

# PHOENIX DEBRIS-FLOW HAZARD ASSESSMENT: HOUSE LOCATION MATTERS

*Matthew Moore*,<sup>1</sup> *Gregory Kraetz*, and *Ronald I. Dorn*  
**School of Geographical Sciences and Urban Planning**  
**Arizona State University**  
**PO Box 875302**  
**Tempe, Arizona 85287-5302**

*Abstract:* Three catchments that debouch into Phoenix housing developments from the Ma Ha Tuak Range, South Mountain show a consistent pattern of declines in the magnitude of debris flows over time. We used a mix of field and geospatial methods to estimate volume, and the varnish microlamination technique to estimate minimum ages of debris deposits. Estimates of debris-flow volumes show a drop of more than two orders of magnitude from latest Pleistocene to 20th century or Little Ice Age. Debris-flow run-out lengths also shortened tremendously, with the most recent events stopping inside incised channels. In contrast, a catchment above houses in the Gila Range, South Mountain, where houses were built very close to the debris-flow source area, reveals an increase in debris-flow magnitude over time. These contrasting findings emphasize the importance of the location of home sites with respect to the debris-flow system in the type of small desert mountain catchments that interface with the sprawling urbanism found in Southwestern USA deserts. [Key words: debris flow, hazard assessment, rock varnish microlamination, Phoenix, Arizona.]

## INTRODUCTION

Debris flows consist of mud and rock that move rapidly down steep mountain slopes (Innes, 1983; Costa, 1984; Wohl and Pearthree, 1991; Iverson, 1997). Where development occurs next to steep mountains, debris flows are often recognized as important natural hazards (Cooke, 1984; McCall, 1997; Glassey et al., 2002; Jakob and Hungr, 2005). However, debris flows are generally not viewed as hazardous in southwestern USA cities, such as metropolitan Phoenix, where sprawling homes and urban infrastructure now abut over 50 different mountain masses. Instead, the urban wealthy purchase homes at the base of steep mountain slopes to enjoy the amenities of enhanced views and being able to walk from a backyard into mountain preserves originally designed to protect open space (Ewan et al., 2004).

Prior to the housing boom of the early 21st century, the Arizona Geological Survey home owner's guide appropriately indicated that "[m]ost of the debris flows that have occurred in Arizona in the past several decades have been restricted to mountain valleys and canyons" (Harris and Pearthree, 2002). The housing boom that preceded the Great Recession of 2007–2009 (Elsby et al., 2010) changed the landscape context of many homebuilding sites. Instead of being in subdivisions built

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<sup>1</sup>Corresponding author; email: matthew.moore-1@mnsu.edu

distant from steep slopes, homes were built on the piedmont slopes or inside mountain canyons. With this changing reality and following a major debris-flow event outside of Tucson (Pearthree and Young, 2006; Webb et al., 2008; Youberg et al., 2008), the Arizona Geological Survey now considers it possible that debris flows could potentially be an underappreciated hazard in Arizona (Pearthree et al., 2007).

The first steps in a hazards analysis involve understanding whether a potential debris-flow hazard exists and estimating recurrence rates (Jakob, 2005). A recent study of debris flows on the northern, Phoenix-adjacent side of the Ma Ha Tuak Range of South Mountain, central Arizona, revealed a minimum occurrence rate of 56 flows in the last century. Another study of mountains scattered throughout metropolitan Phoenix revealed the presence of 20th-century debris flows in four of the nine randomly selected catchments above home sites (Dorn, 2010, 2012). This prior work, thus, identified the existence of a debris-flow hazard in metropolitan Phoenix and provided some idea of potentially hazardous recurrence rates.

The next step in a hazards analysis, carried out in this study, involves developing a better understanding of debris-flow magnitude over time and mapping these relationships (Jakob, 2005). This paper presents an initial study testing the hypothesis that debris-flow volume and run-out lengths in the Ma Ha Tuak Range have declined substantially since the end of the last ice age. The study site section explains the context of the studied catchments. The method and results sections explain the approach and data gathered in measuring ages and estimating volumes. The discussion section then turns to the issue of whether or not debris flows pose a hazard to homes and infrastructure in metropolitan Phoenix—and, by extension, homes placed in similar context in other cities next to desert mountains.

## STUDY SITES

A partial inventory of debris-flow pathways determined that hundreds of debris flow-producing catchments interface with metropolitan Phoenix (Dorn, 2012). An ideal site selection process would be to use a random sampling procedure based on explicit criteria, such as distance from range crest to homes, rock type, the presence of exposures to constrain volume, and other factors. However, because students helped carry out this study, ease of access and proximity to Arizona State University were factors in the site selection.

Another constraint in the selection of catchments for this study was the existence of age control on debris-flow deposits. Study sites were limited to catchments with extant varnish microlamination age control. Rock varnish microlamination (VML) dating and lead-profile dating had previously dated debris flows on the north side of the Ma Ha Tuak range and in randomly selected catchments scattered through metropolitan Phoenix (Dorn, 2010, 2012).

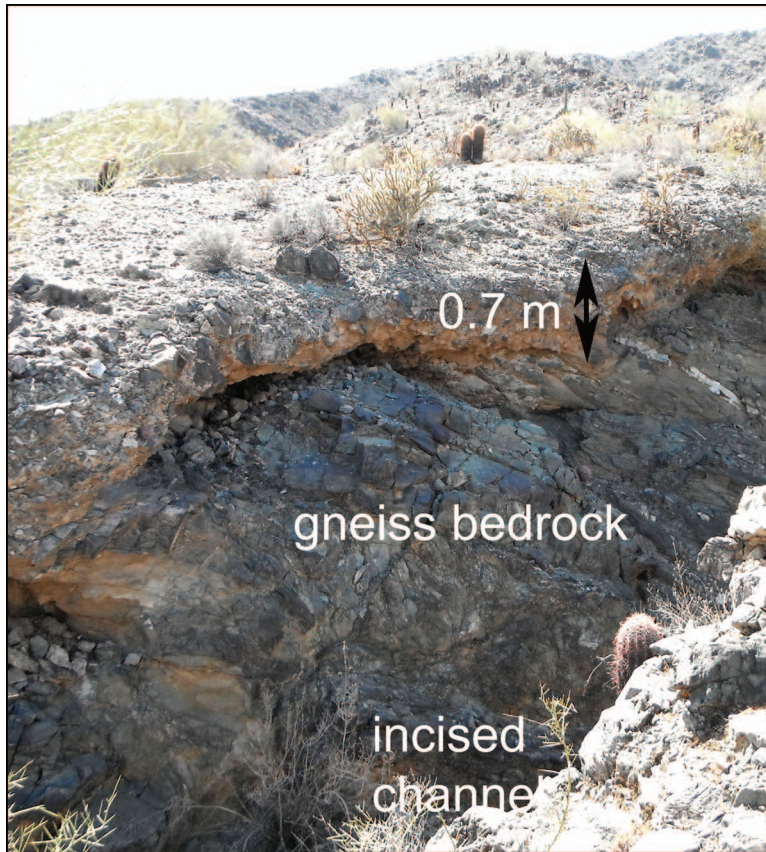
We first selected three catchments in the Ma Ha Tuak range (Fig. 1) using as the selection criterion the best exposures of debris-flow thicknesses. A hazards analysis (Jakob, 2005) requires understanding changes in volumes over time, and volumes require reasonable estimates of flow thicknesses. The selected basins contain locales with the cleanest cross-sections of debris-flow units resting directly on top of bedrock (Fig. 2) or deposited on top of petrocalcic calcrete representing the top of an



**Fig. 1.** South Mountain is in the southwestern portion of metropolitan Phoenix, surrounded by a sprawling city. The studied catchments are the southern and northern sides, respectively, of South Mountain Park's Gila and Ma Ha Tuak ranges. The images are used following permission guidelines for Google Earth [<http://www.google.com/permissions/geoguidelines.html>].

older unit (Fig. 3). We refer to the basin numbers indicated on Figure 1 throughout this paper.

We also include a catchment at South Mountain (Fig. 1) that was selected through a random site selection procedure (Dorn, 2012). There were several reasons for



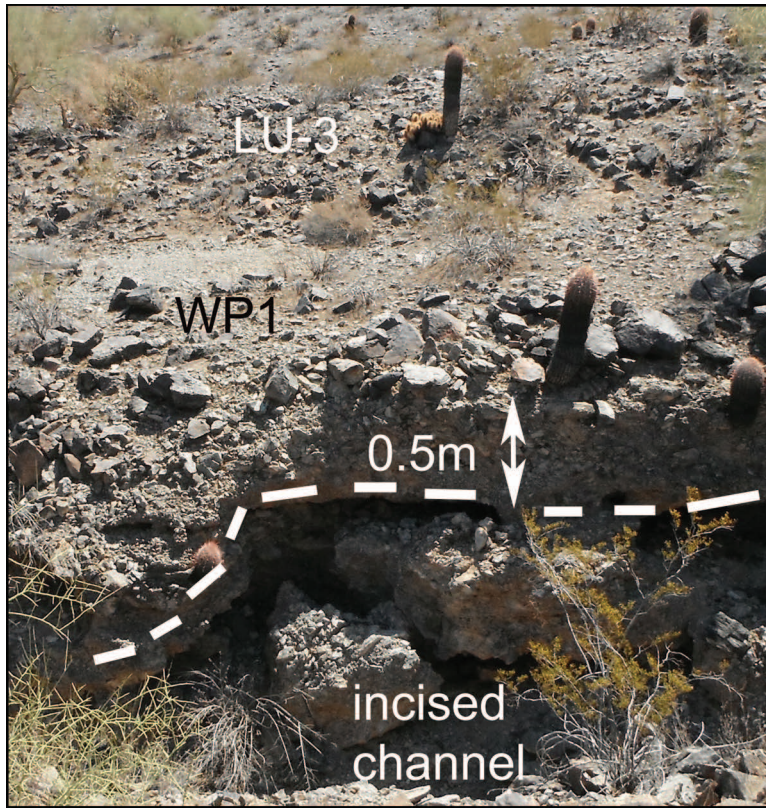
**Fig. 2.** The incision of the major wash exposes a cross-section of the LU-3 debris-flow unit directly on top of bedrock in basin 1. This particular exposure is of a swale (low area) that contains smaller particle sizes. Boulder levees add another 1–2 m to the unit thickness.

including Gila Range site 4 in this pilot analysis. First, this site also abuts development in the city of Phoenix. Second, the catchment is much smaller than those found in the taller Ma Ha Tuak range. Third, home sites at Gila Range site 4 lie much closer to steep mountain slopes and inside a mountain canyon. Fourth, the Xm early Proterozoic gneissic lithology is the same as that of the Ma Ha Tuak drainages. Lastly, VML ages have been determined for different debris-flow deposits at site 4 (Dorn, 2012).

## METHODS

### *Identify and Measure the Age of Debris-Flow Units*

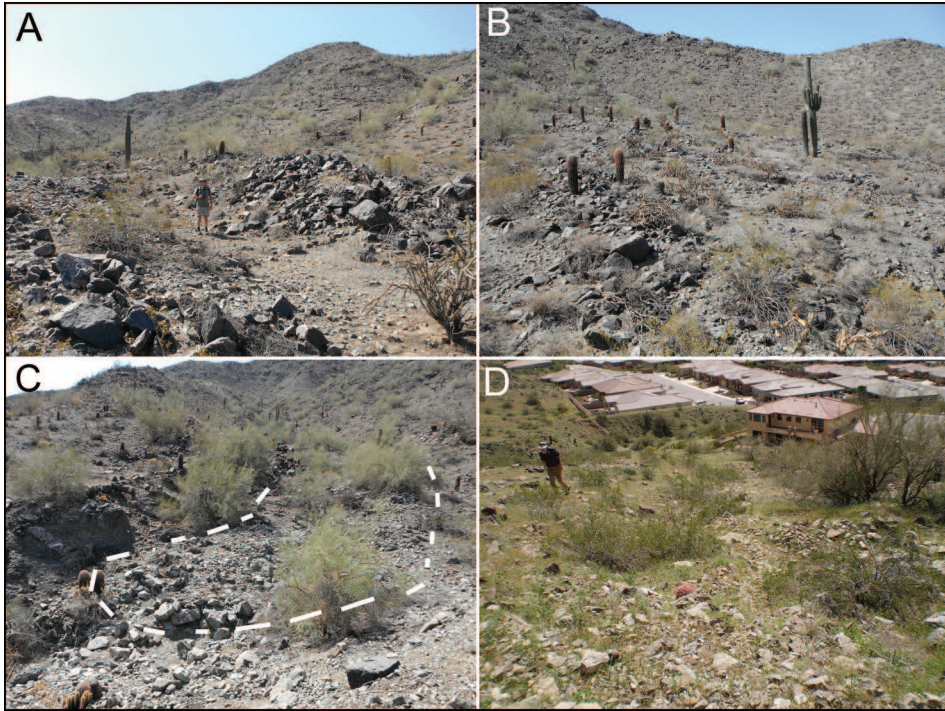
Each of the different units with a distinctive morphology and position had been previously analyzed for VML dating (Dorn, 2010, 2012), with the presented ages



**Fig. 3.** The incision of the major wash exposes a cross-section of the WP1 debris-flow unit directly on top of a calcrete in basin 2. The dashed line indicates the contact, where the calcrete represents the top of an older unit. The WP1 unit is inset inside of a much more extensive and older LU-3 debris flow unit.

based on three VML cross-sections. The general concept of VML dating is that climatic changes alter rock varnish layering patterns. Wetter periods produce manganese-rich black layers. Semi-arid climates generate orange, Mn-intermediate layers. The driest periods generate yellow layers with the least amount of manganese. The patterns have been calibrated at locations using independent age control (Liu, 2003, 2012; Liu and Broecker, 2007, 2008a, 2008b). The VML method generates age brackets, such as younger than 350 years, between 350 and 650 years ago, or between 900 and 1100 years ago.

All VML ages are minimums, because rock varnish formation post-dates deposition of the debris flow. Although the VML technique only provides rough minimum ages, it is one of the few methods available for estimating debris-flow ages in metropolitan Phoenix. This is because organic matter appropriate for radiocarbon dating is extraordinarily rare, and cosmogenic nuclide analyses suffers from the problem of



**Fig. 4.** Debris-flow deposits with different ages often have a distinctive surface characteristics. A. LU-3 deposit from basin 2. B. WP1 (Heinrich Event 1) unit from basin 3. C. WH1 (Little Ice Age) unit from basin 2. D. Post-WH1 (20th century) unit from basin 4. Saguaro (*Carnegiea gigantea*), creosote bush (*Larrea tridentata*), Palo Verde (*Parkinsonia aculeata*), and humans provide a sense of scale.

prior exposure history being a far more dominant factor than the potentially young ages of the debris flows.

Where the VML method revealed ages younger than the Little Ice Age, lead-profile dating is able to assess whether the flow dated from the 20th century. Lead pollution in the 20th century leaves behind a spike in lead and other heavy metals. This is a nominal dating method, in that either the sample contains only a lead-contaminated signal throughout the rock coating and is 20th century, or the varnish contains “background” levels of lead underneath the contaminated surface and is pre-20th century. This method (Dorn, 1998) has been replicated throughout the western United States (Fleisher et al., 1999; Nowinski et al., 2010; Hoar et al., 2011). More detail on the lead-profile and VML dating as applied to debris flows can be found in prior work (Dorn, 2010, 2012).

The different debris-flow units in the studied basins have distinctive morphologies and ages as measured by varnish microlaminations. We used VML ages for our nomenclature in mapping different debris-flow units. For example, the most aerially extensive unit from the latest Pleistocene (LU-3) is characterized by boulder levees as high as 2 m (Fig. 4A) that alternate with swales that contain much smaller particle

sizes (Fig. 2). The terminal Pleistocene, Heinrich event 1 deposit (WP1) also has boulder levees alternating with swales, but the boulder sizes and levee heights are much more subdued (Figs. 3 and 4B). Holocene units in basins 1, 2 and 3 in the Ma Ha Tuak range are mostly deposited inside entrenched channels, as exemplified by the Little Ice Age (WH1) deposit in basin 2 (Fig. 4C). In contrast, in Holocene units at the Gila Range site, such a series of 20th-century debris-flow lobes in basin 4 (Fig. 4D) are not found in incised channels.

### *Radiocarbon Dating*

Finds of woody tissue appropriate for radiocarbon dating are rare in the Sonoran Desert. However, we did find one branch of a Palo Verde (*Parkinsonia aculeata*) tree embedded in a debris-flow levee that was truncated by an ephemeral wash. The sample came from a levee in the WH1 unit in Basin 2 (Fig. 1) and was submitted to Beta Analytic for conventional radiocarbon counting.

### *Mapping and Measuring Volumes of Debris-Flow Units*

Mapping and measurement of volume was limited to the area above house sites, either constructed homes or housing pads. While understanding the volumetric changes of the entire debris-flow system is an important basic science question, our focus rests on understanding the potential hazard for those houses that could potentially suffer damage or destruction.

The various debris flow units were mapped on aerial imagery embedded in ArcGIS. Boundaries between different units were identified in the field and mapped on high-resolution imagery. Each mapped unit consists of a polygon. The measure tool in ArcGIS provides area for each unit. For each basin, we compiled the total area of each of the different-aged units.

The measurement of volume requires an estimate of the depth of each mapped unit. Depth measurements of the LU-3 and WP1 units were possible where these units were exposed in cross-sections on top of bedrock (Fig. 2) or in a petrocalcic horizon representing the top of an older, buried unit (Fig. 3).

Unfortunately, cross sections were not available for the oldest WP3 unit, which consists of large, isolated levees. The height, top width, and bottom width of the WP3 levees were measured at multiple positions, and the cross-sectional area of each levee was calculated assuming the levee had the shape of a trapezoid. The average cross-sectional area was then multiplied by the cumulative length of all of the WP3 levees to yield the volume of the oldest unit.

We used a similar strategy to estimate the volumes of the Holocene deposits. Levee heights were measured at multiple positions and averaged. Cross-sectional areas varied, depending on the shape of each levee deposit. While levees do naturally occur in simple geometric shapes, we made approximations to facilitate volume estimates. In plan views, some levees consisted of broad lobes and resembled rectangles, whereas others were narrow and resembled triangles. These interpreted shapes provided different cross-sectional areas to then be multiplied by levee lengths.

The volumes of the varied shapes were compiled and the total volume of each aged unit was estimated by summing the volumes of the interpreted shapes.

## RESULTS

### *VML Ages of Debris-Flow Units*

The VML ages reported here are based on ultrathin varnish cross-sections measured from each of the sampled units. The oldest VML age of WP3 obtained for a debris-flow unit is a minimum age of 30 ka (thousands of calendar years ago) that corresponds with Heinrich Event 3 (Fig. 5). The WP3 unit consists of linear islands of 2 m tall levees surrounded by younger deposits. As is typical, the oldest preserved units occur closest to the mountain front and distant from the largest drainage.

The most extensive unit of the three Ma Ha Tuak basins has a distinctive VML pattern of LU-3, a climatic period between Heinrich Events 2 and 1, roughly constrained to have occurred between 24 ka and 16.5 ka (Fig. 6). This deposit is characterized by boulder levees higher than 1 m, separated by swales with much smaller particle sizes (Figs. 2 and 4A).

The second most aerially extensive debris flow unit (Fig. 4B) was deposited during the Heinrich Event 1 wet climate period (WP1), about 16.5 ka ago (Fig. 7). The WP1 deposit forms most of the surface of basin 3, but also occurs as deposits inset into the older LU-3 unit (Fig. 3) in basin 2.

The Holocene units with distinctive VML ages (Fig. 7) typically occur within the incised channels of basins 1, 2 and 3 of the Ma Ha Tuak Range. These Ma Ha Tuak deposits range in age from 2800 calendar years before present (cal yr BP, WH4 in Fig. 7) to 20th century in age (post-WH1 in Fig. 7).

### *Radiocarbon Age of WH1 Unit*

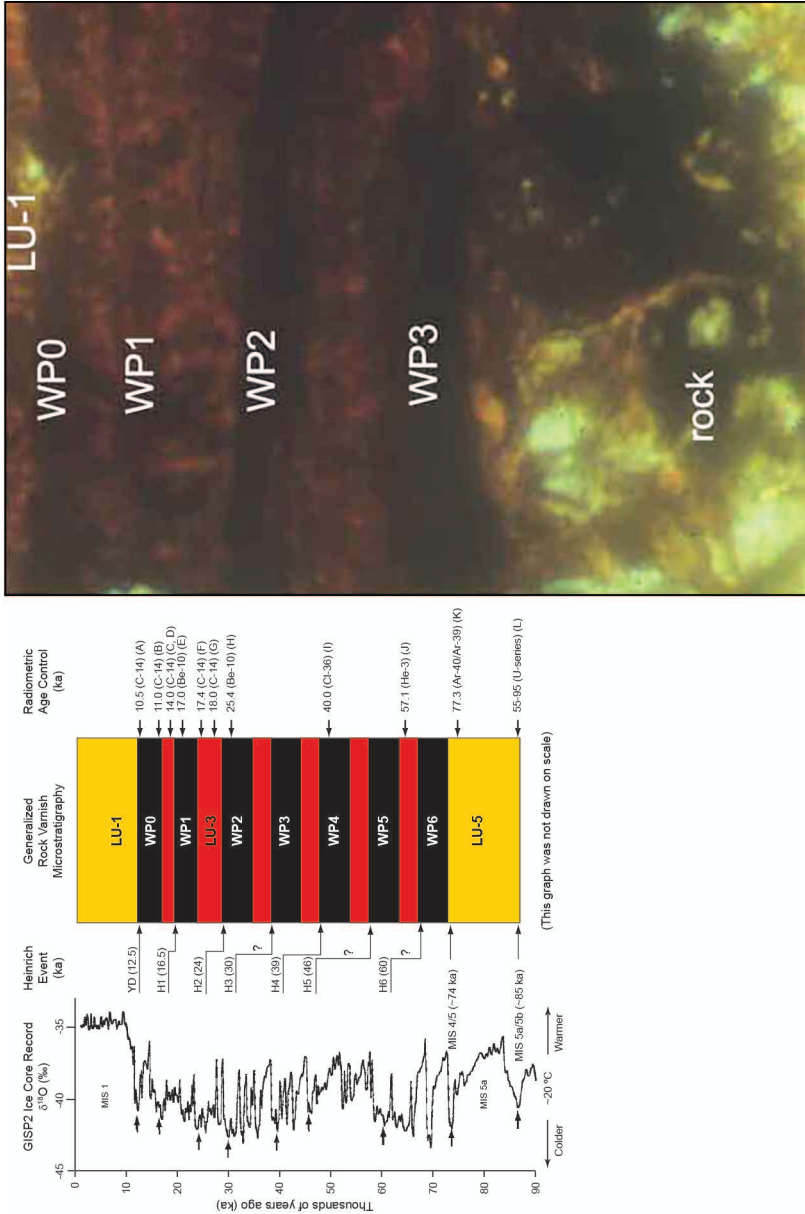
The single sample of Palo Verde (*Parkinsonia aculeata*) wood from the WH1 unit in Basin 2 yielded a conventional radiocarbon age of  $110 \pm 30$  (Beta 322780). The 2-sigma calibrated calendar age has several possibilities in this time frame, including: Cal AD 1680 to 1760, Cal AD 1770 to 1780, Cal AD 1800 to 1940, and Cal AD post-1950. These results are consistent with the Little Ice Age time frame indicated by VML.

### *Mapping Results of the Four Basins*

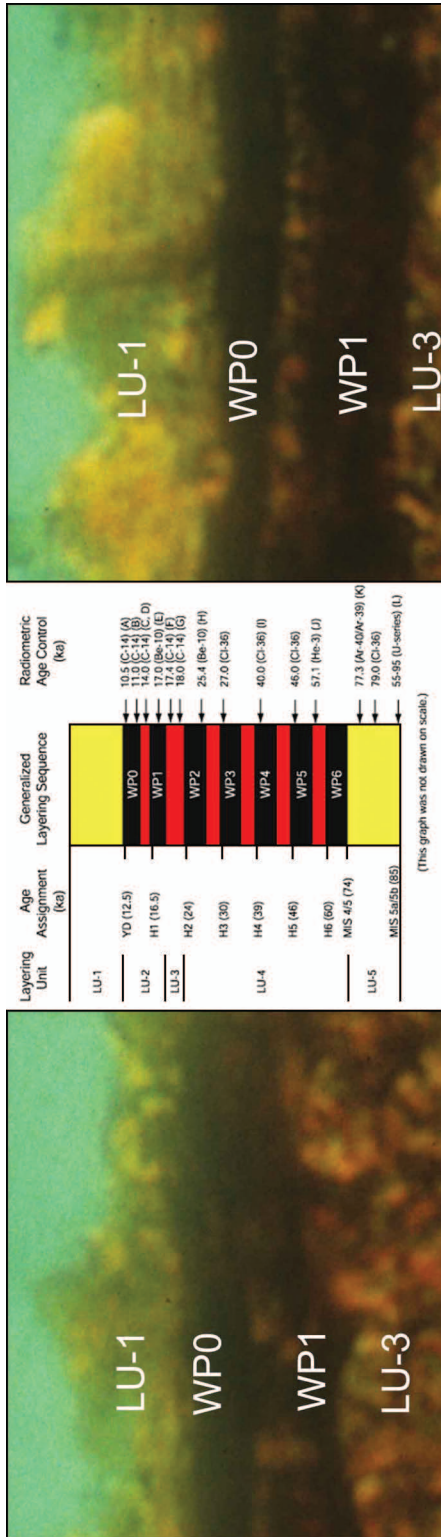
Figures 8–10 present the surficial occurrence of debris-flow deposits of different ages for basins 1, 2, and 3 in the Ma Ha Tuak Range (Fig. 1). Each basin reveals a slightly different pattern, where mapping was limited to areas above the highest house or house pad.

The most voluminous unit in Basin 1 (Fig. 8) is the latest Pleistocene LU-3 unit. Although many more debris flows likely moved through the channel incised into LU-3, only two are preserved: a late Holocene unit deposited between 1400 and

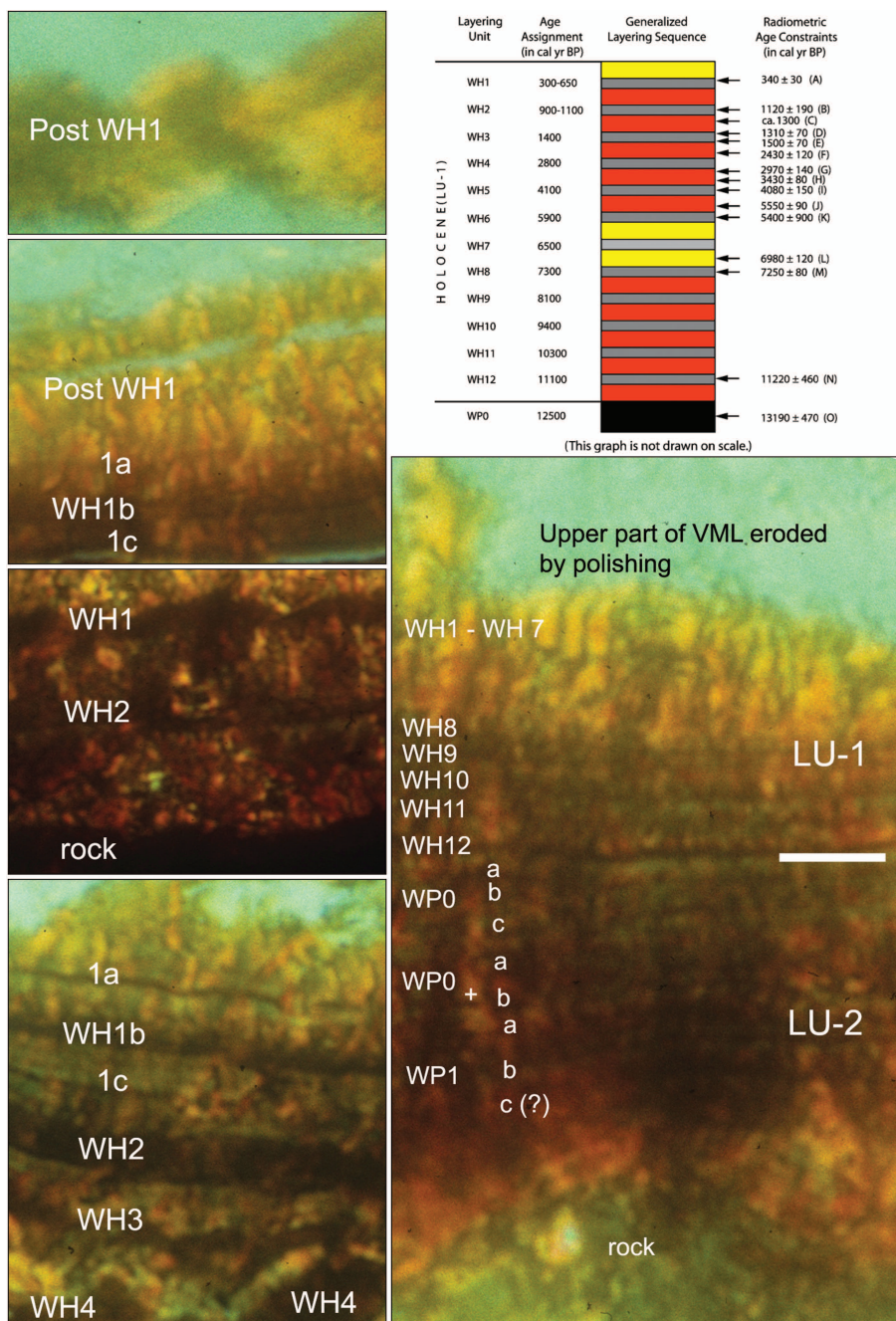




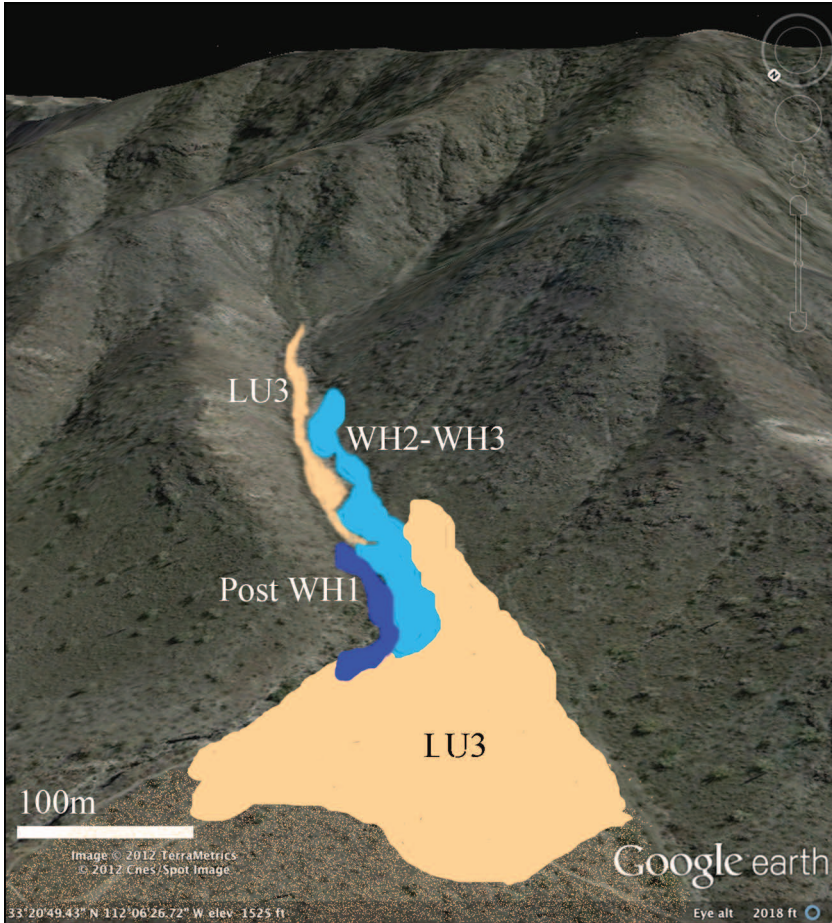
**Fig. 5.** The WP3 unit is the oldest deposit found in the Ma Ha Tuak catchments, with a VML age that corresponds with Heinrich Event 3 at about 31 ka. This unit exists as islands of ca. 2 m tall debris-flow levees surrounded by younger deposits. We thank Tanzhuo Liu for permission to use the climatic and calibration portion of the VML graphic.



**Fig. 6.** The LU-3 unit is the second oldest deposit found in the Ma Ha Tuak catchments, with a VML age between 24 and 16.5 ka. We thank Tanzhuo Liu for permission to use the climatic and calibration portion of the VML graphic.



**Fig. 7.** Five debris-flow units occur in the Ma Ha Tuak basins 1, 2, and 3 that postdate the LU-3 time. The oldest formed during the wet Pleistocene period associated with Heinrich Event 1 (WP1) about 16.5 ka. The remaining are four Holocene units of WH3 (1400 cal yr BP), between WH2 and WH3 (1100 to 1400 cal yr BP), WH1 or Little Ice Age (650-300 cal yr BP) and post WH1 (<300 cal yr BP). We thank Tanzhuo Liu for permission to use the climatic and calibration portion of the VML graphic.

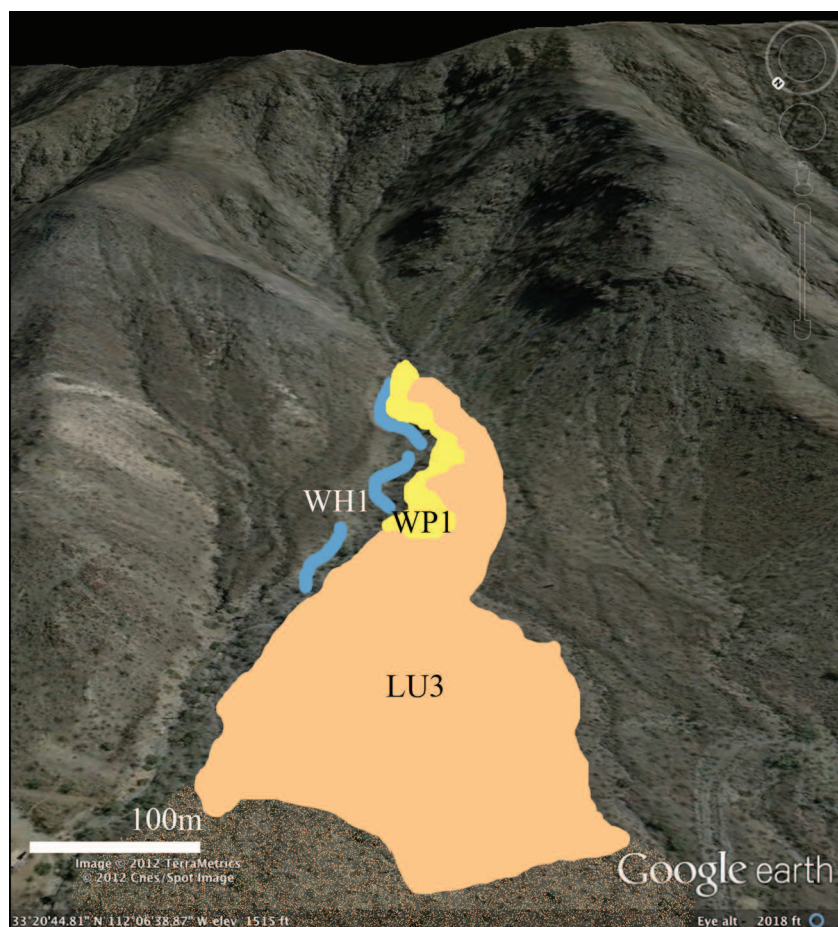


**Fig. 8.** Debris flows of Ma Ha Tuak basin 1. Most of the debris flows above the highest house pads have the LU3 varnish layering pattern diagnostic of an age between 24 ka to 16.5 ka (LU3). Following incision of the ephemeral channel, the next oldest preserved debris-flow unit (WH2–WH3) was deposited between 1100 and 1400 calendar years before present. Remobilization of this late Holocene deposit occurred during the 20th century (post-WH1).

1100 cal yr BP and a 20th-century debris flow. This youngest deposit represents the remobilization of the late Holocene unit; the initiation location suggests that water had ponded behind a levee that subsequently liquefied and then traveled a short distance.

Basin 2 (Fig. 9) is quite similar to Basin 1 in that the LU-3 unit dominates volumetrically above the location of house pads. However, the WP1 unit is slightly inset into the LU-3 deposit, by about a meter. The incised channel only contains discontinuous levees deposited during the Little Ice Age (WH1 unit).

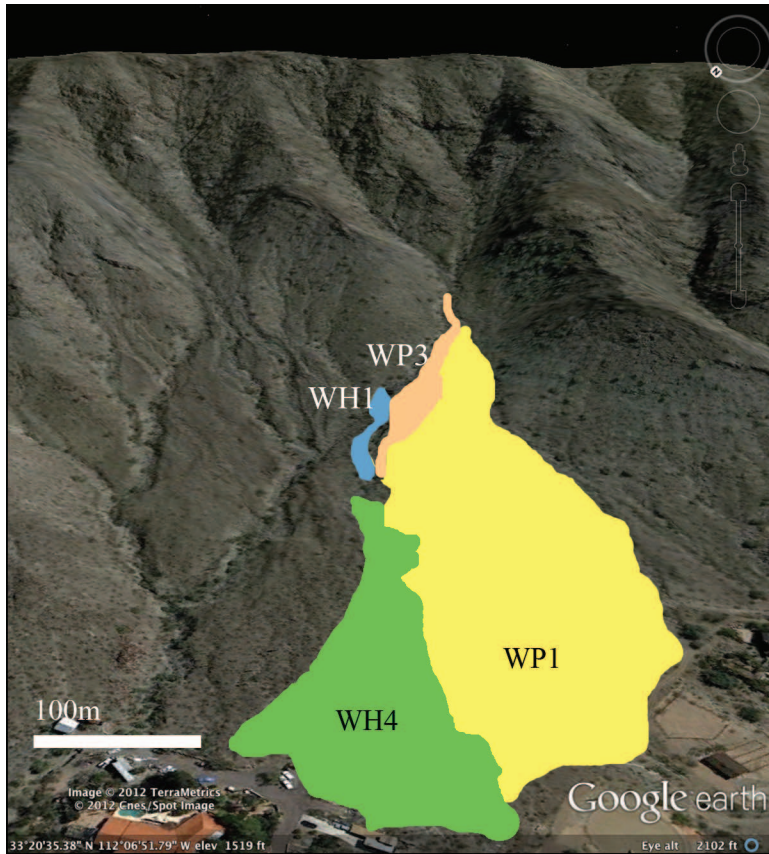
Basin 3 (Fig. 10) contains a very different pattern, because it lacks any surface expression of the LU-3 deposit. Instead, small islands of a last glacial maxima



**Fig. 9.** Debris flows of Ma Ha Tuak basin 2. Most of the debris flows above the highest house pads were deposited from 24 ka to 16.5 ka (LU3). The ephemeral channel incised into the LU3 unit about a meter and deposited the late Pleistocene WP1 unit about 16.5 ka. Further incision of the ephemeral channel occurred, but the only preserved deposit inside this channel took place during the Little Ice Age (WH1).

(WP3) deposit are preserved. The WP1 unit, often inset into LU-3 in other basins, is the most voluminous deposit. The incised channel between Basin 3 and the basin immediately to the east (left side of Fig. 10) contains the most voluminous Holocene unit of WH4, deposited about 2800 cal yr BP. Small Little Ice Age (WH1) levees are inset into the WH4 deposit, but these levees stopped well away from the houses or house pads.

Figure 11 shows the distribution of 20th-century and Holocene debris flows in Basin 4 in the Gila Range. The position of the home sites, so close to the debris-flow source, means that younger debris flows are able to bury previous debris flows. Thus, for the debris-flow chutes that saw activity in the 20th century, the youngest deposits naturally dominate the area immediately down slope. The different Holocene flows

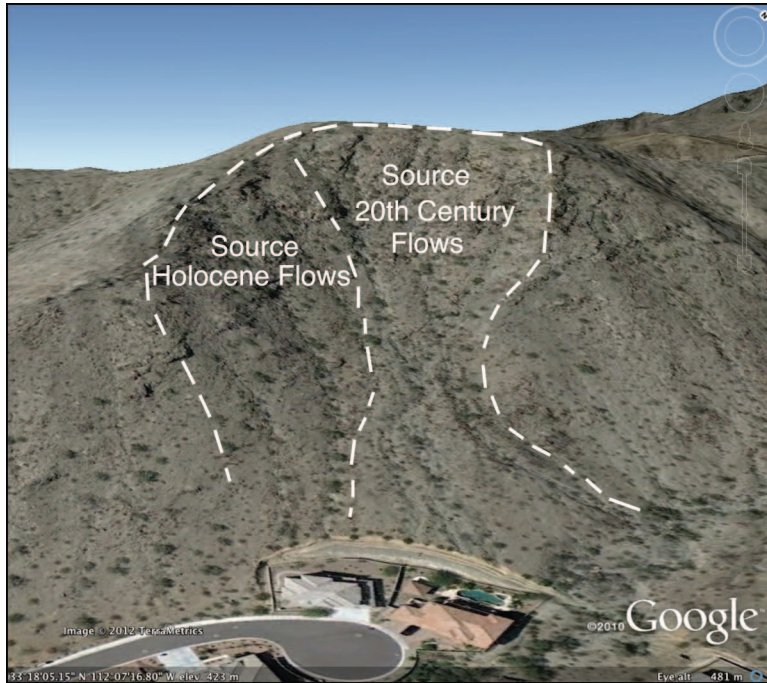


**Fig. 10.** Debris flows of Ma Ha Tuak basin 3. A few levees from about 30 ka (WP3) are preserved. However, the most extensive debris-flow unit above the houses and house pads was deposited about 16.5 ka (WP1 unit). An extensive area of debris-flow deposition occurred around 2800 calendar years ago (WH4). In addition, a small Little Ice Age deposit is preserved inside the incised channel.

are only preserved because some of the debris-flow chutes were not active during the past century.

#### *Volume Variations over Time*

The general pattern of debris-flow volume change over time varies dramatically between the Ma Ha Tuak basins (Fig. 12) and the studied Gila catchment (Fig. 13). For the Ma Ha Tuak basins, the late Pleistocene LU-3 period between 24 ka and 16.5 ka generated debris-flow volumes more than two orders of magnitude greater than those seen in the Little Ice Age and the 20th century. Viewed from the perspective of three combined basins, there appears to be a steady decline in volume over time on the north side of South Mountain (Fig. 12). Similarly, viewed from the perspective



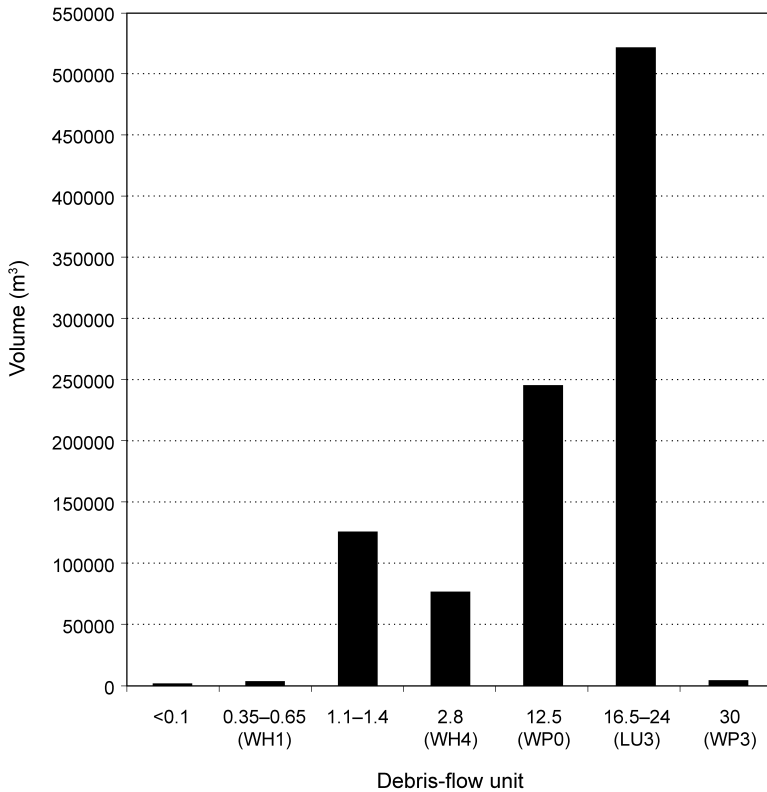
**Fig. 11.** Gila Range study site contains five distinct units. The two youngest units are 20th century (post-WH1), followed by between 900 and 1100 years (WH2). Lastly, the 2800 years (WH4), and small levees of 8100 years (WH9) comprise the five distinct units. The two houses at the base of the debris-flow system provide scale.

of run-out length, the youngest Ma Ha Tuak deposits did not travel far and remain limited to the incised channels.

The single small basin studied on the south side of South Mountain shows a much different pattern. Unlike catchments in the Ma Ha Tuak basins, this small catchment does not have an incised channel. Younger debris flow units aggrade on top of older deposits. Thus, the youngest debris flows of the 20th century are more voluminous than the exposed Holocene debris flows (Fig. 13).

## DISCUSSION

This pilot research includes considerable uncertainties. First, uncertainties related to the volume estimates stem from (1) having only a limited number of clear cross-sections by which to estimate unit thickness, (2) using geometric shape approximations to estimate cross-sectional areas of levees, and (3) needing to assume that Holocene levee heights (difference between lowest point in a swale and the levee crest) represents the true thickness of a unit that could have additional volume contributed by material under the swale. Second, the selection of the studied basins was not random, and only a randomized selection of drainage basins would remove

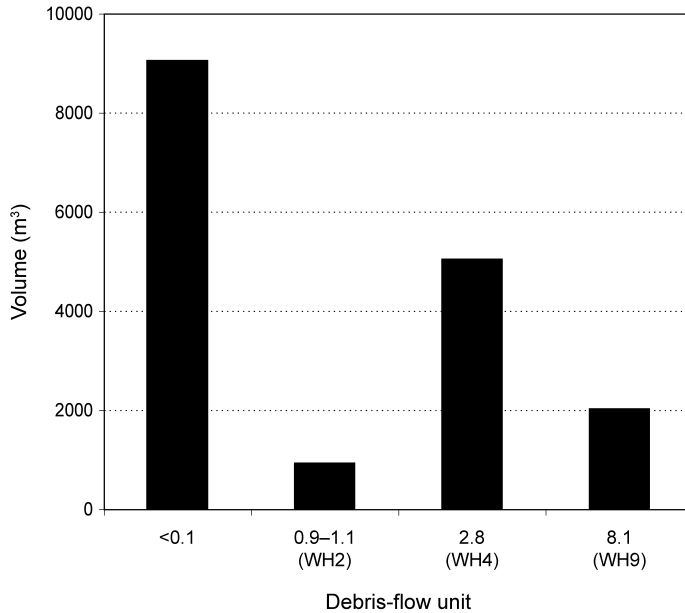


**Fig. 12.** Volumes of the different-aged debris-flow units in the three Ma Ha Tuak basins reveal a distinctive age trend. With the exception of the oldest debris-flow unit, a dramatic reduction in volume occurs over time. Minimum ages of the different units are presented in calendar thousands of years before present and also the corresponding VML nomenclature. For example, the Little Ice Age unit is 0.35–0.65 ka (WH1).

potential bias associated with selection criteria, such as having VML ages and some exposures of cross-sections. Third, it is unlikely that the youngest deposits represent the full range of debris flows in these basins. Each successive debris flow destroys pieces of older units. In the case of the Ma Ha Tuak basins, it is highly unlikely that the WH4 (2800 cal yr BP) unit represents the oldest Holocene debris flows that occurred in basins 1, 2, and 3. In the case of the Gila Range basin 4, it is likely that older Holocene units are buried underneath the 20th-century flows. Fourth, the VML and lead dating methods can only provide minimum ages at best. In this case, also, the reported ages are based on three VML cross sections from three different rocks in each of the basins. Despite these uncertainties, we are confident that our findings provide an accurate perspective for the studied basins and hence provide unique insights into the volumetric and chronometric trends.

The apparent contradiction of age-volume trends of the Ma Ha Tuak (Fig. 12) versus the Gila (Fig. 13) basins can be resolved by considering position within a

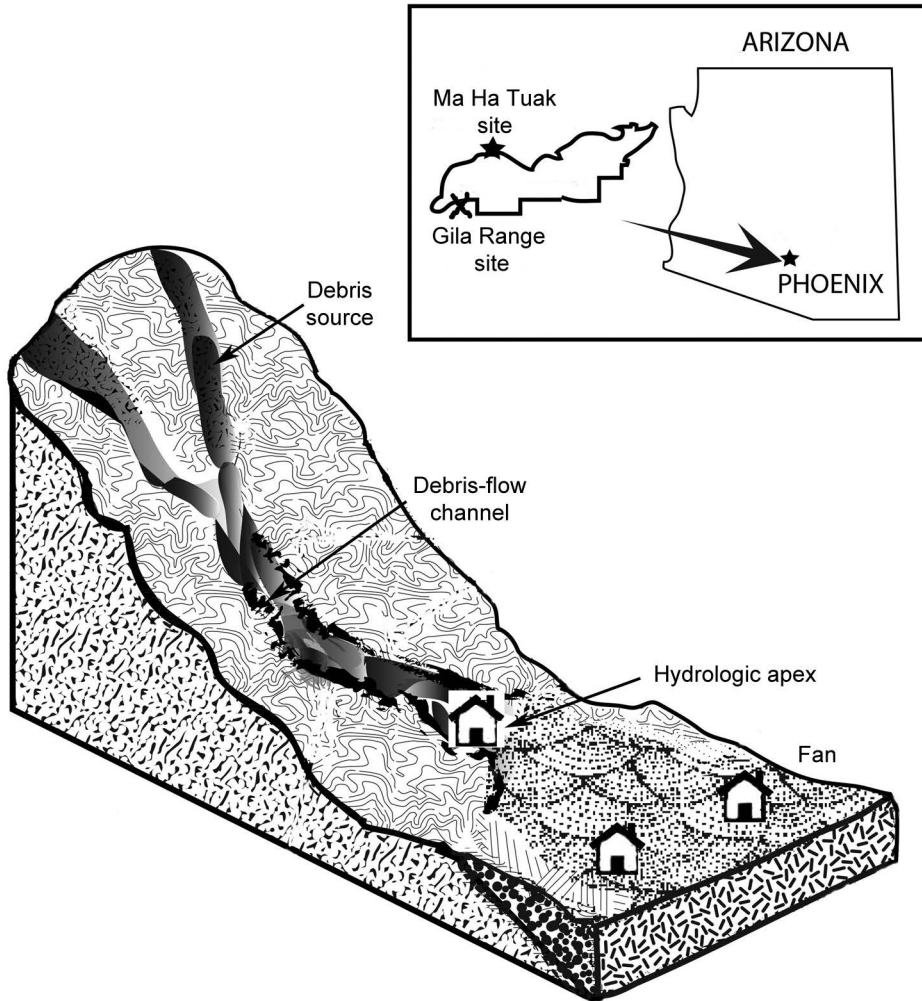




**Fig. 13.** Volumes of the different-aged debris-flow units in Gila Range basin 4 show a trend toward increasing debris-flow volume over time.

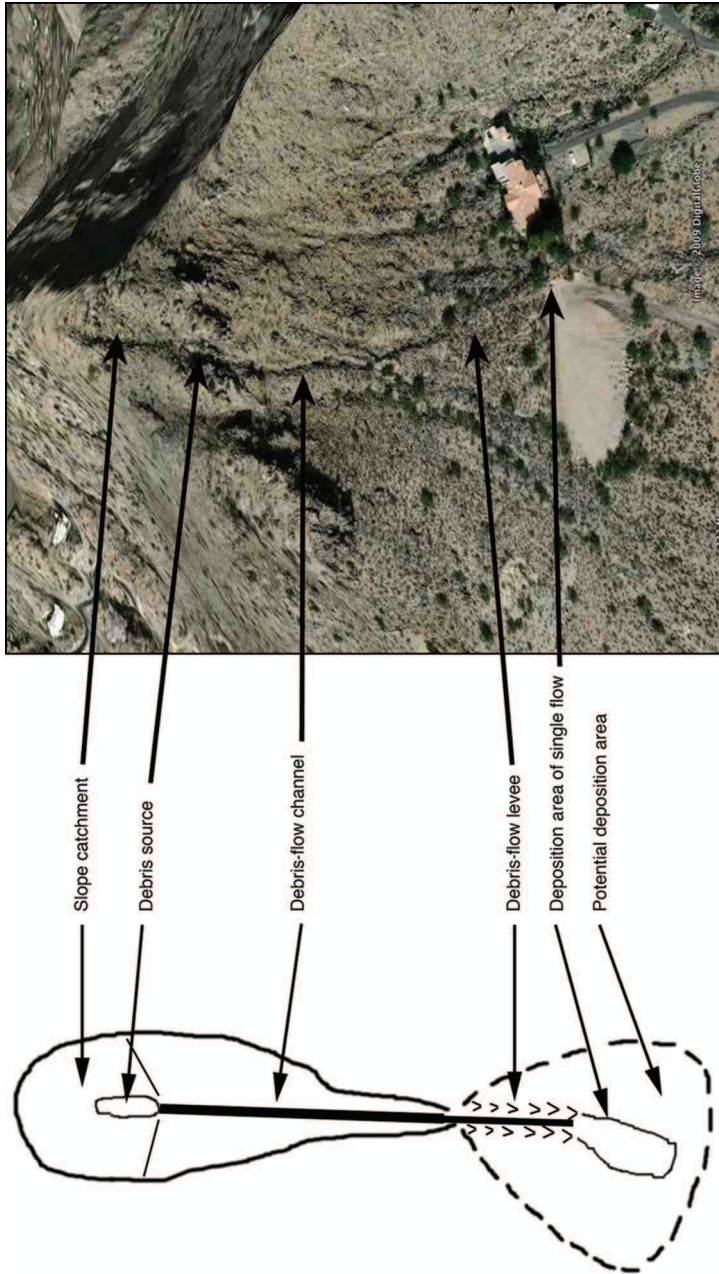
debris-flow system (Fig. 15). The Gila range site 4 backs up right next to the slope catchment (Fig. 11), directly underneath potential debris sources. This is likely the most hazardous position for urban infrastructure, because of the minimal transport length between source and house. In contrast, the Ma Ha Tuak basins 1, 2, and 3 include the incised debris-flow channel and also debris-flow deposits that are currently not hydraulically connected to catchment slopes (Fig. 14). For these Ma Ha Tuak basins, the declining volume over time indicates decreased hazard risk for the homes built farther from the debris-flow source regions. Smaller and smaller volumes over time would mean that a hazard would exist only if infrastructure were built above the hydrological apex and within the deeply incised channel walls. Fortunately, that landscape configuration exists inside a mountain preserve where building is not permitted.

Our strategy of focusing on the location of homes with respect to the debris flow system could help understand the potential risk of another sort of context—where homes are built across an incised channel or right where an incised channel ends and levee deposition begins. Many small mountain masses across metropolitan Phoenix have conditions similar to those of the debris-flow system at Mummy Mountain (Fig. 15). In the case shown in Figure 15, home construction occurs right where the debris-flow channel ends and the deposition of levees starts. This position is even slightly above the position of homes at Gila basin 4 and thus represents an even more dangerous location.

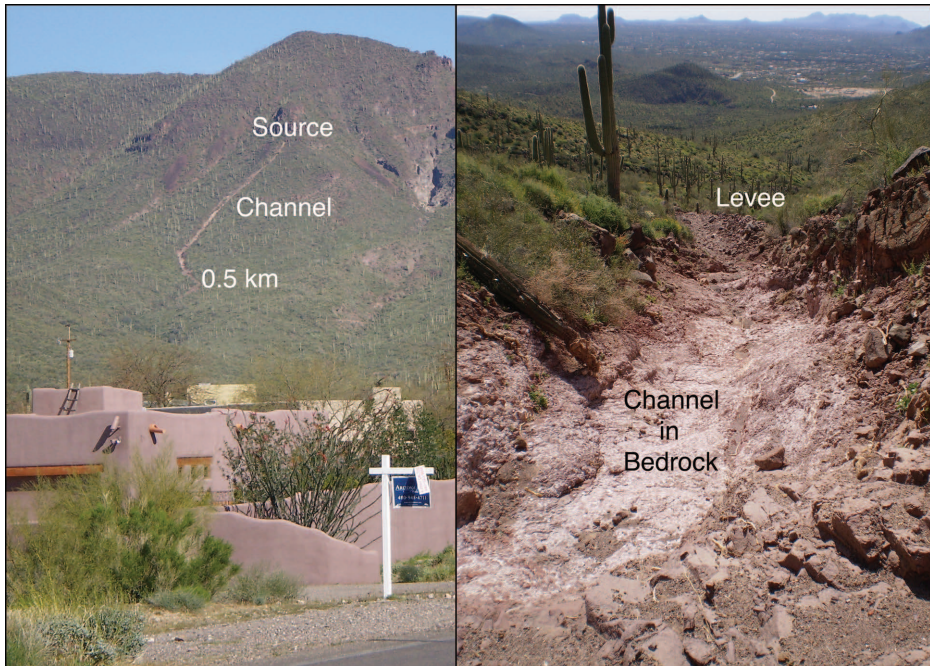


**Fig. 14.** General conceptualization of the debris-flow system of the Ma Ha Tuak Range, South Mountain, Phoenix. A deeply incised channel constrains the hazards of future debris flows to the inside of the channel walls and sites downstream of the hydrologic apex of where the channel debauches onto the piedmont. Thus, homes constructed within an incised channel and immediately down drainage at the Gila Range site, are in a hazardous position. In contrast, homes on the abandoned section of an alluvial fan at the Ma Ha Tuak sites are in no danger from debris flows.

An important next step in understanding debris-flow hazards associated with small desert catchments, even beyond extending this initial research into other basins in metropolitan Phoenix, would be to try to better understand the possible flow dynamics through terrestrial laser scanning. Ongoing research has illustrated the power of detailed digital terrain models to analyze debris flow deposits (Staley et al., 2006; Wasklewicz and Hattanji, 2009) and to also understand debris-flow surges as they move (McCoy et al., 2010). A similar research strategy on debris-flow



**Fig. 15.** Debris-flow system at Mummy Mountain, Phoenix, where some house sites are located in the incised debris-flow channel. The image is used following permission guidelines for Google Earth [<http://www.google.com/permissions/geoguidelines.html>].



**Fig. 16.** A half-km-long debris flow occurred from Elephant Mountain near Cave Creek, metropolitan Phoenix, during January 2010. This event was not noted in any newspaper. Like those deposits in basins 1–4 at South Mountain, these levees never reached the piedmont but aggraded inside an incised channel.

deposits proximate to houses would likely provide additional insight into the processes, and associated hazards, involved in the types of debris flows generated by small desert catchments. Specifically, laser terrestrial scanning would provide insight into potential sources of a future debris flow.

A common question is asked about the hazard of debris flows in metropolitan Phoenix: if such a hazard truly exists, why have I never seen historic reports of debris flows? Troy Pewe (pers. comm., 1990) noted debris flows in the 1970s in the McDowell Mountains distant from any home construction. Consider, also, Figure 16, which depicts a debris flow that occurred within sight of Cave Creek, Arizona in 2010 but was not reported in local papers. The answer to the question is that historic debris flows occur without much notice because they do not travel far from the incised channel (Figs. 8–11, 16). One commonsense solution, then, for alleviating the potential hazard of debris flows rests in ensuring that urban infrastructure is not placed directly underneath incised channels fed by potential debris source regions.

## CONCLUSION

The basic finding of this study is that debris-flow volumes and run-out lengths have declined precipitously from the late Pleistocene to the present time in the

studied basins at South Mountain, Phoenix, Arizona. Thus, although many debris flows have occurred in the mountain masses of metropolitan Phoenix during the 20th century, they have been restricted spatially to incised channels and locations immediately beneath source regions. The most hazardous locations surrounding the city of Phoenix are those directly underneath debris source areas or within incised debris-flow channels on steep mountain slopes.

Home sites have been slowly, but steadily creeping toward the base of steep mountain basins and into the pathways of debris flows. Those home sites placed within incised debris-flow channels or immediately downslope from these channels are at risk from the sorts of debris flows that have occurred historically. At some point in the not-too-distant future, perhaps during an intense winter or tropical storm, we expect debris flows will reach these homes. We consider the appropriate hazard descriptor (cf. Fell et al., 2008) to be “moderate” for these locations. The obvious policy solution is to prevent mountain-front home sites from being built in the paths of debris flows just by moving the site tens of meters laterally, or to create a buffer based on further research on run-out lengths.

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