MAP SHOWING INVENTORY AND REGIONAL SUSCEPTIBILITY FOR HOLOCENE DEBRIS FLOWS AND RELATED FAST-MOVING LANDSLIDES IN THE CONTERMINOUS UNITED STATES

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INTRODUCTION

Debris flows, debris avalanches, mud flows, and lahars are fast-moving landslides that occur in a wide variety of environments throughout the world. They are particularly dangerous to life and property because they move quickly, destroy objects in their paths, and can strike with little warning. U.S. Geological Survey scientists are assessing debris-flow hazards and developing real-time techniques for monitoring hazardous areas so that road closures, evacuations, or corrective actions can be taken (Highland and others, 1997).

According to the classifications of Varnes (1978) and Cruden and Varnes (1996), a debris flow is a type of slope movement that contains a significant proportion of particles larger than 2 mm and that resembles a viscous fluid. Debris avalanches are extremely rapid, tend to be large, and often occur on open slopes rather than down channels. A lahar is a debris flow from a volcano. A mudflow is a flowing mass of predominantly fine-grained material that possesses a high degree of fluidity (Jackson, 1997). In the interest of brevity, the term "debris flow" will be used in this report for all of the rapid slope movements described above.

WHAT CAUSES DEBRIS FLOWS?

Debris flows in the Appalachian Mountains are often triggered by hurricanes, which dump large amounts of rain on the ground in a short period of time, such as the November 1977 storm in North Carolina (Neary and Swift, 1987) and Hurricane Camille in Virginia (Williams and Guy, 1973). Both of these storms caused large numbers of debris flows and extensive damage. High-intensity rainfall is also a common trigger for debris flows in the Coast Ranges from California to Washington, such as the 1982 storm in the San Francisco Bay region, which triggered 18,000 debris flows, killed 25 people, and caused at least $65,000,000 in damages (Ellen and Wieczorek, 1988). Debris flows in arid and semi-arid regions of the American West seem to be caused primarily by locally intense storms between the months of June and October. Examples include flows along the Colorado River and its tributaries (Webb and others, 1989), flows in central Utah (Baum and Fleming, 1989), and those in other desert areas of Utah, Arizona, Nevada, Oregon, and California (Blackwelder, 1928). Rapid snowmelt was the main trigger for the 1983 debris flows in Utah (Brabb and others, 1989b). Earthquakes and volcanic eruptions commonly trigger debris avalanches, which can also be initiated by heavy or prolonged rainfall.

Some of the lahars triggered by the 1980 eruption of Mount St. Helens were generated when snow avalanches were rapidly melted and mixed with pyroclastic material during the initial eruption. Other lahars formed more than four hours later when avalanche debris saturated with melted ice was set in motion by another eruption and harmonic tremors (Fairchild, 1987). These lahars extended as much as 22 km from their source on the volcano down the various forks of the Toutle River. Other volcanoes in Washington and California, such as Mt. Rainier (Crandell and Waldron, 1956) and Mount Shasta (Crandell and others, 1984), have runout distances in excess of 40 km.

Fire can increase the danger of debris flows by accelerating surface erosion and causing water-repellent soils to develop on burned areas. These water-repellent soils can facilitate small debris flows during mild rainstorms or after very little rain has fallen, according to Wells (1987).

NEED FOR A DEBRIS FLOW MAP

A new responsibility to evaluate landslide hazards in the United States, combined with a statement by Radbruch-Hall and others (1982, p. 2) that debris flows in arid regions had not been included in their overview of landslides in the United States, led the first author to make a reconnaissance of landslide problems in all 50 states in the early 1980's. Conversations with state highway engineers and members of state geological surveys were supplemented by visits to landslides described by them and in published reports (compiled by Alger and Brabb, 1985) and to other areas where landslides could be expected. Debris flows and other landslides visited were plotted on topographic maps, mostly at 1:500,000 scale. The results of this investigation (Brabb, 1989) constituted the first comprehensive report to give a state-by-state analysis of landslide problems in the United States and different ways to evaluate the impact of those problems on each state. This was in contrast to the Radbruch-Hall report, which discussed the spatial occurrence of landsliding within physiographic provinces. A slope map in the 1989 report showed mountainous areas where landslides had occurred or could be expected, but debris flows were not described separately. The purpose of the present map, therefore, is to show where debris flows have occurred in the United States and where these slope movements might be expected in the future.

PREPARATION OF THIS MAP

In 1984, Best and Brabb prepared an inventory of past debris flows using data from the reconnaissance field investigations and a list of published and unpublished reports, a list which was eventually published by Alger and Brabb (1985). This information was plotted on 1:500,000-scale USGS state maps and transferred by hand to a 1:2,500,000-scale greenline base map of the United States. In 1997, A. Barron and M. Sinor digitized this greenline base map, but no new information was added to the map at that time.

In 1998 and 1999, new information was added to bring the map up-to-date. The data were gathered from published and unpublished reports of debris flows primarily covering the years 1984-1999. Many older reports that had been overlooked in the original map were also included. In addition, all state geologists were contacted to find out if they had information on debris flows. Several state geologists and members of their staff provided significant new information.

No distinction was made between debris flow scars, made shortly after the events, and debris flow deposits, which may be thousands of years old. We believe that all of the debris flows described in this report formed during the past 10,000 years (Holocene), but some of them could be older.

Mudflows are included even though this term is widely misused by the media and others for debris flows and sediment-laden floods. See the discussion by Campbell and others (1989).

If a report included a map at a scale larger than that of the compilation (1:2,500,000), the map or a photocopy was scanned. Other reports contained only the names of places where debris flows had occurred, or a map at a scale smaller than 1:2,500,000, or a map with no geographic coordinates. In those cases, the debris flows were located approximately on the appropriate 1:500,000-scale USGS state map or a 1:100,000-scale USGS topographic map and plotted by hand on a Mylar overlay. This overlay was then scanned. Details of the scanning process and a description of other database techniques and data are provided in Appendix 1.

The inventory map shows the locations of debris flows in two different ways, as points representing the locations of individual flows or small groups of flows, and as areas or polygons containing one or more debris flows. Different symbols are used to indicate uncertainty in location or the identification of the feature as a debris flow. In the digital database, a reference number ties each point and polygon on the map to the bibliography for each state, but these numbers are omitted from the published map for clarity. In those places where detailed debris-flow mapping was available in digital form, such as New Mexico and Utah, we plotted individual flows to illustrate their number and extent. In the San Francisco Bay area (Ellen and Wieczorek, 1988), we used a polygon because the 18,000 debris flows would plot as a large red blob.

Many of the other polygons represent areas in which less than fifty debris flows have been recognized or in areas where authors of reports have not provided sufficient information to locate the flows. Rectangular boxes represent 7.5-minute quadrangles where one to several hundred debris flows have been mapped at 1: 24,000 scale. Most of these quadrangles are in Appalachian states and in California.

Only New Mexico has a systematic inventory of debris flows (Cardinali and others, 1990) for the entire state. The comparison of New Mexico with surrounding states having a similar climate and similar steep slopes suggests that most of the mountainous states have not been adequately mapped and that debris flows are far more common than depicted. This idea is reinforced by the large number of debris flows recorded in specific storms in Utah (Brabb and others, 1989b), California (Ellen and Wieczorek, 1988), and Virginia (Morgan and others, 1999).

SUSCEPTIBILITY

The incompleteness of the inventory of debris flows makes educating decision-makers and the public about the extent of debris-flow hazard in the United States difficult. Fortunately, Clark (1987) and Corominas and others (1996) have compiled information on the slope angles of debris-flow source areas, indicating that debris flows initiate mainly on slopes steeper than 25 degrees. Therefore, a map showing slopes greater than 25 degrees would be expected to show most debris-flow source areas in the United States.

A Digital Elevation Model (DEM) released by the National Oceanic and Atmospheric Administration (NOAA) provides convenient nationwide data for the preparation of a slope map. The database consists of ground-surface elevations at 30 arc-second (approximately 1 km by 1 km) grid cells. Apparently these data were derived from the Army Map Service 1:250,000 topographic maps. Several slope maps were prepared from this database using ARC/INFO, a commercial GIS software program. To calculate the slope at each one-kilometer grid cell, the process fits a quadratic surface to the elevation values of a 3 cell by 3 cell box surrounding the grid cell for which the slope is to be calculated. The slope assigned to the middle cell is the maximum slope of the quadratic surface at that point.

Brabb and others (1989b) have discussed several problems with the database. One of these concerns the average value for the slope over a 9-km-square area. This figure is generally much flatter than the actual value for slopes within the selected area. Map values of one or two degrees may correspond to slopes steeper than the 25- degree value targeted for the susceptibility map. Because of this discrepancy, the map is referred to as a slope index map, giving relative slope rather than actual slope in any specific area.

Several slope index maps were prepared to try to find slopes steeper than 25 degrees where debris flows might be expected in the future. The maps were adjusted by trial and error to incorporate the largest number of debris-flow points without including large, gently sloping areas where no debris flows are expected. We eventually adopted a map with a slope index steeper than 3 percent, which includes about 75 percent of the debris flows mapped. Only individual debris-flow locations were used to compute the percentage of debris flows in each slope category, because the locations of debris flows within the polygon areas are too uncertain for this purpose. The other debris flows may occur in areas where more gentle average slopes contain steep slopes of limited extent, such as cliffs along rivers and lakes that are too small to be detected in the one-kilometer grid cell. Alternatively, some features mapped as debris flows may not be debris flows.

SPATIAL RESOLUTION AND POTENTIAL MISUSE OF MAP INFORMATION

Users of this digital map should not violate the spatial resolution of the data. Although the digital form of the data removes the constraint imposed by the scale of a paper map, the detail and accuracy inherent in map scale are also present in the digital data. The fact that this database was edited at a scale of 1:2,500,000 means that higher resolution information is not present in the data. Plotting at scales larger than 1:2,500,000 will not yield greater real detail, and it may reveal fine-scale irregularities below the intended resolution of the database. Similarly, where this database is used in combination with other data of higher resolution, the resolution of the combined output will be limited by the lower resolution of these data.

Users are also warned that gently sloping or even flat areas adjacent to steeper slopes where debris flows may occur are not necessarily safe. Debris flows may extend several kilometers from the mountains out into the flat areas.

CONCLUSIONS

This map provides a preliminary overview of debris flows and debris-flow susceptibility in the conterminous United States. It is not intended for hazard evaluation or other site-specific work, and should not be used for such. It can be used to determine where debris flow processes may be a problem and where additional information and investigation are warranted.

Twenty-eight of the forty-eight conterminous United States have documented debris flows. They are most abundant in the Coast Ranges, Rocky Mountains, and Appalachian Mountains but occur in other places where slopes are steep, including bluffs along rivers and the slopes beneath mesas and other escarpments. Moreover, gently sloping or flat areas adjacent to these steep slopes are also at risk. Debris flows are rare or absent on the plains and gently rolling hills of Middle America. In California, Utah, and the Southern Appalachians, debris flows are a common hazard that kills people and causes extensive property damage. References and map locations in the digital database provide a foundation for understanding the extent of the debris flow hazard, but much more systematic mapping of debris flows in every vulnerable state is needed before the full extent of the problem can be determined.

ACKNOWLEDGEMENTS

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TRADE, PRODUCT, OR FIRM NAMES

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APPENDIX 1

TECHNICAL DESCRIPTION OF THE DATABASE

SCANNING

The scanning was done at 400 dpi on either a UMAX color flatbed scanner or a Contex FSC-8000dsp color scanner, depending on the size of the map or tracing. The scanned images were transformed from scanner coordinates to geographic coordinates in ARC/INFO with digital tics placed by hand. The scanned lines and/or points were edited interactively using ALACARTE (Wentworth and Fitzgibbon, 1991), and the database fields (tables 3, 4, and 5) were filled in as appropriate

PROJECTION

The digital map databases consist of ARC coverages and supporting INFO files, which are stored in a Lambert Azimuthal projection (table 1). Digital tics every 9 degrees of latitude and 20 degrees of longitude define a grid in the coverages. For more information about map projections, see Snyder (1987).

Table 1. Map Projection Information

Projection	Lambert_Azimuthal
Datum	North American Datum of 1983 (NAD83)
Units	Meters
Zunits None	
Xshift 0.0000000000	
Yshift 0.0000000000	

<u>Parameters</u>

6370997.00000	Radius of the sphere of reference
-100 0 0.000	Longitude of center of projection
45 0 0.000	Latitude at center of projection
0.00000	False easting (meters)
0.00000	False northing (meters)

DATABASE FIELDS

The content of the geologic database can be described in terms of the points and the areas that compose the map. Descriptions of the database fields in each table are explained in table 2.

Table 2. Field Definition Terms in Tables

Item Name	Name of the database field (item)
Width	Maximum number of digits or characters stored
Output	Output width
Type	B-binary integer, F-binary floating-point number, I-ASCII integer, C-ASCII character string
NDP	Number of decimal places maintained for floating-point numbers

POINTS

Data representing information at a single locality (points) are described in the point attribute table (table 3). The identities of the points from compilation sources are recorded in the REF and STATE fields. The STATE field indicates the state under which the source data for that point is referenced, and the REF field indicates the number of the reference for that point. Because several published sources of data can refer to the same geographic location, the REF field may contain multiple entries separated by commas. The subjective quality of the source data for a point is stored in the DFTYPE field (table 4).

Table 3. Content of the Point Attribute Tables

Item Name	Width	Output	Type	NDP	Explanation
AREA	4	12	F	3	Area of polygon in square meters
PERIMETER	4	12	F	3	Length of perimeter in meters
DFIPTSCMP#	4	5	B		Unique internal control number
DFIPTSCMP-ID	4	5	B		Unique identification number
STATE	2	2	C		Two-letter state abbreviation
REF	45	45	C		Reference numbers
DFTYPE	1	1	I		Nature of point data (table 4)

Table 4. Point Types Recorded in the DFTYPE field.

1. Location of debris flows(s) and related fast-moving landslide(s)
2. Approximate location of debris flow(s) and related fast-moving landslide(s)
3. Identification as debris flow(s)) and related fast-moving landslide(s) uncertain
4. Approximate location, and uncertain identification as debris flow(s) and related fast-moving landslide(s)
5. Location of debris flow(s) and related fast-moving landslide(s) specific only by county
6. Identification as debris flow(s) and related fast-moving landslide(s) uncertain and specific only by county
7. Location of debris flow(s) and related fast-moving landslide(s) from field investigations
8. Approximate location and uncertain identification as debris flow(s) and related fast-moving landslide(s) from field investigations

AREAS

The identities of the areas from compilation sources are recorded in the REF and STATE fields. The STATE field indicates the state under which the source data for that area is referenced, and the REF field indicates the number of the reference for that area. Because several published sources of data can refer to the same geographic location, the REF field may contain multiple entries separated by commas. Because the location of individual debris flows is uncertain within the polygon boundary, the information in table 4 is not recorded in a DFTYPE field as it is for point data. Note that ARC/INFO coverages cannot contain both point and polygon information, so only coverages with polygon information will have a polygon attribute table, and those coverages will not have a point attribute table.

Table 5. Content of the Polygon Attribute Tables

Item Name	Width	Output	Type	NDP	Explanation
AREA	4	12	F	3	Area of polygon in square meters
PERIMETER	4	12	F	3	Length of perimeter in meters
DFIPTSCMP#	4	5	B		Unique internal control number
DFIPTSCMP-ID	4	5	B		Unique identification number
STATE	2	2	C		Two-letter state abbreviation
REF	45	45	C		Reference numbers

LINES

The lines (arcs) are recorded as strings of vectors and are described in the arc attribute table (table 6). They define the boundaries of the areas containing debris flows.

Table 6. Content of the Arc Attribute Tables

Item Name	Width	Output	Type	NDP	Explanation
FNODE#	4	5	B		Starting node of arc (from node)
TNODE#	4	5	B		Ending node of arc (to node)
LPOLY#	4	5	B		Polygon to the left of the arc
RPOLY#	4	5	B		Polygon to the right of the arc
LENGTH	4	12	F	3	Length of arc in meters
DFIPLYCOMP#	4	5	B		Unique internal control number
DFIPLYCOMP-ID	4	5	B		Unique identification number
SYMB	3	3	I		Symbol number
SEL	3	3	I		Select number (1 or 0)

SHADED RELIEF BASE MAP

The shaded-relief base map was derived from NOAA digital elevation data for northern North America, available from: http://www.ngdc.noaa.gov:80/seg/fliers/se-1104.html. The altitude data were downloaded from the NOAA web site and imported into ARC/INFO by Andrew Barron in the manner described here: Using the .HDR file downloaded, an ARC-compatible .HDR file was created. The raw data was treated as a .BIL image, and IMAGEGRID was used to convert it. For an unknown reason, negative elevation values (for example, elevations at Death Valley in California) were a huge number. By experimenting, this number was determined to be:

(LARGE_NUMBER) = 65,536 + (Negative Elevation)

This is intrinsic to the 16 bit data source, 2 to the 16th power (2^16) = 65,536.This problem was fixed by using the following GRID statement, where <ingrid> is the uncorrected elevation data and <outgrid> is the corrected data:

<outgrid> = con(<ingrid> gt 4500,<ingrid> - 65536, <ingrid>)

The 'gt 4500' part is related to the maximum elevation in meters, listed as 4328 in the NOAA HDR file. After correcting the grid values, the elevation data was projected using the parameters in Table 1.

The shaded-relief base map was made from the digital elevation model with the HILLSHADE command in ARC/INFO, using sun azimuth 315 degrees and altitude 45 degrees. The resulting grid was then processed to lighten the gray shades but preserve the topographic data, using the procedure described by Graham and Pike (1997). In the procedure described below, 'ltgrid' is the original shaded-relief, and 'final_grid' is the lightened version:

Step 1:
ltgrid = SLICE(usa-hs_val, EQINTERVAL, 100)

Step 2: (use &describe on ltgrid before running this step)
temp_grid = (ltgrid - [value GRD$MEAN]) * 15 / [value GRD$STDV] + 90

Step 3:
final_grid = con(isnull(temp_grid), 99, temp_grid <= 60, 60,temp_grid <=
99, int(temp_grid),99)

SUSCEPTIBILITY MAP

The debris-flow susceptibility areas and the shaded relief background were plotted together using the ARCPLOT command GRIDCOMPOSITE HSV (hue, saturation, and value) to make the base for the final map.

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APPENDIX 2

BIBLIOGRAPHY OF DEBRIS FLOWS BY STATE

References listed below are the data sources for each landslide or group of landslides in each state. References for individual landslides are shown as points on the map and references for groups of landslides are shown as areas or quadrangles on the map. Each reference is provided with a number in the order the material was received. This reference number is also provided in the digital database so that the sources of data can be linked to the individual landslide or group of landslides. The numbers are not shown on the plot for the map because they would overwhelm the data in several areas. The numbers in parentheses and brackets following each reference indicate the number of points or polygons in the database for that reference and the actual reference number(s) in the database for that point or polygon. For example, reference number 27 for California is: [6 PT (27), 1 PT (25,27,85)]. This means that 7 debris flow locations in the point database are from reference 27 and one is also mentioned in references 25 and 85.

Nearly all the references are in the files of the U. S. Geological Survey Landslide Information Center in Golden, Colorado. The current curator of these files is Lynn Highland, P.O. Box 25046, MS 966, Lakewood, CO 80225, phone 303-273-8588. Email: highland@usgs.gov.

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Arkansas

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California

2. Applied Earth Sciences, Inc., no date, Landslide inventory maps for Six Rivers National Forest: unpublished report. [1 PT (2)]

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