Automated Drainage Extraction in Mapping the Monterey Submarine Drainage System, California Margin

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Abstract. Drainage-extraction algorithms traditionally used for extracting river networks and watersheds from gridded land topography are applied to gridded multibeam bathymetry of the mid-California margin. The algorithms are used to automatically map two regional tributary networks of submarine canyons and deep-sea channels draining Monterey Bay, the principal conduits of which are Acension and Monterey Canyons. The algorithms reliably map subaqueous drainage areas, but are prone to error in mapping the extent of submarine canyon and channel thalwegs due to operator subjectivity and algorithm limitations. A geomorphic comparison of the Acension and Monterey Canyon networks, with 12 river networks in the continental U.S., illustrates both the potential and weaknesses of using drainage extraction algorithms to analyze sediment pathways in gridded bathymetry.

Introduction

Early bathymetric maps of submarine canyons (e.g., Veatch and Smith, 1939) were the first to document the terrestrial attributes of seafloor features cut by sediment drainage along continental margins. Since then, extensive echo-sounding and swath-mapping surveys of continental margins have revealed canyon-cut terrains resembling semi-arid landscapes (Bellaiche *et al.*, 1983) and deep-sea channels with river-like morphologies (Damuth *et al.*, 1983). Such surveys have also led to the recent recognition of regional tributary networks of submarine canyons and deep-sea channels (Hesse, 1989; Schlee and Robb, 1991). In contrast to submarine fans, these networks act to collect sediment drainage rather than distribute it. Because of their similarity to large river networks on land, the networks have been termed submarine drainage systems (Hesse, 1989).

An example of a submarine drainage system is the network of submarine canyons and deep-sea channels draining Monterey Bay, California, which collect seaward into a central deep-sea channel that feeds the Monterey Fan. The system is referred to here as the Monterey Submarine Drainage System (MSDS), and is depicted in the National Oceanic and Atmospheric Administration's (NOAA, 1988a-g) gridded multibeam bathymetry of the mid-California margin (35.5°–37.5° N, 122°–124° W) (Figure 1). While the areal extent and detail of the NOAA grid is equivalent to that of a coarse digital elevation model (DEM) of land topography, it and similar multibeam bathymetric grids provide the most complete and accurate representations of deep-sea topography to date. These grids also permit seafloor features such as the MSDS to now be examined with computer techniques used by terrestrial geologists for analyzing landforms in DEMs.

The purpose of this paper is to demonstrate the potential of drainage extraction algorithms for mapping and quantifying the morphology of submarine canyons and deep-sea channels in gridded bathymetry. The algorithms were originally designed for automatically mapping river networks and watersheds in DEMs of land surfaces (e.g., O'Callaghan and Mark, 1984), but have been shown to be equally suited for mapping channel systems in DEMs of both Mars (Jenson, 1991) and the seafloor (Pratson and Ryan, 1992; Pratson and Ryan, 1994). In this study, we attempt to use drainage extraction algorithms as an objective means for extracting comparative geomorphic measures of the MSDS and twelve river networks in the continental U.S. The comparison is conducted in an effort to quantify the morphologic similarity between submarine and subaerial drainage systems noted above. As will be shown, results of the comparison prove inconclusive, in part because of inaccuracies in the extent of submarine canyons and channels mapped by the algorithms.

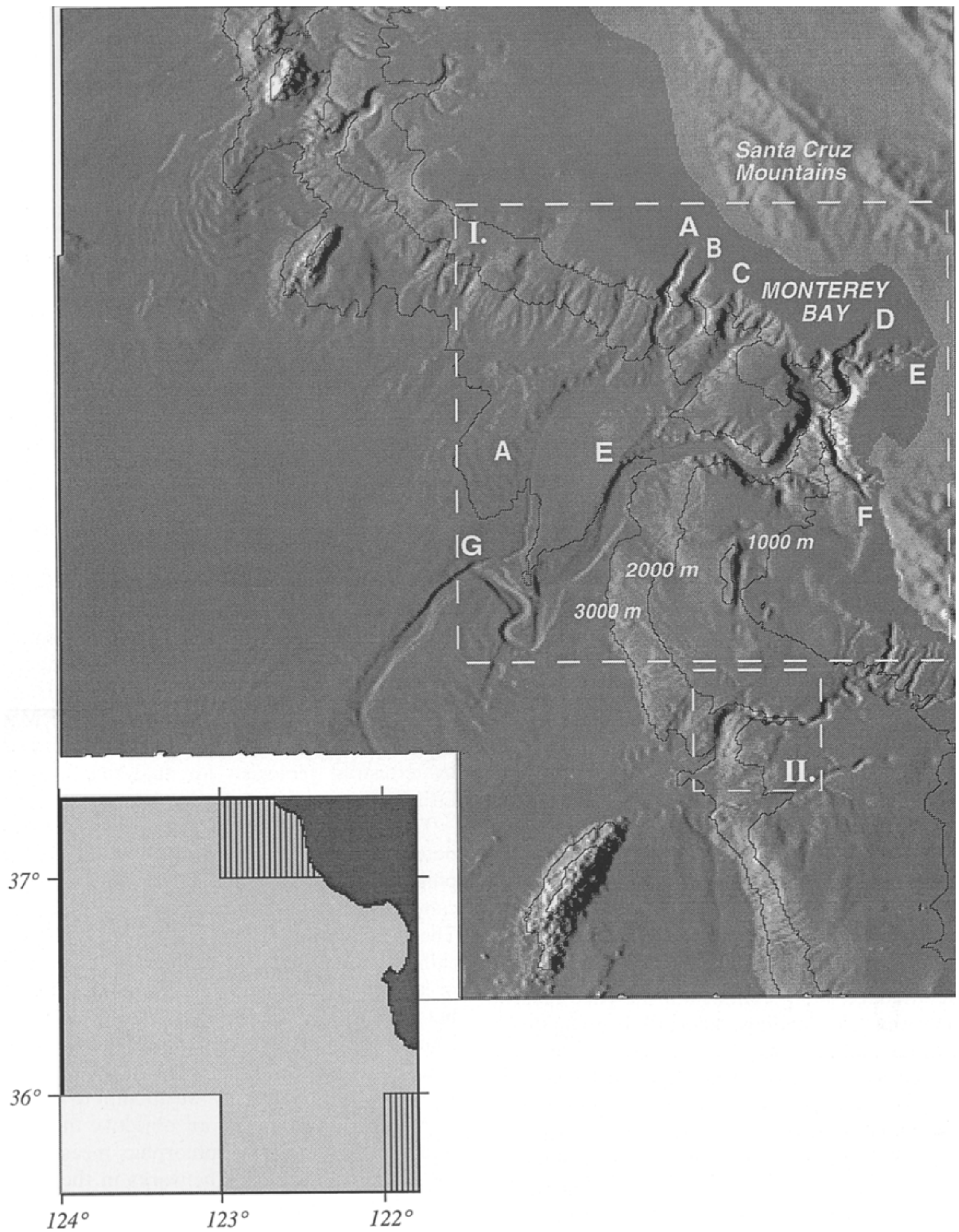

Fig. 1. Shaded image of NOAA bathymetry off Monterey, California (west illumination): A. Nuevo Canyon, B. Cabrillo Canyon, C. Acension Canyon, D. Soquel Canyon, E. Monterey Canyon, F. Carmel Canyon, G. Monterey-Acension Canyon confluence. Inset shows coverage of data used to create image: light grey area is NOAA bathymetry, vertical lined areas are bathymetry derived from Lamont-Doherty Earth Observatory's GeoBase (Menke *et al.*, 1991). Gridded using the surface routine of Smith and Wessel (1990). Dark area is NOAA 30 arc-second gridded topography of the U.S.

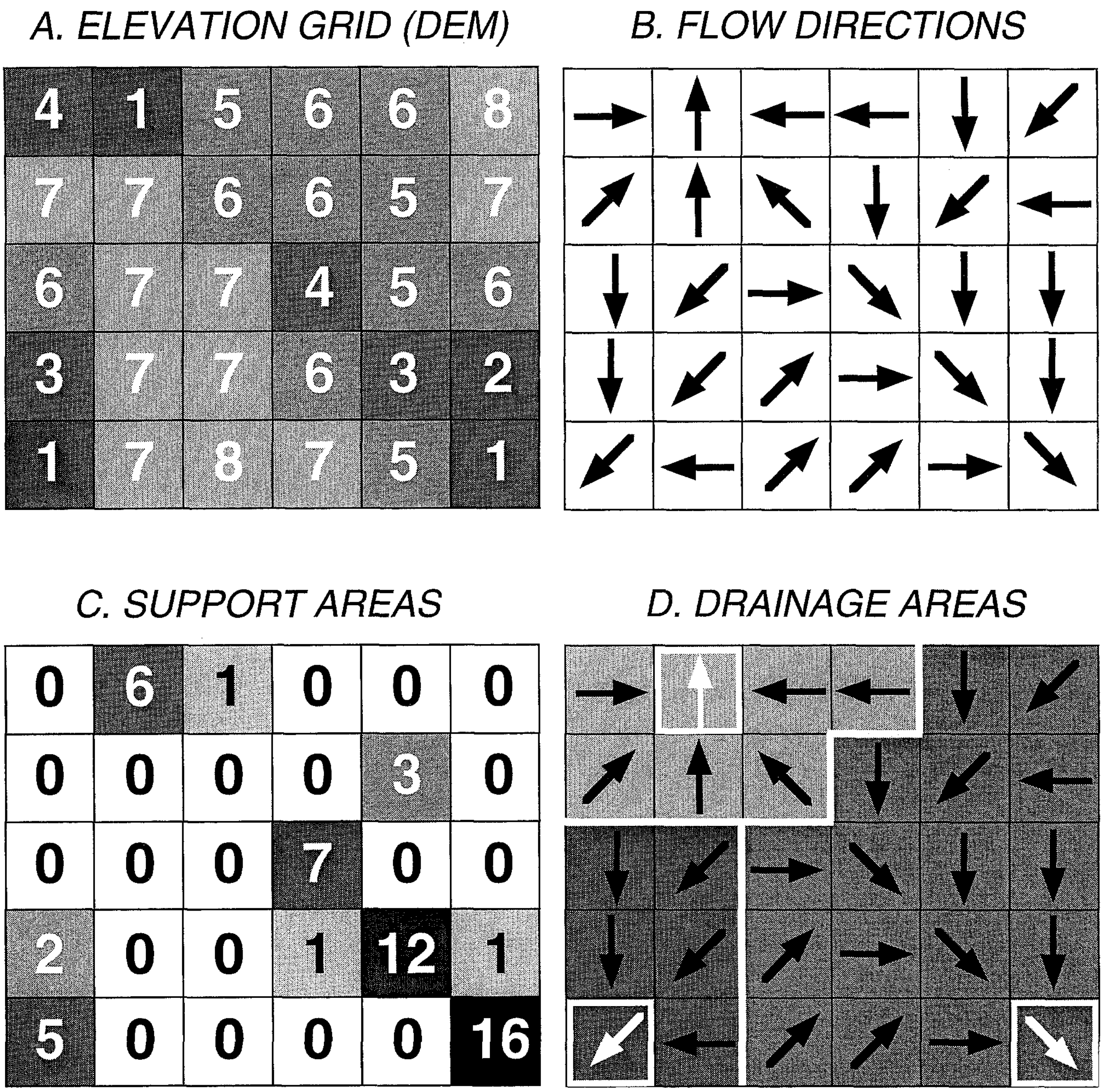

Fig. 2. Illustration of how drainage extraction is accomplished. A. Example grid of elevations (numbers), or digital elevation model (DEM). B. Arrows indicate flow direction from each grid cell to its lowest neighboring cell. C. Support area, or number of grid cells that drain into each grid cell along paths defined by flow directions. D. Drainage areas, or regions within DEM that direct flow to a common outflow point (white boxes with white arrows). White lines are drainage divides. See text for detailed explanation.

The Monterey Submarine Drainage System

The MSDS is principally composed of two submarine canyons: Acension and Monterey (Figure 1). Into these feed a number of tributary canyons including Nuevo and Cabrillo which enter Acension Canyon, and Soquel and Carmel, which enter Monterey Canyon (Figure 1A-F). Acension and Monterey join at approximately 3200 m water depth (Figure 1G) to form the main channel that feeds the Monterey Fan. Together, these two canyon networks drain roughly 6500 km^2 of seafloor.

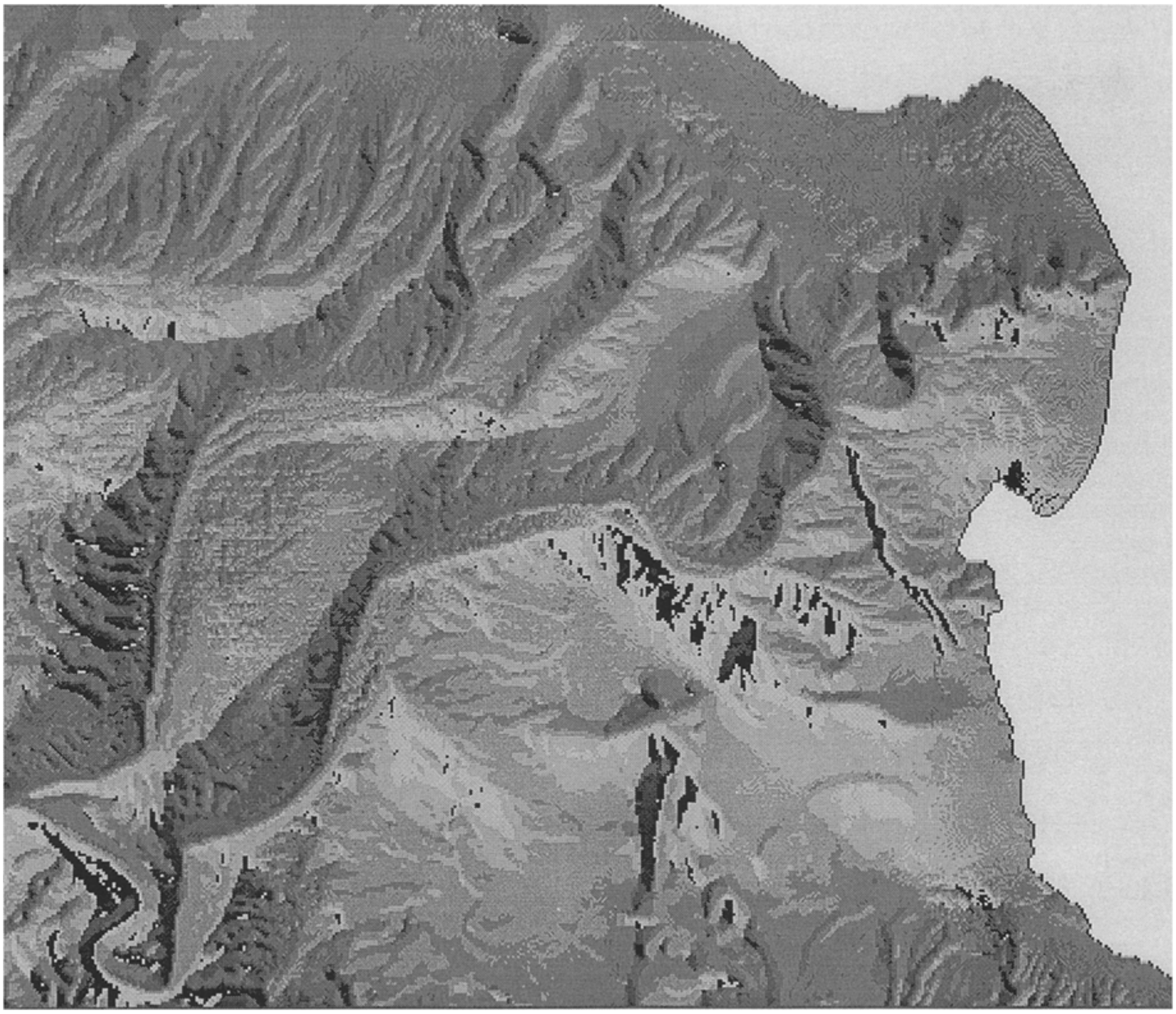

Fig. 3A.

The source of sediments to the MSDS has been the California coastal highlands surrounding Monterey Bay. Materials have been delivered to the MSDS by rivers and shallow marine currents, which because of the region's narrow continental shelf (≤ 15 km), continue to transport sediments to the upper reaches of the drainage system despite the present sea level highstand (McHugh *et al.*, 1992). Build-ups of these sediments have been redistributed within and out of the drainage system by sediment gravity flows (e.g., turbidity currents, debris flows, etc.), some of which appear to have been triggered by earthquakes along the San Andreas Fault Zone (Normark and Gutmacher, 1988). While the lower part of Acension Canyon is presently filled, turbidity currents have continued to pass through both Canyon networks during the Holocene (Hess and Normark, 1976).

Bathymetry

NOAA bathymetry of the MSDS (light grey area, inset, Figure 1) is primarily based on soundings collected in water depths greater than 600 m using the SeaBeam swath mapping system (Grim, 1992). In water depths less than 600 m, soundings are from pre-multibeam hydrographic surveys and surveys using a 36 kHz shallow-water multibeam echo sounder. Where multibeam systems were used, adjacent swaths overlapped 10%.

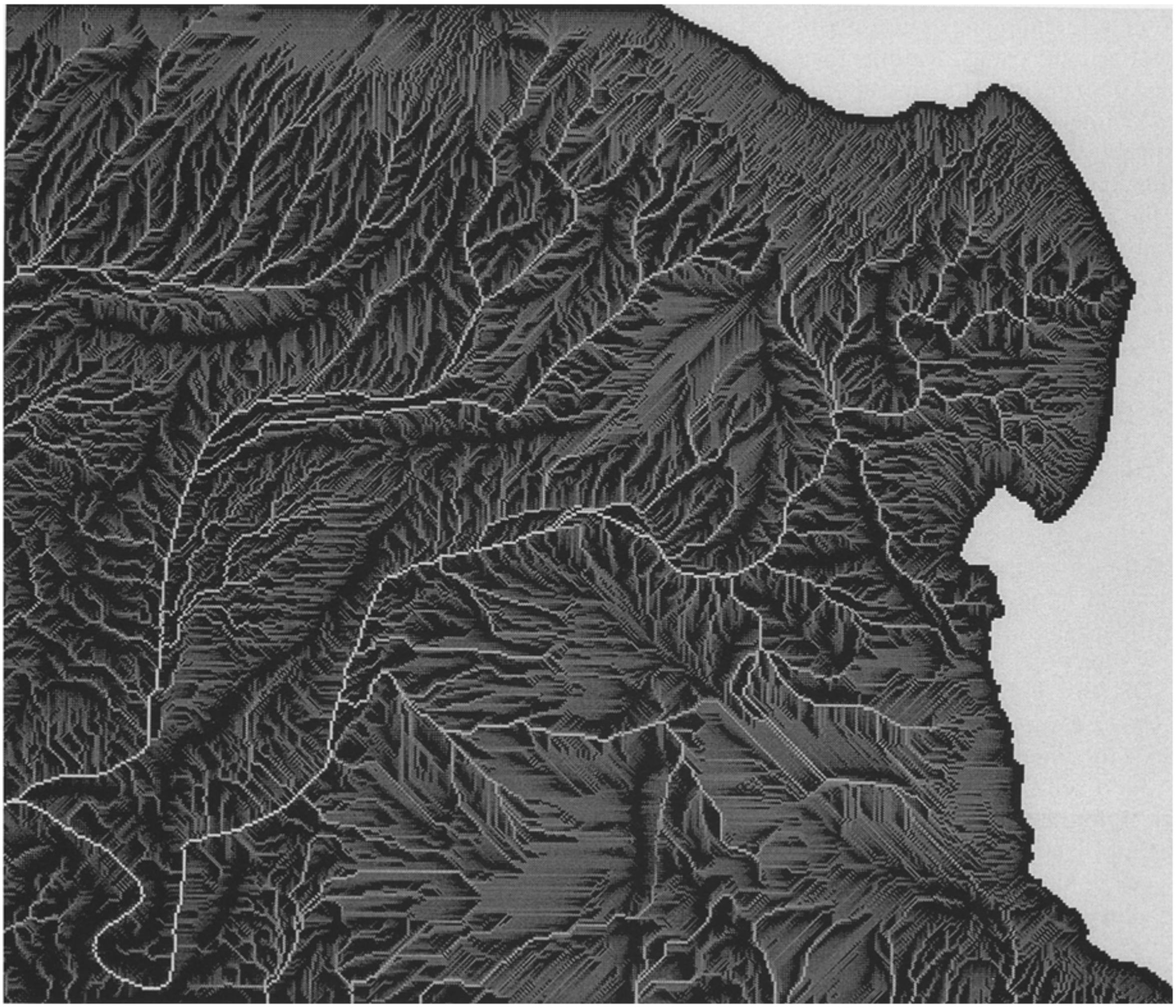

Fig. 3B.

Fig. 3 A. Flow directions for the gridded bathymetry of the MSDS in dashed box area I of Figure 1. Eight shades of grey represent the eight possible directions of flow, beginning with black which points towards the northeast, and proceeding clockwise at 45° increments to white which points to the north. B. Support areas for the same area computed from the flow directions in Figure 3A. Grid cell support areas increase from zero along interbasin ridges (displayed as black) to >100,000 grid cells at the downstream point of the MSDS in the image (displayed as white).

From the soundings, NOAA has constructed seven bathymetric grids (NOAA, 1988a-g), the composite of which is shown in Figure 1. This composite grid is based on roughly 1.8 million soundings selected from 30–60 million "raw soundings", each of which have a positional accuracy of within 50 m and depth accuracy of within 1% actual water depth (Grim, 1992). The grid projection is Universal Transverse Mercator (UTM) and cell spacing is 250 m.

Automated Drainage Extraction

Drainage information on the MSDS can be automatically extracted from the NOAA bathymetry using a sequence of computer algorithms that predict directions of gravity-driven fluid flow based on local slopes. A variety of such algorithms have been developed for extracting drainage information on fluvial systems from DEMs (see Moore *et al.*, 1991). The algorithms used in this study are based on the scheme proposed by Jenson and Dominique (1988), which incorporates a technique for mapping drainage pathways across grid depressions and plains; features that are common in gridded bathymetry. The general proceedure for automated drainage extraction is:

1. *Assign each grid cell a flow direction.* Flow directions define the paths fluid would flow from one grid cell to the next (Figure 2B), and are unit vectors that point from a grid cell towards the one of its eight nearest neighbors with the steepest descent in elevation (Figure 2A). Descents to lower neighboring cells are weighted as a function of distance from the center cell: east-west neighbors are weighted by the grid cell spacing in the x-direction (dx), north-south neighbors by the grid cell spacing in the y-direction (dy), and diagonal neighbors by $\sqrt{dx^2+dy^2}$. This study resolves cases in which two or more neighboring cells share the same distance weighted drop in elevation by selecting the one closest in line with the mean trend of flow directions pre-determined for the neighboring cells upslope of the center cell. Flow directions for the NOAA bathymetry of the MSDS (Box I, Figure 1) are shown in Figure 3A.
2. *Calculate the area drained by each grid cell.* This area is the summed area of all the grid cells upslope of a grid cell that lead flow into the grid cell. The area is commonly referred to as the cell's support area and is analogous to the amount of discharge the cell could potentially receive. Figure 2C shows the support areas determined for the hypothetical grid shown in Figure 1A. These support areas are determined by using the flow directions for the grid (Figure 2B) to count the number of upslope cells that direct flow into each grid cell. These numbers then represents the grid cells' support areas. The support areas for the MSDS, which are derived from the flow directions in Figure 3A, are shown in Figure 3B.
3. *Extract drainage networks.* Drainage networks are extracted by specifying a support area threshold. All grid cells having support areas equal to or greater than the threshold constitute part of the drainage network. Grid cells with support areas less than the threshold constitute the interfluves between channels in the network. If the support area threshold is high, the drainage network that is extracted is sparse. If the threshold is low, the drainage network is dense. Figure 4 shows the drainage network corresponding to the MSDS extracted from the support areas in Figure 3B using a threshold of 50 cells.
4. *Delineate network drainage areas.* Network drainage areas are delineated by grouping all grid cells with flow directions that direct flow to the outlet cell at the end of the network (Figure 2D). Those cells that do not direct flow to the outlet cell are considered to be outside the network's drainage area. Figure 4 shows the drainage areas of the Acension and Monterey Canyon networks.

Prior to the steps outlined above, a DEM is often preconditioned to infill all grid depressions up to their spill point, which is the lowest elevation along a depression's rim. If depressions are not infilled, local flow directions oppose one another on either side of the depressions. This breaks the downslope path of flow directions that mark the course of canyons and channels, resulting in the extraction of segmented drainage networks. Infilling of depressions prior to steps 1–4 ensures extraction of continuous drainage networks by approximating the natural behavior of fluid flows, which infill depressions up to their spill points before exiting downslope. The reader is referred to Jenson and Dominque (1988) and Pratson and Ryan (1992) for further details on preconditioning DEMs.

Representation of the Monterey Submarine Drainage System

Figure 4 shows drainage networks and drainage areas extracted from the NOAA bathymetry in the region surrounding the MSDS (Box I, Figure 1) using a support area threshold of 50 cells. The drainage networks in this figure correspond to the networks of the submarine canyons and canyon tributaries that form the MSDS. The canyons and most of the large canyon tributaries are shown to initiate near the shelf break. The canyons are mapped seaward into deep-sea channels on the Monterey Fan that are fed laterally by shorter tributaries corresponding to gullies incising the channel walls. The MSDS is clearly seen in the center of the figure as the regional tributary network formed by the collection of canyons, channels and gullies. The system can be subdivided into the Acension and Monterey Canyon systems, whose subaqueous drainage areas span the light and dark grey regions (respectively) in Figure 4.

Closer inspection reveals discrepancies between the extent of the canyons and channels mapped in Figure 4 and the NOAA bathymetry (Figure 1). An example is the small tributary network mapped on the northwestern levee of Acension Canyon (dashed box, mid-left, Figure 4). This network is not evident in the corresponding bathymetry.

The mapping of the tributary network highlights two important limitations associated with automatic drainage extraction. The first is that the drainage ex-

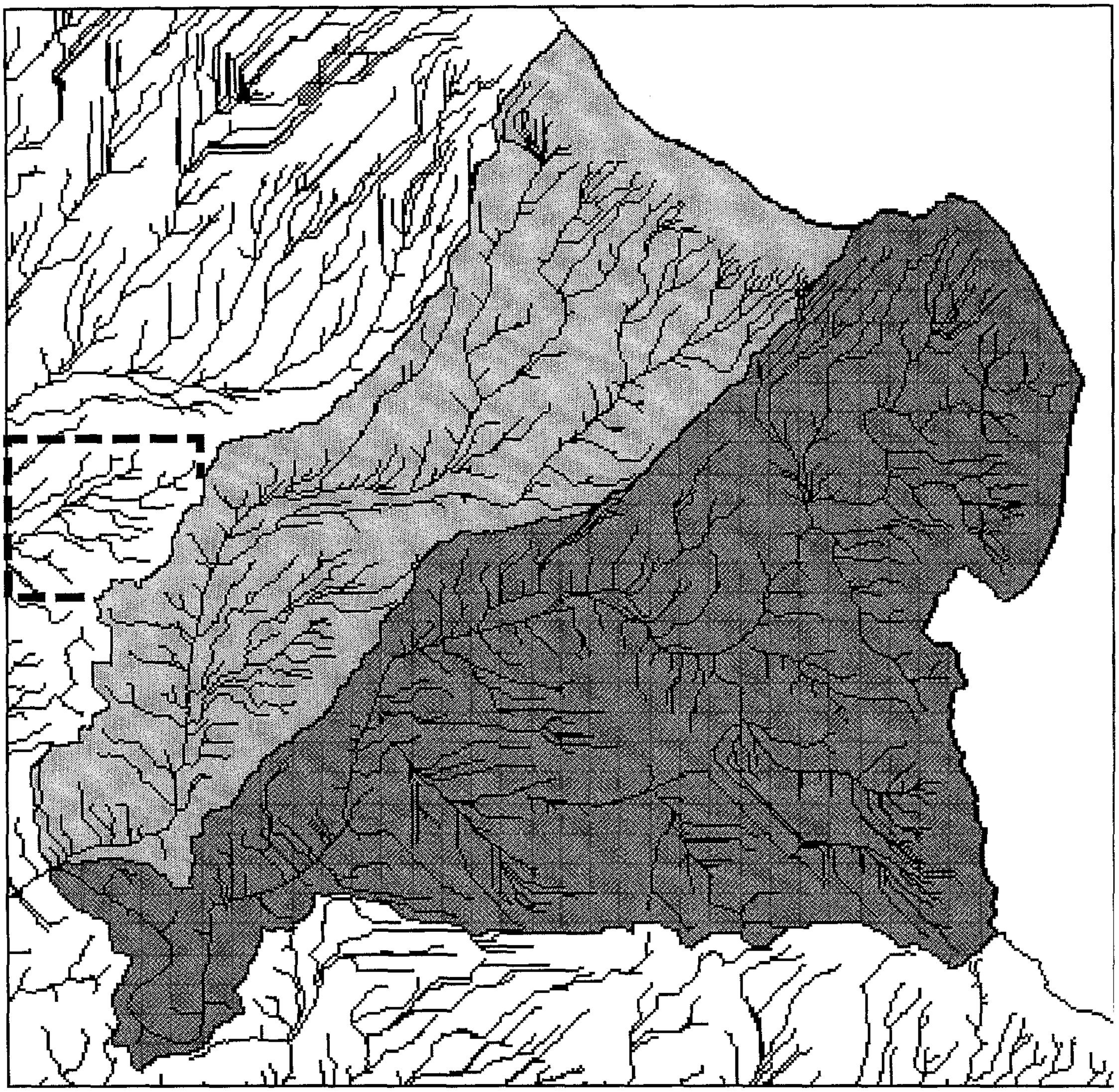

Fig. 4. MSDS canyon-channel networks extracted from the gridded bathymetry in dashed box area I of Figure 1 using a support area threshold of 50 grid cells. Shaded regions are the subaqueous drainage areas of the Acension (light grey) and Monterey (dark grey) Canyon networks.

traction algorithms assign each grid cell only one flow direction. As a result, the algorithms can only map parallel and tributary channel geometries. Distributary or braided channel geometries, which would require multiple flow directions, are not mapped. This presents a problem on the Monterey Fan levees where gradients are low and sediment waves form obstructions to turbidity current overbank flows, making distributary and/or braided sediment pathways more likely.

The second and more serious limitation is that the drainage extraction algorithms map channel pathways purely as a function of grid cell support area, a measure that is independent of whether a grid cell actually falls within an eroded channel or occurs on an uneroded slope. The tributary network extracted over the northwestern levee of Acension Canyon is composed of grid cells in troughs between depositional sediment waves with support areas that exceed 50 cells. Evidence that such a network actually exists is not seen in either the bathymetry or in side-scan sonar imagery of levees just to the south collected by the authors aboard the R/V *Point Sur* in September of 1990. Other artificial channels mapped by drainage extraction are commonly straight. Such channels are evident in Figure 4 and

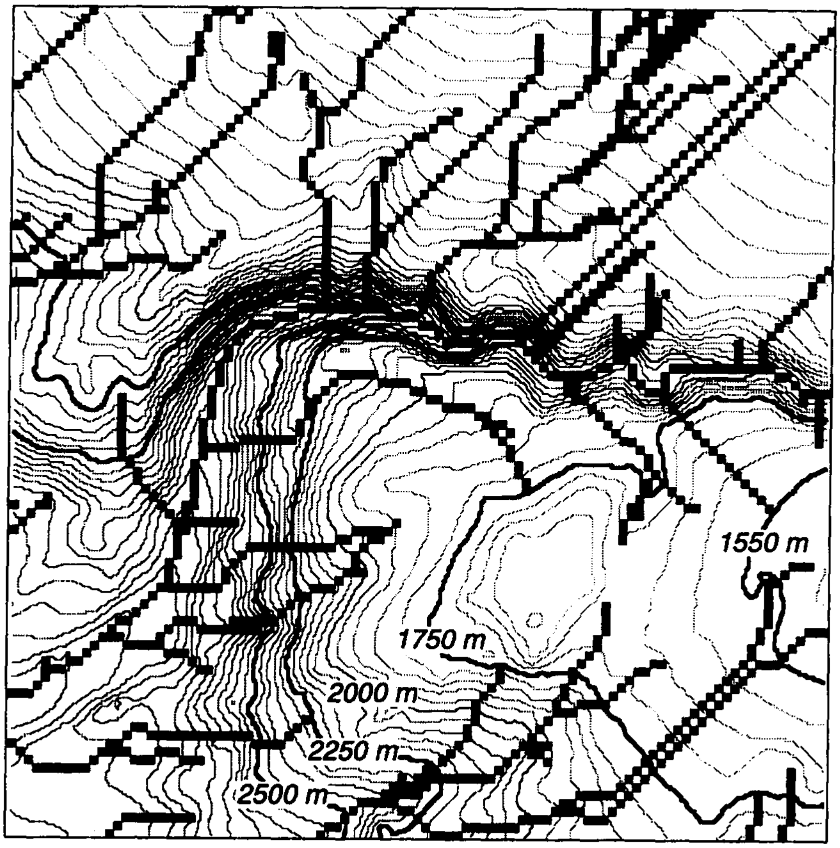

Fig. 5A.

are a consequence of using a support area threshold which is too low for regions in the DEM. Figure 5A shows the drainage network extracted for Sur Canyon to the south (Box II, Figure 1) using the same support area threshold of 50 cells. The network contains several straight channels on slopes leading into the canyon, which at the resolution of the grid (250 m) appear to be uneroded. When the support area threshold is raised to 500 cells, the artificial channels are absent. As a consequence of this high threshold, however, several real erosional channels are not mapped either (Figure 5B).

Figure 5 illustrates that the accuracy of drainage information extracted by the algorithms is influenced by two factors: the resolution of the DEM and the support area threshold used to map drainage networks. The effect of DEM resolution on the measurement of drainage area and channel length is demonstrated in Figures 6A and B. The figures show results from a sensitivity experiment in which the resolution of the NOAA bathymetry was degraded from its initial grid cell spacing of 250 m to a coarser grid cell spacing of 1 km. At each grid resolution, a constant support area threshold of 50 cells was used to extract channel networks within the Acension and Monterey Canyon basins (grey areas, Figure 4). Results show that with decreasing grid resolution, measurement of drainage area remains relatively constant (for both the Acension and Monterey Canyon basins, drainage area decreases at a rate of 0.1 km^2 with decreasing grid resolution, Figure 6A), but total channel length decreases rapidly (Figure 6B). This indicates grid resolution has a minor influence on the measurement of drainage area, but a significant influence on the measurement of channel length.

A second sensitivity experiment demonstrates how channel length is also effected by the support area threshold used to map channel networks (drainage area is independent of support area threshold). In this experiment, grid resolution was held constant at a grid cell spacing of 250 m, while the support area threshold for mapping channel networks in the Acension and Monterey basins, was reduced from 500 to 0 cells. Figure 6C shows that as the threshold is decreased, total channel length increases slowly and almost linearly until reaching a narrow range of transition

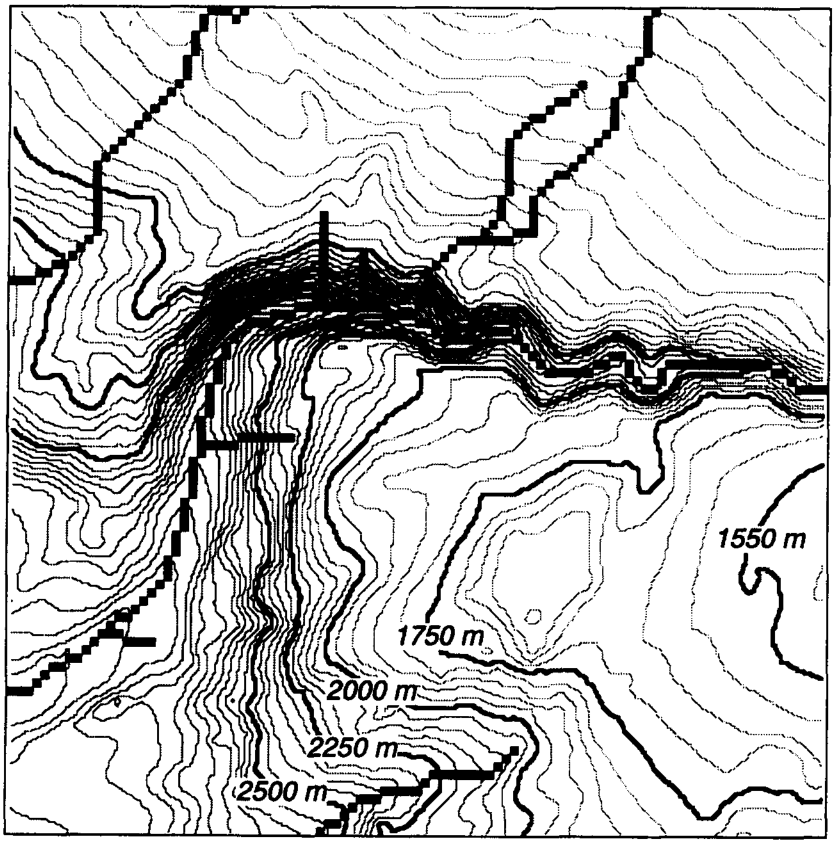

Fig. 5B.

Fig. 5 A. Canyon-channel networks extracted from the gridded bathymetry of Big Sur Canyon south of the MSDS in dashed box area II of Figure 1 using a support area threshold of 50 cells. Note straight, "artificial" channels defined in regions where contours show no evidence of a channel. B. Canyon-channel networks extracted for the same area using a support area threshold of 500 cells. The higher threshold eliminates artificial channels, but prevents mapping of several real channels defined by contours.

thresholds below which channel length increases rapidly. The transition thresholds may represent basin-specific support area thresholds, over which extracted drainage paths change from principally conforming to eroded channels to occuring along both eroded channels and uneroded slopes.

Comparison to Subaerial Drainage Systems

Objective

In the first description of a submarine drainage system, Hesse (1989) noted that the regional organization of submarine canyons and channels feeding the Northwest Atlantic Mid-Ocean Channel was similar to that of the Mississippi River and its satellite tributaries. The regional organization of the MSDS is equally reminiscent of subaerial drainage systems and its Monterey Canyon has often been compared to Arizona's Grand Canyon (e.g., Shepard and Dill, 1966). An implication of these similarities is that aspects of continental margin evolution by gravity-driven sediment flows beneath the sea parallel topographic evolution by rivers on land. In contrast to subaerial drainage systems, the seafloor surfaces upon which submarine drainage systems form are essentially free of vegetation, have a relatively homogeneous surfacial lithology generally consisting of unconsolidated sediments, and are overlain by a marine climate that is comparatively uniform for long periods of time (months to tens of years vs. days). Given these differences, a quantitative geomorphic comparison of submarine and subaerial drainage morphology might illuminate some previously unrecognized erosional mechanism in either environment. In an attempt to address this issue, the geomorphology of the Acension and Monterey Canyon networks was compared with twelve river networks from the continental U.S. (Table I).

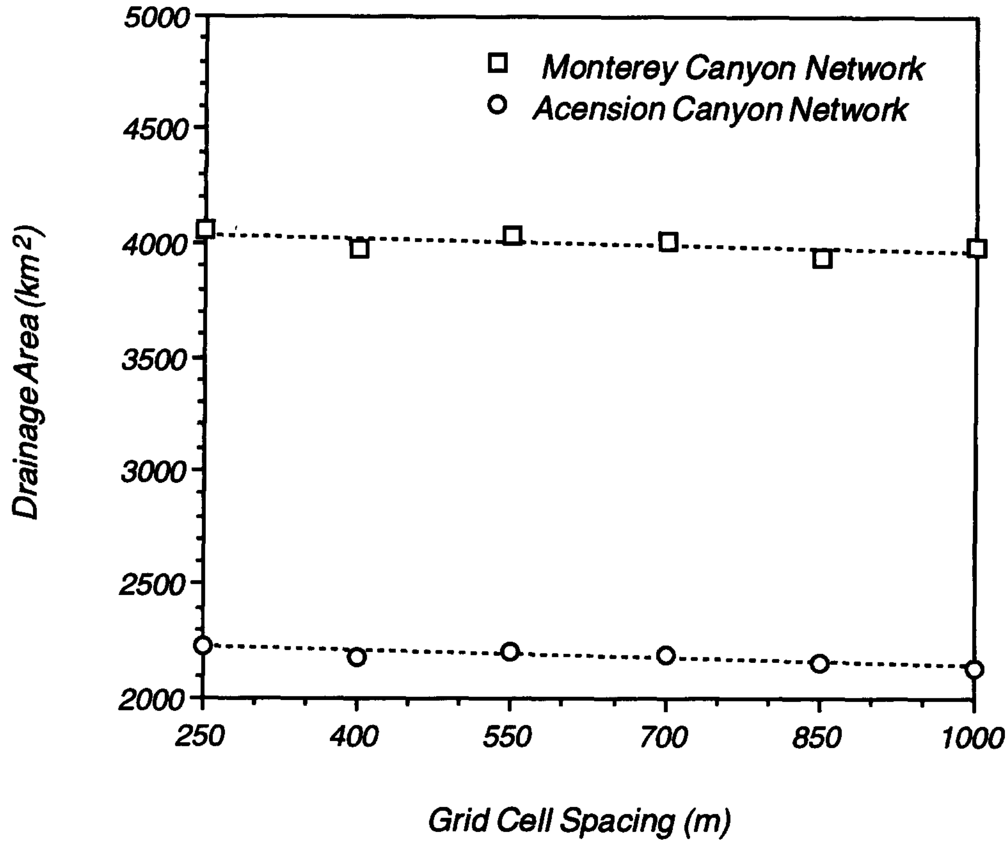
Monterey Canyon Network
Acension Canyon Network
Drainage Area (km2)
5000
4500
4000
3500
3000
2500
2000
250
400
550
700
850
1000
Grid Cell Spacing (m)

Fig. 6A.

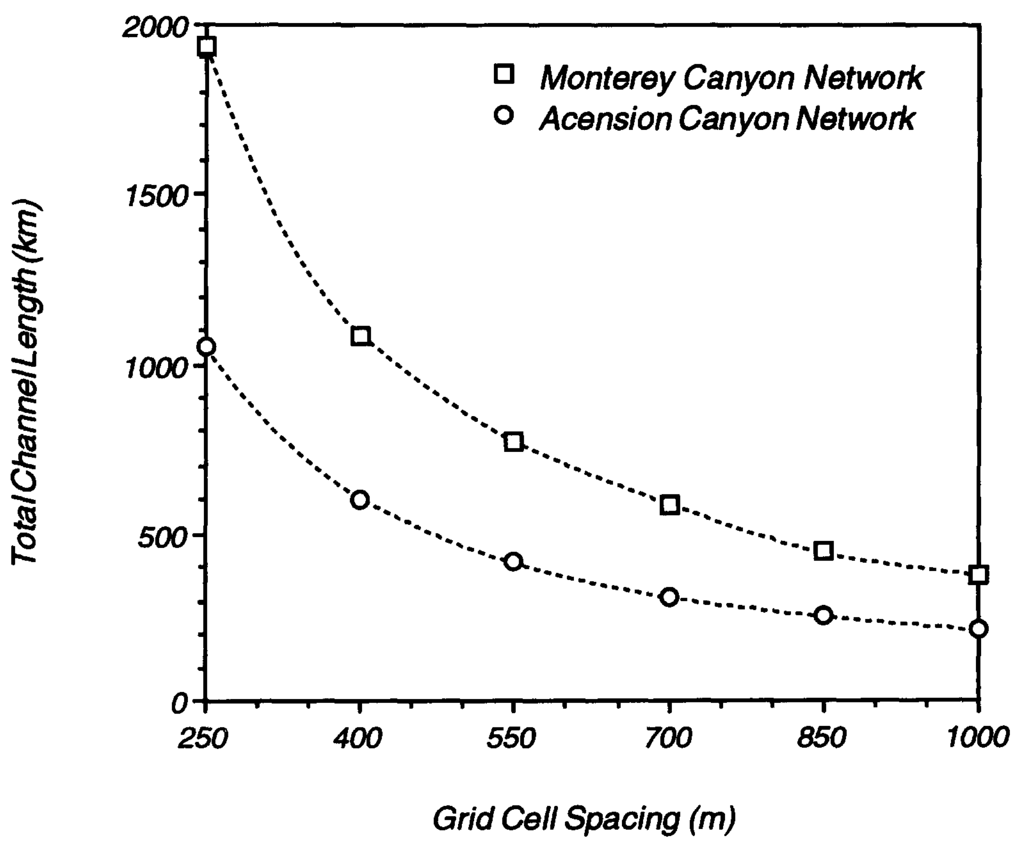
Monterey Canyon Network
Acension Canyon Network
Total Channel Length (km)
2000
1500
1000
500
0
250
400
550
700
850
1000
Grid Cell Spacing (m)

Fig. 6B.

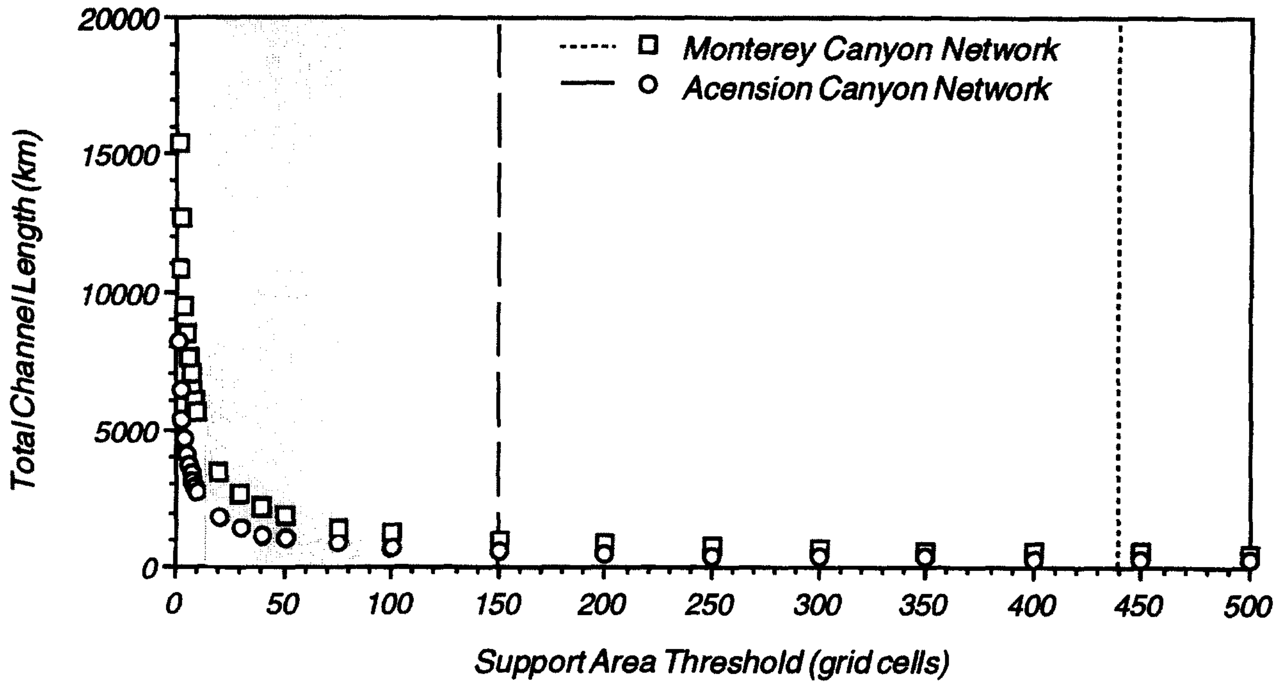

Fig. 6C.

Fig. 6. A. Plot of grid resolution versus drainage areas of the Acension and Monterey Canyon networks extracted from the gridded bathymetry. B. Plot of grid resolution versus total channel lengths extracted for the Acension and Monterey Canyon networks. C. Plot of support area threshold versus total channel lengths extracted for the Acension and Monterey Canyon networks. Grey area highlights transition thresholds over which measures of total channel length increase rapidly with decreasing support area threshold. Dashed and dotted lines mark minimum support area thresholds for extracting the Acension and Monterey Canyon networks from the NOAA bathymetry at a grid cell spacing of 250 m determined using the constant channel drop procedure of Tarboton *et al.* (1991).

Methodology

The river networks selected for comparison to the Acension and Monterey Canyon networks come from four climatically different regions representing a variety of lithologies and vegetation, but having the same relief and general physiography as the California margin. The river networks were automatically extracted from the NOAA 30 arc-second DEM of the continental U.S. (an available and comprehensive source of U.S. topography) after re-mapping it to an equivalent grid cell spacing of 926 m in UTM projection. The Acension and Monterey Canyon networks were extracted at the same resolution by first re-mapping the NOAA gridded bathymetry to the 926 m grid cell spacing using a bilinear interpolant.

To remove the subjectivity in selecting an appropriate support area threshold while maximizing the mapping of resolvable channels, the constant channel drop procedure of Tarboton *et al.* (1991) was used in extracting the channel networks from the individual drainage basins in the DEMs. The procedure required that channel segments in both river and canyon networks be ordered according to the Strahler (1952a) scheme of channel hierarchy. In this scheme, headwater channels are first order channels, and higher order channels begin at the confluence between channels of equal order. Broscoe (1959) observed that when channels are ordered this way, the mean drop in elevation along channels of a given order is statistically the same from one channel order to the next. In the Tarboton *et al.* (1991) procedure, extraction of the highest resolution drainage network is accomplished by selecting the smallest support area threshold for which the constant channel-drop property still holds. This threshold is found by reducing the support area threshold until the mean drop in elevation between channels of successive orders is determined to be statistically different by a Student t test with a 95% confidence interval. As an example, support area thresholds determined by this technique for extracting the Acension and Monterey Canyon networks from the NOAA bathymetry at a grid cell spacing of 250 m are shown in Figure 6C. The support area thresholds determined for extracting the fourteen drainage net-

Table I

Location, support area threshold, and geomorphic measures of the twelve subaerial and two submarine drainage networks

Drainage Basin	Outlet latitude	Outlet longitude	Support Area Threshold (cells)	Total Channel Length (km)	Drainage Area (km²)	R_b	R_L	R_S	D_d (km^{-1})
Hudson River, NY			8	1310	5367	3.7	2.2	1.1	0.244
Hoosic River, NY, VM, NH	43°13′01″ N	73°34′48″ W	4	844	2551	3.7	1.9	1.5	0.331
Contoocoock River, NH	42°54′58″ N	73°39′24″ W	6	492	1728	4.6	2.4	1.3	0.285
Little Tennesee River, TN, NC, GA	43°16′04″ N	71°35′02″ W	9	1478	6638	5.9	3.3	2.0	0.223
French Broad River, TN, NC	35°45′18″ N	84°15′53″ W	30	1414	6677	3.9	2.3	1.6	0.131
Enoree River, SC	35°59′13″ N	83°10′46″ W	20	328	1935	5.0	3.8	1.2	0.170
Salmon River, ID	34°25′56″ N	81°25′58″ W	10	3834	16718	4.8	2.4	1.8	0.229
Middle Fork River, ID	45°17′31″ N	114°35′28″ W	7	1576	6556	4.0	2.1	1.7	0.240
South Fork Boise River, ID	45°17′01″ N	114°36′10″ W	20	527	3454	3.8	2.4	1.7	0.153
Cataract Creek, AZ	43°35′11″ N	115°50′09″ W	40	983	7779	3.9	2.1	1.2	0.126
Big Sandy River, AZ	36°17′36″ N	112°46′05″ W	60	651	7562	3.3	2.2	1.2	0.086
Chevelon Creek, AZ	34°13′52″ N	113°37′24″ W	20	292	1365	2.5	1.2	1.0	0.214
Acension Canyon (submarine), CA	34°56′33″ N	110°30′51″ W	20	362	2161	3.2	2.3	1.4	0.168
Monterey Canyon (submarine), CA	37°21′02″ N	122°56′42″ W	60	354	3811	4.1	3.9	2.4	0.093

Table II

Geomorphic measures

Drainage density:	$D_d = \Sigma L/A$
Bifurcation ratio:	$R_B = N_w/N_{w+1}$
Length ratio:	$R_L = L_w/L_{w+1}$
Slope ratio:	$R_S = S_w/S_{w+1}$

L = total channel length in a channel network
A = area drained by the channel network
N_w = number of channels in network of order w
L_w = mean length of channels in network of order w
S_w = mean slope of channels in network of order w

works at a grid cell spacing of 926 m are listed in Table I.

Once the river and canyon networks were extracted and ordered, four standard geomorphic measures defined in Table II were then made of network geometry: drainage density, bifurcation ratio, length ratio, and slope ratio. These measures are used to characterize channel patterns, variations in which are thought to reflect regional tectonics (Ollier, 1981; Cox, 1989; Burbank, 1992), geologic structure (Abrahams and Flint, 1983), erosional mechanisms (Dunne, 1980) and prevailing climate (Gregory, 1976; Daniel, 1981). Drainage density is the average length of channels per unit drainage area and represents the spacing of the channelways (Ritter, 1986). The latter three ratios, referred to as Horton ratios after Horton (1945), are dimensionless, hold over a range of length scales, and are designed to characterize the channel composition of a drainage net. The Horton ratios are derived empirically by plotting semilog plots of the number, mean length and mean slope of channels versus channel order. For river networks, these plots generally follow straight lines, the slopes of which equal the logarithm of the ratios. Such plots for the Ascension and Monterey Canyon networks exhibit the same linear trends (Figure 7).

Results

The geomorphic measures for the drainage networks are listed in Table I and are shown along with the regional means in bar graphs in Figure 8. The regional means suggest that on average, the Acension and Monterey Canyon networks have lower drainage densities and bifurcation ratios, and slightly higher length and slope ratios than the river networks. If true, this would imply that the Canyon networks tend to have lesser numbers of tributaries, which are proportionally shorter and steeper in relation to their main channels than subaerial networks. However, the regional means are based on few measures that vary in magnitude. The regional means for the Horton ratios are even somewhat less robust because of the errors in the linear regressions (goodness-of-fit > 85% in all cases) used to

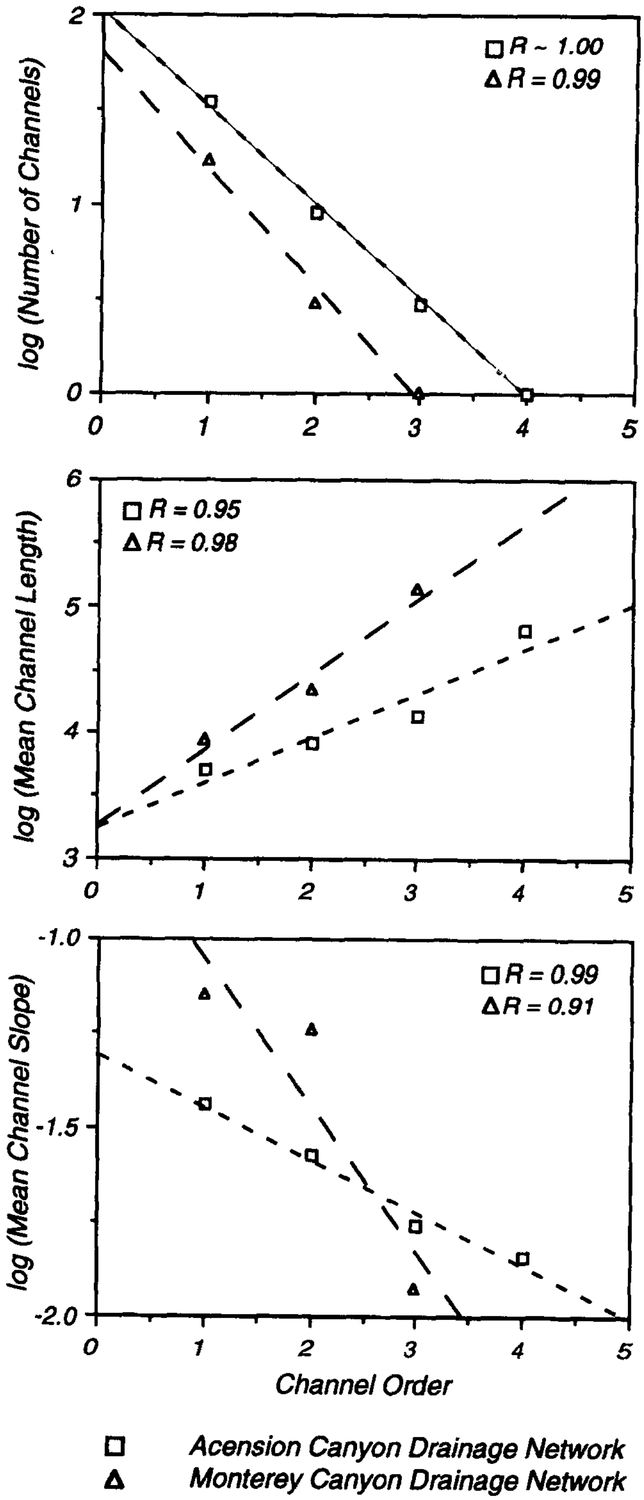

Fig. 7. Semilog plots of the bifurcation, length and slope ratios for the Acension and Monterey Canyon drainage networks extracted from the NOAA bathymetry at a grid cell spacing of 926 m using the support area thresholds listed in Table I. *R* is the correlation coefficient for the best-fit line through the individual plots (dashed lines).

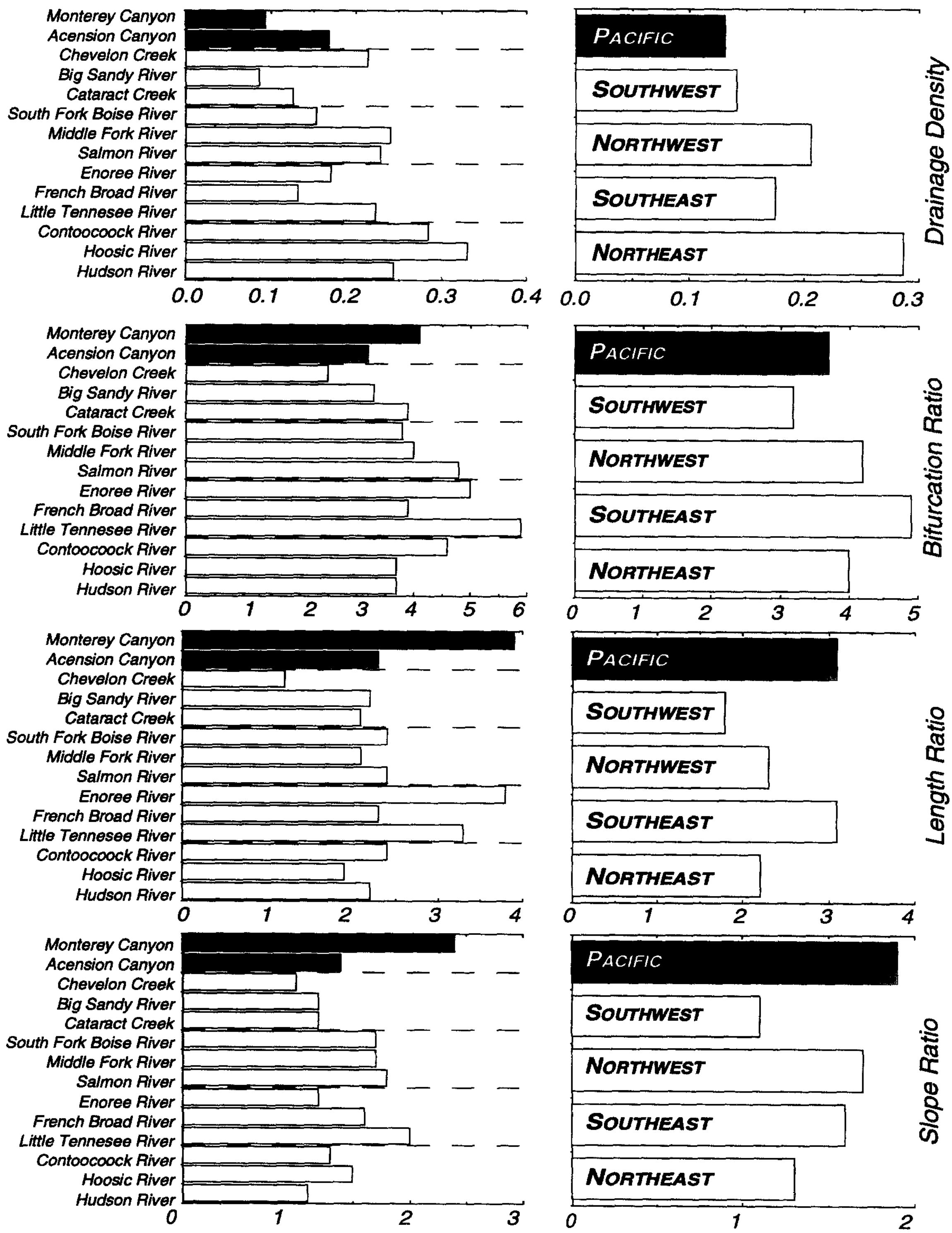

Fig. 8. Bar plots graphically depicting the geomorphic measures of the Acension and Monterey Canyon networks versus those for the twelve U.S. river networks listed in Table I. Bar plots to the left are of the measures for the individual drainage networks. Bar plots to the right are of the regional means.

calculate the individual ratios. Given their uncertainties, the only observation that can be made of the results is that the drainage densities and Horton ratios determined for the Canyon networks by drainage extraction occur within the variability of those determined for the 12 river networks at a DEM resolution ≈ 1 km.

Discussion

The question that remains of the comparison is whether the similarity of the geomorphic measures computed for the Canyon and river networks establishes how closely the areal geometry of submarine drainage systems approaches that of subaerial drainage systems. This question requires evaluation of the following factors: the resolution of the DEMs used in the comparison, the accuracy of the channel lengths and drainage areas derived from drainage extraction, and the robustness of the geomorphic measures used to compare the drainage systems.

The first two factors have been addressed in part by the aforementioned sensitivity experiments. Use in the comparison of DEMs with resolutions ≈ 1 km limits the minimum observable width of erosional channels to 5–10 km. On land, channels tend to extend into fine-scale valleys (Montgomery and Dietrich, 1988), and accurate representation of terrestrial channel networks can require DEMs with a grid cell spacing of as little as 10 m, a vertical error of ± 0.5 m and a horizontal error of ± 3 m (Dietrich *et al.*, 1993). Such high resolution DEMs are not yet available for deep-sea bathymetry. The maximum horizontal resolution of a SeaBeam depth sounding in 1000 m of water is ≈ 50 m, while its vertical resolution ≈ 10 m (Tyce, 1986). Horizontal resolution of gridded bathymetry for the same water depths is worse due to interpolation between grid points. As a result, multibeam bathymetric grids probably cannot accurately resolve erosional channels much less than 1/2 km in width and 10 m in depth. By using such coarse resolution DEMs, the comparison does not evaluate differences in network detail even at this scale. Further comparisons need to be done at higher resolutions and with additional submarine and subaerial drainage networks to truely establish the similitude of the two types of systems. The results presented here pertain only to the regional organization of the MSDS and its relation to large river networks at the same kilometer scale.

As Figure 5 shows, automated-drainage extraction compounds the problem of accurately mapping erosional channel networks by introducing errors in channel network extent. Since in deep water (>200 m) the agents of submarine erosion tend to be localized and because, at least seaward of the continental slope, the seafloor is largely a depositional surface, channel network extent may in fact be overestimated when the algorithms are applied to gridded bathymetry. Drainage extraction does define channels in the NOAA bathymetry where there is no observable channel morphology. However, several elements mitigate the effect of these inaccuracies in the comparison of the MSDS with the fluvial systems. First, the comparison is restricted to the Acension and Monterey Canyon networks (shaded areas, Figure 4), which the bathymetry clearly shows are erosional features. Second, drainage extraction of channels on uneroded slopes in these areas is partially compensated by the heads of channels not mapped using the support area threshold determined for each network (e.g., Figure 5B). Third, the river networks extracted from the gridded topography possess the same inaccuracies that mar the submarine canyon networks. And fourth, these inaccuracies are uniform among all the drainage networks compared, because an objective technique, the constant channel drop procedure of Tarboton *et al.* (1991), provided the support area thresholds used to extract each drainage network. In short, due to inaccurracies, the total channel lengths listed in Table I are not exact, but instead are estimates with some unknown degree of error. This unknown error prevents a quantitative assessment of the morphologic closeness of submarine and subaerial drainge systems.

Recognizing this fact, Pratson (1993) argues that because the measures for the submarine canyon networks occur within the variability of those for the river networks, the results could still be construed as a relative indication that the regional organization of submarine and subaerial drainage systems is morphologically similar. His argument is based on the reputation of the ratios listed in Table II as fundamental measures of drainage network structure, particularly the bifurcation, length and slope ratios. Horton (1945) devised the ratios as drainage network descriptors, and they have since been used by geomorphologists to compare channel networks among diverse landscapes (e.g., Strahler, 1952b; Schumm, 1956; Chorley, 1957; Morisawa, 1962). Because of this body of work, the Horton ratios have been termed "laws of drainage network composition" and are considered geomorphic principles in many textbooks (e.g., Chorley *et al.*, 1984; Press and Siever, 1986; Ritter, 1986; Judson and Kaufman, 1990; Summerfield, 1991; Easterbrook, 1993). However, in a study subsequent to that of Pratson (1993), Kirchner (1993) statistically confirms earlier, intuitive arguments (Bowden and Wallis, 1964; Milton, 1966; Smart, 1978) that Horton's laws

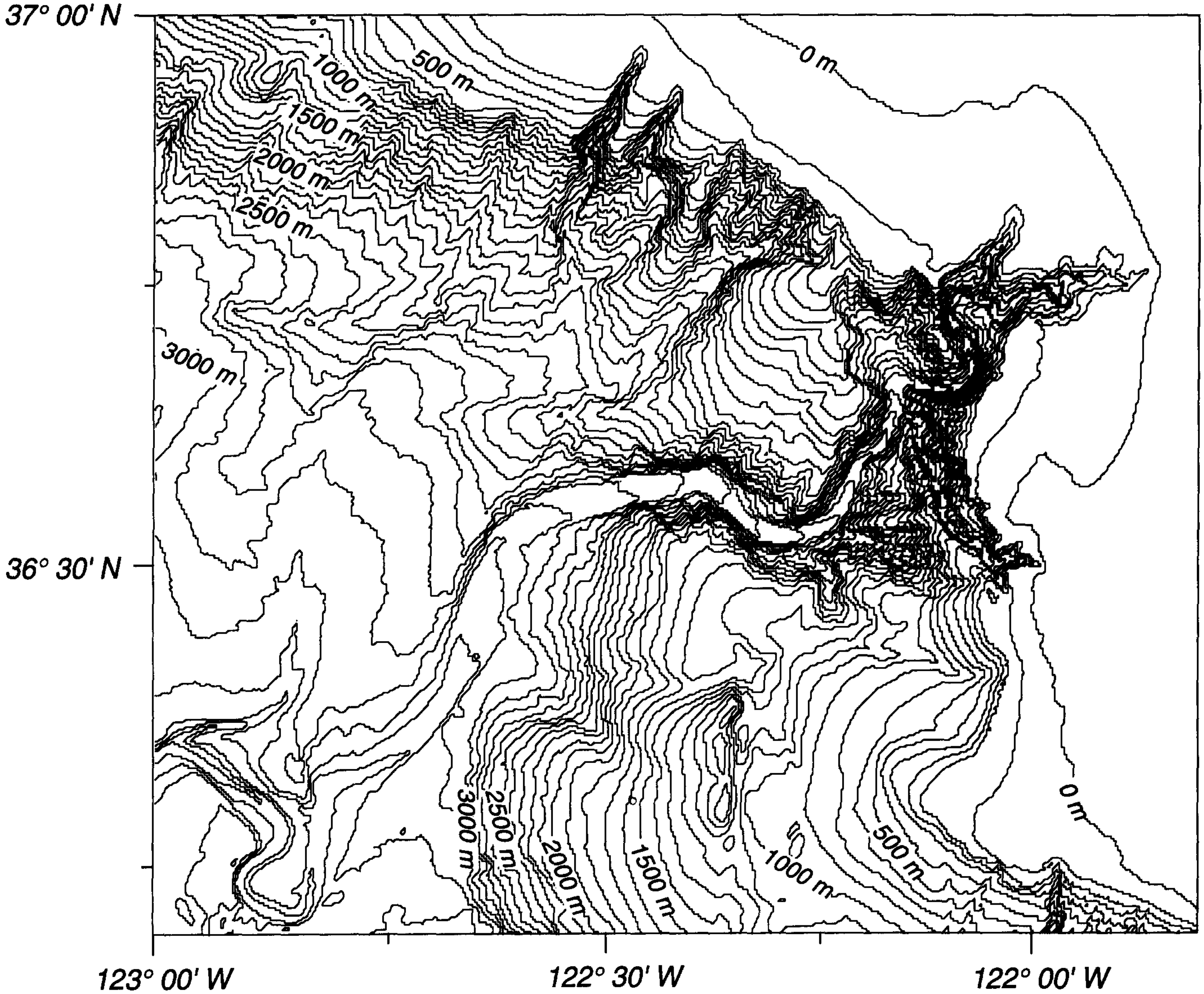

Fig. 9A.

are insensitive to pronounced differences in network structure. This analysis showed that the ratios do not provide distinctive geometric or topologic measures that can be used to contrast channel networks formed under different prevailing geologic and environmental conditions.

Kirchner's (1993) findings remove three benchmarks of "closeness" from the MSDS-fluvial comparison above. Since further investigation needs to be done to establish the error in total channel length resolved by drainage extraction, the drainage density values also cannot be compared without criticism. The geomorphic relation between the MSDS and its fluvial counterparts remains inconclusive.

While the MSDS is visually similar to terrestrial drainage systems, it is also different. For example, Figure 9 shows contour maps of the MSDS (Figure 9A) and the MacLeay River (Figure 9B), which incises the subaerial escarpment bordering the elevated New England Tableland in southeastern Australia. The MacLeay River has formed in a region where the New England Tableland plateau dips towards escarpment (Weissel *et al.*, 1992), approximating the regional form of the California continental shelf-slope-upper rise margin across which the MSDS has formed. In the map of the MacLeay River (Figure 9B), the density of contours is greatest in the dissected, rugged but regionally flat-lying terrain at the base of the escarpment. By contrast, the

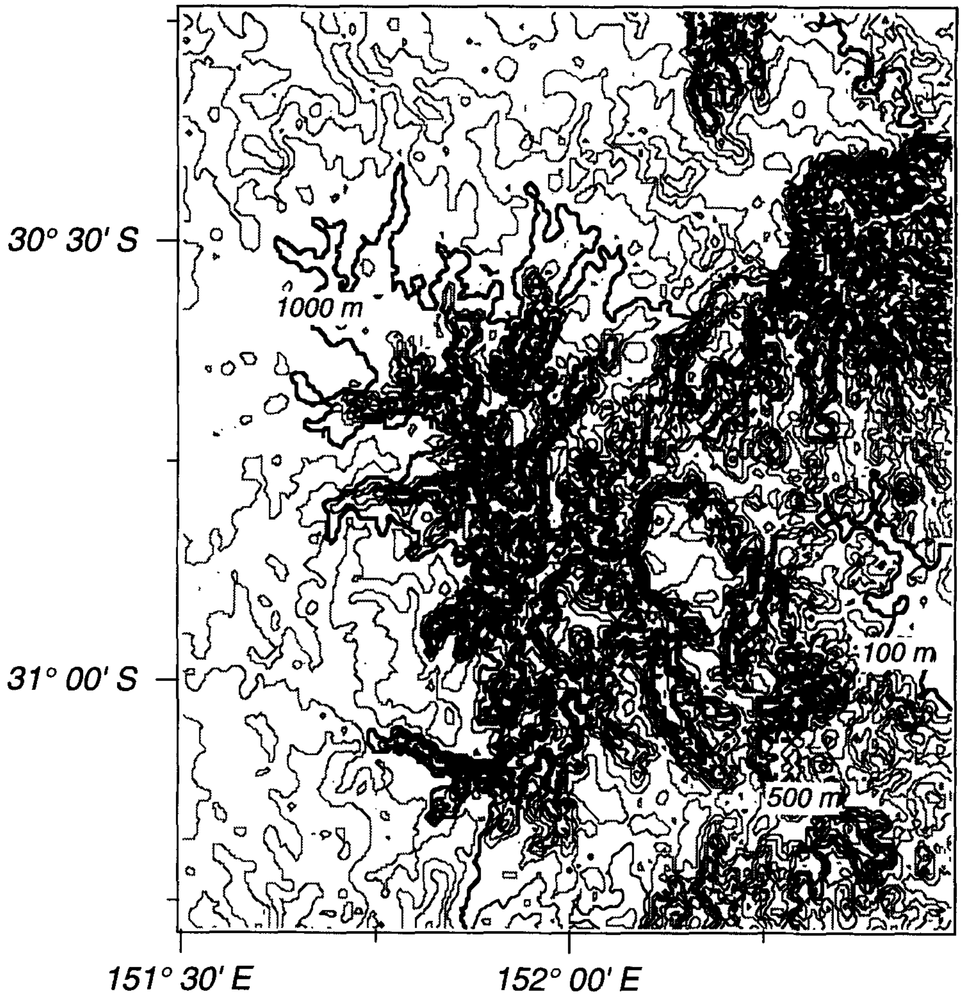

Fig. 9B.

Fig. 9. A. Contour map of the MSDS in dashed box I of Figure 1. B. 1:250,000 scale contour map of the MacLeay River incising the escarpment along the Australian Tablelands, southeast Australia (vicinity of 30° S, 152° E). Both maps have a contour interval of 100 m, and span approximately the same square kilometer area. But relief along the California margin is 3000 m, while that along the Tablelands escarpment is only 400–600 m.

density of contours in the map of the MSDS is greatest along the mid to upper continental slope, where the regional seafloor gradient is steepest.

This distinction between the two types of drainage systems highlights a major difference between channel formation and drainage development in subaerial and submarine environments. On land, channels are carved by running water, the erosive power of which is related to discharge and controlled by drainage area (Howard, 1980): the more water, the greater the erosion of channels. Beneath the sea, channels are carved by failure-induced subaqueous sediment flows, which initiate and derive their erosive power as a consequence of local slope: the steeper the slope, the more likely slope failures leading to sediment flows and the erosion of channels. Devising morphometric techniques to detect the type of drainage network differences seen between the MSDS and the MacLeay River remains a central problem in quantitative fluvial geomorphology (Kirchner, 1993). The same problem now confronts marine geologists attempting to gain insight on subaqueous sedimentary processes through quantitative studies of submarine canyon, channel and drainage system morphology using gridded multibeam bathymetry.

Applied Uses for Drainage Extraction

Keeping the limitations of drainage extraction in mind, there are a number of ways these algorithms can be

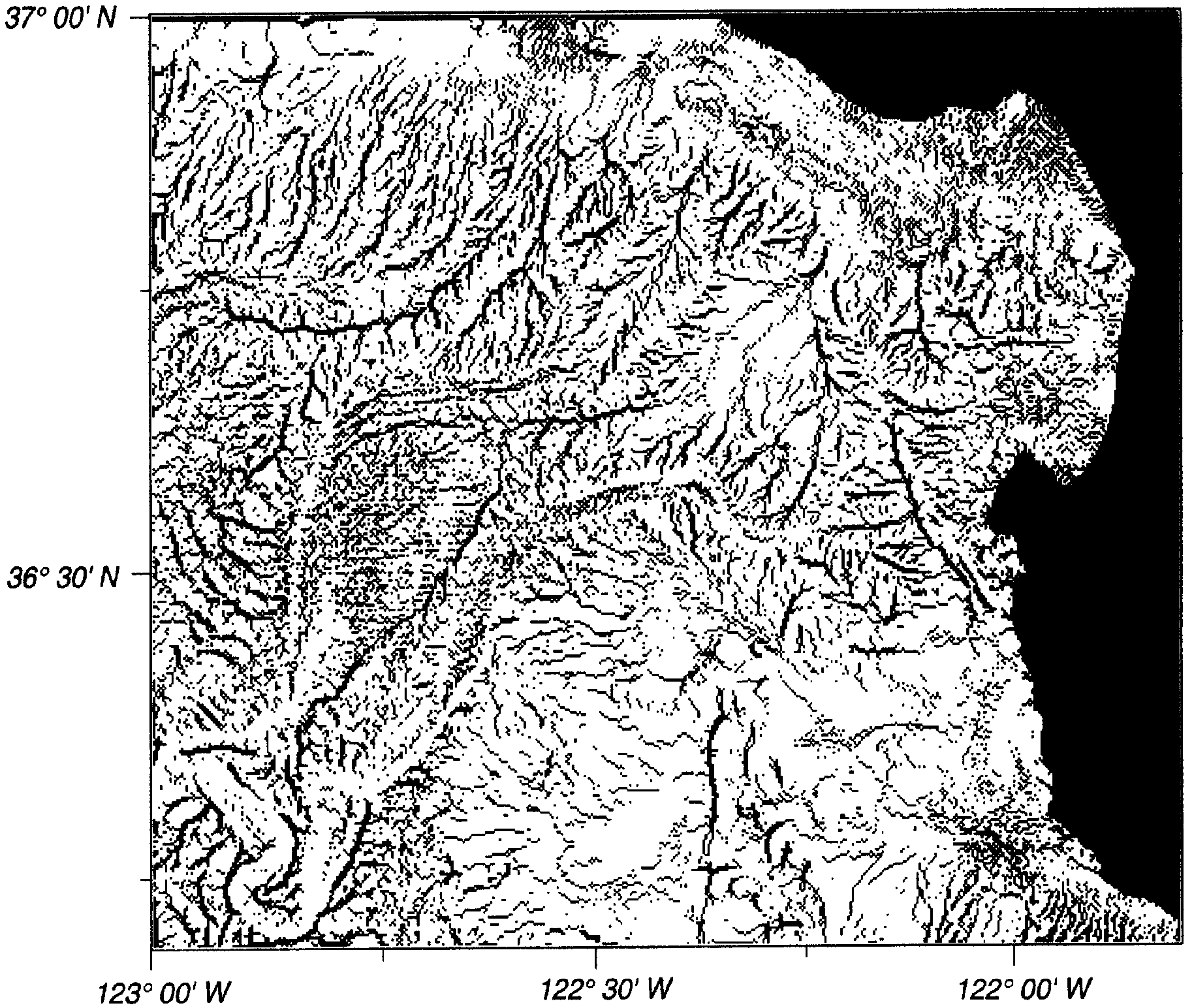

Fig. 10A.

used to analyze gridded bathymetry for both applied and academic interests in seafloor morphology. In terms of applied research, one of the benefits of drainage extraction is that in addition to mapping drainage networks, drainage divides can also be mapped. By setting the flow accumulation threshold equal to zero, it is possible to isolate all grid cells that do not receive input from other cells (Figure 10A). In other words, these cells are relative topographic highs. Such a map could be particularly useful in charting locations which minimize risks to offshore communication cables, hazardous waste disposal sites, or piping from marine oil production platforms.

The drainage extracted from gridded bathymetry can also be used to help interpret side-scan sonar imagery from the same region (Figure 10B). If drainage extracted from the bathymetry is overlain onto the side-scan sonar imagery, it's possible to map sediment pathways hard to detect in the side-scan imagery alone.

Finally by merging gridded bathymetry with gridded topography, drainage extraction algorithms can be used to map drainage areas and sediment pathways from land to sea. With such information, source areas of deep-sea depocenters, such as submarine fans, can be quantified. Additionally, if deep-sea sedimentation rates and denudation rates on land are known, it should be possible to estimate how erosion of a continental margin balances against the development of a submarine fan.

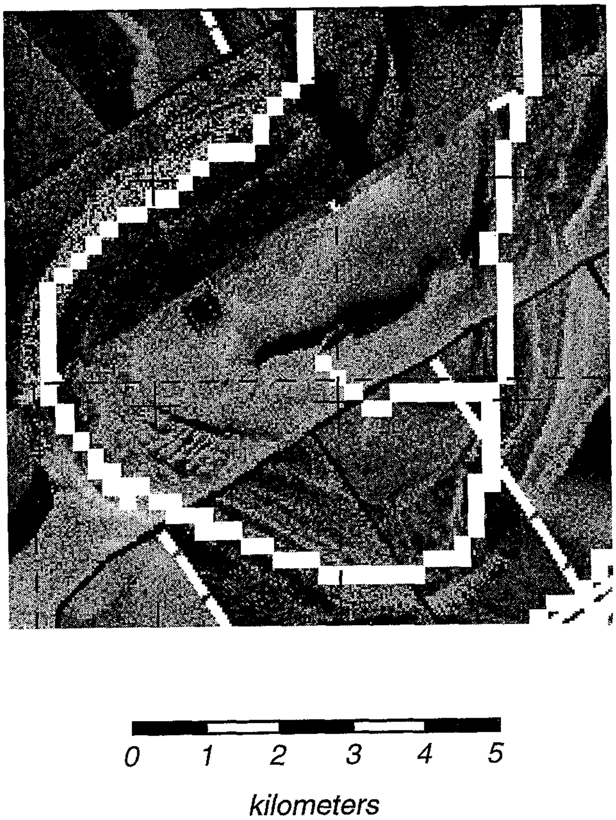

Fig. 10B.

Fig. 10. Examples of other uses for drainage extraction algorithms. A. Relative highs, or peaks and ridges (black areas within white region) extracted from the gridded bathymetry of the Monterey, California margin by setting the flow accumulation threshold to zero. B. Thalweg of the Shepard Meander in Monterey deep-sea channel (lower left in box I of Figure 1) extracted from the bathymetric grid and overlain on top of 30 kHz sidescan sonar imagery of the same region.

Conclusions

Although already frequently used in hydrologic and geomorphic studies of landscapes, automated drainage extraction algorithms represent a new tool for the analysis of submarine sediment pathways documented in gridded bathymetry. Using local seafloor slopes, the algorithms can rapidly define the paths of submarine canyons and deep-sea channels, and delineate the source areas from which they derive sediment.

The principal limitations of the algorithms are twofold: The first is that the algorithms assign all drainage in each grid cell to flow in the direction of steepest descent to a neighboring grid cell. This assignment excludes the possibility of flow divergence, preventing mapping of braided and distributary channel geometries. Recent experiments (e.g., Moglen *et al.*, 1993) suggest use of multiple flow directions, in which flow from each grid cell is partitioned among lower, neighboring cells as a function of slope, should help correct this inadequacy.

More problematic is the second limitation, which is that the algorithms map channelways based not on channel morphology, but on the area of the grid (i.e., support area) each cell "drains". Drainage area does appear to be an important factor in subaerial channel development (Hack, 1957), but slope failure by oversteepening may be more important in submarine channel development. As a consequence, submarine channel definition using a support area threshold can fail to map the heads of submarine channels with relatively small upslope areas, while erroneously mapping channels on uneroded seafloor slopes with relatively large upslope areas (Figure 5).

In the geomorphic comparison of the MSDS with fluvial drainage systems, an objective criteria meant to minimize these mapping errors is used to select support area thresholds appropriate for individual drainage basins depicted in DEMs. The comparison shows that inaccuracies in channel networks defined by automated drainage extraction are compounded by DEM resolution, which while only having a minor influence on the measurement of drainage area, limits the extent to which channels within a drainage area can be resolved. The comparison also illustrates, that even without inaccuracies, difficulty exists in quantifying submarine drainage morphology for lack of geomorphic measures that can characterize distinctive channel network attributes.

Despite their present limitations, drainage extraction algorithms have the potential to be a useful tool in seafloor mapping. They can already be used to isolate bathymetric ridges (grid cells with zero flow accumulation), a capability that would be helpful in determining seafloor locations where risks of hazards to offshore communication cables, waste disposal sites, and piping from offshore hydrocarbon production platforms are minimized. The future challenge lies in not only improving the mapping capabilities of drainage extraction, but in exploring new ways to gain geologic insight from the morphologic information the algorithms already provide.

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