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Debris flows from small catchments of the Ma Ha Tuak Range, metropolitan Phoenix, Arizona

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ABSTRACT

Debris flows debauch from tiny but steep mountain catchments throughout metropolitan Phoenix, Arizona, USA. Urban growth in the past half-decade has led to home construction directly underneath hundreds of debris-flow channels, but debris flows are not recognized as a potential hazard at present. One of the first steps in a hazard assessment is to determine occurrence rates. The north flank of the Ma Ha Tuak Range, just 10 km from downtown Phoenix, was selected to determine the feasibility of using the varnish microlaminations (VML) method to date every debris-flow levee from 127 catchment areas. Only 152 of the 780 debris-flow levees yielded VML ages in a first round of sampling; this high failure rate is due to erosion of VML by microcolonial fungi. The temporal pattern of preserved debris-flow levees indicates anomalously high production of debris flows at about 8.1 ka and about 2.8 ka, corresponding to Northern Hemisphere climatic anomalies. Because many prior debris flows are obliterated by newer events, the *minimum* overall occurrence rates of 1.3 debris flows per century for the last 60 ka, 2.2 flows/century for the latest Pleistocene, and 5 flows/century for the last 8.1 ka has little meaning in assessment of a contemporary hazard. This is because newer debris flows have obliterated an unknown number of past deposits. More meaningful to a hazards analysis is the estimate that 56 flows have occurred in the last 100 years on the north side of the range, an estimate that is consistent with direct observations of three small debris flows resulting events from a January 18–22, 2010 storm producing 70 mm of precipitation in the Ma Ha Tuak Range, and a 500 m long debris flow in a northern metropolitan Phoenix location that received over 150 mm of precipitation in this same storm. These findings support the need for a more extensive hazard assessment of debris flows in metropolitan Phoenix.

1. Introduction

Hazards research has long been a part of geomorphology (Cooke, 1984; Graf, 1985; Vuichard, 1986; Baker et al., 1990; Kenny, 1990; Graf, 1994; Ohmori and Shimazu, 1994; Butler and Malanson, 1996; Gill, 1996; Fiebiger, 1997; Lang et al., 1999; Schick et al., 1999; Glade, 2005; Chinn, 2006; Bollschweiler and Stoffel, 2007). Sometimes, the research focuses explicitly on hazards. In other contexts, geomorphic research on processes can be thrust into a position where basic research contributes to the welfare of the society that initially invested in the pursuit of scholarship. For example, the drylands of the southwestern USA exemplify the importance of applying basic research to understand and mitigate infrequent but dangerous flooding impacts to individuals, private property and societal infrastructure (McPherson and Saarinen, 1977; Committee on Public Works and Transportation. Subcommittee on Water Resources, 1979; Saarinen et al., 1984; Rhoads, 1986; Ely, 1997; Graf, 2000; Honker, 2002; Robins et al., 2009).

Debris flows are common hazards (Cooke, 1984; Glade, 2005; Hürlimann et al., 2006), but they are not a generally recognized urban hazard in Arizona. This is due, in part, because debris flows have been historically restricted to mountain settings distant from Arizona urban development (Harris and Pearthree, 2002). The state of Arizona has experienced substantial recent urban growth (Helm, 2003; Gober, 2005). Some of this population explosion has taken place on alluvial fans, and the vast majority of hazard assessment associated with Arizona alluvial fans has focused on fluvial flooding on large fans with drainage areas of tens of square kilometers or more (Rhoads, 1986; Committee on Alluvial Fan Flooding, 1996; Field, 2001; House, 2005; Pelletier et al., 2005). A major precipitation event in 2006 generated debris flows on large alluvial fans on the doorstep of metropolitan Tucson (Magirl et al., 2007; Webb et al., 2008; Youberg et al., 2008; Griffiths et al., 2009), leading to the conclusion that debris flows may be an underappreciated hazard (Pearthree et al., 2007).

A different debris-flow context occurs throughout metropolitan Phoenix, where urban expansion in just the last half-decade has led to placement of homes at the base of steep desert slopes (Fig. 1). Debris-

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Fig. 1. A home built in 2006 and 2007 in a suburban neighborhood of Phoenix, AZ., directly on the depositional area of debris flows. Although the slope catchment area is <10,000 m^2, at least five distinctive sets of debris-flow levees occur immediately above this home, with no structures above the home to divert future debris flows.

flow deposits are commonly found on these mountain slopes throughout metropolitan Phoenix and are not associated with large alluvial fans. Instead, urban-fringe debris flows are associated with catchments of only a few thousand square meters and debris-flow depositional areas that are only slightly larger.

I suggest five possible reasons why the sort of circumstance seen in Fig. 1 has not been perceived as potentially hazardous in urbanizing Arizona and the desert southwestern USA — leading to the widespread placement of homes at the base of debris-flow channels. First, recent urban growth has been taking place in previously unsettled geomorphic settings. The home buyer's guide to geological hazards in Arizona *does* identify these sorts of debris flows as a possible hazard, but does not indicate that they are relevant to homes because these debris flows were once distant from development (Harris and Pearthree, 2002). Many of the homes found directly on debris-flow depositional areas were built after this home buyer's guide was published.

Second, the sort of small debris-flow systems illustrated in Fig. 2 have not been well studied in urban environments in the southwestern USA. Studies of small catchments in other urbanizing regions, such as the Negev Desert, do note that "… scenarios of large sediment-laden floods cum debris flows rushing down the steep (slope 0.06 – 0.10) mountain channels are difficult to predict" (Schick et al., 1999, p. 333). Study of a modern debris flow from a similarly sized small catchment (at Yucca Mountain, Nevada) generated the conclusion that it took rainfall intensities of 73 mm/h on the first day and another 15 mm/h on the second day, where failure might have occurred on either day (Coe et al., 1997); the authors thought that the recurrence interval was over 500 years. The initiation of this well-studied debris flow at Yucca Mountain probably involved saturation of the colluvial mantle, as well as water being added to the debris-source area from fractures in a caprock above the catchment.

A third reason why homes underneath debris-flow channels have not been perceived as hazardous has to do with available data about when desert debris flows have occurred. What little is known about the chronology of debris-flow events in Arizona's deserts suggests that most of the activity is thousands of years old (Cerling et al., 1999; Youberg et al., 2008). This research, however, was conducted in the Grand Canyon and on fans debauching from large mountain drainages near Tucson and not the tiny, steep mountain catchments found throughout the fringes of metropolitan Phoenix. Prior to this study, no chronometric data existed for metropolitan Phoenix on the ages of debris-flow levees that are ubiquitous on steep mountain catchments of a few thousand square meters.

A fourth reason is the paradigm held by many southwestern geomorphologists that the last period of extensive hillslope erosion took place during the transition from the wetter late Pleistocene to the Holocene. With increased aridity, infiltration capacity decreases and the location of the channel head moves upslope and excavates weathered material (Huntington, 1907; Eckis, 1928; Melton, 1965; Knox, 1983; Wells et al., 1987; Bull, 1991, 1996). The hypothesis of regional post-glacial desiccation as the key process forcing hillslope erosion continues to dominate the conclusions of southwestern USA research (Throckmorton and Reheis, 1993; Dorn, 1994; Harvey and Wells, 1994; Harvey et al., 1999; Monger and Buck, 1999; Baker et al., 2000; McDonald et al., 2003; Western Earth Surface Processes Team, 2004) with this typical wording:

> Thus, 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).

Many southwestern geomorphologists have largely restricted themselves to this narrow, theoretical, climatically driven framework (Bull, 1984, 1991, 1996) that may have affected perception of hazards associated with desert hillslopes.

A fifth reason why debris flows are not perceived as an urban southwestern USA hazard relates to the general thinking that it takes a long time to "rearm" hillslope catchments in these weathering-limited landscapes (Fig. 3). If geomorphologists accept the aforementioned climatic paradigm (Huntington, 1907; Eckis, 1928; Melton, 1965; Knox, 1983; Wells et al., 1987; Bull, 1991, 1996; Throckmorton and Reheis, 1993; Miller et al., 2001; Harvey, 2002; McDonald et al.,

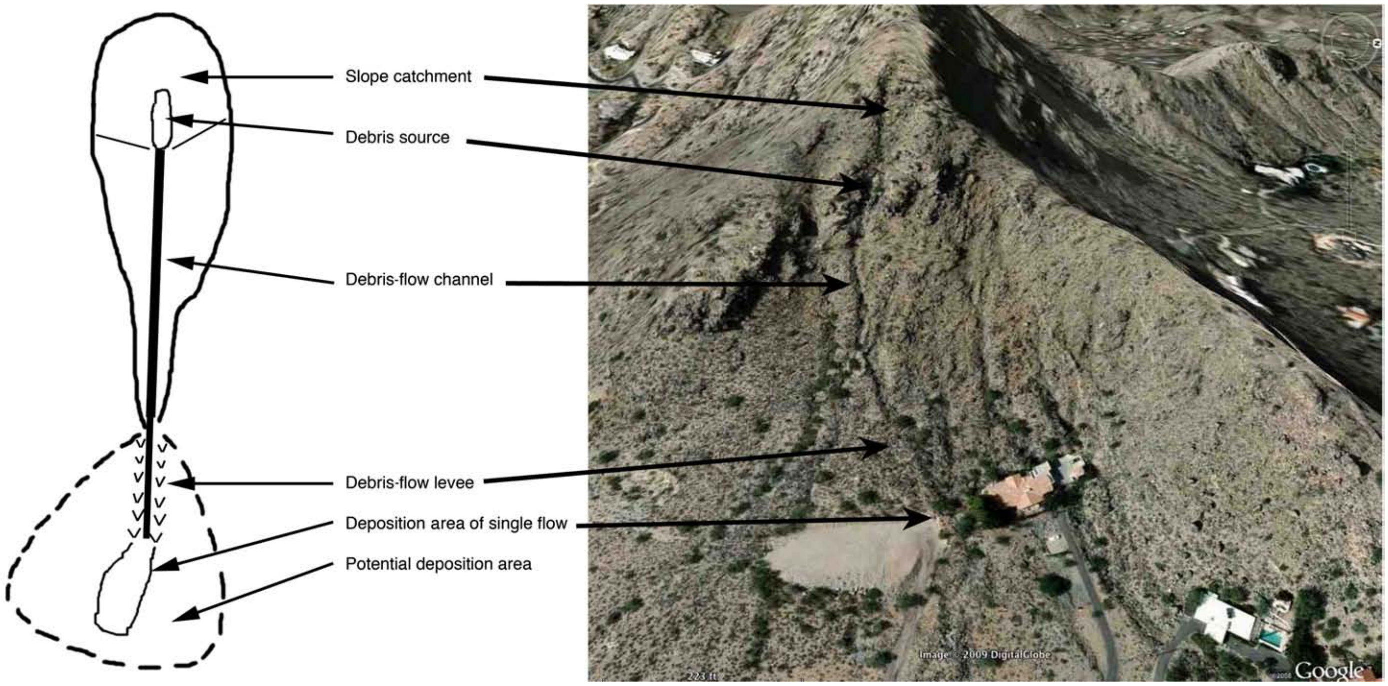

Fig. 2. Idealized diagram of a debris-flow system in small, steep drainages of central Arizona, juxtaposed against a house pad and new home construction site at Mummy Mountain, in the heart of metropolitan Phoenix. The right image is used following permission guidelines for Google Earth [http://www.google.com/permissions/geoguidelines.html].

2003), a corollary belief comes into play that a wetter climate – such as found during glacial intervals – is necessary to produce the fines and coarse debris needed to refill slope catchments that generate debris flows. The perception of time needed to resupply colluvium and fines exists, despite a lack of data on rates of physical weathering to produce coarse debris or on rates of accumulation of clay- and silt-sized dust in debris-flow catchments.

A number of reasons justify this initial assessment of small catchments in metropolitan Phoenix. First, the greater societal investment into scholarship on Arizona's earth surface processes demands that at least a pilot research project take place to assess whether tiny mountain catchments pose a hazard to lives, private property, or infrastructure. Second, this potential hazard will likely grow as other desert cities mimic the land development pattern in Phoenix, AZ. of placing high-priced homes at the aesthetic locations at the base of small desert ranges. Third, the settings where prior research has identified these small debris-flow systems as once being in mountain settings “have been restricted to mountain valleys and canyons” (Harris and Pearthree, 2002, p. 16) predates much of the mountain-front development of the last half-decade in metropolitan Phoenix (Figs. 1 and 2). These settings now juxtapose steep slopes against homes and infrastructure. Fourth, the general assumption that the debris flows are too old to be a contemporary hazard is just that, an assumption that requires assessment. Similarly, the thought that weathering processes are too slow to rearm debris-flow source catchments with fines and clasts is based on an absence of quantitative data on rates of debris production in these geomorphic settings.

An investigation into an urban debris-flow hazard is timely, because a new technique of varnish microlaminations (VML) dating has been developed recently that makes it possible to assess the ages of the debris-flow levees; key papers on this method published in this journal (Liu and Broecker, 2007, 2008c) and elsewhere (Liu and Broecker, 2008a; Liu, 2009a) include a blind test of the method (Liu, 2003; Marston, 2003; Phillips, 2003). VML measures the ages of debris-flow levees and hence can provide minimum occurrence rates for debris-flow events.

For the above reasons, pilot studies were initiated to assess the feasibility of determining the chronology of these urban debris flows, as a first step towards understanding debris flows as urban hazards in southwestern desert cities. This effort started in 2003 after publication of VML calibrations for the western USA (Liu, 2003; Liu and Broecker, 2007; Liu, 2009b) that made it possible to compile a chronology of debris flows.

Two different pilot studies were designed using two different sampling approaches. One strategy involves random selection of debris-flow catchments above urban development throughout the entire metropolitan Phoenix region. Every debris flow debauching from these randomly selected catchments is then sampled for VML dating. This metropolitan-wide pilot study is still underway. A second strategy – reported in this paper – involves every identifiable debris-flow source catchment in a single mountain range that abuts urban development.

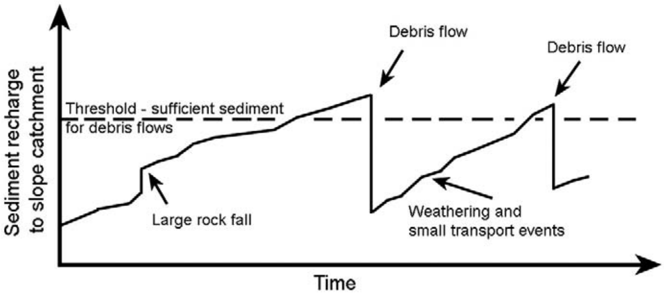

Fig. 3. A conceptual model for weathering-limited landscapes, modified from Jakob (2005), where a considerable, but unknown amount of time is required to “rearm” catchment areas with enough debris to pose a hazard. The solid line represents the notion that weathering and slope transport gradually refills the slope catchment; debris flows then empty slope catchments below this threshold. The position of the dashed line represents two often-made assumptions for slopes such as found in Phoenix: (i) that some threshold of enough fines and clasts exists to generate future debris flows of sufficient volume to reach home sites, and (ii) that debris-flow events lower catchments below this threshold.

The reason for adopting these dual strategies is two fold. First, a strategy of random sampling sites is cost effective; however, dense sampling of a single range is needed to determine if a less-intensive random sampling approach would yield comparable findings. Second, a National Research Council study on flooding hazards associated with large alluvial fans concluded that each large fan complex has its own personality – with peculiar behaviors (Committee on Alluvial Fan Flooding, 1996) – and these local characteristics should be included in a hazard assessment. While the size of the catchments and debris-flow nature of the drainages studied in this pilot research is in orders of magnitude smaller in size, not enough is known about the small debris-flow catchment systems in metropolitan Phoenix to ignore this larger research recommendation. The study of a number of drainages might make it possible to discern if different types of catchments in different types of ranges behave differently with respect to posing a systematic geomorphic hazard.

The Study site section of this paper explains the reason for the selection of the studied range and overviews the range's character. The Methods section presents field methods and summarizes the laboratory method used in VML dating. After presenting basic results, the Discussion section addresses the basic research question of whether or not small debris-flow generating catchment source areas pose a hazard to development next to small steep mountain catchments in metropolitan Phoenix — findings that may be relevant to similarly situated urban growth in desert regions in Arizona and elsewhere (Schick et al., 1999; Robins et al., 2009).

2. Study site

The Ma Ha Tuak Range is part of the South Mountain metamorphic core complex (MCC) (Reynolds, 1985) (Fig. 4). This range consists of Early Proterozoic (1600–1800 Ma) metamorphic gneiss with some granite (Reynolds, 1985; Richards et al., 2000), and the range is only 10 km south of downtown Phoenix. Much of the mylonitization that dominates the MCC took place between 24 and 19 Ma (Reynolds et al., 1986). Subsequent drainage development (Pain, 1985; Spencer, 2000) helped lead to the current parallel Gila and Ma Ha Tuak ranges at the western end of this antiformal MCC.

The range crest and the south-facing bajada rest within the largest metropolitan park in the USA, South Mountain Park. The north-facing debris-fan bajada, in contrast, is private land. Close proximity to downtown Phoenix eventually drove gentrification of the south Phoenix area in the early and mid-2000s, leading to placement of isolated homes on upper portions of fans and more densely packed single family homes on the lower sections of alluvial and debris fans.

Crest to piedmont relief in the Ma Ha Tuak Range varies from 300 to 360 m. Slopes in the debris-flow catchment areas near the crest ranges from 14° to 47°. The debris-flow transport system in the Ma Ha Tuak Range is generalized in Fig. 5. Steep catchments consist of exposed bedrock slopes and pockets of accumulated colluvium and fines. Down drainage of the debris-flow source is a debris-flow channel, typically only a few hundred meters long that is often eroded into bedrock. While levees do occur in the transport zone, in the Ma Ha Tuak Range they are more common where debris flows exit bedrock channels; these debris-flow levees lead down to depositional zones only slightly larger than catchments.

This study does not focus on initiation processes of Ma Ha Tuak debris flows. However, field inspection of each of the steep catchments indicates that the vast majority of the most recent debris flows appear to have initiated from colluvium saturation and progressive entrainment of sediment from hillslopes and channels by surface water runoff. A few of the most recent debris flows observed in these basins may have started from a landslide. Although there is no caprock in the study area, the observation that movement of water through fractures in bedrock (Coe et al., 1997) could apply in some catchments of the Ma Ha Tuak Range. Similarly, a few catchments have enough bedrock exposure to have the possibility of a small fire hose effect (Griffiths and Webb, 2004); however, the type of fire hose effect in the Ma Ha Tuak Range would be very different from the Grand Canyon. Instead of having extensive exposures of bare sedimentary rock funneling water, laminar calcrete and patches of bedrock can redirect water rapidly to the center of the catchments. There is no evidence, however, that wildfire (Wohl and Pearthree, 1991) has played a role in debris-flow generation in the study area.

The north flank of the Ma Ha Tuak Range was selected for this pilot study because of its presence adjacent to ongoing development and, more importantly, because of the presence of over 100 debris-flow-producing catchments. These catchments appear as shadowed pockets in Fig. 4. As discussed in the previous section, a sufficient sampling size in a single range is needed as a basis for future comparison with a strategy of random selection of debris-flow events throughout the Phoenix metropolitan region.

3. Methods

3.1. Field methods

Every catchment that generated a recognizable debris flow on the north side of the Ma Ha Tuak Range was located in the field with the aid of 1:1200-scale aerial photography. Debris flows were followed up drainage until each source area of the most recent debris flow could be identified. The slope of the last source area in each catchment was measured in the field. Drainage areas upslope from the last source area was measured with NIH Image (NIH, 2010) using 1:1200 scale aerial photography. Because only the most recent source area could be identified, all area and slope measurements relate to the most recent failure in each catchment.

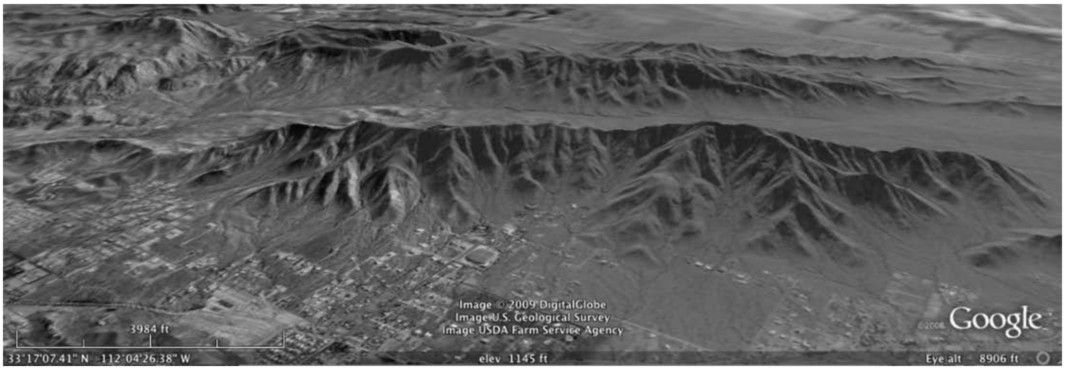

Fig. 4. A south-looking view of the 7-km-long Ma Ha Tuak Range of South Mountain, AZ., Arizona. Single family dwellings sprinkle the north-facing piedmont. Also seen in the background of this image is the parallel Gila range. The image follows permission guidelines for Google Earth [http://www.google.com/permissions/geoguidelines.html].

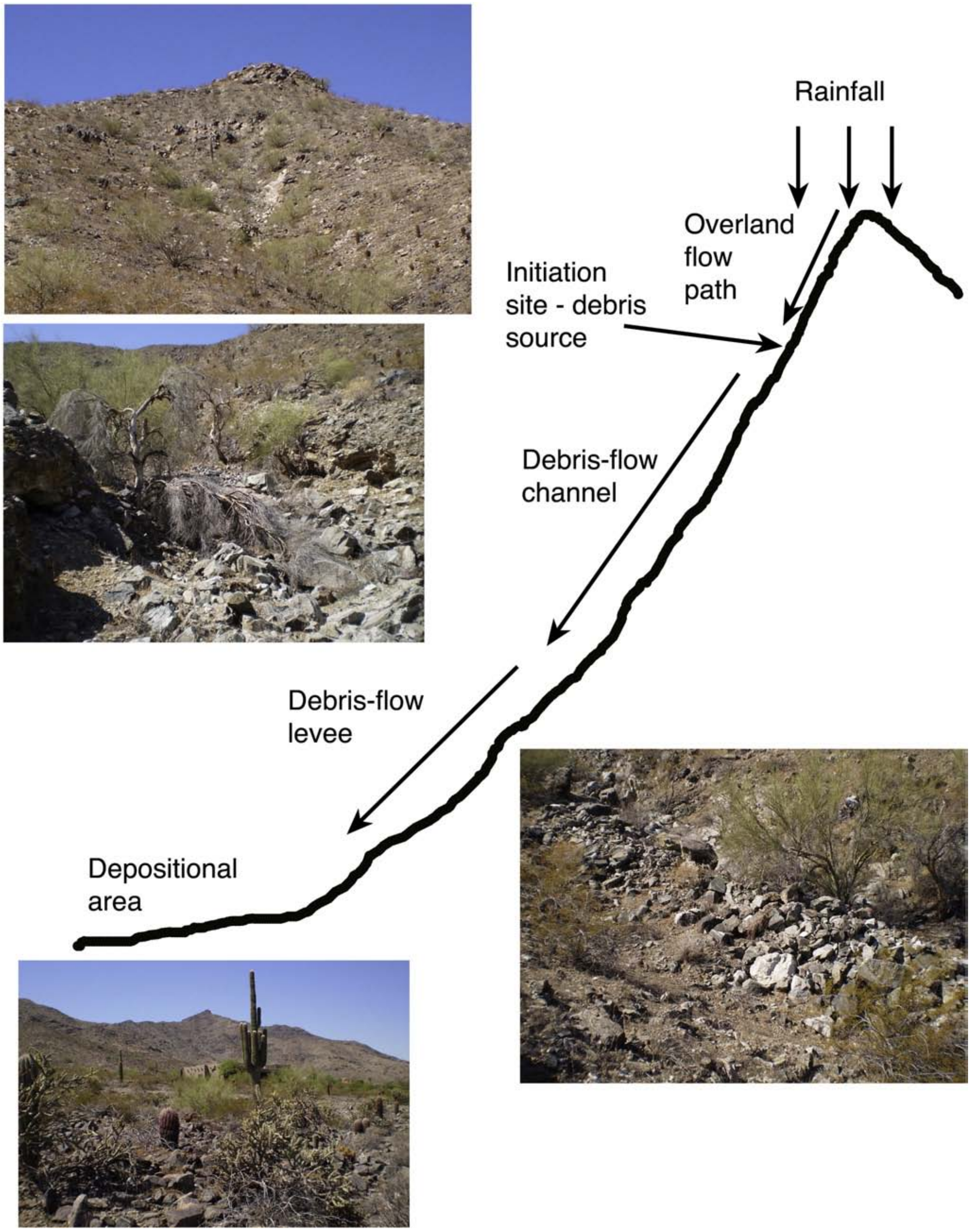

Fig. 5. The debris-flow system in the Ma Ha Tuak Range illustrated with field examples. The depositional end of the system often hosts picturesque single family homes placed directly on a depositional area dominated by debris-flow levees, exemplified here by a southwestern-style structure to the left of the saguaro.

Cosmogenic nuclides have been used to date debris flows from large source regions, with the assumption that transported clasts did not have a prior exposure history (Cerling et al., 1999; Youberg et al., 2008). Such an assumption is not reasonable for these very tiny catchments. Even the most cursory field examination of source locations reveals that much of the transported material derives from the upper meter of slope colluvium and hence would have experienced substantial prior exposure to cosmogenic nuclides. Because boulders in debris flows were likely excavated from positions on hillslopes that experienced an unknown exposure to cosmic rays, cosmogenic nuclides would yield ages far older than the failure.

The strategy used here to estimate minimum ages of debris flows in the Ma Ha Tuak Range involves characteristics of the rock coating called rock varnish (Dorn, 2007, 2009). In contrast to the problem of inheritance of an age signal with cosmogenic nuclides, the VML signal is surficial and is reset by the abrasive nature of debris-flow transport processes in the Ma Ha Tuak Range. This study became possible with the development of VML calibrations in the last few years (Liu, 2009b).

Every identifiable debris flow on the north side of the Ma Ha Tuak coming from mapped source areas was sampled for varnish microlamination (VML) dating. The sampling criteria follows the work of Liu and Broecker (2000), Liu et al. (2000), Liu (2003), Liu and Broecker (2007), Liu and Broecker (2008a,b), Liu (2008), and Liu (2009b). Chips were taken from rock-surface depressions that are a few millimeters wide. Careful examination with a hand lens resulted in the rejection of more than 90% of the boulder chips because of the obvious growth of lichen and microcolonial fungi (MCF) that are known to dissolve varnish and hence disrupt the VML layering (Dragovich, 1987, 1993; Dorn, 1998, 2007).

Examination of 300 boulders entrained by the most recent debris flows in the Ma Ha Tuak Range revealed that 67% were completely cleaned of dark black rock varnish that would have been inherited from a previous position on a hillslope. This general condition

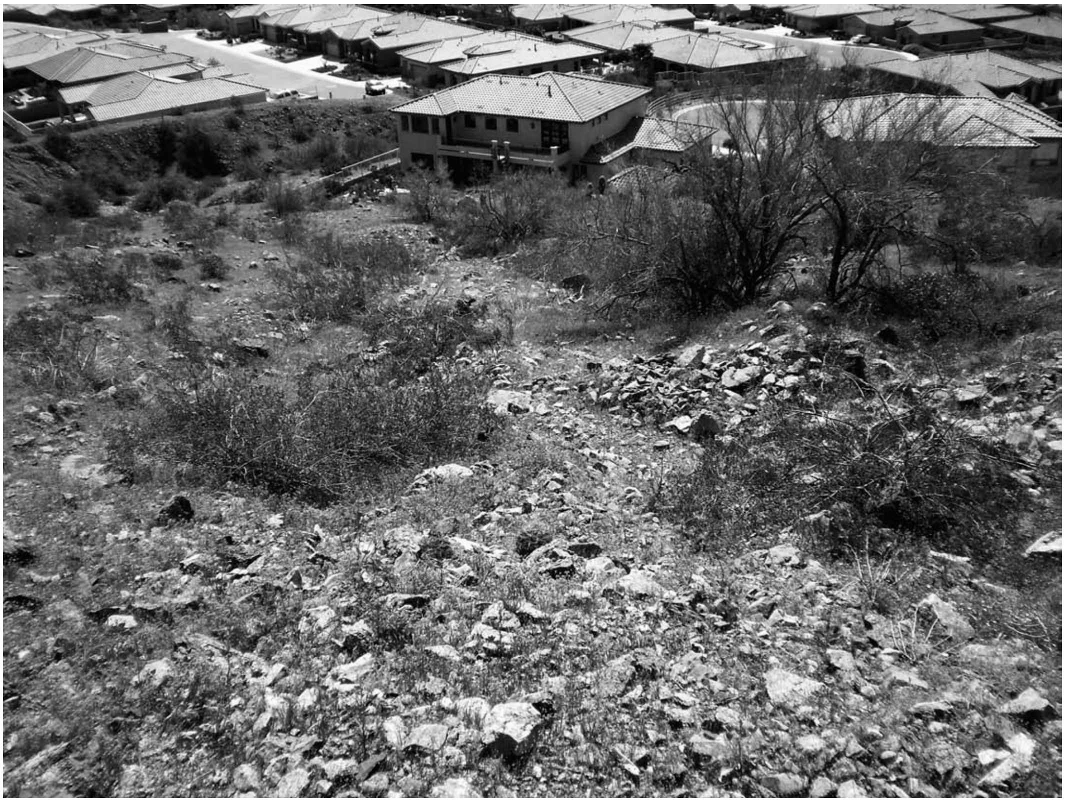

Fig. 6. Multiple debris-flow lobes from a twentieth century event, from the same site as Fig. 1. These lobes are found within larger, older levees. The light color of the clasts comes from the erosion of prior varnish, abraded during transport.

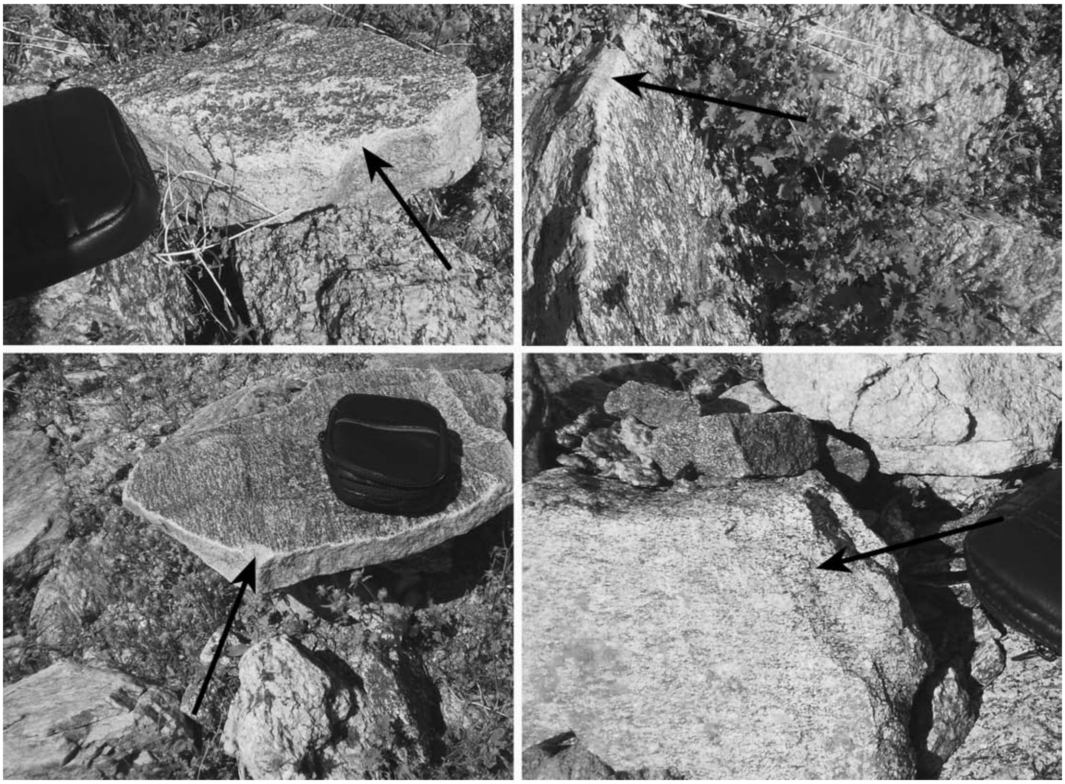

Fig. 7. The debris-flow boulders that have not had prior varnish completely obliterated by transport show removal of prior varnish on their edges (arrows). These boulders are from the debris-flow lobes in Fig. 6.

explains the overall light appearance of debris-flow lobes (Fig. 6). For those debris flows that are Holocene in age — any inherited dark black varnish surviving transport looks very different than the light brown to orange patches of newly formed varnish. Furthermore, the dark black inherited varnish has an irregular pattern of eroded varnish indicative of abrasion during transport.

The greatest difficulty in sorting out inherited from newly formed varnish rests in VML analysis of late Pleistocene debris-flow boulders where darkness is not a good tool to recognize obviously inherited varnish (Dorn, 2007). Thus, samples were collected only from the edges of the largest boulders on the debris-flow levees. Sampling on edges minimizes the chance of varnish surviving the abrasive debris-flow transport process, as illustrated in images of those boulders that did retain blotches of varnish in the most recent debris-flow events (Fig. 7).

Debris flows in small central Arizona mountains do produce multiple nested levees from debris-flow surges (Fig. 6). Nested levees for the most recent inset flow are treated as a single event, because the complex levee morphology is obviously a product of a one event. However, this assumption cannot be made for older levees. Each nested levee is thus sampled separately, realizing the possibility that each levee could be a separate debris flow to be distinguished by VML analyses.

3.2. Laboratory methods

VML dating has been detailed elsewhere (Liu and Broecker, 2007, 2008b), including the publication of a blind test (Liu, 2003; Marston, 2003; Phillips, 2003). In brief, rock varnishes with undisturbed layering are turned into ultrathin sections by polishing two sides of a sample until the varnish is thin enough to identify VML patterns. Then, the VML patterns are compared with the latest calibrations established for the western USA (Liu, 2009b).

VML dating is a correlative age-determination method that provides minimum ages. This means that particular VML patterns are compared with calibrations obtained at sites of known age. This method does not assign specific ages. Instead, varnish sequences can only be placed in age ranges. The precision of an age range can vary tremendously. In the Holocene VML calibration for the western USA (Fig. 8), the longest calibration gap of 4000 calendar years exists between layering units wet Holocene layering unit 9 (WH9) through wet Holocene layering unit 11 (WH11). In these calibration gaps, VML sequences are assigned ages based on a correlation with global climatic changes (Liu and Broecker, 2007). Fig. 9 illustrates VML patterns of varnishes with different rates of accumulation and hence different degrees of resolution. Fig. 9 presents both a rapidly forming varnish that records the three main wet phases of the WH1 Little Ice Age event (Liu and Broecker, 2007) and also a slower-forming varnish that records just the main wet Holocene events.

A second varnish dating method was used for samples where the VML age determination indicated that the debris flow was <350 calendar years, or after the WH1 (most recent wet Holocene layering unit). This VML pattern lacks the Mn-rich layer that formed in the Little Ice Age and is just an Fe film with only a little Mn-enhancement. Iron and manganese hydroxides are known to scavenge Pb and other heavy metals. Thus, twentieth century Pb pollution is recorded in the uppermost microns of rock varnish (Fig. 9). This "spike" in the very surface micron(s) from twentieth century pollution typically drops to background levels in the varnish underneath. Some samples, however, only record this contaminated varnish — with the interpretation that such contaminated samples are twentieth century in age. Confidence is reasonably high in this interpretation because

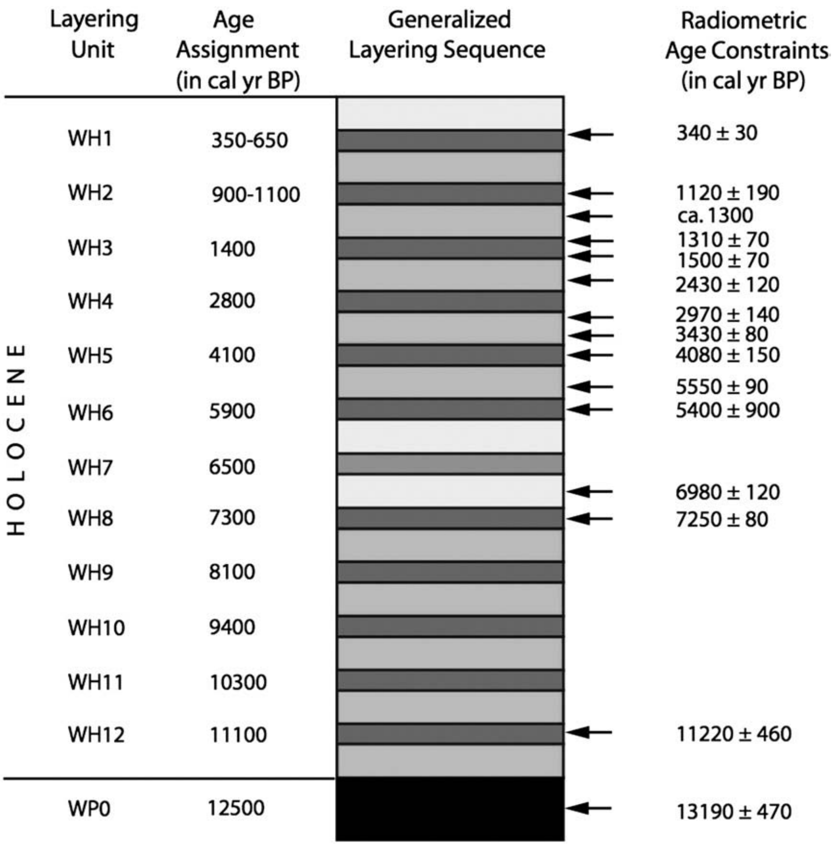

Fig. 8. The Holocene VML sequence for western USA drylands, where the different radiocarbon-based calibration sites are reflected in this stratigraphic sequence (Liu and Broecker, 2007). This figure is used with permission from Tanzhuo Liu.

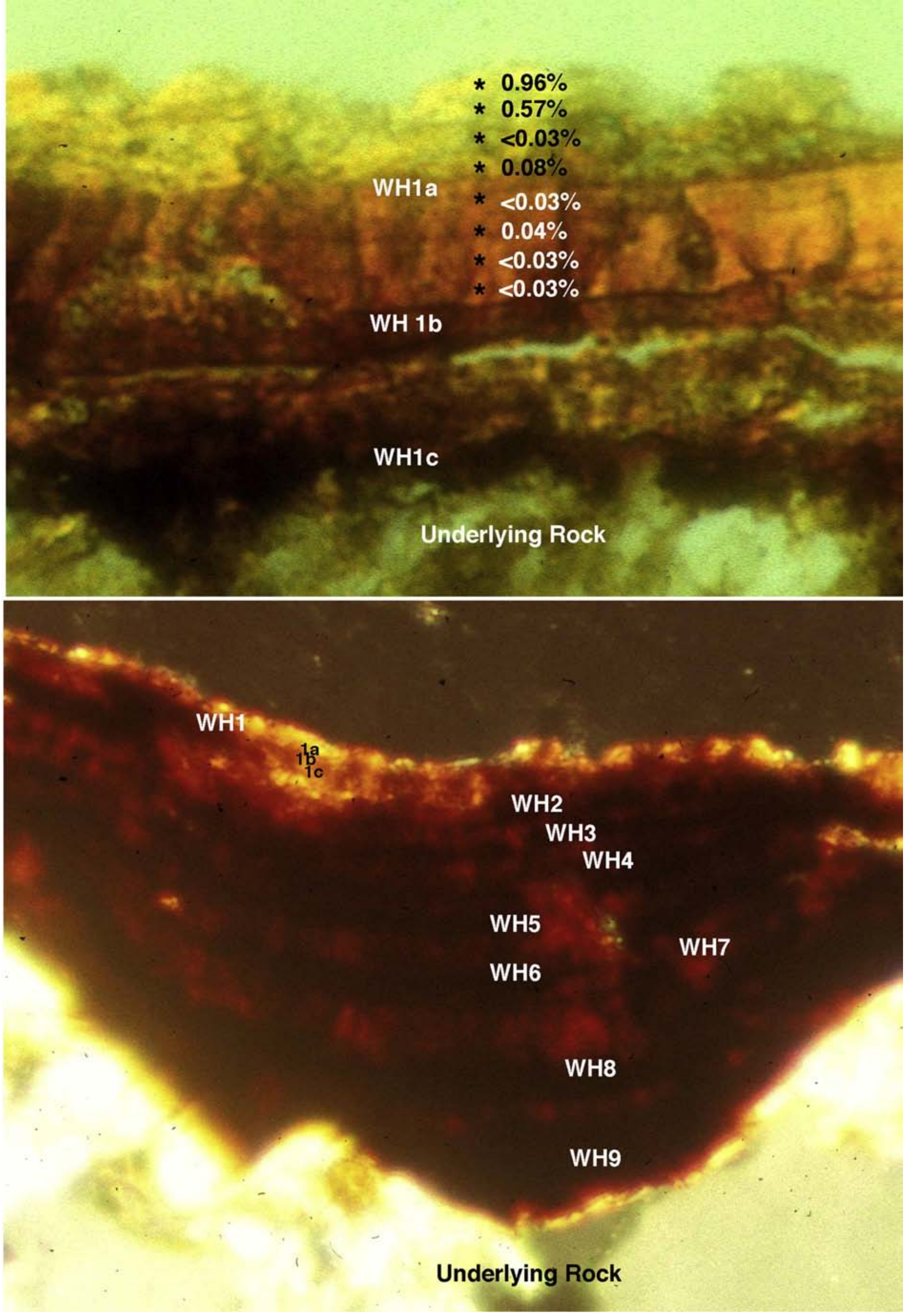

Fig. 9. Varnish microlaminations can form at very different rates. In wetter microenvironments, the rate of varnishing can preserve relatively fine paleoclimatic information. The upper section (thickness ~28 µm) shows all three wet phases of the Little Ice Age WH1 signal (Liu and Broecker, 2007): WH1a, WH1b, and WH1c. Also annotated on this section are wavelength dispersive electron microprobe analyses of PbO; these analyses show the typical pattern of lead contamination of the uppermost microns in varnish from twentieth century automobile pollution. The values are in PbO weight percent, and the approximate distance between the probe spots are 2 µm. Note how PbO drops down close to or below minimum detection limits underneath this twentieth century varnish. In contrast to the upper section, drier microenvironments slows rates of varnishing to the point where only the major wet Holocene (WH) periods are recorded, as in the lower section (thickness ~40 µm).

the method (Dorn, 1998: 139) has been replicated (Fleisher et al., 1999; Thiagarajan and Lee, 2004; Hodge et al., 2005; Wayne et al., 2006) with no publications yet critical of this nominal dating technique that discriminates twentieth century from pre-twentieth century surfaces. This technique has been used to discriminate twentieth century from pre-twentieth century petroglyphs (Dorn, 2006; Merrell and Dorn, 2009).

This study used a wavelength dispersive microprobe with a focused beam and 120-second counting time to measure lead profiles. A complication with Pb-profile dating is that the microns-per-millennium rate of varnish formation in millimeter-diameter basins favored for VML sampling will not work for Pb-profile dating. Thus, a different sampling strategy was employed for only the very youngest debris flows with just a minimal amount of varnish formation. These debris flows are particularly important to the research question because young debris flows would indicate the need for more in-depth hazard assessments. Thus, six additional samples were collected from flows that had very little varnish. The Pb-profile sampling sites were very different; the microdepressions were much larger in order to enhance water collection and rates of varnish formation. In essence, each microdepression has a race between varnishing and colonization of varnish-destroying lithobionts. Basins that have not yet had lithobiont colonization had varnishes that formed rapidly enough to date with Pb-profile dating.

In the end, Pb-profile dating only yields one of two outcomes. Either the varnish has twentieth century signal of only contaminated varnish, or some of the varnish is older than the period twentieth century pollution. Thus, if VML indicates that the varnish is <350 years (no Little Ice Age signal), but is pre-twentieth century (has underlying varnish without Pb contamination), then the varnish on debris flow would have started to form in the eighteenth or nineteenth centuries.

4. Results

The 127 catchment areas that generated identifiable debris-flow levees ranged in the slope of the debris-flow source areas from <15° to >45° with an average source area of 27° (Fig. 10). The median size of a slope catchment generating a debris flow is 1890 m^2 with 20% of the areas under 1000 m^2 (Fig. 10). No statistically significant relationship exists between drainage area and the slope of the source areas.

Of the 780 debris-flow levees identified on the north side of the Ma Ha Tuak Range, only 152 yielded VML ages (Fig. 11). In addition, those varnishes in the youngest VML category of <350 years are subdivided in Fig. 11 into those that only show a Pb-contaminated signature reflecting a twentieth century age and those coatings that have an uncontaminated layer underneath.

The reason for a 20% success rate in VML dating is the influence of MCF that bores holes into varnish and erodes VML patterns. Hand lens examination of rock chips in the field only avoids surficial growths of MCF. Unfortunately, field assessments cannot identify former MCF colonization where later varnish coated previously dissolved VML patterns. Such assessments can only be made by examining varnish cross-sections or ultrathin sections. In the end, only about one out of five samples originally collected from debris flows were suitable for VML dating because of the problem of MCF erosion of varnish microlaminae seen in cross-sections and ultrathin sections.

The research design of this study analyzes only those samples datable in a first pass at collection in order to assess the feasibility of using VML to construct a chronology of debris flows and to analyze general temporal trends of debris-flow generation. One implication of this pilot project is that future studies aiming for a more complete dating coverage should plan for iterative collection and sample preparation work to increase the number of successfully dated debris flows.

5. Discussion

5.1. Drainage area relationships

The 127 catchment areas that generated identifiable debris-flow levees did not reveal a statistically significant relationship between drainage area and the slope of the source areas, although the steepest failure slopes are found in smaller catchments. The slope measurements were made in the field of the most recent source area and are not a reflection of the slope of the catchment itself. Thus, this unclear relationship is only valid for the most recent debris flows generated in these catchments. As noted previously, only a few of most recent debris flows appear to have initiated by landslides. The remainder appears to have initiated from colluvium saturation and surface water runoff progressively entraining sediment from hillslopes and then channels.

A stronger connection could exist between drainage area and debris-flow volume. Anecdotal observations of the most recent events suggest that the largest areas generated flows that traveled further and hosted larger levees. Measurement of volume and other flow characteristics is an important next step in a hazards assessment, but one beyond the scope of this research project focused on assessing VML as a tool to measure debris-flow timing.

Catchment area does appear to be related to the age of the most recent debris-flow event. The 27 catchments generating debris flows in the last 350 years, and the nine generating debris flows during the Little Ice Age (wet Holocene layer 1, WH1) all had areas larger than 1500 m^2, and more than two-thirds came from catchments larger than 2500 m^2. Reasons may derive from the need for a larger catchment to collect precipitation during drier periods, from a dwindling supply of debris-flow materials in this weathering-limited landscape (cf. Fig. 3), from debris-flow initiation processes that are not well studied in metropolitan Phoenix, or from a combination.

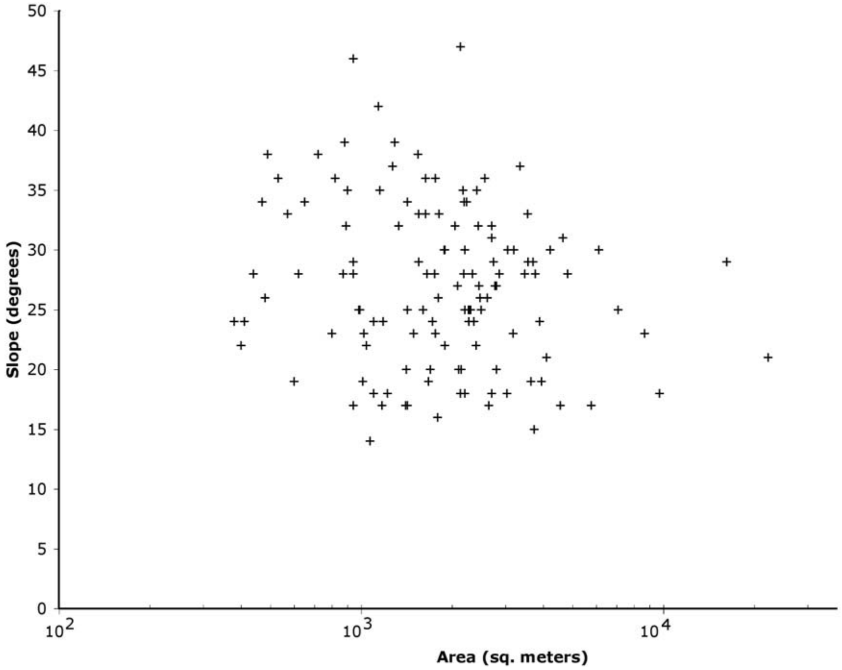

Fig. 10. Slope and area characteristics of catchments that have generated debris flows on the north side of the Ma Ha Tuak Range.

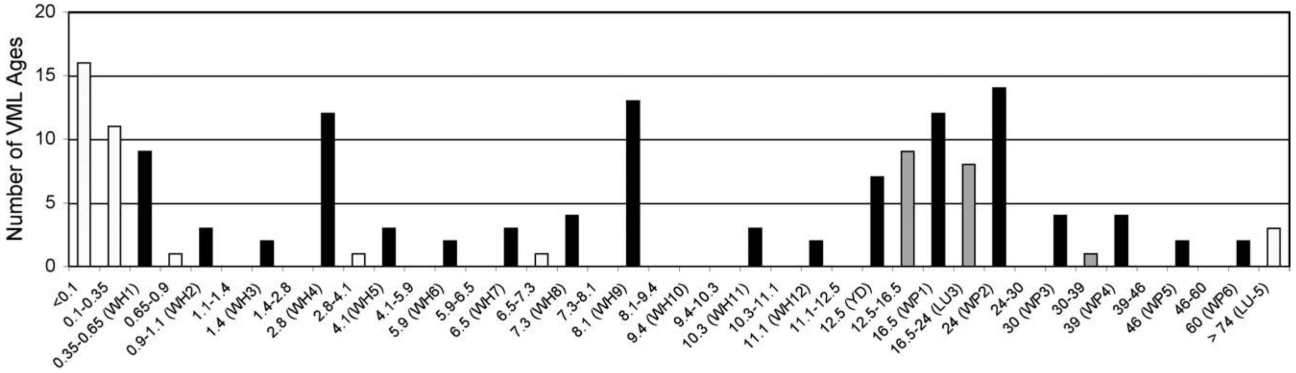

Fig. 11. Histogram of VML ages for all datable debris-flow levees on the north side of the Ma Ha Tuak Range. Ages are listed in thousands of calendar years before present. Light shading indicates that the oldest laminae formed in a dry climate period; black shading indicates the oldest varnish formed in a wet period; and grey shading reflects formation during a semiarid period. Following the Holocene and Late Pleistocene calibration studies (Liu, 2003; Liu and Broecker, 2007, 2008b; Liu, 2009b), nomenclature of WH stands for wet Holocene period, WP stands for wet Pleistocene period, YD stands for the Younger Dryas, LU3 stands for varnish layering unit 3 in the terminal Pleistocene, and LU-5 stands for layering unit 5.

5.2. Difficulties in analyzing occurrence rates

Future assessments of urban debris-flow hazards in metropolitan Phoenix and other desert cities abutting steep drainages will face a number of difficulties associated with obtaining accurate estimates of occurrence rates. One problem rests in determining how many prior debris-flow levees have been obliterated by newer flows. In the small catchments of central Arizona (e.g., Figs. 1, 2, 5), debris flows travel down the same channel; evidence of multiple events (in the form of multiple levees with different VML ages) are preserved only when older flows travel farther or when flows take different paths in a depositional area.

The observed average number of about six preserved debris flows per catchment on the north flank of the Ma Ha Tuak Range is likely a tremendous underestimate of the true number of debris flows that have occurred during the time period of levee preservation, or during the last 60,000 years (Fig. 11). The three debris-flow levees older than 74 ka that display the very dry yellow signature of layering unit 5 (LU-5) (Fig. 11) are not considered in this discussion, which is restricted to the last 60 ka. Three levees with a greater age are too few for any substantive analysis or discussion, other than to note that preservation of such ancient debris-flow levees is possible.

An argument could be made that sampled nested levees could duplicate an event. This is possible in 4 locations studied here where 2 nested levees produced the same VML ages of 2.8 ka, 8.1 ka, 8.1 ka, and 24 ka. Thus, future studies must compile VML ages of each nested levee in order to assess this potential duplication. Even with potential nested levees in four locations, an implication of this analysis is that occurrence rates, based solely on the results of preserved and dated levees, significantly underestimates the true occurrence of debris flows.

With only 152 of the 780 debris flows being datable in this first iteration of sample preparation, a reasonable assumption is that the distribution of VML ages for the remaining 528 levees should be similar to the dated debris flows. The justification for this assumption is that the flows were undatable, not because of their geomorphic position but because of the prior growth of microorganisms that secrete varnish-dissolving acids. With this assumption of a similar age distribution, 765 debris flows would have occurred over the last 60 ka with a minimum overall occurrence rate of about 1.3 debris flows per century for the entire north side of the Ma Ha Tuak Range. Although the use of this calculation in analyzing debris-flow hazards is flawed by the reality of extensive climate change in the last 60 ka, this minimum estimate may be useful in future modeling studies of Quaternary landscape evolution in deserts.

One strategy to understand occurrence rates is to split data into the Pleistocene and Holocene. Fifty datable debris flows are preserved from the latest Pleistocene, lasting from the wet Pleistocene WP2 (24 ka) to the Younger Dryas (12.5 ka). This is about one-third of the dated debris flows. With the assumption of a similar age distribution for the undated levees, the *minimum* occurrence rate of debris flows in the latest Pleistocene would be about 2.2 debris flows per century.

Considering the entire Holocene, 81 datable debris flows, or more than half, occurred in the last 8.1 ka. Assuming that the undated flows have the same temporal distribution, the *minimum* occurrence rate during the last 8.1 ka would be about 5 per century.

Twenty-seven datable debris flows occurred after deposition of Little Ice Age WH1 layer, and 11 of those contain only a Pb-contaminated signal reflecting a twentieth century age. Using the above assumptions, the *minimum* occurrence of debris flows in the last 350 years is 40/century and in the period of Pb pollution, 56/century for the entire north side of the Ma Ha Tuak Range.

The apparent increase in *minimum* occurrence rates of 1.3/century over the last 60,000 years, 5/century over the last 8000 years, 40/century in the last 350 years, and 56 in the last century of Pb pollution likely has nothing to do with an increasing threat of debris-flow activity. These figures simply underscore the superior preservation of the most recent debris-flow levees. Debris flows that occurred most recently have not been obliterated by subsequent flows. Thus, future attempts to analyze hazards might have to focus on the late Holocene, simply because of superior preservation of debris flows.

Any further study evaluating urban Phoenix debris flows in the late Holocene with VML should account for a high failure rate due to the abundance of microcolonial fungi in central Arizona. While determining a success rate in VML sample preparation was a part of this study, a failure rate of 80% might not be acceptable in a study designed to date every single preserved event in a particular catchment above houses. Future studies would need to be planned to undertake additional sample preparation in order to accommodate the destructive effects of acid-producing organisms.

5.3. Influence of climate change

A distinct advantage of the VML method is that climatic change information is an inherent component of the dating process. Analyses of thousands of sedimentary microbasins in western USA varnishes (at calibration sites) have revealed a clear correlation between VML patterns and climatic changes (Liu et al., 2000; Liu, 2003; Liu and Broecker, 2008a). Slower-forming varnishes on late Pleistocene landforms record major wet periods that correspond roughly with Heinrich Events (Liu, 2003; Liu and Broecker, 2008a,b). Faster-forming varnishes on Holocene surfaces record 11 wet intervals that roughly correspond with major northern hemisphere climatic fluctuations (Liu and Broecker, 2007). The lowest lamination, then, informs on the general climatic condition when the levee was first exposed to subaerial varnishing. The slow rate of varnishing does not permit a correlation with climatic events of a higher resolution than those seen in Fig. 8. Thus, only general conclusions are possible: such as a debris-flow event that occurred during a wetter or a drier period of the Holocene.

Even a cursory glance at Fig. 11 shows three distinct Holocene wet intervals with a greater number of preserved debris-flow levees. One spike during the Little Ice Age (WH1) could be explained by greater preservation of the most recent debris flows. However, wet periods at 2.8 ka and 8.1 ka clearly stand out as anomalous periods of likely higher production of debris flows. The ~8.1 ka event is pervasive across the Northern Hemisphere (Bond et al., 1997; Alley and Ágústsdóttir, 2005; Dergachev and van Geel, 2006), and evidence also exists for the ~2.8 ka event (Viau et al., 2002; Walker and Pellatt, 2003; Wanner et al., 2008). Still, these apparent spikes in debris-flow production would represent the first recognized geomorphic expression of these millennial-scale climatic changes in central Arizona.

The histogram in Fig. 11 reveals that only 3 of the 59 preserved debris-flow levees were deposited during dry intervals of the Holocene between WH11 and WH1. Ninety-five percent of these levee-forming events occurred during wet Holocene intervals. This analysis excludes the debris-flow levees that were generated during the period since the Little Ice Age because the histogram spikes for post-WH1 levees simply reflect obliteration of previous debris-flow levees by the most recent events.

Preserved late Pleistocene debris flows show a similar pattern of more debris flows from periods corresponding with Heinrich events. Only 36% of late Pleistocene levees time to relatively drier intervals. However, these relatively drier periods were substantially wetter than the dry intervals during the Holocene.

Two possible reasons could explain the relative paucity of preserved dry-period Holocene debris flows. One reason could be that fewer debris flows occurred during drier Holocene intervals. A second reason could be that the drier Holocene interval debris flows were not preserved as well because they were smaller and hence were

Fig. 12. Contemporary debris flow in metropolitan Phoenix that would have been extensive enough to do substantial property damage if it had occurred in context similar to Fig. 2. (A) The January 18–22, 2010 precipitation event generated a 0.5 km-long debris flow at Elephant Mountain on the northern margin of metropolitan Phoenix. (B) Although the source rests underneath basalt bedrock, it does not appear as though a landslide initiated this debris flow. (C) Failure occurred in weathered basalt, where movement of water through fractures in bedrock (cf. Coe et al., 1997) likely contributed to the more than 100 mm of precipitation that fell in one day. (D) The bedrock channel lacks levees. (E) The sudden transition from bedrock channel to levee deposition is similar to the Ma Ha Tuak Range. Examination of 100 boulders in levee deposits indicate that only 11 shows evidence of inherited varnish, and the edges of those boulders with inherited varnish all show abrasion of inherited varnish.

more easily obliterated by the subsequent debris flows generated during wetter Holocene intervals. This is also the case in southern Arizona, where Youberg et al. (2008) similarly found that older Pleistocene debris flows were more extensive than the younger, smaller, inset Holocene events. The most recent Ma Ha Tuak debris flows, from the last 350 years, are typically in positions inset inside of more extensive older levees. These two explanations are, thus, not mutually exclusive.

One implication of this analysis is that debris flows produced during wetter intervals would pose a greater danger to development. Debris flows with larger volumes would travel the greatest distance toward homes. More frequent debris-flow events would similarly place more homes in danger. A detailed analysis of debris-flow volume and distance traveled would be a next important step in assessing the hazard of these debris-flow channels.

6. Is there or is there not a debris-flow hazardous condition in metropolitan Phoenix?

Is the occurrence rate of a minimum of 56 debris flows in the last century considered a hazard for property owners on the north flank of the Ma Ha Tuak Range? Rain gauges at South Mountain recorded ~70 mm of precipitation from January 18–22, 2010, leading to three small debris flows on the north side of Ma Ha Tuak Range that traveled 40 m, 80 m, and 130 m. Since properties and infrastructure are located far down the piedmont where these and larger twentieth century debris flows had insufficient volume and distance to impact home sites, the answer to the hazard question is probably not.

On the other hand, if results for the Ma Ha Tuak Range are representative of metropolitan Phoenix's smaller steep drainages, then would a debris-flow event in the last century in 13% of the catchments be considered a hazard for property owners? If the home is in a position similar to those seen in Figs. 1 or 2, resting at the base of a debris-flow channel and requiring relatively little flow volume or distance to impact a dwelling, perhaps yes. An estimate of 56 flows in the twentieth century debauching from the north side of the Ma Ha Tuak range should make any owner of a home underneath a debris-flow channel nervous.

At this point, unfortunately, too many uncertainties exist to make a solid hazard assessment. First, although observations of catchments suggest that landslides are not the major process of debris-flow initiation and that processes saturation of colluvium from prolonged or intense precipitation (cf. Griffiths et al., 2009) appear to have generated the most recent Ma Ha Tuak debris flows, more research is needed on processes of debris-flow initiation in the tiny catchments in urban Phoenix. Second, little is known about precipitation intensities needed to generate debris flows in these small catchments. In metropolitan Phoenix, a number of small debris-flow events occurred in response to the January 18–22, 2010 precipitation events, including the three aforementioned flows on the north side of the Ma Ha Tuak Range. The synoptic conditions associated with this precipitation event were such that the northern portions of metropolitan Phoenix recorded the most precipitation. The most extensive debris-flow event yet identified took place at Elephant Mountain on the northern fringe of metropolitan Phoenix, traveling ~0.5 km with an elevation drop of 270 m (Fig. 12). The nearest precipitation gauge recorded 158 mm on precipitation during this period, with 104 mm taking place in one day. The debris flow was first observed on January 23, so it is not known when failure occurred. However, a debris flow of this size – if it had occurred in catchments of Ma Ha Tuak Range closest to private property – could have reached home sites. Certainly, a debris flow of this size would have had tragic consequences if it had occurred where homes are found underneath debris-flow channels (e.g. Figs. 1, 2, 6).

A third uncertainty has been the lack of analysis of available rainfall data to model the probability of the type of rare precipitation event generating the type of debris-flow event as seen at Elephant Mountain (Fig. 12). Fourth, no study has analyzed the size of a catchment that would have a sufficient amount of debris and fine materials to “arm” a debris flow capable of reaching homes downslope from channels. Fifth, rates of physical weathering to generate the debris-flow boulders and rates of dust accumulation in catchment areas are unknown at present. Hence, no estimates exist for the length-of-time needed to rearm catchments with debris-flow material. Sixth, studies of debris-flow volume and distance traveled are needed to assess connections between flow age and hazard.

An added complication is the general lack of consistency in how to conduct a debris-flow hazard analysis. Although some countries such as Austria have specific guides on how to map and quantify debris-flow hazards (Fiebiger, 1997), in “North America, debris-flow recognition, hazard assessment, and mitigation design are, in comparison, still in their infancy …” (Jakob and Hungr, 2005). There is agreement, however, on the six general steps in analyzing debris-flow hazards (Jakob, 2005): (i) recognizing that debris-flow hazards exist in an area; (ii) start the process of estimating the occurrence rates and hence probability of a future debris flow; (iii) estimate debris-flow magnitude/intensity; (iv) calculate frequency–magnitude relationships; (v) understand design issues related to magnitude/intensity issues; and (vi) present a mapping of these quantified relationships. This research project has started the first two of Jakob's (2005) steps.

Declaring that a serious hazard does or does not exist would require first addressing the aforementioned uncertainties and completing Jakob's (2005) hazard assessment steps. The findings of this research, however, do make a strong case that additional studies of debris-flow hazards in metropolitan Phoenix are needed.

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