From "Digital Mapping Techniques '10—Workshop Proceedings"
U.S. Geological Survey Open-File Report 2012–1171
http://pubs.usgs.gov/of/2012/1171/

Using Digital Geologic Maps to Assess Alluvial-Fan Flood Hazards

By Jeremy T. Lancaster, Thomas E. Spittler, and William R. Short

California Geological Survey
801 K. Street, MS12-32
Sacramento, CA 95814
Telephone: (916) 322-9309
Fax: (916) 322-4765
email: *Jeremy.Lancaster@conservation.ca.gov*

Introduction

The factors that make alluvial fans desirable for development—relatively planar slopes, good surface drainage characteristics, and excellent views—are the result of natural processes such as floods and debris flows, which can negatively affect lives and property. Currently, alluvial-fan floodplains are mapped by the Federal Emergency Management Agency (FEMA), in coordination with local flood control agencies where communities participate in the National Flood Insurance Program (NFIP). However, FEMA mapping is rarely conducted in undeveloped areas, and therefore, alluvial-fan flood-hazard information is often unavailable for long-term planning.

The California Geological Survey (CGS) served as a technical consultant to the Alluvial Fan Task Force (AFTF), an interagency, multidisciplinary effort that provided planning and flood control departments with guidelines for minimizing loss of life and property while also preserving beneficial resources on alluvial fans. As part of this effort, CGS proposed an approach for land-use planners that may be used to establish a preliminary site assessment in the absence of FEMA flood hazard data. The approach includes integrating digital Quaternary geologic map data with first-order alluvial-fan flood-hazard assessments, resulting in derivative maps showing (1) areas underlain by Quaternary sediments that may include alluvial fans and (2) the relative magnitude of alluvial-fan flooding hazards. The flood hazard map is supported by a proposed methodology for determining the relative hazard. These two map products are designed to assist landowners, developers, regulators, and the public in identifying those areas where quantitative studies are likely to document an alluvial-fan flood hazard. By characterizing potentially hazardous areas, the maps are intended to promote best practices in land use and floodplain management.

Background

Alluvial-Fan Flooding

Alluvial fans form where streams emerge from mountain fronts onto relatively flat valley bottoms. Within a mountain range, particularly in areas experiencing tectonic uplift, a stream is often steeply inclined and confined to a single channel by narrow canyon walls. Once a stream reaches the mountain front, its gradient typically flattens and waters may spread into a distributary network of channels below the apex of the fan, both of which reduce the depth and velocity of stream waters and reduce size and volume of sediment that the stream is capable of carrying. It is this change in gradient and confinement that result in conditions where sediment builds up into the characteristic fan-shaped pattern of an alluvial fan. During a major flood, water can entrain sediment as a hyperconcentrated flood (debris flood; Pierson and Costa, 1987), where roughly 20 to 60 percent of the volume is sediment and debris. Flood waters may also evolve into a debris flow, where over 60 percent of the flow volume is sediment and debris. The interplay between these processes is exacerbated by channel instability, where banks between adjacent channels (interfluves) are relatively low and are susceptible to failure by (1) the rise in the channel base from sediment deposition from hyperconcentrated floods and debris flows (aggradation) and (2) by overland flow on adjacent surfaces that create small side channels heading into these unstable areas (Field, 2001). These processes lead to avulsion—the sudden cutting off of an existing channel, and the formation of new channel that diverts part or all of the flow. On relatively lower gradient fans, such as those in Arizona that have been used to characterize avulsive processes (Field, 2001), a relatively longer time may be required for these processes to occur than for higher gradient and geomorphically active fans common in southern

California that are dominated by debris flow processes (NRC, 1996; Pelletier and others, 2005). This is because on a debris fan, a single debris flow deposit may block a shallowly incised channel after one rainfall event, so that in subsequent events flow is immediately diverted to a new channel. In contrast, multiple events may be required to sufficiently raise a channel base on a water-flood dominated fan or to cause side channel incision into a main channel such that avulsions occur in the next rainfall event.

After numerous flooding events on alluvial fans resulting in repetitive losses to life and property, FEMA sought to better define the hazard as "…flooding occurring on the surface of an alluvial fan or similar landform which originates at the apex and is characterized by high-velocity flows; active processes of erosion, sediment transport, and deposition; and, unpredictable flow paths" (FEMA, 2003). FEMA has formally recognized that modeling this type of flooding is significantly different than riverine-type flooding and requires a cooperative effort between geologists and engineers.

Types of Alluvial Fans

The type of alluvial fan and mode of deposition, whether it is built up from hyperconcentrated flows, debris flows, or both, will differ with geologic setting. Factors that influence the mode of deposition are rainfall frequency/intensity, tectonic activity, upland watershed relief, channel slope, vegetation, and lithology and structure (erodibility) of bedrock in the upland watershed that is the source of sediment. For assessment purposes, alluvial fans are subdivided into three types based on their principal style of flooding and sedimentation: streamflow fans (fig. 1), debris flow fans (fig. 1), and composite fans (Bull, 1977; and NRC, 1996). These are discussed below.

Streamflow fans – Alluvial fans that were built up through successive water floods with sediment by volume concentrations that may reach into hyperconcentrated thresholds. Slopes on streamflow fans are generally less than 3-4 degrees, which is considered to be the threshold between streamflow fan deposition and debris flow deposition (Jackson and others, 1987). Stream channels on streamflow fans have large width-to-depth ratios and are typically braided. Erosion and deposition can alter channel flow during a single flood event (NRC, 1996) where deposition occurs as bars along the margins or center of the channel.

Debris flow fans – Alluvial fans that were built up through successive hyperconcentrated, transitional, and debris flow events (Keaton and Lowe, 1998; Staley and others, 2006). Slopes on debris flow fans may be as steep as 6 to 8 degrees (or greater) and may have terminal lobes, marginal levees, and trapezoidal or U-shaped channels with relatively low width-to-depth ratios. Deposition is episodic, and rapid aggradation or plugging may occur in much deeper channels than is the case for streamflow fans. Even channels that appear to be stable during flood events may be subject to avulsion during or after debris flow, and this contributes to the uncertainty in down-fan flow direction typical for alluvial fans.

Composite fans – Alluvial fans that were built up through water floods, hyperconcentrated flows, transitional flows, and debris flows and contain features found on both stream debris flow fans and debris flow fans. Slopes on composite fans typically range from 4 to 8 degrees (Jackson and others, 1987). In general, the proximal portions of the fan consist of coarse debris flow deposits that are interlayered with hyperconcentrated flow deposits. Stratified finer grained flood deposits are distributed randomly but with higher concentrations at the distal portions of the fan. Proximal areas typically contain rough surfaces as are apparent on aerial photographs and detailed topographic maps (Giraud, 2005).

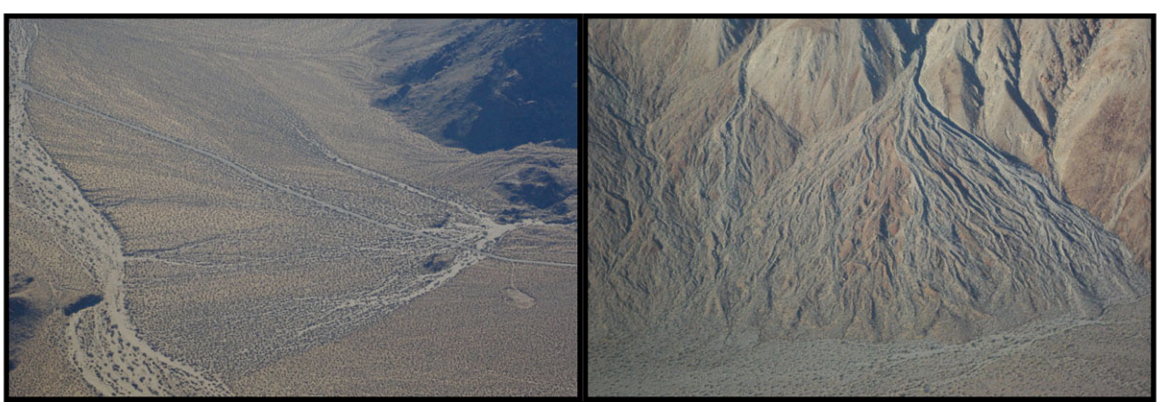

Figure 1. Left side shows a streamflow fan in Riverside County, California. Right side shows a debris flow fan in San Diego County, California.

AFTF Derivative Digital Geologic Map Products

Alluvial Fan Footprint Advisory Map: An Alluvial Fan Screening Tool

For the benefit of the land-use planner, maps that indicate areas underlain by alluvial-fan sediments (fig. 2) provide information about the potential for a proposed development to be located where alluvial-fan flooding may occur, indicating a need for additional studies. These advisory maps of Quaternary alluvial-fan deposits are based on digital surficial geologic maps by the CGS and the U.S. Geological Survey (USGS) and are being compiled at 1:100,000 scale (100k) for the 10-county southern California AFTF region (Kern, Los Angeles, San Diego, Santa Barbara, San Luis Obispo, San Bernardino, Riverside, Imperial, Orange, and Ventura).

Derivation of Alluvial-Fan Footprint based on Existing Digital Data

Areas underlain by Quaternary alluvial fans that may be subject to alluvial-fan flooding are produced by using a Geographic Information System (GIS) to select bedrock/Quaternary alluvial-fan contacts and Quaternary alluvial-fan/undifferentiated Quaternary sediment contacts, and then combining the Quaternary alluvial-fan units into a single alluvial-fan unit (the "footprint"). Bedrock units are combined into a single non-alluvial-fan-bedrock map unit. The axial valley deposits, including (among others) peralic, eolian, and stable channel fluvial deposits, are likewise combined to form a map unit depicting undifferentiated Quaternary sediments (figs. 3A-D). The primary concern is to show the alluvial-fan footprint at 100k, as part of the AFTF Integrated Approach planning manual (Longville, 2010).

Digital Mapping of Alluvial-Fan Footprint

Where digital information is not available for an individual 100k quadrangle, manual "heads-up" digitization at a screen scale of approximately 1:24,000 is necessary to complete the advisory map. The areas are mapped by observing alluvial-fan geomorphic features and following National Research Council (NRC) and FEMA guidelines for identifying the presence of alluvial fans; these are:

Composition – Is the area underlain by Quaternary alluvium?

Morphology – Is the geomorphic expression of the landform fan-shaped on topographic maps or DEM?

Location – Is the landform located adjacent to a topographic break?

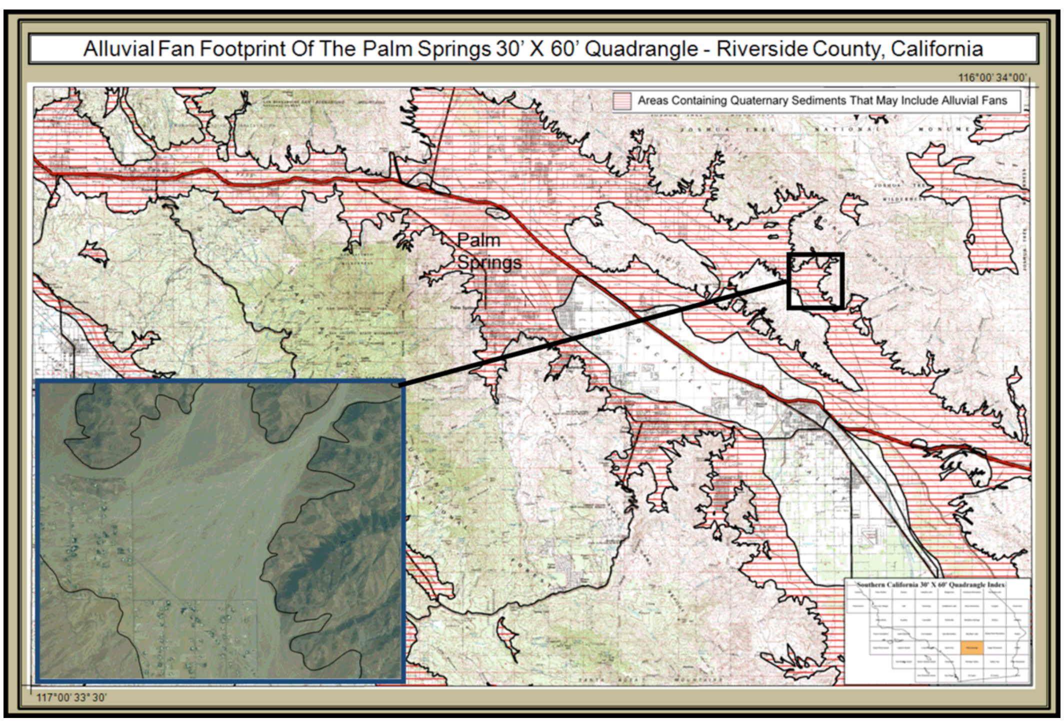

Figure 2. Alluvial fan footprint advisory map of a portion of the Palm Springs 1:100,000-scale quadrangle. Inset figure shows digitized extent of Quaternary alluvial-fan deposits drawn on 2005 National Agriculture Imagery Program (NAIP) imagery.

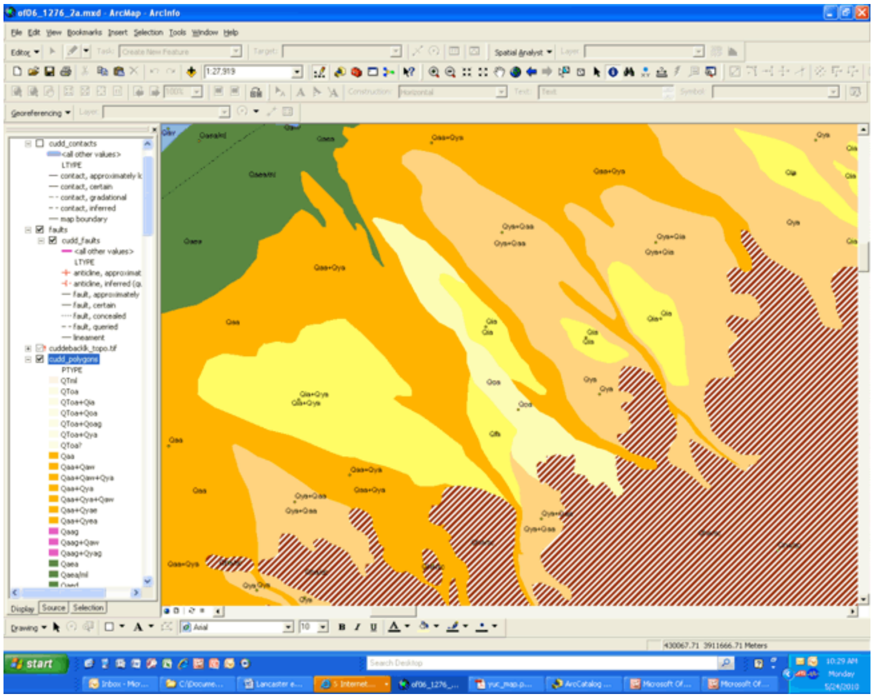

Figure 3A. Digital representation of the Surficial Geologic Map of the Cuddeback Lake 1:100,000-scale quadrangle (data taken from Amaroso and Miller, 2006). Green and blue colors represent Quaternary eolian and axial valley deposits; orange, yellow, and tan colors represent Quaternary alluvial-fan deposits; red hachured unit represents metamorphic bedrock.

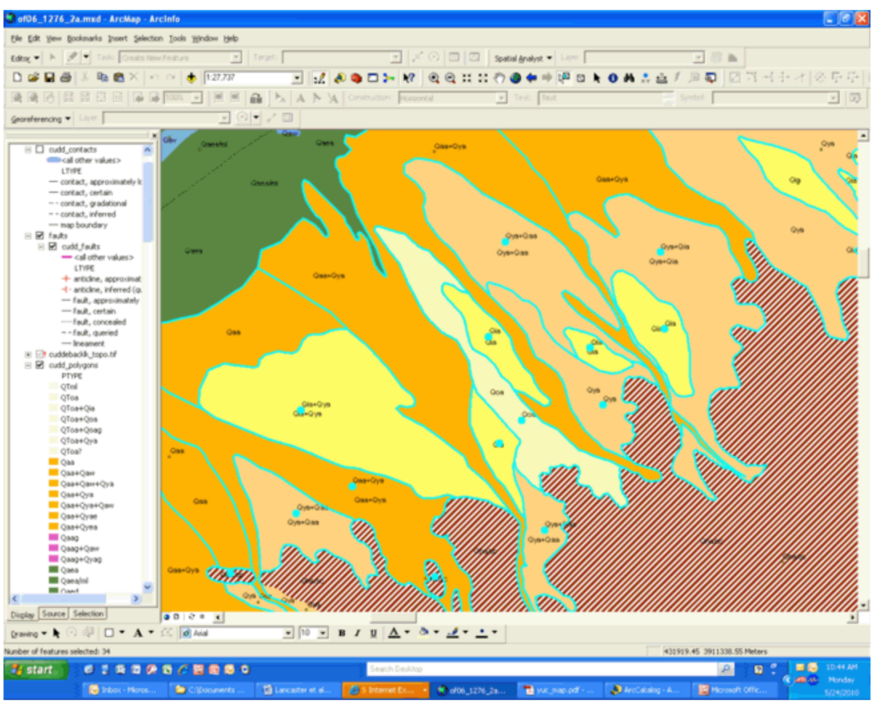

Figure 3B. Selection of all Quaternary alluvial-fan units.

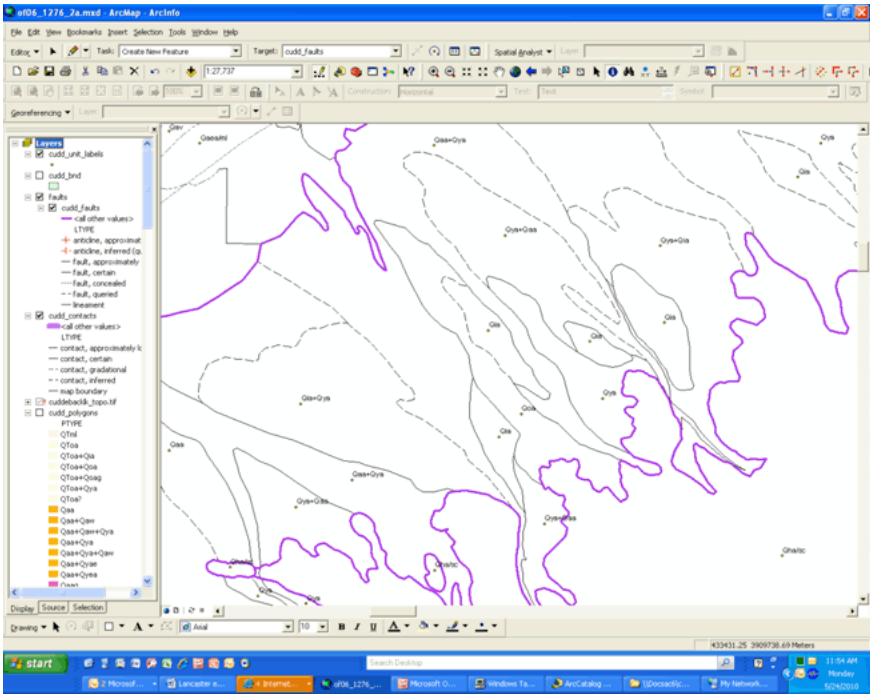

Figure 3C. Merged units (Quaternary alluvial-fan unit shown between the purple lines).

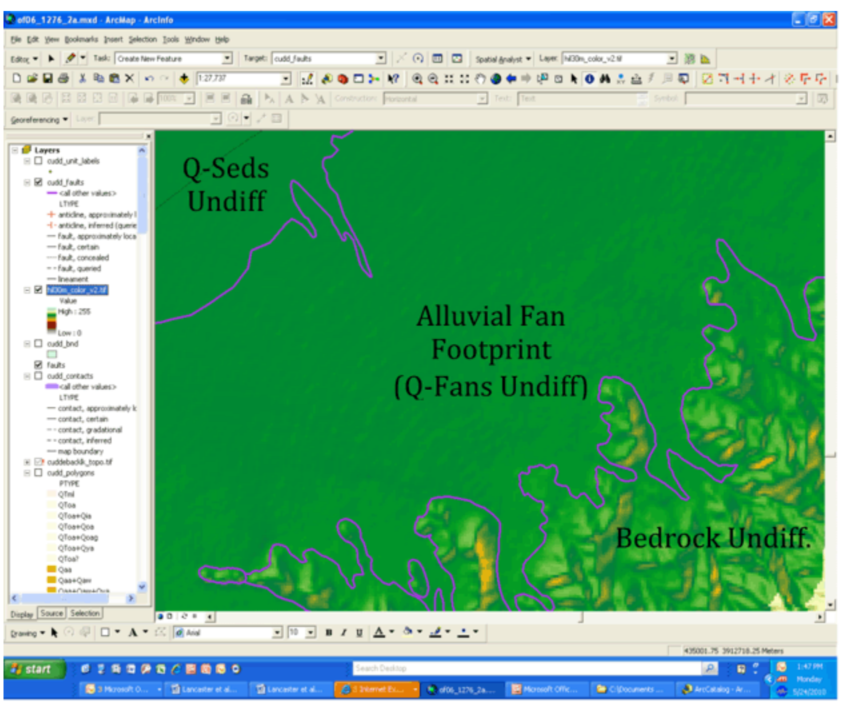

Figure 3D. Representation of the final derivative alluvial fan footprint advisory map showing bedrock, Quaternary alluvial fan, and undifferentiated Quaternary sediment polygons.

Digital data available for this type of mapping are many and varied; the most common sources are digital raster graphics (DRGs) such as 7.5-minute USGS topographic maps, 2005 and 2009 1-meter (m) resolution NAIP imagery, and USGS 10-m DEM (from the National Elevation Dataset). Variations to these data include slope and hillshade maps derived from DEM, and color infrared NAIP. These data provide a means to approximate both the bedrock/alluvial-fan contact, and the alluvial-fan/undifferentiated Quaternary sediment contacts.

Deriving Relative Hazard Information From Surficial Geologic Maps And Site Assessments

The Role of Surficial Geologic Maps In Assessing Alluvial-Fan Flooding

Surficial geologic maps of alluvial fans provide a record of the long-term flooding history; the fans are a function of tectonic processes, climate change, and various feedback mechanisms (Pelletier and others, 2005; Bull, 2007). The use of surficial geologic maps and geomorphology in flood hazard analyses on alluvial fans was formally recognized by the National Research Council (NRC, 1996) and by FEMA in their Guidelines and Specifications for Mapping Partners (2003). FEMA guidelines must be followed in all cases, yet the areal extent of FEMA mapping on alluvial fans is limited to where there is community participation in NFIP.

Planning departments and developers, up to this time, have had little available map-based communication of the hazard on alluvial fans other than Flood Insurance Rate Maps (FIRM), which are not available for most undeveloped alluvial-fan areas. To address these issues, the California Geological Survey has developed an engineering geologic approach for land-use planning, using surficial geologic maps and site assessments to determine the general distribution of alluvial fans and the relative potential for alluvial-fan flooding.

The Relative Potential of Alluvial-Fan Flooding

The recent work in Clark County Nevada, by House (2005, 2007) and Robbins and others (2008) identifies that the relative potential for alluvial-fan flooding is a function of the age and geomorphic position of alluvial-fan surfaces. Surficial geologic maps identify areas with flood and debris flow deposits of various ages, including modern drainage systems, their flow paths, and drainage divides (Robbins and others, 2008). As a part of the AFTF work products, CGS developed a similar approach to use surficial geologic maps to address the types and relative ages of alluvial-fan deposits for preliminary assessment of the relative potential for alluvial-fan flooding. CGS also identified additional information from site assessments, such as the potential for avulsion and debris flows, which should be considered in the assessment of alluvial fans. These preliminary studies may be conducted for pre-project assessment or for entire fan regional planning. Based on this approach, surficial geologic maps coupled with site assessments may be used to develop a preliminary ranking of an area as:

Relatively High (for alluvial-fan flooding) – Channels and washes (latest Holocene, <500 years or so), debris flow hazard areas, or entire fan areas subject to historical and future migration of flow paths.

Relatively Moderate – Alluvial-fan terraces that are moderately incised and raised above surrounding latest Holocene channels and washes. These areas are considered to have a moderate hazard. Fan terrace surfaces that are narrow interfluves surrounded by, or interwoven with, latest Holocene channels should be included with the Relatively High areas.

Relatively Low – Relict fans, or adjacent surfaces of deeply entrenched fan heads, containing well-developed soils that are elevated above active washes.

Debris Flow Hazard Area – Areas where Holocene debris flow deposits have been mapped based on geomorphic and geologic evidence, or where debris flows are anticipated.

Uncertain due to Disturbance – Areas where disturbances to natural flow patterns have occurred, and so the relative hazard cannot be reliably mapped at or below the disturbed areas.

These relative hazards designations are illustrated on both an oblique aerial photograph of the north slope of the Santa Rosa Mountains near Travertine Point, Riverside County, Calif. (fig. 4) and a geomorphic profile using surficial geologic map designations (fig. 5).

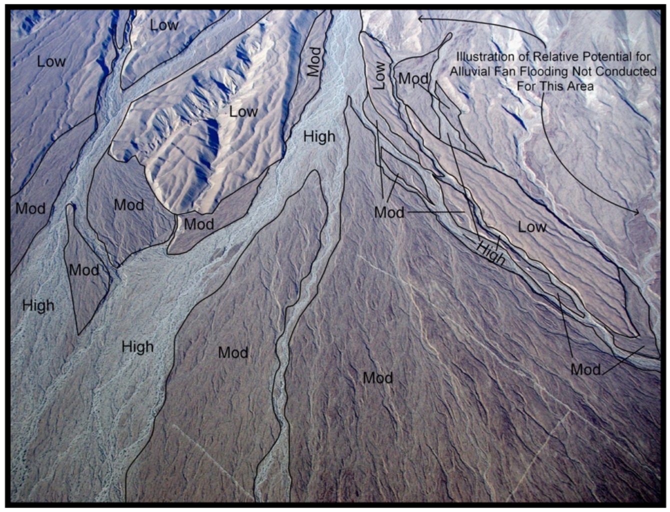

Figure 4. The relative hazard to alluvial-fan flooding in the Santa Rosa Mountains, Riverside County, California. High areas include latest Holocene alluvial-fan and wash deposits; moderate areas include Holocene abandoned alluvial-fan surfaces with faint-to-strong desert varnish development; low areas are relict alluvial-fan surfaces dissected with tributary drainage patterns.

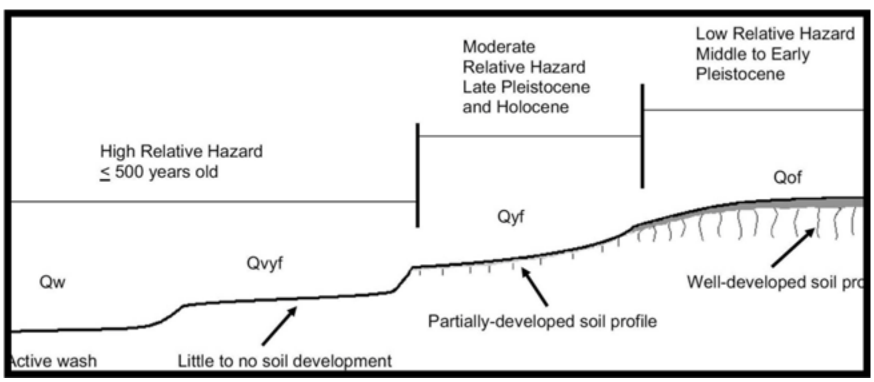

Figure 5. Illustrative geomorphic profile of the relative hazard to alluvial-fan flooding. Surficial units are classified as: Qw, active wash; Qvyf, latest Holocene alluvial fan; Qyf, late Pleistocene and Holocene alluvial fan; Qof, Pleistocene alluvial fan. Surficial mapping nomenclature based on J. Matti and P. Cossette (USGS, unpub. data, 2010).

Assessing the Potential for Debris Flow

The debris flow hazard on alluvial fans is a complex problem, and whereas quantitative site-specific studies may utilize probabilistic analyses, for planning purposes, identifying Holocene debris flow fans provides a preliminary indication of the susceptibility of areas where debris flow may occur (figure 6). This is because Holocene debris flow deposition is indicative of active processes occurring under the current climate regime (Giraud, 2005).

For preliminary indication of the potential for debris flow on an alluvial fan, the focus of study should be to identify the dominant mode of alluvial deposition—streamflow, debris flow, or composite, and then to identify where debris flow deposition has occurred in the Holocene Epoch. From a long-term planning, or pre-project standpoint, this information may then be used as the impetus for quantitative analysis of debris flow volumes during design phase analyses.

The geomorphic expression of debris flows has been documented by many workers in the field. Whipple and Dunne (1992) found that the roughness of alluvial-fan surfaces dominated by debris flow processes is controlled by the viscosity of debris flows. Fan apices and proximal areas tend to contain rougher surfaces expressed as channels with boulder-lined levees, terminal snouts, and boulder fields, due to higher viscosity debris flows (see fig. 7). Lower viscosity flows tend to smooth the lower fan surfaces by depositing less viscous debris farther downfan in low-lying areas and channels.

Assessing the Potential for Fluvial Avulsion

Fluvial avulsion may occur on alluvial fans that are dominated by water floods or flooding that is hyperconcentrated with sediment. They tend to occur at channel bends, where channels have high width-to-depth ratios (Field, 2001), and in areas that are aggrading, thereby causing channel bed elevations to increase relative to channel banks. They may also occur due to stream piracy, where overland flow causes incision and headward erosion into active channels, thus causing a redirection, or redistribution of flow on the fan. Figure 8 shows the process of avulsion via stream piracy.

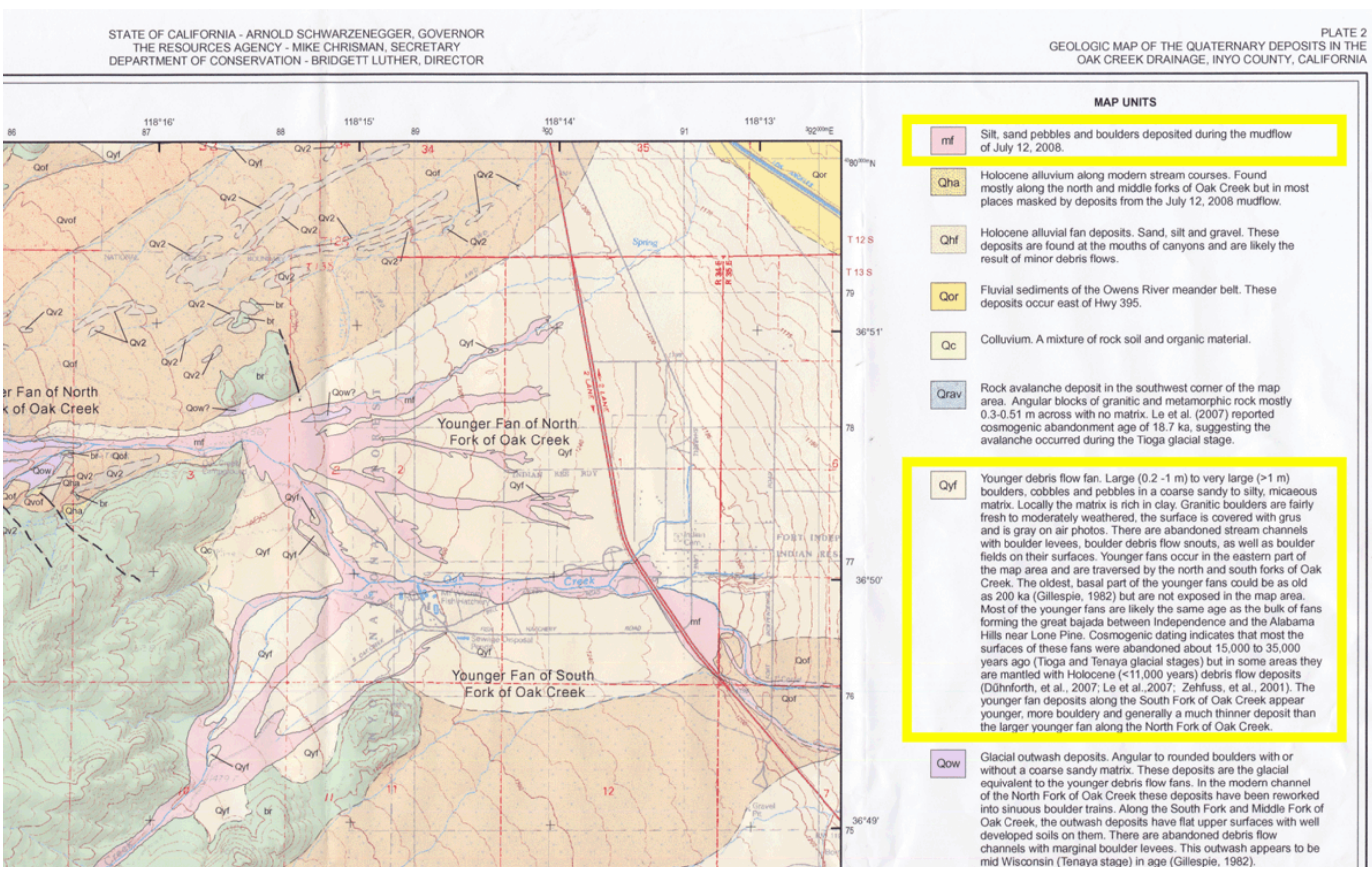

Figure 6. Draft Quaternary geologic map of the Oak Creek alluvial-fan system (Wagner and others, in press), showing the location of historical debris flow deposits, and the designation of Holocene debris-flow deposits. Highlight boxes drawn around the mapped debris-flow deposit of July 2008 and around the mapped Holocene debris fan deposits.

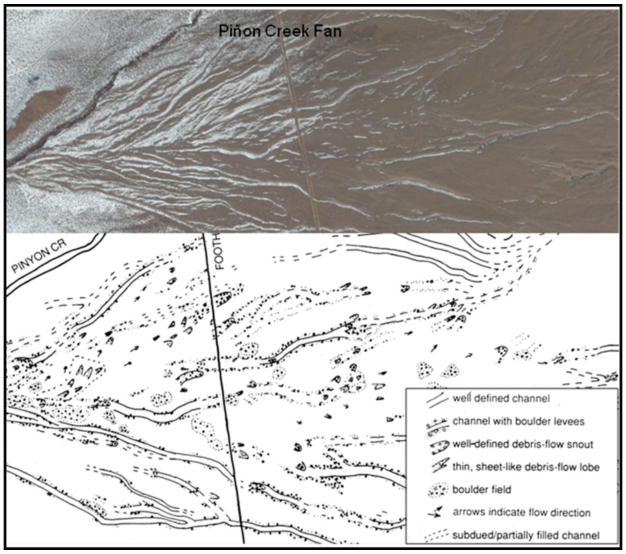

Figure 7. Upper part of figure shows NAIP aerial photograph of the Pinon Creek debris flow fan. Lower part shows map depicting the character and location of debris flow features.

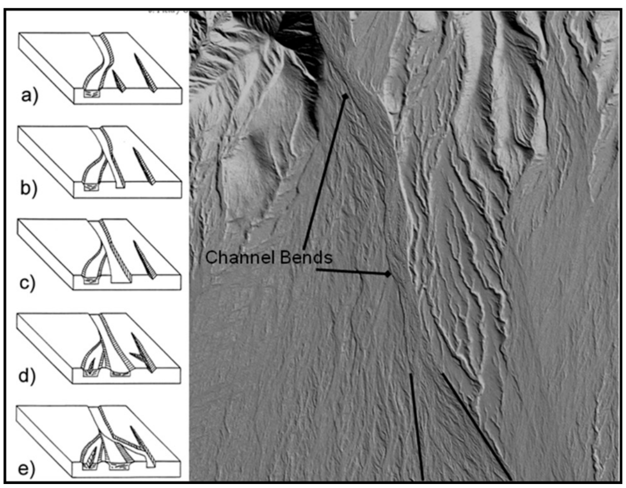

Figure 8. Schematic drawings of the channel processes that lead to fluvial avulsion on alluvial fans (left) (from Field, 2001), and LiDAR shaded DEM illustrating channel bends, where avulsion may occur on alluvial fans (right).

Assessing the Potential for Debris Flow Avulsion

Alluvial fans that are dominated by debris flow processes commonly have incised channels due to more frequent (for example, annual event) fluvial erosion processes. These channels may lead an investigator to falsely conclude that the channels are stable and that, therefore, the hazard is low. However, these channels serve as pathways where debris flows may travel for a limited distance until the channels are overtaxed by the sheer volume of flow. As with fluvial avulsion, debris flow avulsion tends to occur at channel bends but can occur much more frequently at the fan apex and proximal portions of the fan. Figure 9 shows a debris flow that occurred on an alluvial fan in Inyo County, Calif.

Summarizing the Derivative Products

For land-use planning, alluvial-fan footprint maps derived from digital geologic map data provide advisory information on general distribution of alluvial fans and indicate where detailed studies of alluvial-fan flooding potential may be necessary. Where proposed development sites are located within the Quaternary alluvial-fan hazard areas, additional assessments of the relative hazard to alluvial-fan flooding may be conducted by accessing digital geologic map data, analyzing the age and topographic position of geomorphic surfaces, and performing field assessments of the potential for avulsion and Holocene debris flow deposition. Following this approach, derivatives of geologic maps produced by CGS indicate the relative hazard to alluvial-fan flooding as relatively low,

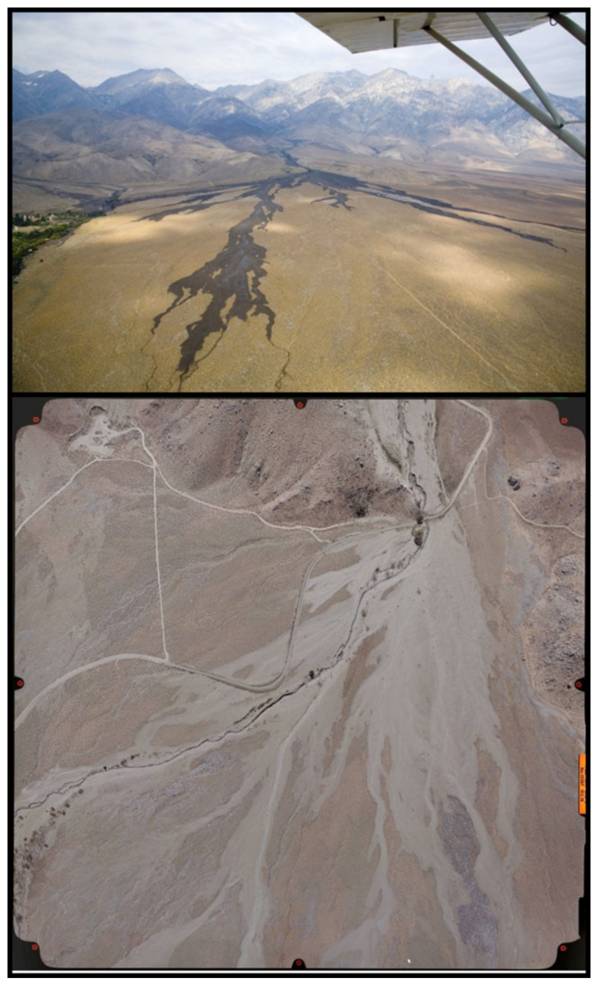

Figure 9. Upper part of figure shows oblique aerial photograph of debris flow on the Oak Creek alluvial fan, Inyo County, California (July 2008, photograph by Ken Babion). Lower part shows aerial photograph of Oak Creek alluvial-fan debris flow, weeks after the event, showing where the debris flow avulsions occurred at the channel bends (photograph by Caltrans, 2008).

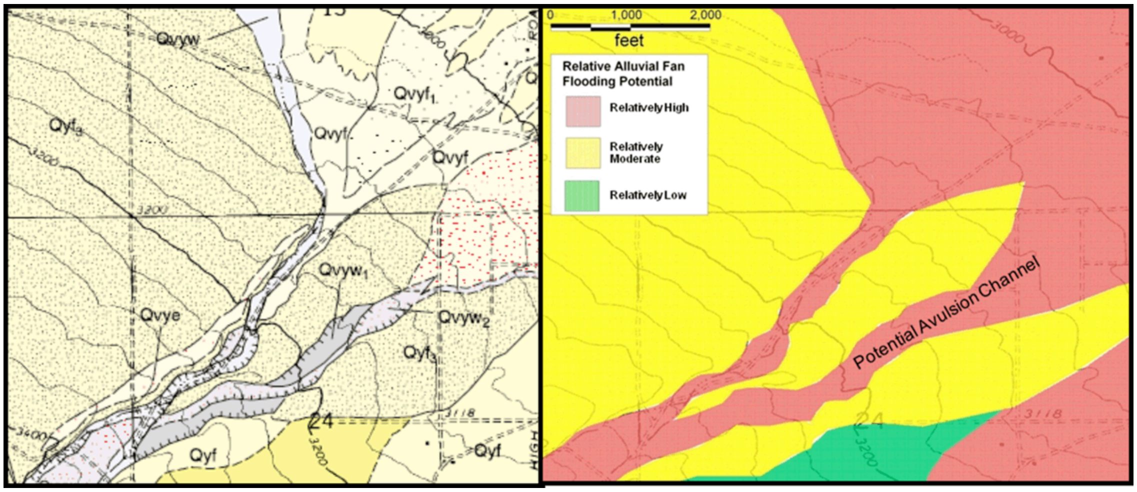

Figure 10. A portion of the geologic map of the Fifteenmile Valley 7.5' quadrangle (left) (Miller and Matti, 2001), and identification of relative alluvial-fan flood-hazard areas for the same area (right).

relatively moderate, relatively high, and the designation of areas susceptible to debris flow (fig. 10). These maps may be used by planners, developers, and homeowners to avoid development of hazardous areas and to design for proper flood and debris flow management facilities.

References

Amoroso Lee, and Miller D.M., 2006, Surficial geologic map and geodatabase of the Cuddeback Lake 30' x 60' quadrangle, San Bernardino and Kern Counties, California: U.S. Geological Survey Open-File Report 2006-1276, Version 1.0, *http://pubs.usgs.gov/of/2006/1276/*.

Bull, W.B., 1977, The alluvial fan environment: Progress in Physical Geography, v. 1, p. 222-270.

Bull, W.B., 2007, Tectonic geomorphology of mountains: A new approach to paleoseismology: Malden, Mass., Blackwell Publishing, 316 p.

FEMA, 2003, Guidelines and specifications for flood hazard mapping partners; Appendix G: Federal Emergency Management Agency, Guidance for alluvial fan flooding analyses and mapping, 33 p.

Field, J., 2001, Channel avulsion on alluvial fans in southern Arizona: Geomorphology, v. 37, p. 93-104.

Giraud, R.E., 2005, Guidelines for the geologic evaluation of debris-flow hazards on alluvial fans in Utah: Utah Geological Survey, Miscellaneous Publication 05-6, 16 p.

House, P.K., 2005, Using geology to improve floodplain management on alluvial fans: An example from Laughlin, Nevada: Journal of the American Water Resources Association, v. 41, no. 6, p. 1-17.

House, P.K., 2007, Geologic assessment of piedmont and playa flood hazards in the Ivanpah Valley area, Clark County, Nevada: Nevada Bureau of Mines and Geology Map 158, scale 1:50,000.

Jackson, L.E., Jr., Kostaschuk, R.A., and MacDonald, G.M., 1987, Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains, *in* Costa, J.E., and Wieczorek, G.F., eds., Debris flows/avalanches: Process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. VII, p. 115–124.

Keaton, J.R., and Lowe, M., 1998, Evaluating debris-flow hazards in Davis County, Utah—Engineering versus geological approaches, *in* Welby, C.W., and Gowan, M.E., eds., A paradox of power—Voices of warning and reason in the geosciences: Geological Society of America, Reviews in Engineering Geology, v. XII, p. 97-121.

Longville, S.L., coordinator, 2010, The integrated approach for sustainable development on alluvial fans: Alluvial Fan Task Force, California Department of Water Resources, 212 p.

Miller, F.K., and Matti, J.C., 2001, Geologic map of the Fifteenmile Valley 7.5' quadrangle, San Bernardino County, California: U.S. Geological Survey Open-File Report 01-132, scale 1:24,000, *http://geopubs.wr.usgs.gov/open-file/of01-132/*.

NRC, 1996, Alluvial fan flooding: National Research Council, Committee on Alluvial Fan Flooding, Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Academy Press, 172 p.

Pelletier, J.D., Mayer, L., Pearthree, P.A., House, P.K., Klawon, J.E., and Vincent, K.R., 2005, An integrated approach to flood hazard assessment on alluvial fans using numerical modeling, field mapping, and remote sensing: Geological Society of America Bulletin, v. 117, no. 9-10, p. 1167-1180.

Pierson, T.D., and Costa, J.E., 1987, A rheologic classification of subaerial sediment-water flows, *in* Costa, J.E. and Wieczorek, G.F. eds., Debris flows/avalanches: Process, recognition, and mitigation: Geological Society of America, Reviews in Engineering Geology, v. VII, p. 1-12.

Robbins, C.R., Buck, B.J., Williams, A.J., Morton, J.L., House, P.K., Howell, M.S., and Yonovitz, M.L., 2008, Comparison of flood hazard assessments on desert piedmonts and playas: A case study in Ivanpah Valley, Nevada: Geomorphology, v. 109, p. 520-532.

Staley, D.M., Wasklewicz, T.A., and Blaszczynski, J.S., 2006, Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping: Geomorphology, v. 74, p. 152-163.

Wagner, D.L., Lancaster, J.L., and DeRose, M.B., in press, The Oak Creek post fire debris and hyperconcentrated flows of July 12, 2008 Inyo County, California: A Geologic Investigation: California Geological Survey, Special Report 225.

Whipple, K.X., and Dunne, T., 1992, The influences of debris flow rheology on fan morphology, Owens Valley, California: Geological Society of America Bulletin, v. 104, p. 887-900.