been weathered with relatively low values for an internal angle of friction and effective cohesion (≤35° internal angle of friction and ≤35,000 kPa effective cohesion).

McDowell Mountains (e.g., Fig. 3) and elsewhere in the lower Sonoran Desert; (ii) intense precipitation events, capable of generating the 320 mm of precipitation needed to set off large landslides even in granitic lithologies (Toll, 2001) can occur during the summer monsoon season; and (iii) human excavations up against mountain slopes could remove key lateral support, destabilizing steep slopes.

6. Significance in future mapping of Sonoran Desert landslide hazards

Besides enhanced moisture and base level change leading to incision at the bottom of the failed slope, the three necessary conditions leading to the Marcus rock avalanche were steep slopes (Fig. 3), steeply dipping prominent bedrock joint planes nearly parallel to steep slopes, and close proximity to relatively unweathered granite beneath weathered regolith (Fig. 4C). Without any one of these preconditions, the rock avalanche would not have occurred. Since these three conditions continue to exist in the source area, dozens of post-rock avalanche mass wasting events ring the upper source area. Most are isolated rock falls, but one exceeds 0.01 km^2. A few of the rock falls appear very recent, because they maintain the very bright appearance of “fresh” granite with little in the way of rock varnish.

Prior landslide hazard assessment in Arizona has explored the importance of joint orientation and slope angle (e.g., Reiche, 1937; Wells, 1960; Welsch and Péwé, 1979; Realmuto, 1985; Welty et al., 1988; Arrowsmith, 2003). The discovery of this large rock avalanche highlights a formerly less appreciated factor in mapping landslide hazards in the Sonoran Desert: proximity to the subsurface weathering front.

Mid-20th century French (e.g., Tricart and Cailleux, 1973) and German (e.g., Büdel, 1982) geomorphologists recognized the importance of extensive deep weathering of granitic lithologies. More recently, Twidale (2002) reminded the geomorphic community of the importance of subsurface weathering in generating dramatic transformations in landscape evolution when relatively unweathered granite emerges into the subaerial environment. Lerner et al. (1986) and Jiao and Nandy (2001) relate the importance of the subsurface weathering front in granite weathering to mass wasting events.

The Sonoran Desert of the USA and Mexico, although defined biologically (cf. Nobel, 2002), is also characterized geomorphically by the virtual lack of subaerial unweathered granitic lithologies. Isolated exposures of fresh granite create locally famous high points such as Pinnacle Peak or Kitt Peak. However, formerly anecdotal observations such as historic rock falls cascading onto houses (e.g., Péwé, 1989) fit our observation of the importance of failure (i) on steep slopes, (ii) where jointing roughly parallels the steep slopes, and (iii) when the boundary between weathered and relatively fresh granite rests close enough to the surface to create a failure plane. The Marcus rock avalanche simply represents a dramatic example of these conditions.

Excluding erosion of soils in response to fires and isolated rock falls, we do not know of the existence of a Sonoran Desert mass wasting event in granite that failed in regolith and not at the subsurface weathering front. The importance of permeability and porosity changes associated with the subsurface weathering front is certainly not new (e.g., Twidale, 1982; Lerner et al., 1986). However, understanding the potential systematic importance of emergence of a subsurface weathering front opens the door to an entirely new criteria in understanding landslide hazards in the Sonoran Desert. Such mapping is an extensive undertaking beyond the scope of this investigation; however, preliminary observations at road and housing construction exposures in the Phoenix metropolitan area reveals both the presence of (i) a subsurface weathering front above less permeable and less weathered granite; (ii) steeply dipping joints, and (iii) steep slopes (e.g., Fig. 11). As Sonoran Desert cities, such as Phoenix, continue their sprawl, growth will continue into granitic lithologies with this buried potential hazard.

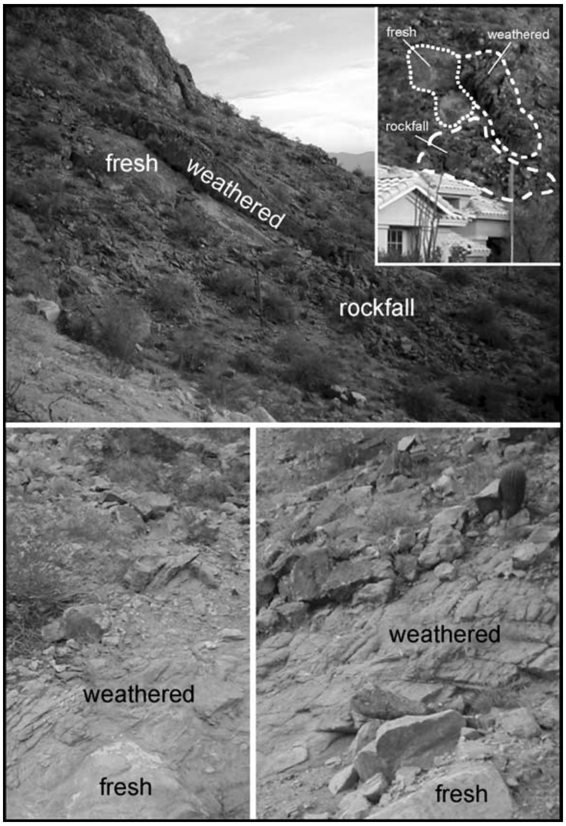

Fig. 11. This site in south Phoenix exemplifies our observation that Sonoran Desert mass wasting in steep granitic terrain is concentrated where three conditions are met: (i) steep slopes; (ii) jointing that parallels the slope; and (iii) close to the surface exists the subsurface weathering front—a boundary between fresh and weathered granite. (upper frames). A small rock avalanche, almost reaching the housing development, exposes the contact between spheroidally weathered granite and the relatively fresh granodiorite. (lower frames) Two roadcuts in the area expose the general condition of weathered granite overlying relatively fresh granite.

7. Conclusion

This paper presents the discovery of a small sturztstrom, with lateral levees and toe pressure ridges, that is being surrounded by growing metropolitan Phoenix. Converging lines of evidence and inference suggest that the rock avalanche failed a little over 500 ka during climatic conditions much wetter than today.

A Pliocene and early Pleistocene of lengthy wetness (e.g., Smith et al., 1993) could have weathered (Fig. 4B) a deep pocket of granitic bedrock, over much less permeable (Fig. 4C) bedrock (cf. Lerner et al., 1986). In addition, the combination of a steep slope and a strong joint orientation that parallels this steep slope established the conditions that facilitated a major rock avalanche event. An additional factor could have been incising streams undermining the base of the eastern McDowell Mountains—all in response to a precipitous drop in base level of a major drainage only 7 km away.

During a particularly wet phase of the period, the regolith could have collected sufficient water at the bedrock/regolith interface at the subsurface weathering front. High moisture content in the regolith then would have increased the weight of the potential rock avalanche deposit, increased pore pressure, and decreased cohesion. The net result decreased the factor of safety below 1 and approximately 5.25 M m^3 of granitic regolith failed along granitic joints with a dip of N44°W.

Once failure initiated, the rock avalanche was undoubtedly sudden and catastrophic. The source area material, released along the joint plane separating weathered and less weathered granite, broke away along the headwall pocket interface. The rock avalanche then traveled over the lower fall zone and down to the piedmont surface. Material collected in levees parallel to the failure direction adjacent to the fall zone. The leading front of the landslide slowed first because it traveled farthest and expended the most energy. As its velocity decreased, material behind the front backed up and formed the subtle pressure ridges observed on the NE portion of the rock avalanche deposit. The entire event probably lasted only seconds.

The rock avalanche deposit interrupted “normal” geomorphic processes operating on the east McDowell piedmont. The embayment on the south side of the rock avalanche deposit stores sediment that probably took ~250,000 to 600,000 years to accumulate, a time frame that fits with the pattern of varnish microlaminations found on the most stable rock avalanche boulders. This varnish pattern places the age of the rock avalanche at slightly greater than 500,000 years. Since the ebb and flow of sediment storage is irregular, we predict that excavations of the south-side embayment might yield some sediment that could date close to the time of the landslide event.

Although metropolitan Phoenix probably does not contain suites of undiscovered massive landslides of the sort found elsewhere (Shang et al., 2003), we cannot rule out finding similar rock avalanches in the region. Nor can we rule out contemporary rock avalanches, because massive excavations at the base of steep mountain ranges combined with high magnitude monsoon precipitation could promote large rock avalanches even in today's dry climate. Future landslide hazard research, thus, need to concentrate where development takes place beneath slopes where weathered granite rests on top of relatively fresh granite, and where major joints parallel steep slopes.

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