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Chronology of rock falls and slides in a desert mountain range: Case study from the Sonoran Desert in south-central Arizona

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ABSTRACT

In order to respond to the general paucity of information on the chronology of ubiquitous small rock falls and slides that litter the slopes of desert mountain ranges, a case study in the Sonoran Desert reveals new insight into the desert geomorphology of mountain slopes. Rock falls and rock slides in the McDowell Mountains that abut metropolitan Phoenix, USA, fall in three chronometric groupings dated by conventional radiocarbon and rock varnish microlamination methods. First, the oldest events are >74 ka and take the form of stable colluvial boulder fields — positive relief features that are tens of meters long and a few meters wide. Second, randomly sampled slides and falls of various sizes and positions wasted during wetter periods of the terminal Pleistocene and Holocene. Third, an anomalous clustering of slides and falls occurred during the late Medieval Warm Period (Medieval Climatic Anomaly) when an extreme storm was a possible but unlikely trigger. One speculative hypothesis for the cluster of Medieval Warm Period events is that a small to moderate sized earthquake shook heavily shattered bedrock — close to failure — just enough to cause a spate of rock falls and slides. A second speculative hypothesis is that this dry period enhanced physical weathering processes such as dirt cracking. However, the reasons for the recent clustering of rock falls remain enigmatic. While the temporal distribution of slides and falls suggests a minimal hazard potential for homes and roads on the margins of the McDowell Mountains, this finding may not necessary match other desert ranges in metropolitan Phoenix or mountains with different rock types and structures that abut other arid urban centers.

1. Introduction

The talus of rock falls and rock slides covers the steep slopes of desert mountain ranges throughout arid North America and desert ranges in general (Bryan, 1922; Melton, 1965a; Cooke et al., 1982, 1993; Oberlander, 1994; Goudie, 2003; Parsons et al., 2009). Chronometric studies provide important insight into the frequency of mass wasting as a geomorphic hazard (Ibsen and Brunsden, 1996; Hungr, 1997; Aleotti and Chowdhury, 1999; Dussauge-Peisser et al., 2002; Crozier, 2013). With some exceptions (e.g., Gutiérrez et al., 1998; Matmon et al., 2005; Stirling et al., 2010; Rinat et al., 2014) desert geomorphology largely currently lacks systematic research on the chronology of rock falls and rock slides in arid mountain ranges. This is true even in metropolitan Phoenix, where urban expansion (Gober, 2005) results in the placement of homes at the bottom of steep slopes (Fig. 1).

Geomorphologists have theorized on broad chronologies of erosion on desert slopes, arguing that the last period of extensive hillslope erosion in the Southwestern USA took place during the transition from the wetter late Pleistocene to the Holocene (Huntington, 1907; Eckis, 1928; Melton, 1965b; Knox, 1983; Wells et al., 1987; Bull, 1991, 1996; McDonald et al., 2003) with a typical generalization being: "[t]hus, it appears that the initiation of hillslope erosion, fan building, and valley deposition was associated with a climatic shift from moister to drier conditions and a significant change in the nature of uplands vegetation." (Miller et al., 2001, p. 385). A few studies have examined the Pleistocene antiquity of mass wasting features such as desert colluvial boulder fields (Whitney and Harrington, 1988; Friend et al., 2000) or large landslides such as the Blackhawk (Shreve, 1968; Stout, 1977) and Marcus (Douglass et al., 2005) sturzstroms. Still, little is known about the frequency or even general timing of rock falls and rock slides in desert mountain ranges.

As urban expansion in metropolitan Phoenix — and elsewhere globally (Cooke and Warren, 1973; Cooke et al., 1982) — continues to thrust infrastructure at the base of steep desert slopes (Fig. 1), an important step in assessing hazards associated with falls and slides involves understanding the frequency of mass wasting. This paper presents the results of one effort to characterize the timing of rock falls and rock slides in one desert mountain range surrounded by cities.

2. Study site

Metropolitan Phoenix, southwestern USA, envelops a number of small ranges that host abundant rock falls and rock slides. The early

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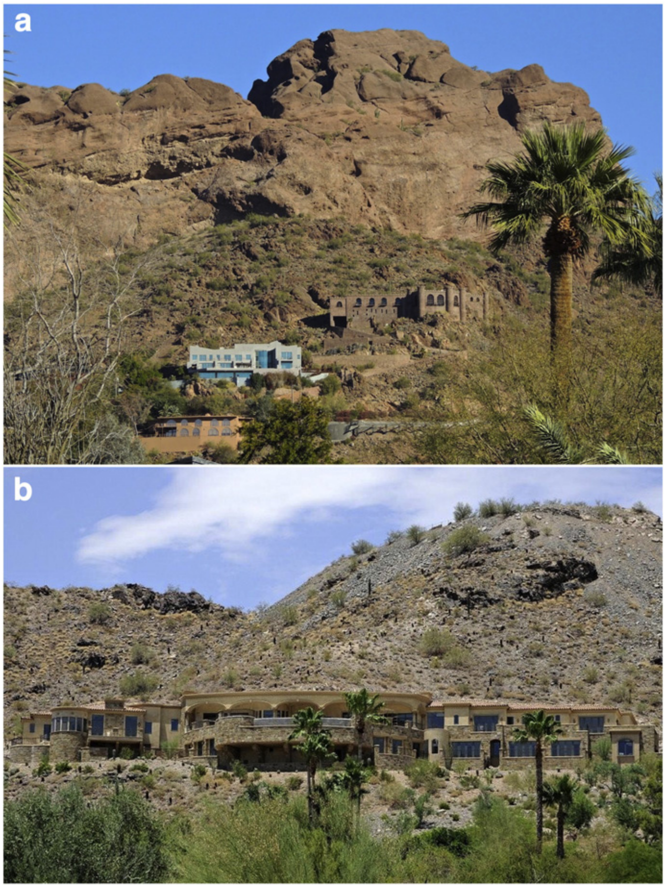


Fig. 1. Urban infrastructure at the foot of desert mountains. Expansive homes, water towers and other urban features often occur directly at the base of steep mountain slopes, exemplified here for mansions in (a) Phoenix and (b) Paradise Valley locations in central Arizona. Note construction of mansions on (a) a talus cone and (b) underneath scree.

Proterozoic metavolcanic and granodiorite McDowell Mountains (Richards et al., 2000; Vance, 2012), bordered by the cities of Scottsdale and Fountain Hills (Fig. 2) form the main field area. The latest major tectonic event, mid-Tertiary extension, created brittle normal faults through the range (Vance, 2012). The McDowell Mountains is an appropriate study area for an initial investigation of the timing of rock falls and rock slides, because it hosts a fairly typical mix of metamorphic and granitic lithologies with a relative ease of access provided by a trail network.

The McDowell Mountains varies in elevation from 600 to 1250 m. Slopes on the southern 90% of the range supply Proterozoic metamorphic quartzite and volcanic rock to the fluvial system through a mixture of debris flows, rock slides, rock falls and some channeled overland flow. Drainages in this metamorphic portion of the range debouch into alluvial fans. In contrast, course-grained Proterozoic granite dominates the northern 10% of the range where the predominant landform consists of domed inselbergs, flanked on the margins by such features as koppies, nubbins, pedastals, tors, a sturzstrom (Douglass et al., 2005), and extensive rock pediments.

The slopes of the McDowell Mountains display many of the characteristics of arid mountain ranges, in that they contain a mix of bedrock and colluvium. Rock varnish and other desert rock coatings (Dorn, 2009) cover the vast majority of the colluvial boulders. Many falls and slides, however, have a 'recent looking' appearance, where the lack of establishment of Palo Verde trees (*Parkinsonia aculeata*) and minimal rock coating development give the rock face and talus a much lighter coloration. Unlike settings with softer rock types (Migoń et al., 2005), boulder disintegration does not occur with the micaceous quartzite (Early Proterozoic), rhyolite (Early Proterozoic), purple quartzite (Early Proterozoic), mafic volcanic rocks (Early Proterozoic), and red quartzite (Early Proterozoic). However, like Migoń et al. (2005), some disintegration does occur on early Holocene and late Pleistocene colluvium with the argillite-phyllite (Early Proterozoic), schist-undivided (Early Proterozoic), and coarse-grained granite (Middle Proterozoic).

While presenting an inventory of mass wasting events in the McDowell Mountains is beyond the scope of this research paper examining the chronology of rock falls and rock slides, the general morphological characteristics are typical of desert slopes in the Sonoran Desert. Rock slide areas range from 40 to 6350 m^2 with the median talus intermediate axis of these slides being 59 cm. Talus from rock falls has a median intermediate axis of 91 cm. Course-grained granite (Middle Proterozoic) and purple quartzite (Early Proterozoic) generated the largest talus often exceeding 3 m in the intermediate axis. Run-out distances for the rock slides range from 12 to 380 m with a median of 40 m. Talus from rock falls typically come to rest within 50 m of the rock face, but the longer run-out distances reached 240 m. In summary, there is nothing geomorphically special or unique about this Sonoran Desert range — making it an appropriate setting to carry out this first investigation of the chronometry of rock falls and rock slides in the desert southwestern USA.

As the study proceeded, an anomalous finding of a cluster of events in the late Medieval Warm Period led to the possibility of a seismic trigger. This clustering generated the need to determine if this chronometric clustering in the McDowell Mountains matched another range in the local area. Thus, section 15 (N 33.34116 W 112.04016) was selected randomly from the Guadalupe Range — 30 km to the southwest — to test the hypothesis that the late Medieval Warm Period clustering might occur in multiple ranges in the Phoenix area.

3. Methods

Two distinct sampling strategies provided different perspectives on rock fall and slide chronology. One strategy involved a random selection of 30 locations in the McDowell Mountains. After gridding the entire McDowell Mountains, a random number generator identified 30 grid cells, where the center of the grid cell identified the locale for sampling. The closest fall or slide to the randomly selected spot was sampled for varnish microlamination (VML) dating and radiocarbon dating of any available Palo Verde (*P. aculeata*) wood crushed by talus.

The second strategy was not random, but subjective in that sampling focused on just 'recent looking' rock falls and rock slides visible from a trail network — a total of 17 events in the McDowell Mountains. As explained in the previous section, the clear temporal clustering of these 17 events (presented in the next section) warranted a second round of sampling from a different mountain range in the area. After random sampling identified Section 15 (N 33.34116 W 112.04016) in the Guadalupe Range, VML samples were collected from the four closest 'recent looking' rock falls and to the center point of Section 15. While many other 'recent looking' rock falls and slides exist throughout central Arizona, time and funding restrictions limited the number of samples.

For each rock fall/rock slide event sampled for dating, a small shovel excavated the edges around talus boulders to assist in finding any evidence of Palo Verde (*P. aculeata*) wood that might have been crushed by talus. Five excavations revealed samples of wood appropriate for conventional radiocarbon dating. One of the randomly selected rock slides generated a debris flow, and the matrix of this flow contained a fragment of wood appropriate for radiocarbon analysis. These six radiocarbon measurements provide estimates of fall and slide ages and also provide local calibrations for the varnish microlaminations (VML) dating method.

VML dating generates age ranges for rock varnish formed on talus boulders derived from rock falls and rock slides. Developed by Tanzhuo Liu, a growing data set links climatic events to micron-scale microstratigraphy in rock varnish (Bell et al., 1998; Liu et al., 2000; Zhou

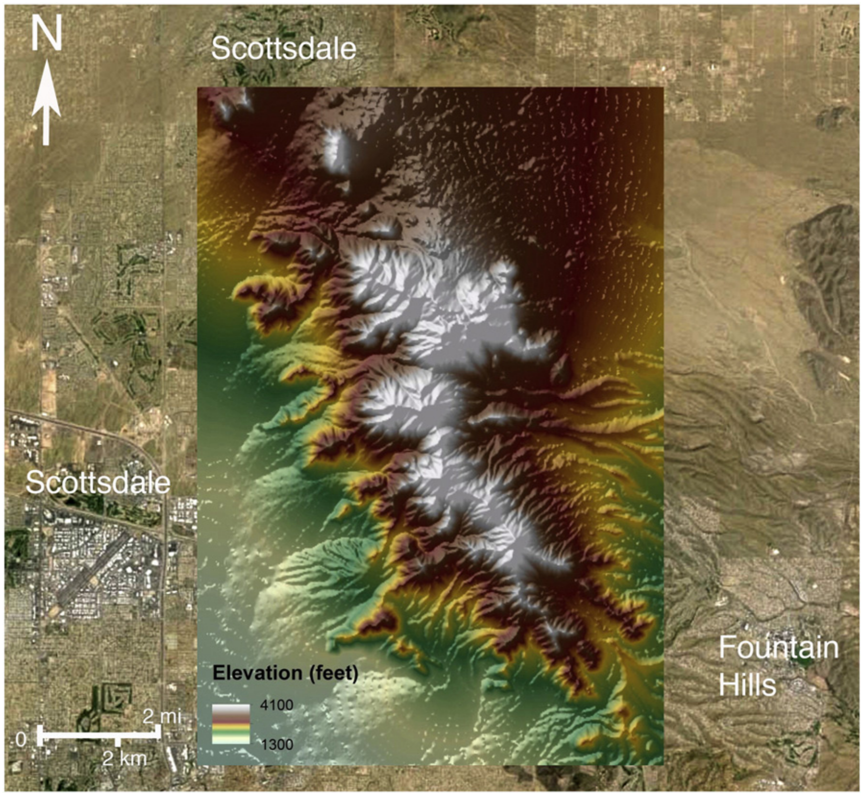


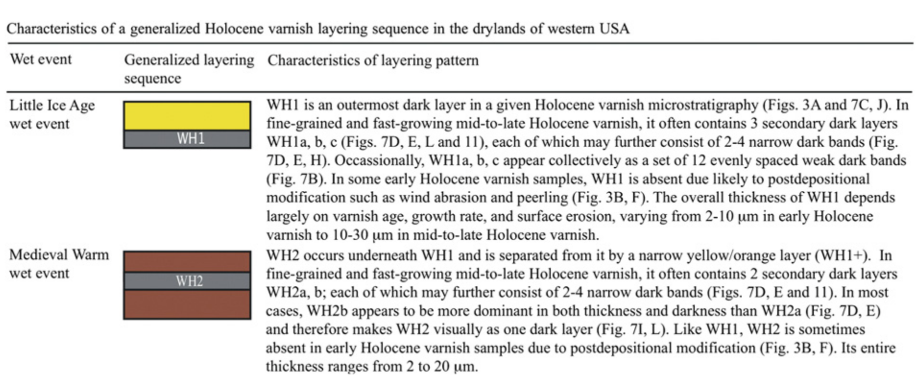
Fig. 2. Shaded relief map of the McDowell Mountains, emplaced in a Google Earth view that shows the adjacent cities of Scottsdale and Fountain Hills. The range is approximately 13 km (8 miles) wide and 18 km (11 miles) long, varying in elevation between 400 and 1250 m.

et al., 2000; Liu and Broecker, 2007; Liu and Broecker, 2008a,b; Stirling et al., 2010; Liu, 2014). VML has been subjected to blind testing (Bell et al., 1998; Liu, 2003; Marston, 2003; Liu and Broecker, 2013) and replication (Diaz et al., 2002; Lee and Bland, 2003; Dietzel et al., 2008; Zerboni, 2008; Dorn, 2010; Somonte and Baied, 2013). The latest Holocene VML patterns, generalized in Fig. 3, are particularly important in this study, because many rock falls and rock slides cluster in the late Medieval Warm Period between the Little Ice Age WH1 microlaminae and the WH2 microlaminae.

The application of VML to the Holocene requires the collection of particularly fast-accumulating varnish. Varnish can form within a few centuries in drylands (Buchun et al., 1986; Dorn and Meek, 1995; Dorn, 1998; Liu and Broecker, 2007; Spilde et al., 2007; Nowinski et al., 2010), but rates at xeric microenvironments preferred for VML analyses are typically so slow — microns per millennia (Liu and Broecker, 2000) — that century-old varnish consists of millimeter-scale patches. Mesic microenvironments, such as north-facing exposures and centimeter-scale depressions that collect and retain water, often foster much faster varnish growth rates (Dorn, 1998, 2010; Liu and Broecker, 2007) that results in a more detailed varnish microstratigraphy for the latest Holocene (Liu and Broecker, 2007).

A methodological complication in central Arizona involves sampling varnish from these faster-accreting mesic locations. Microcolonial fungi and other acid-producing lithobionts often colonize these rock surface microenvironments, resulting in the biochemical degradation of VML patterns. For example, in a study of VML samples collected from 780 debris-flow levees in the Ma Ha Tuak Range of Phoenix, Arizona, only 152 yielded VML ages; 80% of the samples displayed too much biochemical degradation for VML analysis (Dorn, 2010).

For this study, sampling only occurred on talus locations that clearly displayed chipping and abrasion from the rock fall or rock slide event. A sampling focus on north-facing sides with millimeter-scale to



Characteristics of a generalized Holocene varnish layering sequence in the drylands of western USA

Wet event	Generalized layering sequence	Characteristics of layering pattern
Little Ice Age wet event	WH1	WH1 is an outermost dark layer in a given Holocene varnish microstratigraphy (Figs. 3A and 7C, J). In fine-grained and fast-growing mid-to-late Holocene varnish, it often contains 3 secondary dark layers WH1a, b, c (Figs. 7D, E, L and 11), each of which may further consist of 2-4 narrow dark bands (Fig. 7D, E, H). Occassionally, WH1a, b, c appear collectively as a set of 12 evenly spaced weak dark bands (Fig. 7B). In some early Holocene varnish samples, WH1 is absent due likely to postdepositional modification such as wind abrasion and peerling (Fig. 3B, F). The overall thickness of WH1 depends largely on varnish age, growth rate, and surface erosion, varying from 2-10 µm in early Holocene varnish to 10-30 µm in mid-to-late Holocene varnish.
Medieval Warm wet event	WH2	WH2 occurs underneath WH1 and is separated from it by a narrow yellow/orange layer (WH1+). In fine-grained and fast-growing mid-to-late Holocene varnish, it often contains 2 secondary dark layers WH2a, b; each of which may further consist of 2-4 narrow dark bands (Figs. 7D, E and 11). In most cases, WH2b appears to be more dominant in both thickness and darkness than WH2a (Fig. 7D, E) and therefore makes WH2 visually as one dark layer (Fig. 7I, L). Like WH1, WH2 is sometimes absent in early Holocene varnish samples due to postdepositional modification (Fig. 3B, F). Its entire thickness ranges from 2 to 20 µm.

Fig. 3. Characteristics of late Holocene varnish microlaminations, from Liu and Broecker (2007, p. 9). Tanzhuo Liu granted permission to republish this graphic.

centimeter-scale rock-surface depressions resulted in the collection of the fastest-forming varnish on surfaces created by a given mass wasting event. The failure rate of making these VML ultrathin sections was over 90%, due to biochemical erosion by microcolonial fungi growing in these spots. Sampling from drier locations that are less susceptible to biotic erosion, while easier, will not yield samples with sufficiently fast rates of accumulation to record late Holocene VML patterns (Fig. 3).

I also used a third method, lead-profile dating, to determine if rock varnish started to form in the 20th century or prior to the 20th century. This is a nominal dating method, where those varnishes showing *only* contaminated lead throughout started to form during the 20th century. The basis of this method is the observation that "microprobe profiles reveal that lead is a contaminant in the uppermost surfaces of rock varnishes, but these concentrations drop to background levels below the very surface of natural rock coatings that have formed since lead additives were introduced into gasoline in 1922." (Dorn, 1998, p. 139). Another study (Wayne et al., 2004) also noted that "the surface layers of all varnish samples studied display an extreme enrichment in Pb." Multiple researchers have since confirmed that lead and other anthropogenic pollutants contaminate the very surface of rock varnish and other iron-rich rock coatings (Fleisher et al., 1999; Thiagarajan and Lee, 2004; Hodge et al., 2005; Wayne et al., 2006; Spilde et al., 2007, 2013; Nowinski et al., 2010). To measure lead profiles, I used electron microprobe operating conditions of 20 nA, a take-off angle of 40°, accelerating voltage of 15 kV, and a 300 s counting time to increase sensitivity to a detection limit of about 0.03% weight PbO.

In order to better understand the circumstance of the failures sampled for dating, the surfaces of the sampled talus boulders were inspected for evidence of the physical weathering process that originally separated clast from bedrock. In particular, the dirt cracking process (Ollier, 1965) leaves behind a distinctive visual signal of laminar calcrete, orange iron film and rims of black rock varnish (Dorn, 2011). Thus, every clast sampled for dating (either VML, lead profile or radiocarbon dating of crushed wood) was surveyed for the presence of these rock coatings associated with the dirt cracking process.

An estimate for the total number of rock falls and rock slides and the chronology of those events provides initial insight into the recurrence interval of falls and slides. Aerial photography with a resolution better than 0.4 m from the Maricopa County Tax Assessor's Office facilitated two inventories. One inventory involved only those falls and slides on slopes that are above homes, roads and other urban infrastructure. A second inventory involved the entire range. Identifying and tabulating each rock fall talus pile and each rock slide talus accumulation through aerial photography provide a minimum estimate for the total number, because prior slides and falls certainly took place but are now buried.

4. Results

4.1. Radiocarbon ages and VML calibration

Radiocarbon measurements on crushed Paloverde wood provide ages for mass wasting events and also six new VML calibrations for central Arizona (Figs. 4 and 5). One of these ages was modern (Beta 243288) — obtained on wood embedded in a debris flow started by a rock slide; the very minimal varnishing reveals 20th century contamination by lead throughout the varnish (Fig. 4); thus, the modern radiocarbon measurement and the lead-profile both indicate a 20th century age. The other five radiocarbon samples derived from wood trapped underneath talus boulders, where boulder edges abraded by mass wasting transport were sampled for the VML analyses (Figs. 4 and 5). All of these radiocarbon ages with two sigma-calibrated results are late Holocene (Figs. 5 and 6): 300–500 cal year BP (Beta 301105); 850–910, 810–830, and 730–800 cal year BP (Beta 322774); 790–930 cal year BP (Beta 322773); 790–1070 cal year BP (Beta 301103); and 1180–-1290 cal year BP (Beta 301104).

These radiocarbon ages provide new VML calibrations that are consistent with the prior calibration research (Fig. 6) of Liu and Broecker (2007). The same variability for the WH1 (Little Ice Age) signal seen elsewhere in the western USA (Fig. 3) occurs in central Arizona. The most rapidly-formed varnish produces multiple black laminae

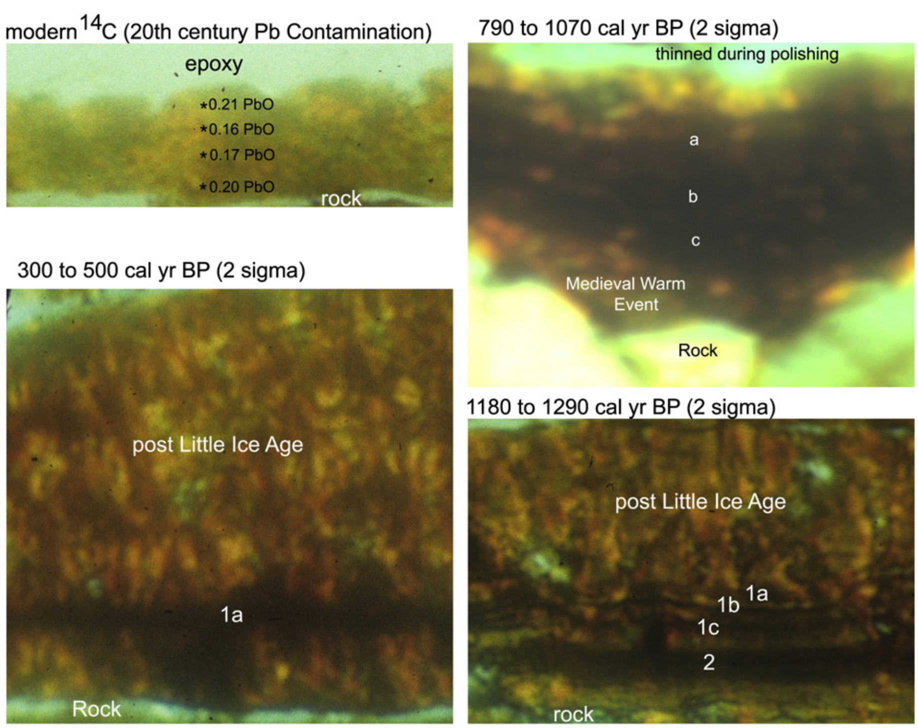


Fig. 4. VML sections of rock varnishes formed on boulders directly on top of radiocarbon dated samples. Varnish thicknesses are ~5 μm (modern; Beta 243288), ~12 μm (300 to 500 cal year BP; Beta 301105), ~16 μm (790 to 1070 cal year BP; Beta 301103), and ~14 μm (1180 to 1290 cal year BP; Beta 301104). Variable rates of varnishing from different microenvironmental collection sites explain these anomalously rapid accretion rates.

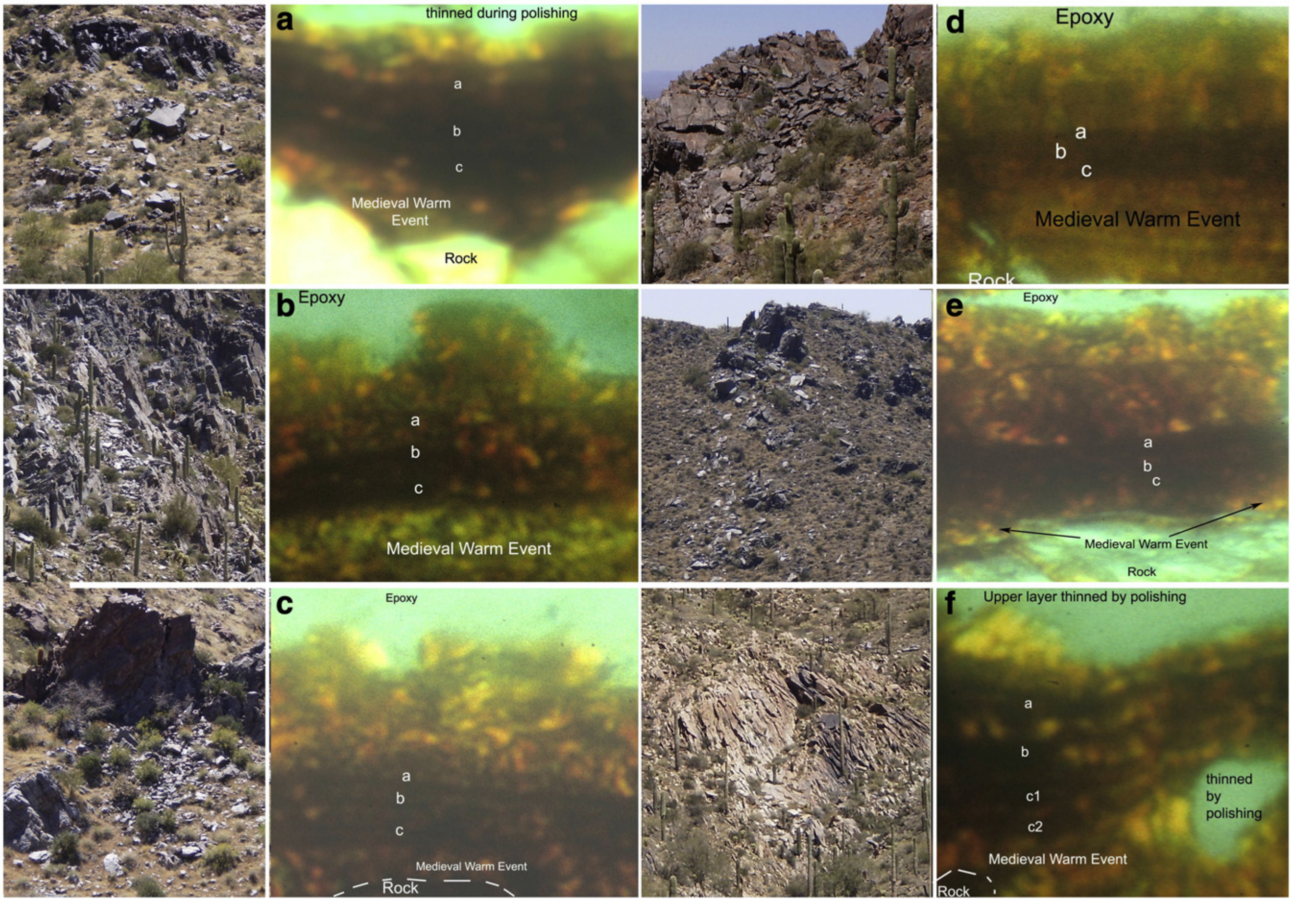


Fig. 5. The rock falls and rock slides in the McDowell Mountains, central Arizona, that had a "recent looking" appearance all derive from bedrock sources. In each case, the basal varnish layer is between the Little Ice Age signal and the WH2 microlamination. (a) Bell Pass Giant Blocks slide at N 33.64925 W 111. 81751. Varnish thickness is approximately 25 μm. (b) Tom's Thumb Saguaro slide at N 33.67689 W 111.81853. Varnish thickness is approximately 20 μm. (c) Tom's Thumb Thistle slide at N 33.67666 W 111.81607. Varnish thickness is approximately 25 μm. (d) Tom's Thumb Shattered slide at N 33.67737 W 111.81624. Varnish thickness is approximately 20 μm. (e) Bell Pass Tables slide at N 33.64638 W 111.81883. Varnish thickness is approximately 35 μm. (f) Tom's Thumb Book slide at N 33.67951 W 111.82142. Varnish thickness is approximately 30 μm. The rock slides in A, B and C have conventional radiocarbon ages for Palo Verde (*Parkinsonia aculeata*) wood crushed by talus of 1030 ± 70 (Beta 301103), 960 ± 30 (Beta 322773), and 880 ± 30 (Beta 322774) year BP, respectively. The Data Repository portrays all of the late Medieval Warm Period slides and falls, as well as the associated VML analyses.

indicating multiple wet pulses throughout the Little Ice Age (Fig. 5). Slightly slower-accreting varnishes display the main 1a, 1b, and 1c wet phases of the Little Ice Age, and still slower-developing varnishes just display just a single WH1 black microlaminae.

4.2. VML ages for randomly selected rock falls and rock slides

While rock falls and rock slides do not require antecedent rainfall events (Bauer et al., 2005), extremely wet periods can and do generate rock falls and rock slides (Dussauge-Peisser et al., 2002). One strategy to

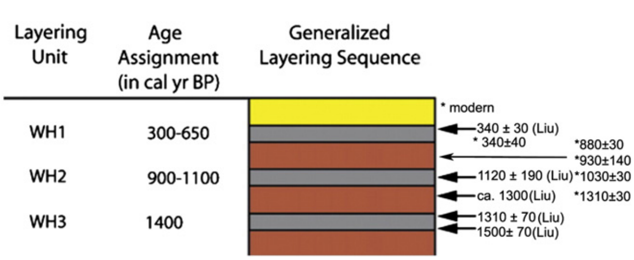


Fig. 6. Placement of new VML conventional radiocarbon calibration points developed for central Arizona (indicated by asterisks) in the context of the original western USA Holocene calibration (Liu and Broecker, 2007). Tanzhuo Liu granted permission to republish the original graphic.

assess the role of a possible precipitation trigger is to compare the frequency of debris flow events with rock falls and slides, since debris flows do require intense rainfall. Fig. 7 compares previous research (Dorn, 2010, 2012) on debris flows in metropolitan Phoenix with the timing of the randomly selected rock falls and slides in the McDowell Mountains.

In general, the timing of the randomly selected rock falls and slides does generally mimic the overall temporal pattern of debris flows — but with some clear differences. First, there are a large number of debris flows timed to the Little Ice Age (WH1) and more recently; this is because smaller, more recent debris flows are better preserved — inset into older and bigger levees (Dorn, 2010, 2012). Second, talus deposits older than 74 ka (17%) are more common than debris flows older than 74 ka (2%). This difference likely also relates to geomorphic preservation, where larger rock slides form colluvial boulder fields that become well-preserved positive relief features over time (Friend et al., 2000), as opposed to older debris flows that occur in geomorphic positions more susceptible to erosion by younger debris flows. Thus, to the limits of the VML method, the randomly sampled wasting events are distributed throughout time in the wetter periods of the latest Pleistocene and Holocene.

The third significant difference relates to the late Medieval Warm Period (also known as the Medieval Climatic Anomaly). Whereas only 0.5% of the debris flows occurred in the Medieval Warm Period, 13% of the randomly selected falls and slides date to this time interval.

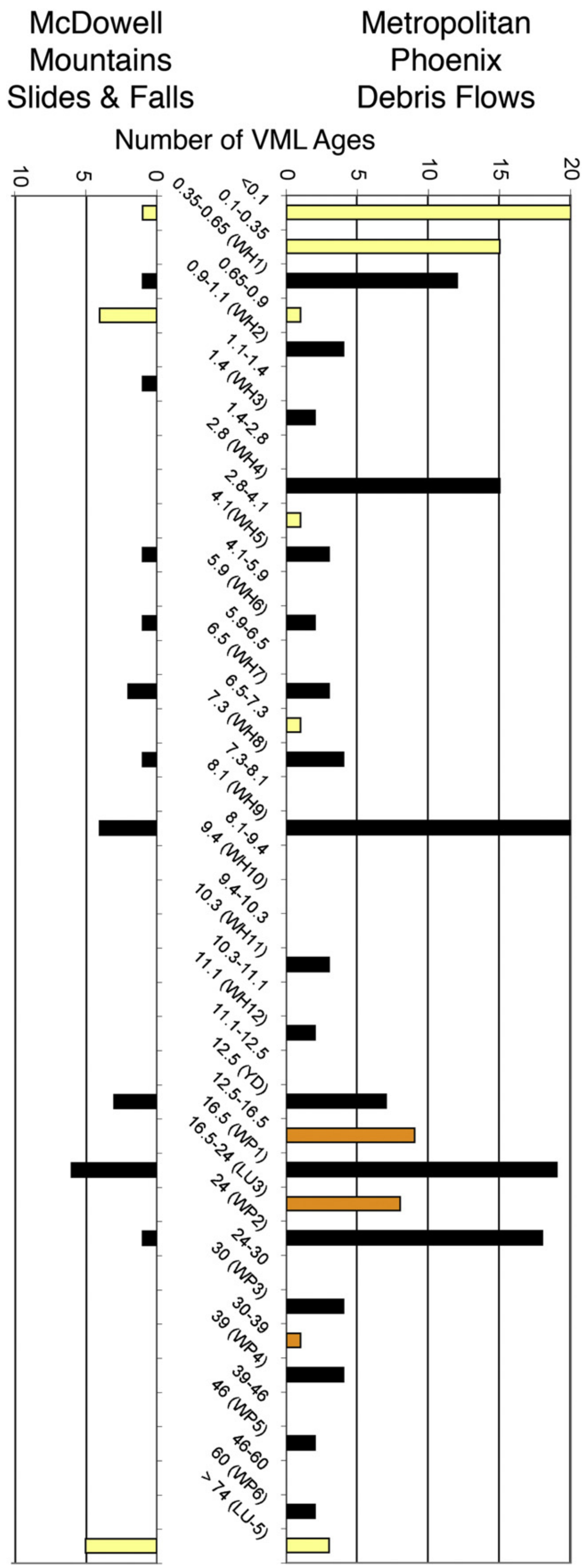


Fig. 7. Histograms of the age distribution of 30 randomly selected rock falls and slides in the McDowell Mountains in metropolitan Phoenix compared with previous research on the timing of debris flows throughout the metropolitan Phoenix, Arizona, region. The age categories in thousands of calendar years before present are based on established VML calibrations.

4.3. Radiocarbon and VML ages showing Late Medieval Warm Period cluster

All seventeen of the 'recent looking' rock falls and rock slides visible from the McDowell Mountain trail system, 13% of the randomly collected falls and slides in the McDowell Mountains, and all four of the 'recent looking' falls and slides collected from the Guadalupe Range host the late Medieval Warm Period VML pattern. All of the late Medieval Warm Period rock slides and falls had bedrock sources (Fig. 5 and the Data Repository at http://alliance.la.asu.edu/temporary/Dorn_DataRepository_MedievalSlides.pdf); they did not derive from the mobilization of prior slope failures. All of the bedrock sources consist of thoroughly shattered rock.

These VML results are consistent with conventional radiocarbon measurements of: 790–1070 cal year BP (Beta 301103), 790–930 cal year BP (Beta 322773), and 730–800, 810–830, and 850–910 cal year BP (Beta 322774). Fig. 5 (and the Data Repository) presents field views of these collection sites and along with the VML imagery.

The VML analyses presented Fig. 5 and the Data Repository reveal that all of these 'recent looking' rock falls and slides are older than 650 cal year BP. According to Liu and Broecker's (2007) calibration work, as well as the radiocarbon samples collected here, the WH1 Little Ice Age wet event started approximately 650 cal year BP. The VML analyses also indicate that the rock falls and slides are younger than wet Holocene event WH2. These data all point to an anomalous concentration of rock falls and rock slides during the late Medieval Warm Period.

Each VML sequence can only be considered a minimum age for the exposure of the underlying rock — in this case the rock slide that created fresh abrasion scars on the talus boulders. Delays in the onset of varnishing could mean that the underlying surface could have been exposed anytime prior to the formation of the lowest VML. This delay can be seen in a few of the sections for radiocarbon-dated events in Data Repository; even though the radiocarbon age indicates that the VML sequence should show the basal orange microlamination indicative of the Medieval Warm Period, the VML sequence only shows the Little Ice Age signal. However, because of the overall consistency of the VML sequences, and because the samples were collected from microenvironments that promote the most rapid varnishing, I interpret these findings to mean that the sampled rock falls and slides occurred after WH2, but before the onset of the Little Ice Age.

There are two possible chronometric interpretations regarding the late Medieval Warm Period clustering. First, the falls and slides occurred throughout the late Medieval Warm Period. Or, second, the falls and slides occurred in a single event. Unfortunately, the chronometric resolution of the available radiocarbon ages and VML patterns cannot distinguish between these alternative interpretations.

4.4. Rock coatings associated with dirt cracking

All of the late Medieval Warm Period clasts sampled for dating contained visual evidence of dirt cracking. All of the clasts showed the sequence of orange iron film surrounded by a rim of black varnish that develops on the walls of fissures experiencing the dirt-cracking process (Dorn, 2011). Similarly, all of the randomly selected rock slides and falls younger than 24 ka showed this same sequence. In contrast, the rock slides and falls 24 ka and older displayed no evidence of dirt cracking. While it is possible that dirt cracking did play a role in the initial separation of these older clasts from bedrock prior to mass wasting, manganese-rich black rock varnish accumulation obscured any such evidence by completely coating the evidence of dirt cracking.

4.5. Partial inventory of falls and slides

A partial inventory of rock falls and rock slides in the McDowell Mountains using aerial photography generated an estimate of 3219 events. Far fewer falls and slides —180 events — occur on slopes above homes and roads. The true number of events must be greater than these totals, because the inventoried deposits could be buried an unknown number of prior events.

5. Discussion

5.1. Speculation on the cause of the Medieval Warm Period clustering

This section presents thinking on three speculative explanations for the recent clustering of rock falls and slides during the overall dry late Medieval Warm Period: (a) an extreme storm; (b) a small to moderate earthquake shook already heavily shattered bedrock, close to failure; (c) or more efficient physical disintegration in the drier environment.

Most paleoclimatic evidence indicates that the late Medieval Warm Period (or Medieval Climatic Anomaly) was anomalously dry in the desert southwestern USA and Arizona (Jones et al., 1999, 2004; Reed, 2004; Benson et al., 2007; MacDonald et al., 2007; Brunelle et al., 2010; Meyer and Frechette, 2010; Pederson et al., 2011). In contrast, reconstructions of flood histories in the southwestern USA reveal that the general time period from 2000 to 0 cal BP experienced increased flooding. Thus, it is possible that a major precipitation event in the Phoenix metropolitan area generated the slide clustering, where this singular event would not be recorded in the paleoclimatic record (Fig. 3).

If a major precipitation event took place, however, it did not generate a debris flow signal in metropolitan Phoenix (Fig. 7). The regional paleoclimatic condition of aridity in the late Medieval Warm Period is consistent with the debris-flow record where only one out of the more than 200 debris flows sampled from around metropolitan Phoenix has a lamination sequence indicative of an age between WH1 and WH2 (Dorn, 2010, 2012).

"[D]ebris flows have a closer relationship to weather impact than rock falls and rock slides, mainly owing to destabilizing processes in the rockslopes that are not directly dependent on the weather conditions (Sanderson et al., 1996, p. 97)." Desert debris flows require intense precipitation as a trigger (Beaty, 1974; Webb et al., 1989, 2008; Sanderson et al., 1996; Coe et al., 1997; Griffiths and Webb, 2004; Blair and McPherson, 2009; Griffiths et al., 2009; Dorn, 2010). Even with major earthquake events, desert environments still require substantive wetting to generate debris flows and other forms of matrix-based transport (Keefer et al., 2003; Keefer and Moseley, 2004). Thus, if the late Medieval Warm Period cluster is driven by precipitation, the amounts were below the threshold to generate debris flows.

Abundant moisture, rock decay, slope steepening due to undercutting, and ground motion from earthquakes can all contribute to rock falls and rock slides (Keefer, 2002; Blair and McPherson, 2009). However, it is possible for earthquakes alone to generate rock falls and rock slides (Keefer, 1994). Thus, a possible explanation for the late Medieval Warm Period anomalous concentration of rock falls and slides is an earthquake.

A study of displaced petroglyph-covered boulders led to the hypothesis that a prehistoric earthquake occurred in central Arizona during the Hohokam Classic Period ca. AD 1200–1300s (Wallace and Holmlund, 1986). The concentration of slides and falls in the McDowell Mountains and Guadalupe Range in this same general period is consistent with Wallace and Holmlund's (1986) hypothesis.

A large difficulty with an earthquake explanation is that Arizona has little large seismic activity (Lockridge et al., 2012) with a paucity of other forms of evidence, such as recent earthquakes or fault scarps. No historic earthquake is known to have caused injuries in central Arizona (Dubois and Smith, 1980), although the 1887 Sonora, Mexico, earthquake likely produced Intensity VI ground shaking on the Modified Mercali Scale of Intensity (Suter and Contreras, 2002). A very large earthquake in proximate fault zones in California and Nevada could have potentially caused enough central Arizona shaking to generate the observed rock falls and slides; however, VML dating analyzed precariously perched boulders found no evidence of substantive earthquakes between the San Andreas and central Arizona since the Younger Dryas (Bell et al., 1998; Stirling et al., 2010). In addition, precariously perched rocks are common throughout the McDowell Mountains and elsewhere in central Arizona (Haddad, 2009), and no substantive late Holocene fault scarps have been found in the central Arizona area.

It is conceivable that a moderate earthquake ~ ML 4 to 5 triggered an extensive array of small rock slides and falls where previously fractured bedrock was right at the threshold of failure. A moderate shake, possibly, might have set in motion the observed small failures. Since the observed failures occur in bedrock on steep slopes, the moderate shaking could have experienced topographic amplification of the seismic waves (Gao et al., 2012). However, the nature of this hypothetical earthquake would have to have been such that a great many of the precariously perched boulders in the study area did not waste.

A third possible explanation for the clustering of rock falls and slides could be the enhancement of physical disintegration during an overall dry period. The predominant physical weathering process in the region is dirt cracking (Ollier, 1965; Dorn, 2011), where laminar calcrete and dust infused into fractures split boulders and bedrock. The dirt cracking process leaves behind a particular set of black and orange rock coatings as evidence of the process (Dorn, 2011). Since all of the Holocene and terminal Pleistocene-dated talus boulders are coated with the evidence of dirt cracking, it is distinctly possible that this process promoted a spate of failures. Of course, the presence of these rock coatings could be a consequence of mass wasting exposing fractures widened by dirt cracking and not the cause. Thus, this explanation — like the other two — remains speculative, and the reasons for the recent clustering of rock falls and slides remain enigmatic.

5.2. Is there a rock fall and rock slide hazard in the McDowell Mountains?

The largest rock slides are older than >74 ka and have evolved into the positive relief feature of colluvial boulder fields (Friend et al., 2000). Most of the randomly sampled talus from rock falls and slides occurred during wetter periods of the Holocene and latest Pleistocene with only one identified as 20th century in age. Excluding the larger >74 ka rock slides, 25 randomly sampled events occurred in the last 30,000 years (Fig. 7).

If the 3219 rock slides and falls in the McDowell Mountains had a similar temporal distribution to the randomly collected materials, then the recurrence interval would be once every ~10 years for the entire range. A partial inventory indicates 180 events on slopes above homes and roads with an estimated recurrence interval of ~once every 170 years. Given that most rock fall deposits consist of a few talus boulders and most rock slides have a small area, an event every two centuries does not indicate the presence of a significant hazard.

Homeowners living beneath steep slopes should be most concerned that the record of mass wasting contains clusters of rock falls. Without knowing the cause of this clustering, it is not possible to assess the hazard. If the cause can be determined, it might be possible to analyze or estimate some sort of a recurrence interval. For example, if an earthquake of a certain intensity generated the spate of failures, then the threshold for that seismic trigger could be estimated. Without understanding why the late Medieval Warm Period cluster occurred, I do not think it is possible to determine if an urban hazard exists.

Similarly, without conducting this sort of a study on other desert ranges in the region, it is not possible to determine whether the ubiquitous rock falls and small slides that dot desert mountain slopes represent a hazard for encroaching urbanization. Determining recurrence intervals in multiple ranges in a region would be the next step.

6. Conclusion

The first investigation of the chronometry of the small rock falls and rock slides that litter the slopes of a desert mountain range, the McDowell Mountains in the Sonoran Desert, revealed distinctive patterns.

An anomalous concentration of rock slides and rock falls took place during the late Medieval Warm Period. The other sampled rock slides and rock falls occurred during wetter periods of the Holocene/late Pleistocene, except for stable colluvial boulder fields that are older than 74 ka.

The anomalous concentration of late Medieval Warm Period falls and slides is hard to explain through the usual suspects of precipitation or earthquakes. The role of enhanced moisture conflicts with regional paleoclimatic data and also the local debris flow chronology — both suggesting that this time period was one of regional drought that did not generate debris flows in the Phoenix region. The role of seismic shaking conflicts with a lack of evidence for an earthquake during late Medieval Warm Period in the area. Still, perhaps a small to moderate seismic event took place along normal faults in the McDowell Range and generated just enough shaking to move shattered bedrock — but not enough shaking to move precariously perched boulders. When faced with no clear explanation, the fictional character Sherlock Homes comes to mind: "when you have eliminated the impossible whatever remains, however improbable, must be the truth (Doyle, 1890, p. 111)." A third possibility is that the dry late Medieval Warm Period enhanced physical weathering processes such as dirt cracking (Ollier, 1965; Dorn, 2011) and destabilized rock faces. Available evidence, however, cannot distinguish between these three alternatives.

The results of this study do not indicate that rock falls or rock slides pose a significant geomorphic hazard for homes and roads on the margins of the McDowell Mountains. Aside from the clustering in the late Medieval Warm Period, the time interval of ~170 years between small events would not warrant substantive concerns. This finding for one range, however, should not discourage a similar study in other desert mountain ranges in metropolitan Phoenix or in other desert settings. It is quite conceivable that the lithologic or tectonic settings in other ranges would generate hazardous conditions that could endanger property and life and justify an examination of engineering solutions to mitigate such potential hazards.

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