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Morphometric landform analysis of New Mexico

by

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with 5 figures and 5 tables

Summary. Morphometric types and map units were computed for the entire state of New Mexico from an eight-million-point digital elevation model (DEM). An automated version of the landform-classification procedure, developed for contour maps over 30 years ago by E. H. HAMMOND, sequentially evaluates the same three descriptive measures: slope, relief and profile type. The DEM, at a spatial resolution of 200 m, was derived from the same 1:250000-scale topographic maps used by HAMMOND. Although size of the 9.8 × 9.8 km moving smaple-space also is close to HAMMOND's (9.65 × 9.65 km), the frequency of its placement by the computer is 2500× greater. Our initial experiment in converting HAMMOND's semi-quantitative system to a computerized and fully numerical procedure yields map patterns resembling HAMMOND's over much of New Mexico. The two outcomes show adequate correspondence in broad-scale meso and macro structures, although the morphometric sub-classes themselves are not the same. Detail differences between the two results – which reflect contrasts in map generalization, coarseness of the sample design, and other effects – remain to be explained.

Zusammenfassung. Auf Basis eines digitalen Höhenmodells mit 8 Millionen Gitterpunkten wurden für den gesamten US-Bundesstaat New Mexico geomorphometrische Typen von Reliefeinheiten berechnet. Eine automatisierte Version des von E. H. HAMMOND vor über 30 Jahren für Höhenlinienkarten entwickelten Verfahrens einer Reliefformklassifikation berechnet folgerrichtig die gleichen drei deskriptiven Maßeinheiten der Neigung, der Höhendifferenz und des Profiltyps. Das digitale Höhenmodell wurde mit einer Auflösung von 200 m vom gleichen topographischen Kartentyp des Maßstabs 1:250000 abgeleitet, der bereits von HAMMOND verwendet wurde. Obwohl die Größe des gleitenden Analyseraumes (gleitendes Fenster) mit 9,8 × 9,8 km ebenfalls der von HAMMOND verwendeten Größe (9,65 × 9,65 km) nahe kommt, wurde die Häufigkeit der räumlichen Versetzung des gleitenden Fensters bei der automatisierten Vorgehensweise 2500mal größer gewählt. Unser ursprüngliches Experiment der Konvertierung von HAMMONDs halbquantitativem System in ein computergestütztes, ausschließlich numerisches Verfahren liefert kartographische Muster, die HAMMONDs Reliefeinheiten für die meisten Gebiete New Mexicos ähneln. Beide Resultate zeigen adäquate Übereinstimmungen in den großdimensionalen Meso- und Makrostrukturen, obwohl die geomorphometrischen Untereinheiten selbst nicht denen von HAMMOND entsprechen. Detailunterschiede zwischen den beiden Ergebnissen, die Unterschiede der Kartengeneralisierung, der räumlichen Auflösung bei der Datengewinnung und andere Einflüsse widerspiegeln, verbleiben weiterhin erklärungsbedürftig.

1 *Introduction*

This paper describes the automation of a manual approach to the numerical modelling of spatial variability in topography. The rationale dates back to ALEXANDER VON HUMBOLDT, who defined *geomorphometry* (or simply morphometry) as the characterization of landforms by qualitative descriptions of the shape of Earth surface forms and by quantitative measurements of the "physical constitution" of the Earth surface (VON HUMBOLDT 1849). The morphometric model presented here is implemented by Geographic Information Systems (GIS) technology and uses a digital elevation model (DEM) as raw data. Our example, the entire state of New Mexico, United States, is regional in its spatial scale.

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Our study evolved from ongoing investigations of geomorphic processes, emphasizing landsliding in California and New Mexico, within a framework of regional classification of topography from DEM data. Morphometry already has contributed in many ways, and at several levels of generalization, to modelling slope instability (BRABB 1991, BRABB et al. 1978, MARK 1994). There are many other examples: CROZIER (1986) has described the change in stress and strength parameters with varying slope height and angle; SPEIGHT (1980) used complex landform patterns to predict natural hazards on a regional scale. This paper describes first experiments with a quantitative regional model of land surface that may, in turn, be used to develop explanations for the role of landsliding in the evolution of a semi-arid landscape.

2 *Previous work*

The concept of landform classification as spatial taxonomy has a long history (e.g., VAN LOPIK & KOLB 1959, WOOD & SNELL 1960, HAMMOND 1964a). Recently, computer implementation has enabled very large areas, of national extent, to be classified morphometrically (e.g. GUZZETTI & REICHENBACH 1994). Landslide processes, which are of particular interest to us, are extensive and diverse in New Mexico (GUZZETTI & BRABB 1987, BRABB et al. 1989, CARDINALI et al. 1990). We speculated that the different processes of slope failure identified in this large state might correlate with regional contrasts in topography. Comparing our maps of landslide occurrence in New Mexico with the physiographic subdivisions of FENNEMAN (1928) or the land-surface types of HAMMOND (1964a, 1964b, Fig. 1), however, failed to adequately isolate the expected correlations of slope failure with topographic form. Accordingly, we have turned to quantitative means, starting with HAMMOND's regional approach, to better seek and identify links between form and process in this area.

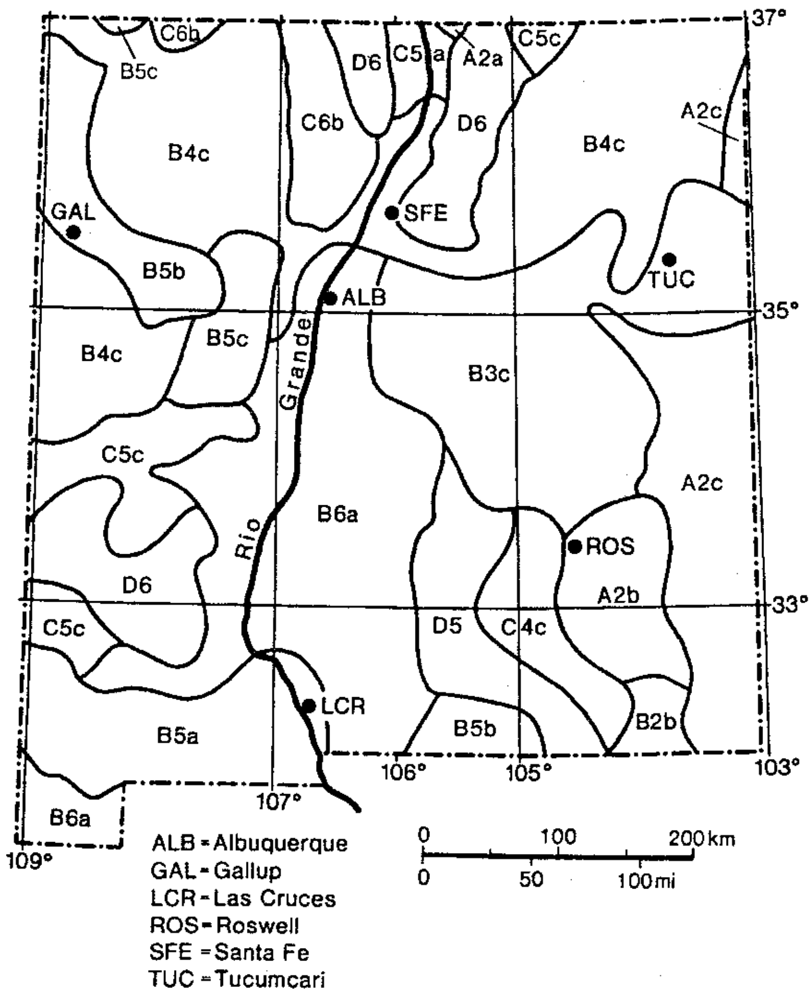
The three-level hierarchy of map units devised by HAMMOND (Table 1) is consistent with the theoretical and methodological approach described by DIKAU (1989, 1992). The hierarchical system of geomorphic forms includes micro, meso, macro and mega units that can be further classified into form facets, form elements and landforms. The eventual goal is to derive these features from DEMs by computer technology in order to link land form with geomorphic processes. For our purposes this link includes (1) deriving morphometric parameters from digital elevation models (PIKE 1988, DIKAU 1989), (2), scaling high-resolution morphometric parameters up to regional models of land form (DIKAU 1994, DIKAU et al. 1991) and (3) regional landslide-hazard assessments based on landform morphometry and geological data (JÄGER & DIKAU 1993, DIKAU & JÄGER 1995).

Background on the geology and geomorphology of New Mexico and related parts of the American southwest is available in such regional treatises as FENNEMAN (1928). More recently, HAWLEY (1986) offers a good summary of the geomorphology of New Mexico. The map by KRON (1987), a Landsat mosaic combined with elevation tint, provides a good regional visualization.

3 *Method*

3.1 *Landform taxonomy of HAMMOND*

There are two diverse approaches to implementing landform morphometry from digital data at different scales. Parameters can be derived from DEMs with different grid resolutions, in which case a landform is explicity related to the resolution of the elevation data. Alternatively, computer-based operations can regionalize parameters derived locally from DEMs within a moving window, by filtering techniques or by aggregating neighboring parameter values or landform elements. The method applied here is based on moving-window operations.



PLAINS:

A1 Flat plains
A2 Smooth plains
B1 Irregular plains, slight relief
B2 Irregular plains

HILLS AND MOUNTAINS:

D3 Hills
D4 High hills
D5 Low mountains
D6 High mountains

OPEN HILLS AND MOUNTAINS:

C2 Open low hills
C3 Open hills
C4 Open high hills
C5 Open low mountains
C6 Open high mountains

PLAINS WITH HILLS OR MOUNTAINS:

A,B3a,b Plains with hills
B4a,b Plains with high hills
B5a,b Plains with low mountains
B6a,b Plains with high mountains

TABLELANDS:

B3c,d Tablelands, moderate relief
B4c,d Tablelands, considerable relief
B5c,d Tablelands, high relief
B6c,d Tablelands, very high relief

Fig. 1. HAMMOND's (1964) original units of land-surface form in New Mexico; 3-digit codes explained in text. Legend lists the 31 units most common in the 48 contiguous United States; not all of them exist in New Mexico.

Table 1. Three-level hierarchy of landform units showing all possible classes (24) and sub-classes (96). Nomenclature modified slightly from that of HAMMOND (1964a, 1964b) (see also Fig. 1).

Landform type	Landform class	Landform sub-classes code
Plains (PLA)	Flat or nearly flat plains	A1a, A1b, A1c, A1d
	Smooth plains with some local relief	A2a, A2b, A2c, A2d
	Irregular plains with low relief	B1a, B1b, B1c, B1d
	Irregular plains with moderate relief	B2a, B2b, B2c, B2d
Tablelands (TAB)	Tablelands with moderate relief	A3c, A3d, B3c, B3d
	Tablelands with considerable relief	A4c, A4b, B4c, B4d
	Tablelands with high relief	A5c, A5d, B5c, B5d
	Tablelands with very high relief	A6c, A6d, B6c, B6d
Plains with Hills or Mountains (PHM)	Plains with hills	A3a, A3b, B3a, B3b
	Plains with high hills	A4a, A4b, B4a, B4b
	Plains with low mountains	A5a, A5b, B5a, B5b
	Plains with high mountains	A6a, A6b, B6a, B6b
Open Hills and Mountains (OPM)	Open very low hills	C1a, C1b, C1c, C1d
	Open low hills	C2a, C2b, C2c, C2d
	Open moderate hills	C3a, C3b, C3c, C3d
	Open high hills	C4a, C4b, C4c, C4d
	Open low mountains	C5a, C5b, C5c, C5d
	Open high mountains	C6a, C6b, C6c, C6d
Hills and Mountains (HMO)	Very low hills	D1a, D1b, D1c, D1d
	Low hills	D2a, D2b, D2c, D2d
	Moderate hills	D3a, D3b, D3c, D3d
	High hills	D4a, D4b, D4c, D4d
	Low mountains	D5a, D5b, D5c, D5d
	High mountains	D6a, D6b, D6c, D6d

Our experiment in regional landform classification employs the three-level system of HAMMOND (1958, 1964a, 1964b), which is based wholly on morphometry (Table 1). HAMMOND, identified landform types for the United States by moving a square window, about 9.65 km (6 miles) on a side, across 1 : 250000-scale U.S. Army Map Service topographic maps with contour intervals from 15.2 m (50 ft) to 61.0 m (200 ft). The chosen window size was "neither too small as to cut individual slopes in two and thus distort the determination of local relief, nor so large as to include areas of excessive diversity or to augment local relief figures by adding in long regional slopes" (HAMMOND 1964a: 17). The window was moved in increments of 9.65 km, with no overlap. For each position of the window HAMMOND calculated three parameters: (1) percentage of area where the ground is flat or gentle (less than 8% slope), (2) local relief (maximum minus minimum elevation), and (3) profile type, (relative proportion of flat or gently-sloping terrain that occurs in lowlands or uplands). He then grouped the resulting values of each parameter for all samples into four, six and 4 classes, respectively.

All possible combinations of these three attributes yield 96 landform subunits (Table 1), but HAMMOND found that fewer than half of them are common in the United States and used only 45 for his map (and 31 in his map legend, Fig. 1). He gave each unit a three-digit code, expressing slope, relief, and profile type, respectively: e.g., B5a. HAMMOND divided the United States into five main landform types: plains, tablelands, plains with hills or mountains, open hills and mountains, and hills and mountains (Table 1). All five types occur in New Mexico (Fig. 1).

The five main categories were subdivided into classes and sub-classes. HAMMOND identified 21 classes in the Unites States and 16 in New Mexico, and found 45 sub-classes in the United States and 16 in New Mexico (Fig. 1). Special features – sand, standing water, high peaks and cones, ridge crests, and escarpments – shown by symbols on HAMMOND's (1964a) map were retained in its subsequent republishing (U.S. GEOLOGICAL SURVEY 1980). HAMMOND generalized his results, by merging areas smaller than 2072 km^2 (800 mi^2) into adjacent units, to avoid a cluttered map at the 1:5000000 scale of publication, but used no spatial-contiguity constraint to insure compactness of his map units (WOOD & SNELL 1960).

EVANS et al. (1979) first proposed automating the HAMMOND scheme using gridded elevation data, but also recommended postponing the task until the quality of the U.S. Geological Survey-distributed Defense Mapping Agency (DMA) digital data (used here) was assessed and other tests performed. The HAMMOND scheme has been since automated, through FORTRAN (and later C) software written in 1990 by LINDA GRAFF (unpublished data, 1991). Her results, tested against small-area 7.5′ DEMs and not extended to regional data sets, have thus far remained unpublished. We did not undertake our computer experiment to duplicate HAMMOND's (1964b) map, which we could easily have done. Rather, we sought to build on his results in working toward an automated system for mapping surface-form types in somewhat greater detail.

3.2 *Computer classification*

Our method follows that of HAMMOND closely, except as indicated below and in Table 2. The differences are few but important: (1) we perfomed the classification by computer; (2) we used digital versions of the 1:250000-scale topographic maps at the 200-m resolution if the DEM; (3) we did not generalize our results; and (4) perhaps most significantly, we moved the sampling window in increments of just 200 m. The latter change, which takes advantage of the computer's speed to obtain greater detail, increased the sampling density over HAMMOND's by a factor of 2500 (Table 2). We also made detail changes in some of HAMMOND's terminology. Initially, like HAMMOND, we calculated out all 96 possible sub-types (Table 1).

We summarize the main hardware and software used for the analyses in Table 3 and the sequence if actual procedures followed in Table 4. None of the computer routines for these procedures, most of which had been written for other applications within the U.S. Geological Survey, has been published.

3.2.1 *Basic data – the digital elevation model*

The only elevation information available in digital form for the entire state of New Mexico is the U.S. Geological Survey one-degree DEM, first prepared by the DMA from the same 1:250000-scale contour maps used by HAMMOND for his manual classification (U.S. Geological Survey 1990). The original spacing of this DEM along north-south and east-west profiles is 3 arc-seconds.

Quality of this DEM is highly variable. Whereas absolute horizontal and vertical accuracies of ± 130 m and ± 30 m, respectively, were anticipated, the relative values "will in many cases conform to the actual hypsographic features with higher integrity than indicated by the absolute accuracy" (U.S. Geological Survey 1990). This was confirmed for mountainous terrain by ISAACSON & RIPPLE (1990) in their comparison of USGS 7.5-minute DEMs with DMA/USGS one-degree DEMs.

However, the one-degree DEM used here is much less accurate in low-relief terrain and also is known to contain many artifacts of the digitizing process, as well as random and systematic errors that potentially affect our results (e.g., ACEVEDO 1991).

Table 2. Manual method of HAMMOND (1964a, 1964b) for classifying land-surface form contrasted with the computer implementation.

	HAMMOND (1964a, b) (48 conterminous United States)	DIGITAL APPROACH (New Mexico: 314,255 km²)
Data source	1:250,000 U.S. Army Map Service topographic maps (> 400 maps)	One-degree USGS (originally DMA) DEM from 64 1:250,000-scale maps (3 arc-seconds resampled to 100 m)
Data resolution	Contour interval = 15.2-61 m (50 ft-200 ft)	200 m spacing on rectangular grid for ca. 8,000,000 terrain heights
Size of sample area (window)	9.65 km (6 mi) on a side	9.8 km on a side
Movement of sample area	9.65-km (6 mi) increments	200-m increments
Sampling density: number of window placements / 1000 km^2 of land area	ca. 110	ca. 250,000
Taxonomic criteria: descriptive measures	Slope, relief, & profile type (slope & profile type estimated)	Slope, relief, & profile type (all three calculated)
Number of subclasses: calculated / retained	NA (probably 96) / 45	96 / 42
Generalization in compilation of final map	Units < 2072 km^2 (800 mi^2) were combined	none
Scale of final map	1:5,000,000, republished at 1:7,500,000 (U.S. GEOL. SURVEY 1980) with Alaska & Hawaii added	Variable (1:1,000,000 in DIKAU et al. 1991)

Table 3. Computer systems used in automation of HAMMOND procedure (* use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government)

HARDWARE	SOFTWARE	FUNCTION
SUN SPARC 2* & VAX 4000*	Grid modelling system: a collection of various routines available locally at USGS	Morphometric derivatives, window operations, grid manipulation, screen display, colored raster plots, and shaded relief
MICROVAX II*	AID* image-processing system	Shaded relief and stereomate images, image matching, screen display, and raster plots
PRIME* & SUN SPARC 2*	ARC/INFO* GIS	Created files to mask New Mexico state borders for the geologic data base

*use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

The 3-arc-second DEM for New Mexico was first regridded to 36 million elevations spaced equally at a ground distance of 100 m by the technique described in BRABB et al. (1989). To manipulate the data on our limited computer resources, however, this DEM had to be regridded again, to a ground spacing of 200 m. By selecting every other point on the original DEM (Table 3), we computed a final DEM of about 8 million heights.

3.2.2 *Calculation of slope*

The 200 m DEM was converted to a slope map (not shown) by moving a 3 × 3 window of elevation-point positions across the DEM one elevation spacing (200 m) at a time (Table 4). At each placement of the window, aquadratic surface was constructed from the nine elevations. The slope of this surface, in percent, was assigned to the point in the center of the window (see MARK et al. 1988, for details).

Areas where slopes are less than 8 % (gentle slopes in the HAMMOND classification) were then identified by moving a 49 × 49 window of slope grid-positions across the data set in 200-m increments. The size of this window, 9.8 km (6 mi) on a side, is close to the 9.65 km used by HAMMOND. To reproduce HAMMOND's method, the values obtained by this procedure were divided into intervals according to the following code letters and limits:

A: > 80 % of area gently sloping
B: 50–80 % of area gently sloping
C: 20–50 % of area gently sloping
D: < 20 % of area gently sloping

3.2.3 *Calculation of local relief*

A window of 49 × 49 elevation point-positions was moved across the DEM in 200-m increments to determine relief, the difference between maximum and minimum elevation per unit area. The data thus obtained were divided into intervals where local relief, converted to meters, corresponds to the code number and six ranges chosen by HAMMOND:

1: 0–30 m
2: 30–91 m
3: 91–152 m
4: 152–305 m
5: 305–915 m
6: > 915 m

3.2.4 *Calculation of profile type*

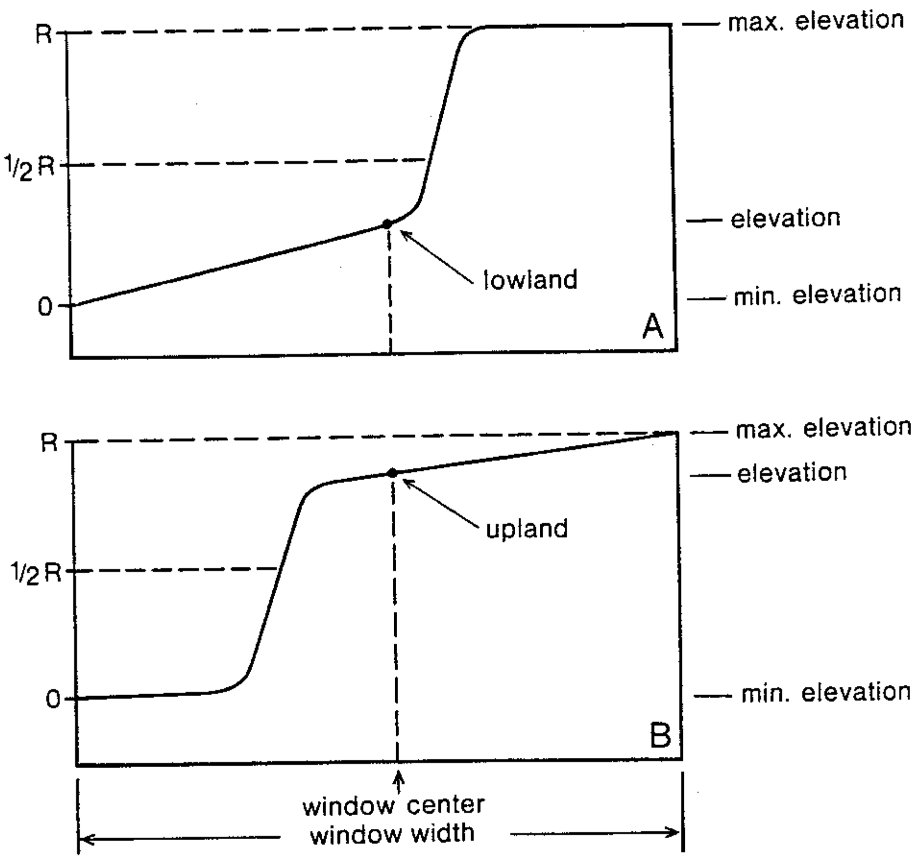
This measure required the most involved calculations (Table 4). Profile type described the amount of gently sloping terrain located in upland or lowland. It is roughly equivalent to percentage-hypsometry as expressed by the curves of STRAHLER (1952), the plan-profile types of VAN LOPIK & KOLB (1959), the elevation/relief ratio of WOOD & SNELL (1960) and the skewness of elevation (EVANS et al. 1979, PIKE 1988). Here, profile type separates fundamentally upland units, e.g. Tablelands (designated TAB in Tables 1 and 4), from lowland units, e.g. Plains with Hills or Mountains (PHM). The code letter and four-fold scheme of classification are:

a: > 75 % of gentle slope is in lowland
b: 50–75 % of gentle slope is in lowland
c: 50–75 % of gentle slope is on upland
d: < 75 % of gentle slope is on upland

Table 4. Sequence of procedures automating the HAMMOND (1958, 1964a, 1964b) classification from a DEM. Basic operations only; such minor procedures as rescaling are omitted.

RESULT	DERIVED ATTRIBUTE	GRID MODELLING PROCEDURE	DATA SET OR LAYER
Slope	Slope (in percent)	Computing quadratic surface on 3x3 moving window of elevations (DEM)	A
	Percentage of gentle slopes (<8%) within unit area	49x49 moving window of slope values; sorting slopes into the HAMMOND intervals	B
Local relief	Range of elevation (local relief): elevation maxmum minus minimum within unit area)	Sorting 49x49 moving window of DEM; subtraction and sorting relief values into the HAMMOND intervals	C
Profile type	*• Distinguishing lowland & upland:*		
	Maximum and minimum elevation within unit area	Sorting in 49x49 moving window on DEM	D
	Difference between maximum elevation and mid-point elevation	Sorting and subtraction within 49x49 DEM window	E
	Difference between maximum and minimum elevation (range of elevation)	Subtraction within 49x49 DEM window	F
	One-half of elevation range within unit area	Scaling elevation range within 49x49 DEM window	G
	Lowland/upland within unit area	Subtraction of G from E in 49x49 window	H
	• Identifying profile type:		
	Frequency distribution of A (slope)	49x49 moving window of slope values	I
	Profile type within unit area	Linear combination of H and I	J
	Profile type within unit area, reclassed	Sorting J into the HAMMOND profile-type intervals	K
Surface-form type	Combining all three attributes	Linear combination of B, C, K	L
	Final landform classes	Sorting L into the 96 landform subclasses, 24 classes and 5 types	M

Like HAMMOND, we used numerical criteria to first make a basic distinction between upland and lowland and then assign each sample to one of the four classes (Table 4). In uplands, maximum elevation within a sampling square minus that in its center is less than half the local relief. In lowlands, this value exceeds half the local relief. We show this difference graphically (Fig. 2), by



with: max. elevation = maximum elevation within the moving window
min. elevation = minimum elevation within the moving window
elevation = elevation at moving window center
R = local relief within the moving window

upland:	max. elevation − elevation < 1/2 R
lowland:	max. elevation − elevation > 1/2 R

Fig. 2. Schematic diagram of a cuesta scarp showing criteria by which the computer might place a slope in a lowland (A) or an upland (B) class.

the simplified scheme of a cruesta-scarp slope. Minimum and maximum elevations and the window center are aligned diagonally across the moving window. If the maximum elevation is 2000 m and that at the window center is 1800 m, subtraction yields 200 m, which is less than half of 2000. Thus, the area is an upland. In most cases, maximum and minimum elevations and the mid-point of the window will not lie along a linear profile as in Fig. 2, but the criteria still apply.

3.2.5 *Computing landform types and units*

By sequentially incorporating results calculated in each window operation for slope, local relief, and profile type (Table 4), the computer assigns each of the 8000000 digital picture-elements (or *pixels*, computed from the raw elevations) to one of the 96 landform subclasses in the HAMMOND scheme (Table 1). This automated sorting procedure is outlined in Table 4 as a series of operations, moving from top to bottom, where the succession of data layers or maps thus computed is designed by capital letters, A-M. The software routines required for the calculations were available at the U.S. Geological Survey, although some modifications were required for our application.

The procedure in Table 4 largely reproduces the broad-scale map patterns obtained manually by HAMMOND (Fig. 1), although not necessarily the identical landform types, classes and sub-classes (Table 1). As expected, similarly classified pixels tend to cluster spatially into landform units (e.g. WOOD & SNELL 1960). No contiguity constraint was applied to delimit our spatial units (generalized in the example given here in Fig. 3).

We created two DEM-based computer visualizations of the terrain to aid in evaluating the accuracy and information content of the landform map (Fig. 3). The shaded relief map (Fig. 4) was prepared from the 200 m DEM by a method described by MARK & AITKEN (1990). The sun azimuth of the image is 315 degrees, located 30 degrees above the horizon, and the vertical exaggeration is 2 ×. The DEM was also converted to a red/blue stereo shaded-relief picture (not shown) by an image processing system (Table 3). The stereo image was viewed frequently to check accuracy of the landform units.

4 *Results*

Table 5 gives the percentage occurrence of the landform types, classes, and sub-classes in New Mexico according to our computer classification of all 8000000 pixels. We distinguished five major landform types here for the state of New Mexico, similar to HAMMOND's (1964a, 1964b): Plains (PLA), Tablelands (TAB), Plains With Hills and Mountains (PHM), Open Hills and Mountains (OPM), and Hills and Mountains (HMO). Types PLA, TAB, and PHM comprise 86% of the state; the rest is largely HMO and OPM (Fig. 3). We further identified 14 landform classes in New Mexico, compared with the 16 mapped by HAMMOND. We had some occurrence of three rare classes (C1, open very low hills; D1, very low hills, and D2, low hills) not included in HAMMOND's (1964b) map legend and added them, for consistency (Table 1) to his 21 (Fig. 1). The names of some of his classes were modified slightly.

We mapped many fewer sub-units than the number of possible landform sub-classes in Table 1. Initially, like HAMMOND, we provided for all 96 possible sub-classes, but 40 of them do not occur in New Mexico and an additional 14 are so rare (less than 0.1% of the total area) that they are excluded. Our 42 landform sub-types (in contrast to HAMMOND's 45 for the entire country) include 99.4% of New Mexico (Table 5). We displayed the occurrences of our computer sub-classes for all 8000000 pixels in color on an unpublished 1:750000-scale working map (not shown), printed on an electrostatic plotter. Because this map is too large and detailed to procedure here, a representative part of it, generalized to the major-type level, is shown in monochrome in Fig. 3. The overall patterns of this 2° × 2° area may be compared with the appropriate part of HAMMOND's original map (Fig. 1).

The two monochrome maps excerpted here (Figs. 3, 4) are available for the entire state of New Mexico at 1:1000000 scale. A high-quality contact photographic print (90 cm × 120 cm; 24 in × 30 in) of the shaded-relief image (overlain with detailed place names and survey grid-lines) can be obtained for $US 58 each (price subject to change without notice) by sending a check payable in US funds to C-L Custom Photo Co., c/o U.S. Geological Survey Photo Library, Mailstop 914, Box 25046, Federal Center, Denver, CO 80225 USA (tel. 303-236-1010). A raster image of New Mexico showing our five major HAMMOND surface-form types (released previously in DIKAU et al. 1991) can be obtained at the following Internet address: rdikau@geo0.geog.uni-heidelberg.de.

Table 5. Relative frequency (%) of the five landform types, 14 classes and 42 sub-classes identified in New Mexico by computer classification. Nomenclature modified after HAMMOND (1964a, 1964b).

Landform type	Landform class	Landform sub-class
Plains (PLA)	Flat or nearly flat plains	A1a (0.4)
(15.8)	(1.2)	A1b (0.4)
		A1c (0.3)
	Smooth plains with some local relief	A2a (4.9)
	(14.6)	A2b (4.6)
		A2c (3.7)
		A2d (1.4)
Tablelands (TAB)	Tablelands with moderate relief	A3c (4.7)
(14.5)	(5.9)	A3d (1.2)
	Tablelands with considerable relief	A4c (3.6)
	(6.1)	A4d (1.2)
		B4c (0.8)
		B4d (0.5)
	Tablelands with high relief	A5c (0.2)
	(2.5)	A5d (0.2)
		B5c (1.3)
		B5d (0.8)
Plains with Hills	Plains with hills	A3a (6.4)
or Mountains (PHM)	(12.8)	A3b (6.4)
(55.5)	Plains with high hills	A4a (13.1)
	(21.7)	A4b (6.7)
		B4a (1.0)
		B4b (0.9)
	Plains with low mountains	A5a (6.9)
	(20.5)	A5b (0.8)
		B5a (10.1)
		B5b (2.7)
	Plains with high mountains	B6a (0.5)
	(0.5)	
Open Hills	Open low mountains	C5a (3.7)
and Mountains (OPM)	(8.6)	C5b (2.5)
(10.4)		C5c (1.6)
		C5d (0.8)
	Open high mountains	C6a (1.4)
	(1.7)	C6b (0.2)
Hills and Mountains (HMO)	Very low hills	D1d (0.3)
(3.7)	(0.3)	
	Low mountains	D5a (0.4)
	(1.2)	D5b (0.4)
		D5c (0.3)
		D5d (0.1)
	High mountains	D6a (1.0)
	(2.1)	D6b (0.6)
		D6c (0.4)

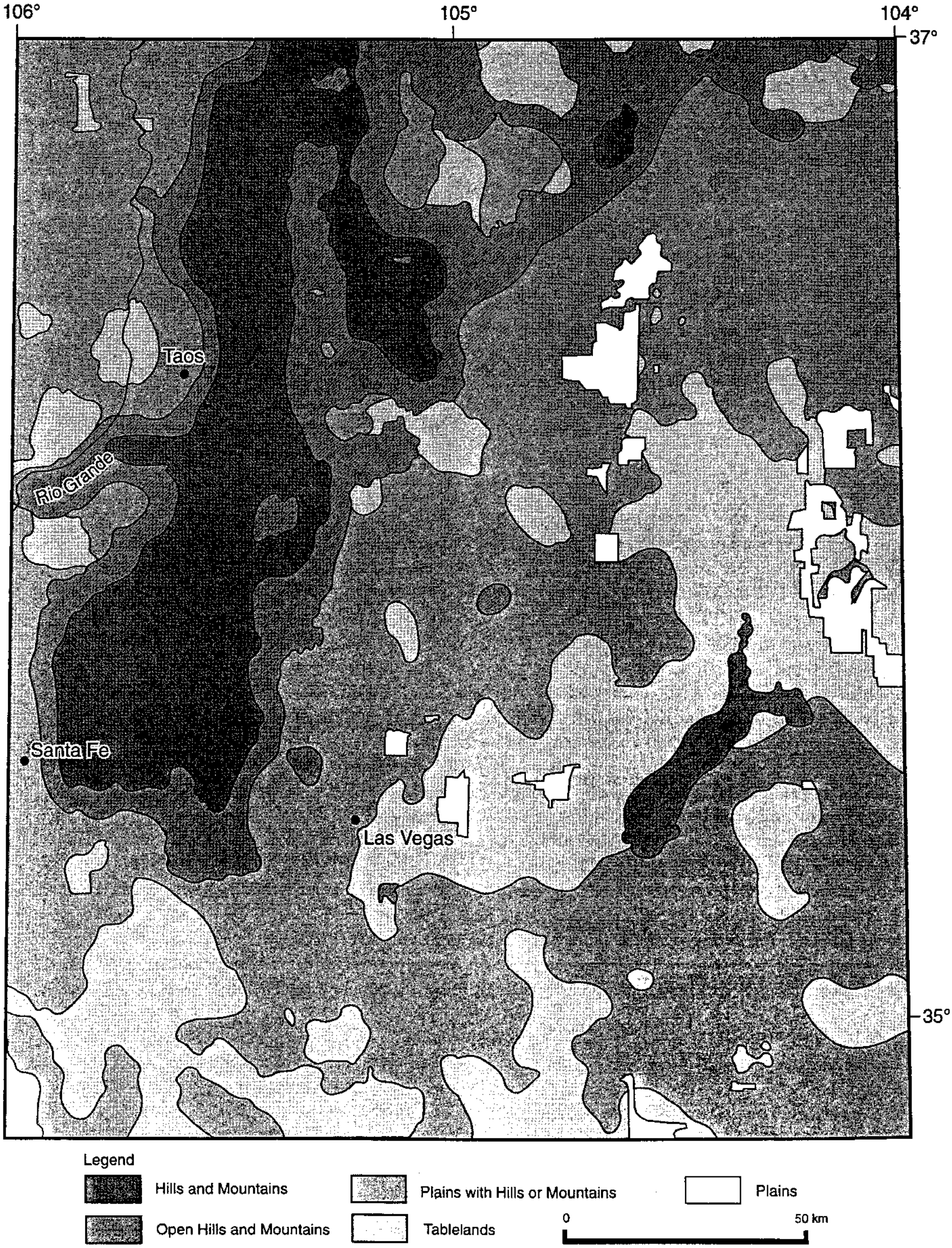


Fig. 3. Map of the five major landform types (Tables 1, 5), derived from a DEM by computer, for an approximately 2° × 2° area in north-central New Mexico.

Fig. 4. Shaded-relief image of the 2° × 2° area in Figure 3. Illumination from the northwest.

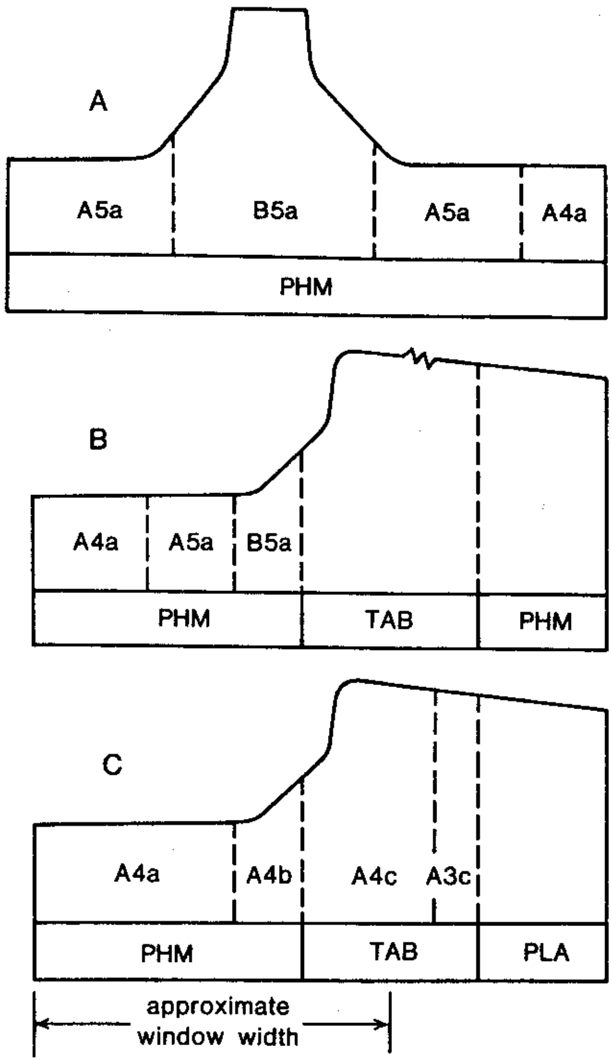


Fig. 5. Different proportions of flat and steep terrain within the moving window can put similar features (B and C) into different classes (Tables 1, 5). See text. Schematic profiles of (A) a mesa (sub-class B5a) in class PHM (Plains with Hills and Mountains), (B) a cuesta scarp 100 km east of Las Vegas; and (C) a cuesta scarp 50 km southeast of Las Vegas.

4.1 *Physiographic summary*

Our digital maps of landform types and the shaded-relief portrayal of New Mexico sampled in Fig. 3 and 4 suggest some general observations on the state's major physical features:

(1) Hills and Mountains (HMO) areas (< 20 % gently sloping land) form the core areas, as the term is used by WOOD & SNELL (1960), of the nine principal mountain chains: Sangre de Christo Mountains northeast of Santa Fe (Fig. 3), San Juan, San Pedro and San Jemez, Chuska, San Mateo (Mt. Taylor), Monzano and Sandia, Mogollon (including the Black Range, San Mateo and Magdalena Mountains), San Andres and Sacremento Mountains.

(2) The core areas of these mountains chains (HMO) are surrounded by Open Hills and Mountains (OPM) which may vary significantly in size and shape. For example, the west-facing slopes of the Sangre de Christo range (Fig. 3) are characterized by OPM units with a width of 2 to 5 km, whereas the northeast-facing slopes have a very broad OPM transition to plains, as wide as 10 to 50 km, extending to the TAB and PHM of the western Raton Mesa region.

(3) The principal Plain (PLA) regions are located in the southeast and south-central parts of the state (Fig. 1), including the upper Pecos River drainage and central parts of the Tularosa Valley, White Sands area (not shown in Fig. 3).

(4) Landform types intermediate in relief between Hills and Mountains (HMO) and Plain regions (PLA) cover about 70 % of the state and include Tablelands (TAB; 14.5 %) and Plains with

Hills and Mountains (PHM; 55.5 %). They reflect combinations of > 50 % gently sloping land and local relief exceeding 91.5 m.

Sub-types A4a, A5a and B5a comprise most of type PHM and 30 % of the entire state. They are areas of much gently sloping land in close proximity to high local relief. Other occurrences are single hills and mountains on flat plains (Figs. 3, 5A). Comparison with topographic maps at 1:100000 scale reveals transition zones, belts of gentle terrain surrounding hills, mountains and tablelands (Fig. 3). Such zones, which might be used to delimit the steeper units, are an artifact of the simultaneous coverage of flat and high-relief areas by the moving window (Fig. 5).

Unexpected differences between our results and HAMMOND's exist in the frequencies of landform types of intermediate relief. Although HAMMOND does not show units A4 and A5 in New Mexico (Fig. 1), we found these types to comprise 33 % of the state (Table 5). We speculate that our A4 and A5 correspond largely to units B2b and especially B3c, common on HAMMOND's map but absent in our results. Also, unit B4c, rare in Table 5, is widespread on HAMMOND's map. The differences may arise from contrasts in technique of slope measurement: HAMMOND (1964a) estimated his values with a contour scale, whereas we computed ours analytically. HAMMOND also may have absorbed some areas of A4 and A5 into adjacent classes because their occurrences were all less than 2072 km^2. We placed both sub-types provisionally in the corresponding major classes TAB and PHM (Table 5).

(5) Type TAB occurs exclusively in upland areas, mostly in northeast New Mexico. This part of the state is characterized by extensive cuesta-scarp (mesa) landforms, such as those east of Las Vegas (Fig. 3).

(6) A 50-km-long mesa area about 100 km east of Las Vegas (Fig. 5) has been classified as Open Hills and Mountains (OPM). This contrasting type within a typical PHM and TAB landscape is explained by incision of the mesa border and a lower percentage of gentle slope area. TAB is replaced by PHM 20 to 40 km behind the mesa border as the relief diminishes, reflecting the change from upland to lowland. A similar difference is observed in other regions where a tableland strip 5 km wide (including the upper cuesta-scarp slopes) merges into the large plain areas of southeast New Mexico (see Fig. 5).

4.2 *Comparison of computer map with that of HAMMOND*

Expectedly, there are many differences between terrain units recognized on our map (Fig. 3) and that of HAMMOND (1964b, Fig. 1). Such contrasts probably reflect those in data resolution and increments of the moving window. Again, HAMMOND estimated values of slope and profile type rather than computing them out as we have. And again, HAMMOND generalized his map, which was created for broader scales than ours (Fig. 1). Because we performed no generalization, the two maps are comparable only with respect to the broad-scale morphometric structures. Further examination of these and other differences noted above lies beyond the scope of this paper.

(1) Our Plains (PLA) units show good correspondance with HAMMOND's classes in the east-southeast part of the state. Both maps identify these regions with A2 attribute combinations. A larger difference is in the flat areas of the Tularosa Valley (about 4000 km^2) which is, according to FENNEMAN (1928), part of the southwest Basin and Range province. In that area our map shows A1 and A2 units where HAMMOND mapped type B6a (PHM).

(2) Tablelands (TAB) on HAMMOND's map cover large parts of northeast and northwest New Mexico. On our map this unit is reproduced adequately in the northeast (Fig. 3) but not in the northwest. In northwest New Mexico, classified by FENNEMAN (1928) as part of the Colorado Plateau, the digital approach created large areas of PHM and only small TAB areas.

(3) Plains with Hills or Mountains (PHM) were modelled adequately. This moderate-relief terrain type is the dominant unit in southwest, south-central, and northwest parts of New Mexico.
(4) Similarly, Open Hills and Mountains (OHM) on the digital map correspond very well with the equivalent units of HAMMOND. These areas are located in the southwest and north of the state. Significant differences are present in the southern San Luis Valley (C5a) between the Sangre de Christo Mountains and the Rio Grande Valley (Fig. 3) and in the foothill regions of the east Sacramento Mountains (C5c), where the digital map shows PHM and TAB terrain.
(5) Most of the Hills and Mountains (HMO) were reproduced adequately, but the areas covered by these units on the digital map are smaller. In general, HAMMOND's map shows HMO units in regions where the digital approach identified both HMO and OPM terrain.

5 *Discussion and conclusions*

A computer-assited classification of surface-form types for an entire state has been prepared by automating the manual method of HAMMOND. To our knowledge, this is the only successful mechanization of the HAMMOND approach yet published. Its initial implementation does not exactly reproduce HAMMOND's map, but that was not the objective. The digital method, does yield broad map patterns resembling HAMMOND's for most of the major landform types in New Mexico and provides greater detail for classes and sub-classes. It works quite well enough to warrant further development.

Much work lies ahead. The contrasts between our results and HAMMOND's, particularly the disparities in mappped sub-classes, require explanation. Other areas for study include the narrow belt of Open Hills and Mountains (OPM) surrounding the large area of Hills and Mountains (HMO) in Fig. 3, which is absent on HAMMOND's map (Fig. 1). Improvements upon the HAMMOND method should be investigated. For example, LINDA GRAFF (pers. comm.) found the Tablelands criteria often misleading, in that tablelands are better indicated by flat slopes occurring in the upper 1/3 or 1/4 of the elevation range than in the upper 1/2. Experiments should be carried out to evaluate this possible change. It may also prove helpful to modify the HAMMOND method for smaller study areas, where the mix of significant parameters may differ from that appropriate to broad scales.

New Mexico provides only one test of the HAMMOND approach. Because the DMA/USGS 3-arc-second DEM is now freely available for the entire United States from the U.S. Geological Survey over the Internet, the whole country could be reclassified in greater detail at minimum cost. Indeed, a HAMMOND hierarchy of landform types and units could be similarly established for any country or area covered by a DEM. The recently published Digital Chart of the World provides the opportunity to extend the HAMMOND system worldwide at a resolution of perhaps 1–2 km.

Our automated HAMMOND maps are a first step in addressing the issue raised at the outset of this paper: the role of topography in accounting for the spatial distribution of slope-failure in New Mexico. Further work is needed to forge the form-process links required by geomorphology. The efficacy of HAMMOND-type landform units in studying the effects of slope failure and other geomorphic processes in a spatial context remains to be demonstrated. The first step is to digitally overlay maps of landslide occurrences in New Mexico on our HAMMOND classes (DIKAU & JÄGER 1995). Should the expected correlations emerge, then more detailed analyses can be undertaken. These might include the application of geometric signatures (PIKE 1988) to fine-scale DEMs.

First approaches towards higher order landform modeling for the entire United States and the global topography has been prepared by SCHROEDER & DIKAU (1995). These experiments are part of the research of the International Association of Geomorphologists (I.A.G.) working group on Geometric Global Relief Classification (GGRC).

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