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INSIDE

Regular Canyon Spacing in the Submarine Environment: The Link Between Hydrology and Geomorphology

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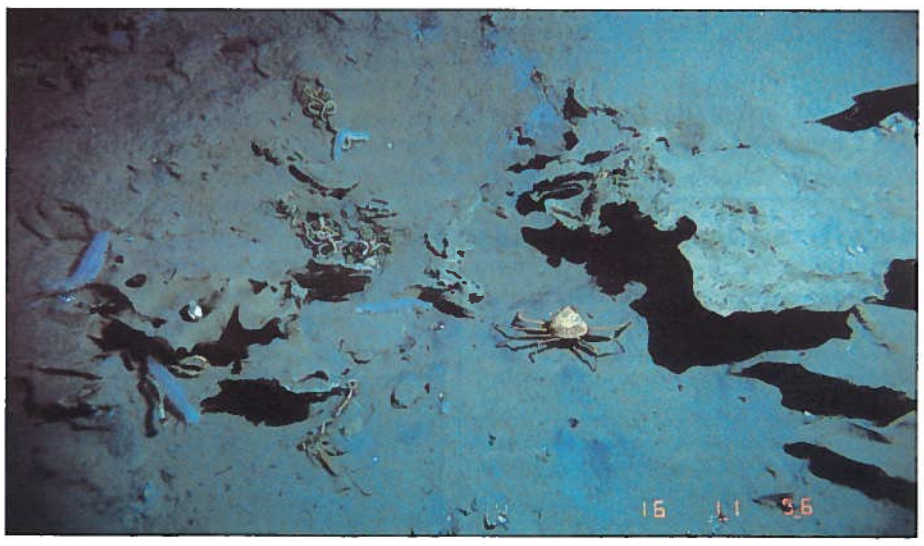
ABSTRACT

The strikingly regular spacing of headless submarine canyons on both active and passive margins implies self-organizing feedback between hydrologic and geomorphic processes. Canyons formed at the toe of the Cascadia accretionary complex, a submarine fold and thrust belt north of Hispaniola, the western Florida Escarpment, and the continental slope east of Maryland–New Jersey all exhibit steep sidewalls, abrupt headwalls, and linear trends perpendicular to the local slope. These canyons show no evidence of channel erosion as a canyon-forming mechanism. The mean distance between adjacent canyons ranges from 8.85 ±2.63 km on the western Florida Escarpment to 335 ±200 m north of Hispaniola. Regular spacing of headless submarine canyons in diverse geologic settings implies an interaction between the conditions necessary for slope failure and the influence a canyon has on the surrounding area. Creation of a canyon dramatically increases the head gradient at its head, thereby facilitating further failure. This increase in head gradient (and convergence of flow lines) affects the regional flow field, leading to a corresponding decrease in head gradient (a divergence of flow lines) in a "shadowed" region surrounding the canyon, which prevents neighboring failures. Closer average canyon spacing could be due to a higher overall slope, higher ambient head gradient, or lower material strength. As canyons grow, the convergence of flow lines will further increase toward the canyon head, leading to a larger reduction in head gradient surrounding the canyon and a larger overall spacing of actively propagating canyons. The fastest growing canyons can capture the flow of smaller neighboring canyons, thereby terminating their growth. Canyon growth can also stop if the material into which the canyon is propagating becomes strong enough to resist seepage failure.



DS/RV *Alvin* photo of a cold seep community (tube worms and carbonate crusts) located within a headless submarine canyon on the toe of the Oregon accretionary complex. The same fluid expulsion that supports the cold seep community may lead to slope failure and canyon formation; in turn, the presence of a canyon affects the regional flow field and therefore the presence and absence of cold seeps.

INTRODUCTION

Submarine canyons are common features of almost every continental margin. Although some channels formed by downslope erosional processes, the geometry of many canyons suggests that they formed by means of internal rather than external causes. These canyons are similar to headless canyons well documented in the subaerial setting (e.g., Laity and Malin, 1985; Baker et al., 1990) in that they display a distinct geomorphic style with steep headwalls and flat floors. The term "headless" is applied to canyons that are isolated from downslope erosive flows and channel-cutting activity. These canyons tend to be straight and oriented downslope, and they branch but do not meander. Many such canyons may originate on the slope and grow headward (Orange and Breen, 1992; Moore et al., 1990).

On land, many headless canyons may result from seepage-induced spring sapping, particularly in the spectacular theater-headed valleys of the Colorado Plateau (Laity and Malin, 1985). Headless submarine canyons are present both on passive continental slopes (Florida, U.S. East Coast) and on convergent margins (southern Cascadia [U.S. West Coast], northern Hispaniola). These canyons may have formed by dissolution by fluid flow (Florida; Paull et al., 1990), diagenetic fluid expulsion leading to fracturing and exfoliation (New Jersey; McHugh et al., 1993), or seepage-induced slope failure (Cascadia, Hispaniola; Orange and Breen, 1992). Both dissolution and diagenetic fracturing can lead to slope failure, but they cannot account for nonrandom canyon spacing. We focus here on seepage-induced failure, but the hydrologic approach outlined is equally appropriate for any mechanism that includes a component of fluid flow (e.g., dissolution, diagenetic fracturing) because the presence of a canyon affects the regional flow field.

Seepage-induced slope failure occurs where the fluid head gradient (excess pore pressure) offsets the gravitational and frictional forces of the surface material (Denlinger and Iverson, 1990; Iverson and Major, 1986; Dahlen, 1984); that is, the failure is caused by the excessive pore pressure gradient rather than fluid flow per se. In active margins, excess fluid pressure may result from tectonically induced porosity reduction, loading by sediments or thrust faults, or both (Bray and Karig,

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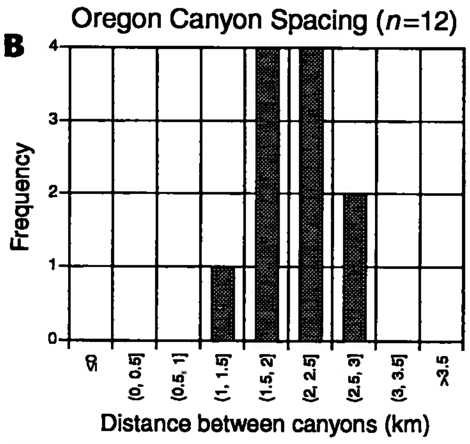

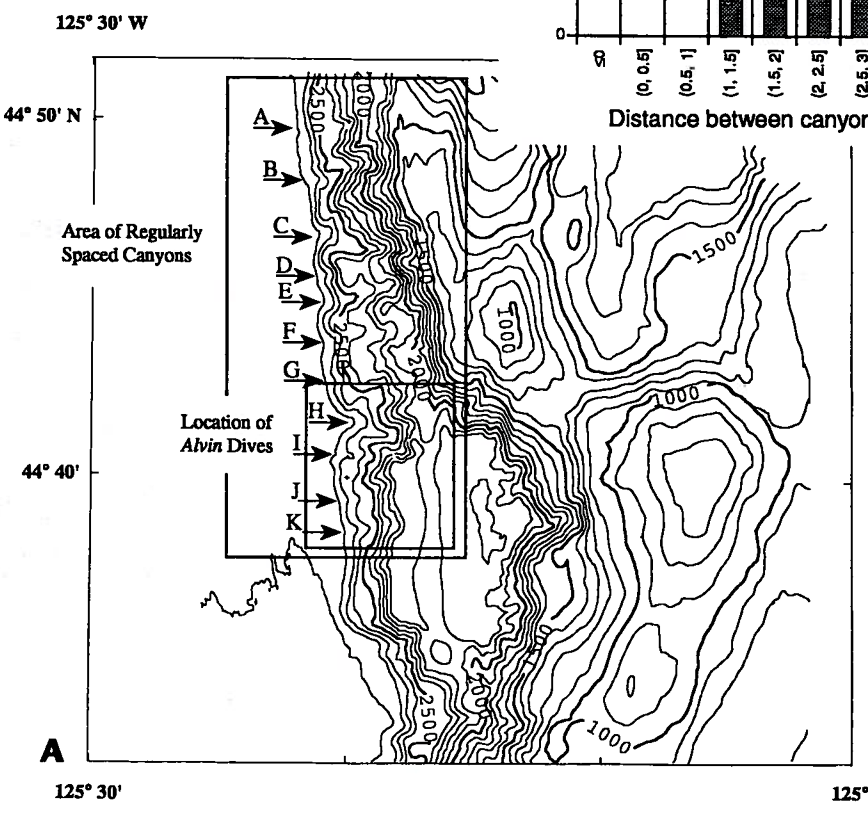

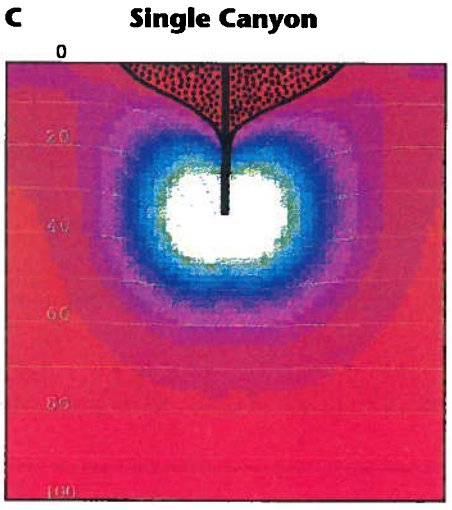

Figure 1. A: Composite SeaBeam map of the toe of the Cascadia accretionary complex (offshore Oregon); contours are in metres. Arrows indicate headless submarine canyons isolated from downslope flow. B: Histogram of canyon spacing. C: Flow field and head-gradient field due to a single canyon incised into the seafloor. Contours are equipotentials. The flow is driven from depth toward the constant-head seafloor and canyon incision. The colors reflect the pattern of head gradients; the highest gradients (brightest) are near the canyon tip. The stipple patterns indicate values of head gradients below the originally uniform gradient and indicate the region where seepage-induced failures will be impeded.

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1985); on passive margins high fluid pressures can result from diagenetic transformations (McHugh et al., 1993), density-driven flow (Paull et al., 1990), rapid sedimentation (Fertl, 1976), or aquifer-driven flow (Magara, 1987; Robb, 1990). Fluid flow leading to cement dissolution and a decrease in the material strength may also cause internally driven slope failure.

In the four areas described here, headless submarine canyons are regularly spaced and self-organized; i.e., canyon spacing arises from feedback between hydrologic and geomorphic systems. In this paper we examine the regularity of canyon spacing and discuss how differences in permeability, head gradient, slope, and material strength may control the observed variations in regular spacing.

HEADLESS SUBMARINE CANYONS—EXAMPLES

Southern Cascadia

Upper Miocene to Pliocene oceanic crust is currently subducting beneath coastal Washington and Oregon (DeMets et al., 1990). The thick section of incoming sediment provides an abundant source of fluids during accretion (Kulm, von Huene, et al., 1973). At the toe of the Cascadia accretionary complex off central Oregon, numerous headless submarine canyons are present seaward of anticlinal ridge crests (Fig. 1A; Orange and Breen, 1992). The average slope of the frontal ridge is 14°. In order to identify canyons for our spacing study, we selected features that illustrated an inflection in a single contour and that repeated this inflection in adjacent contours. Some canyons (e.g., B and F in Fig. 1) display large, linear cuts, with straight sidewalls and an abrupt headwall; others (e.g., C and H) illustrate a branching morphology midway up the canyon. Canyon sizes also vary, ranging from large (several kilometres long; e.g., C and H) to relatively minor (G and J). Most canyons are >500 m deep. Submarine vents within two canyons (H and K; Fig. 1A; Moore et al., 1990), indicate local active seepage and fluid-pressure gradients that are higher than hydrostatic.

The distance between adjacent canyons in this region ranges from 1.5 to 3.5 km (Fig. 1B), with a mean and standard deviation of 2.0 ±0.7 km.

Northern Hispaniola Margin

Dewatering associated with folding and thrusting of Hispaniola Basin sedimentary deposits has also resulted in the development of regularly spaced headless canyons, although with a much smaller average spacing. Compression along the Caribbean–North American plate boundary in northern Hispaniola has caused uplift and compression onshore (Mann et al., 1984) and the development of a seaward-vergent fold and thrust belt between the Hispaniola Basin and the shelf (Austin, 1983; Dillon et al., 1987; Breen et al., 1991). Hispaniola Basin sediments (Mullins et al., 1992) may be an excellent source of water, because they are thrust-loaded and compacted.

Canyons and slope failures are widespread in this fold and thrust belt (Orange and Breen, 1992). Small headless canyons (Fig. 2) are present on the seaward flanks of seaward-vergent folds spaced about 6–7 km apart. Headless canyons are narrow (several tens of metres wide), straight, only rarely branching features originating abruptly at the base of the slope and terminating on the slopes beneath anticlinal ridge crests. Canyons are generally 1–2 km long; a few are as long as 3–4 km. Headless canyons thus differ in form and probably origin from larger, sinuous, highly reflective canyons that result from downslope erosive flow.

The regular spacing of headless canyons increases with landward distance from the toe of the thrust belt (Fig. 3). The variation in canyon spacing is independent of slope, as all ridges have mean slopes of 12° to 13°. On the second ridge, canyon spacing ranges from 100 to 900 m, with a non-Gaussian distribution about a mean of 280 m (±200 m; Fig. 3A). Canyons on the third ridge range from 150 to 600 m apart, with a nearly Gaussian distribution about a mean of 300 m (±220 m; Fig. 3B). On the fourth ridge, which is the beginning of the continental rise, headless canyons are spaced 580 ±160 m apart, with a distribution skewed to larger spacing (Fig. 3C). All Hispaniola canyons taken together show a spacing with mean and standard deviation of 335 ±200 m (Fig. 3D), approximately six times smaller than the Cascadia canyons.

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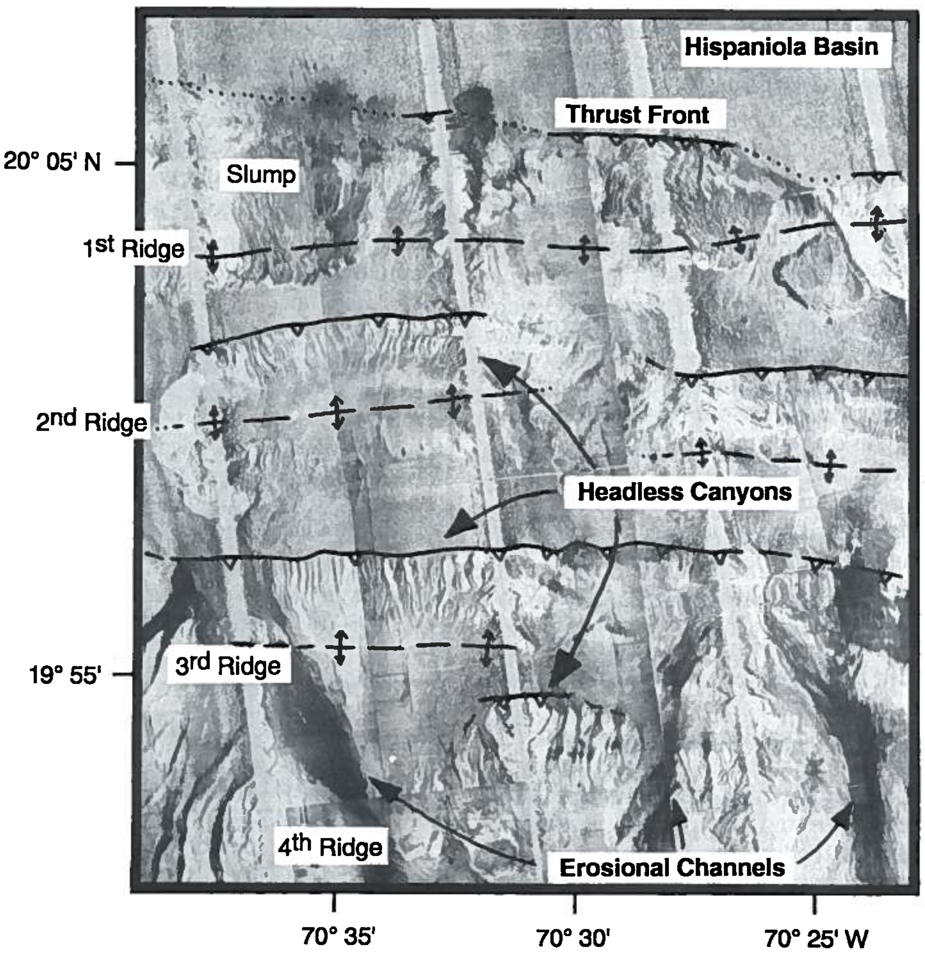

Figure 2. SeaMARC II side-scan survey of a fold and thrust belt north of Hispaniola (see Orange and Breen, 1992, Fig. 11). Areas of higher reflectivity are dark and include large, sinuous, erosional channels that traverse the slope. Four seaward-vergent thrust faults and associated anticlinal ridges are shown. On the first ridge slope failure occurs by massive regional landsliding (e.g., area labeled "Slump"), whereas on the second, third, and fourth ridges the slope is cut by numerous headless canyons that are linear and rarely branch.

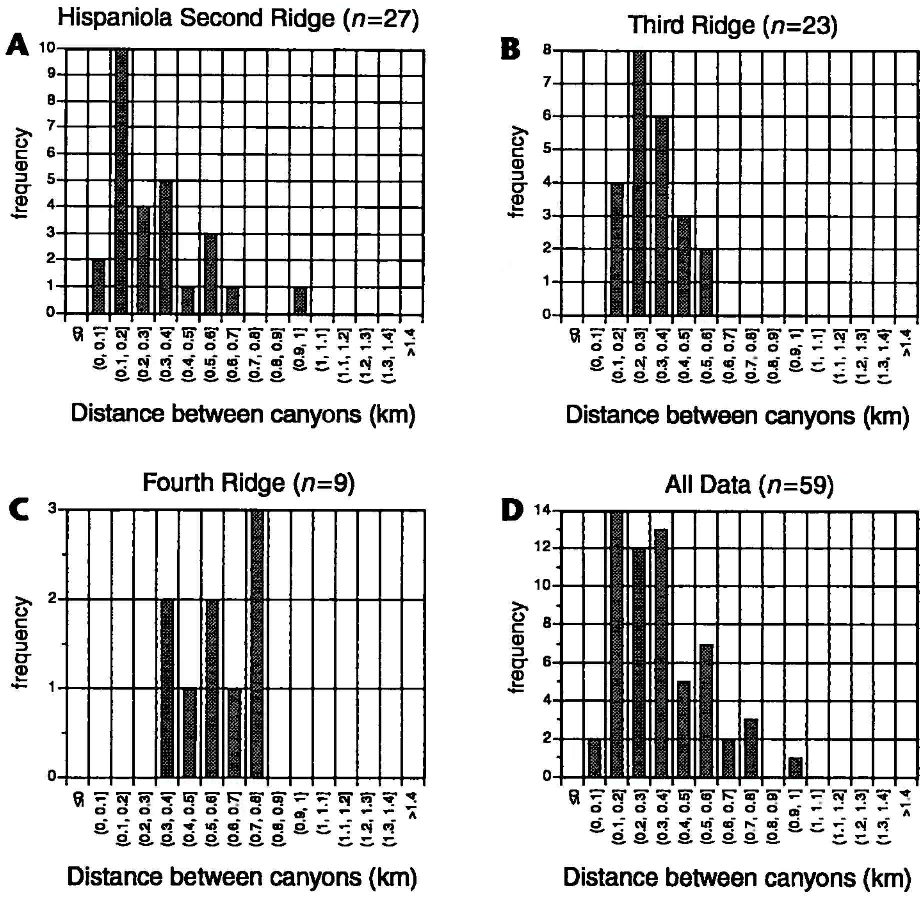

Figure 3. Histograms of distances between headless canyons shown in Fig. 2. A: The slope is 11.5° to 16.1°. B: The slope is 10° to 14°. C: The slope is 10° to 16°. D: The mean spacing between canyons increases landward of the toe, although there is no evidence of slope dependence in this data set.

Florida Escarpment

Headless canyons on the Florida Escarpment (Paull et al., 1990) show a much wider spacing than those of either Cascadia or Hispaniola. The Florida Escarpment, located west of Florida in the Gulf of Mexico, is a passive-margin carbonate platform. Thus, depositional or tectonic loading and resultant porosity reduction cannot have produced the fluids. Paull et al. (1990) inferred instead a density-driven circulation cell composed of platform brines mixing with fresh and sea water as the source of fluid discharge and slope failure at the base of the Florida Escarpment.

Between lat 27° and 24°30'N, the Florida Escarpment displays 14 headless canyons, all trending east-northeast nearly perpendicular to the regional slope. Our analysis of Paull et al.'s data (1990, Figs. 1 and 2) indicates a canyon spacing ranging from 6 to 15 km, with a mean and standard deviation of 8.85 ±2.63 km (Fig. 4).

Paull et al. (1990) suggested that a regional joint pattern exposed on land may have caused the increased flow and consequent cement corrosion. Although this joint set may control the orientation of the canyons subperpendicular to the local slope, we believe that jointing alone cannot be responsible for the wide canyon spacing, which is many times greater than the average joint spacing. We argue that while the propagation mechanism for *individual* canyons may well be as described by Paull et al. (1990), the canyon *spacing* arises from the hydrologic feedback leading to self-organization.

Atlantic Margin of North America

Regularly spaced headless canyons off North America between Georges Bank and Delaware are present within gently seaward dipping chalky Eocene sedimentary rocks and silty Miocene claystones (Twichell and Roberts, 1982; Robb, 1984, 1990; McHugh et al., 1993). Seismic profiling and wells (Hathaway et al., 1979; Grow et al., 1979; Poag, 1985) show that these strata are continuous beneath the continental shelf and extend under the coastal plain. The conditions necessary for ground-water sapping on the slope are most favorable during sea-level lowstands (Robb, 1990).

Headless canyons are incised into the continental slope, but in general do not reach the shelf. On the lower continental slope, canyons are narrow and have straight courses, flat bottoms, and steep sidewalls and headwalls (Robb, 1984). Canyons that reach the shelf break display a modified, sinuous morphology that is distinct from the headless canyons. Although active seeps have not been observed, Robb (1984) speculated that pits in submarine chalk outcrops and fissures along joints may be the result of fluid-induced dissolution. McHugh et al. (1993) presented compelling evidence that diagenetic transformations of opal A to opal CT led to fluid expulsion and resultant hydrofracturing. Exfoliation along these fractures may have led to canyon formation (McHugh et al., 1993) but cannot have caused the regular canyon spacing.

Twichell and Roberts (1982) divided the area of the Atlantic coast between 38° and 39°N into three zones, on the basis of the mean slope and the range in canyon spacing. All zones contain regularly spaced headless submarine canyons except in a 3- to 7-km-wide area directly adjacent to larger shelf-cutting canyons. In analyzing canyon-spacing statistics we have ignored these larger, sinuous canyons. In the southern area, between Baltimore and Wilmington canyons, spacing ranges from 2 to 10 km on a slope of 3°–5° (Twichell and Roberts, 1982, Fig. 5), with a mean and standard deviation of spacing of 2.7 ±0.6 km (Fig. 5A). In the central area, spacing between Wilmington and Lindenkohl canyons ranges from 1.5 to 4 km on a slope of 6° (Twichell and Roberts, 1982), with a mean and standard deviation of 2.2 ±1.6 km (Fig. 5B). In the northern area, spacing between Lindenkohl and Mey canyons ranges from 2 to 10 km on a mean slope of 3°–5° (Twichell and Roberts, 1982), with a mean and standard deviation of 4.5 ±2.1 km (Fig. 5C). Thus, the spacings in the southern and central areas are indistinguishable from each other, and the northern area canyons have a higher mean spacing.

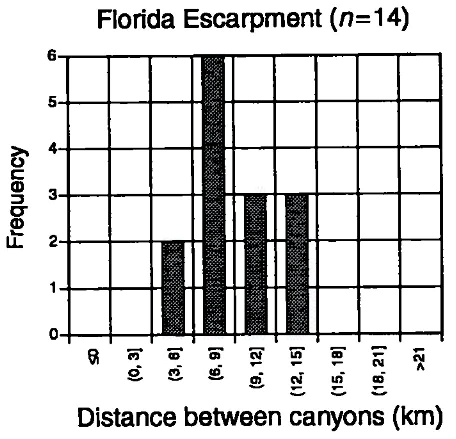

Figure 4. Spacing of the canyons located on the western Florida Escarpment (determined from Paull et al., 1990, Figs. 1 and 2). Canyon spacing is 8.85 ±2.63 km, an order of magnitude larger than the Hispaniola features.

DISCUSSION

The presence of regularly spaced headless canyons in the diverse environments discussed above—carbonate-platform shelf edge, a clastic passive margin, and two convergent margins—suggests that these canyons are related by a common process. In each region the canyons have a geometry created by hydrologic forcing and seepage-induced spring sapping, where the increase of head gradient at the canyon head drives failure. For Hispaniola and Oregon, rapid tectonic compaction of accreting sediments may increase the hydrologic forcing and lead to failure, whereas in Florida and the Atlantic margin, fluid flow may lead to cement dissolution (a weakening of the matrix material) and decrease the resistance to failure. Such canyons may interact during their growth so that the presence of one canyon can influence the probability of failure elsewhere on the slope.

Interaction of Submarine Canyons

Localized failure implies that there are areas where the head gradient attains the critical value for slope failure. Regular canyon spacing requires feedback mechanisms that affect the probability of repeated failure not only in the same locality, but also along the adjacent slope. That is, the presence of one canyon must affect the hydrologic conditions in neighboring canyons.

We can model the interaction between canyons by examining the effect of an existing canyon on the flow field, as has been modeled for the subaerial case graphically by Dunne (1980, 1990), experimentally by Howard (1988) and Kochel et al. (1988), and numerically by Howard (1988). The boundary conditions for the submarine case, however, are different from the subaerial. In the submarine case the surface slope is a constant head boundary, whereas in the subaerial case the surface head gradient is unconstrained in both direction and magnitude. This additional constraint in the submarine case makes the modeling more straightforward by eliminating a degree of freedom.

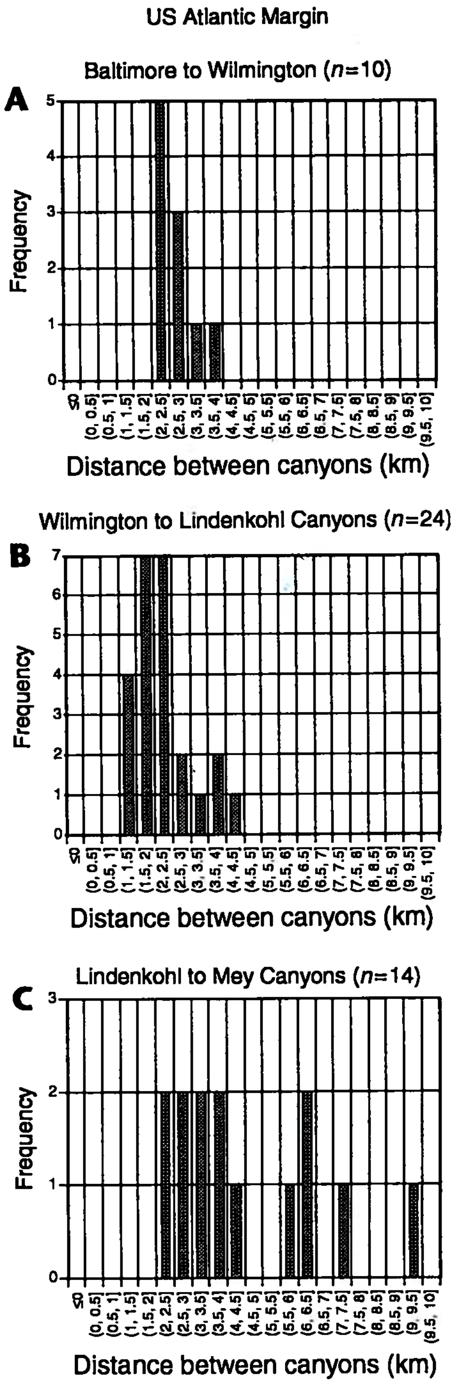

Figure 5. Spacing between canyons on the continental shelf off New Jersey, between Baltimore and Mey canyons (determined from Twichell and Roberts, 1982, Fig. 5). A: The spacing is 2.7 ±0.6 km on a slope of 3°–5°. B: The spacing is 2.2 ±1.6 km on a slope of 6°. C: The spacing is 4.5 ±2.1 km on a slope of 3–5°.

Any indentation in a constant head boundary leads to an increase in the head gradient and a convergence of flow within the indentation (Fig. 6; Dunne, 1980, 1990). Figure 6 presents results of a simple model illustrating the response of an initially uniform gradient in the fluid head field to the incision of a single canyon. Because the model space is two-dimensional, this model only crudely represents the real geometry, which would involve incision of a triangular wedge into a uniform slope to which planes of equal head would be initially parallel. The model space therefore corresponds to a section through the canyon, taken normal to the regional slope and normal to the trend of the canyon. The steady-state head field shown is calculated by finite difference on a square grid following algorithms presented in Freeze and Cherry (1979). The hydraulic conductivity is isotropic. Boundary conditions imposed include a hydraulic head of 100 (units are arbitrary) on the basal boundary, zero flux on the sides, and zero head on both the top and the entire length of the incision representing the canyon. The lines of equal head are warped significantly by the presence of the incision, focusing fluid flow toward the canyon tip. Also shown is the associated head gradient field, |∇H|, demonstrating the extreme enhancement of the head gradients near the tip of the topographic incision. It is important to note that whereas the tip shows enhanced gradients, a zone along the depth of the canyon and along the top boundary for some distance displays significant reduction in head gradient, as implied by the divergence of lines of equal head near the canyon.

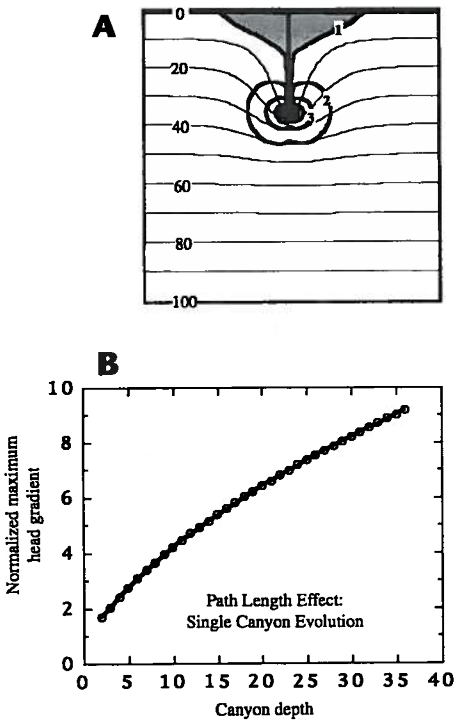

Figure 6. Effect of a single canyon on the flow field. A: Cross-sectional view through a region, taken normal to the sea bottom, and normal to the trend of the canyon. Light contours are equipotentials at steady state, the flow being driven by a head gradient from 100 at the base to 0 along the top boundary, including the surface of the canyon. Heavy lines contour the magnitude of the head gradient, |∇H|, normalized against the original uniform gradient. Values >1 represent enhanced head gradient and increased seepage forces; values <1 reflect divergence of the flow lines and reduction of seepage forces. Seepage forces are highest at the canyon tip. B: Maximum head gradient as a function of increasing canyon depth. The increasing effect of deeper incision into the flow field is here solely due to the decreased path length between the uniform source at depth and the equipotential surface of the seafloor and canyon axis.

Figure 6B shows the relative enhancement of the maximum head gradient with increasing incision depth, owing to the reduction in path length. This relation illustrates the nature of the feedback that will lead to the enhanced probability of failure as a canyon etches into the ground-water flow field.

The decrease in head gradient on the flanks of the canyon reduces the probability that another canyon can grow close by, because the conditions necessary to initiate failure will be more difficult to achieve. The average spacing of canyons will be controlled by the tradeoff between the decline in head gradient along strike due to one canyon and the enhancement of head gradient at the next canyon head. The parameters affecting the sphere of influence of a canyon include the

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physical dimensions and geometry of the canyons, the regional slope, and the regional hydrologic conditions.

We now illustrate the feedback that can lead to canyon spacing (Fig. 7). Three snapshots of the head gradient field associated with the canyon system are shown, in the same cross-sectional view depicted in Figure 6. The initial head gradient is shaded medium gray; darker values represent reduced head gradient, and lighter values depict enhanced gradients. Three canyons have initial lengths of 5, 4, and 4. They are located such that the deepest canyon is in the middle, and the two slightly less deep canyons are placed 5 and 20 units away. We impose the simple rule that the growth rate of a canyon tip, U, is proportional to the excess head gradient; i.e., $U = \alpha(|\overline{\nabla H}| - |\nabla H|_c)$, where a is a proportionality factor reflecting the efficiency of the canyon-cutting process, $|\overline{\nabla H}|$ is the mean head gradient at the canyon tip, and $|\nabla H|_c$ is the critical head gradient necessary to cause failure. This simple hypothesis links the probability and frequency of failure with excess head gradient. At time 2 the canyons have all grown; while the initially deepest canyon is outpacing its nearest neighbor, the other neighbor is keeping up. The near neighbor has fallen more and more deeply into the head-gradient shadow of the larger canyon, and it shuts off after time 2. Later in time, the two surviving canyons continue to be active, while the small canyon remains shut off. The steady-state spacing between active canyons in the mature setting is thus greater than the initial spacing, as early canyons that are triggered by mass-wasting processes may be shut down by the faster growth of nearby larger canyons.

The higher the ambient head gradient, the smaller the eventual canyon spacing will be. If the original head gradient was high (or the slope close to failure), then a new failure (with its own increase in head gradient associated with it) can offset the drawdown of an adjacent canyon at closer intervals. Any mechanism that places the regional slope closer to overall failure (higher regional slope, weaker material), can be viewed in the same way and will lead to closer overall canyon spacing.

Seepage-induced slope failure results from an increase in head gradient. Recall that head gradient is related to fluid discharge and permeability via Darcy's law. Thus, for a given constant fluid discharge, a lower permeability will lead to higher head gradient and higher seepage force, thereby placing a slope closer to failure and leading to closer canyon spacing. Similarly, if permeability is held constant and the fluid discharge increases, then the overall head gradient will increase, leading to a closer spacing of canyons.

Applying this analysis to the New Jersey margin, the decrease in canyon spacing adjacent to the large downslope canyons suggests that the latter dominate the flow field, thereby hindering canyon growth near them (see Twichell and Roberts, 1982, Fig. 2). Some differences in the sizes of the Cascadia canyons (Fig. 1A) may result from canyon competition, where the lateral impingement of recharge zones leads to the "capture" of one canyon's flow by another.

The growth of small canyons may have been arrested by theft of recharge zones. In the end-member case, the larger canyon could eventually capture all of the flow going into the smaller canyon, and as the sidewalls approach, erosional collapse may result in a much wider canyon. This new, large canyon might then show two headwalls, such as the branching morphology observed off Hispaniola (fourth ridge, Fig. 2) and Cascadia (Fig. 1A). As Dunne (1980) has illustrated, a branching morphology can result if a region along the canyon sidewall becomes unstable and fails. This failure creates a second region of focused flow and increased head gradient, and thus continued failure. Our calculations show that this process is most likely to happen at or near the heads of the canyons.

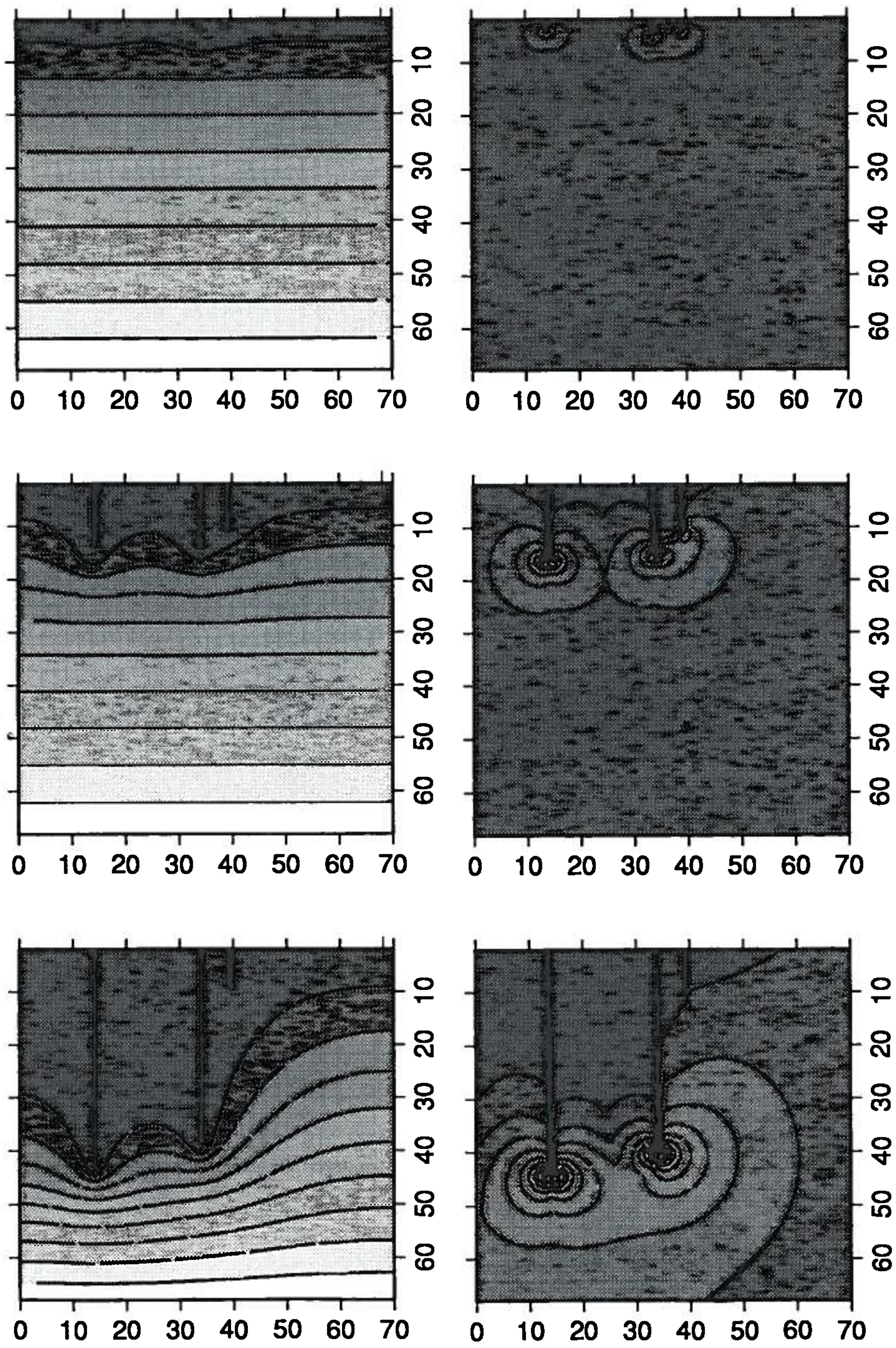

Figure 7. Simulation illustrating the effects of canyon growth on the flow field, leading to preferred canyon spacing. A: Equipotential fields are shown at initial and two subsequent times. B: Contours of head gradients at initial and two subsequent times. Rules in the simulation are discussed in the text. Of the three initial canyons, two continue to grow, but the third (the closest neighbor to the initially longest canyon) becomes dormant at roughly time 2. Canyons will interact in such a way as to evolve toward some final spacing over time. Canyons will continue to grow until either the head gradient decreases below a critical value or the material that the canyon encounters becomes strong enough to withstand the seepage-induced forces.

This competition for regional flow is analogous to the mechanics of crystal growth and the evolution of salt diapirs, where the presence of one crystal or diapir affects the growth of its neighbors (e.g., Christian, 1981; Seni and Jackson, 1983). Within the past decade, the geomorphic community has also become aware of examples of self-organization in the natural landscape at many scales (Hallet, 1990). Examples calling upon the feedbacks between adjacent features, and/or between a solid substrate and a fluid include eolian ripples (e.g., Anderson, 1990; Forrest and Haff, 1992) and other bedforms, beach cusps (Werner and Fink, 1993), and sorted stripes (Werner and Hallet, 1993) and patterned ground (Hallet, 1990) in the periglacial environment. Headless submarine canyons may be the largest geomorphic example of self-organization so far described.

Relevance to Hazards and Subaerial Canyons

Submarine slope failures are a serious hazard to ocean platforms as well as cables and other structures. We suggest that any investigation of sites for the placement of submarine assets take into account the submarine geomorphology. Any slope that contains geomorphic features suggestive of internally driven failure could represent a region with high probability of future failure due to the positive feedback mechanisms mentioned above. In addition to being hazardous to submarine installations, such failures could also trigger tsunamis.

Headless canyons also occur on land, and the above approach may be appropriate for the analysis of regular canyon spacing in the subaerial environment. The necessary hydrologic analysis, however, is more complex, owing to the unknown geometry of the head gradient with respect to the topography.

We note that in some important cases subaerial topography originates as topography established in the submarine world. This is especially true in accretionary settings where uplift caused by telescoping of the prism may lead to eventual emergence. Headless submarine canyons could then set the initial conditions for operation of subaerial geomorphic processes. Given the large amplitude of the submarine headless canyons, they would undoubtedly become the largest of the subaerial channels whose spacing would have been set by processes quite distinct from those that serve to incise these channels subaerially. The same processes of seepage-induced failure may remain active in the subaerial environment, although overland channelized flow will predominate in all but the most arid regimes. Thus, submarine canyons may provide insight into the desired initial conditions of large-scale landscape models.

CONCLUSIONS

The regular spacing of headless submarine canyons on both active and passive margins leads to the question, Are convergent margins really all that different from passive margins in terms of fluid flow? The sources of fluid within active margins (tectonic compaction, dehydration reactions, and exotically derived fluids from depth) may be volumetrically similar to fluids within passive margins, which may be driven by sedimentary compaction, dehydration reactions, subaerial aquifers, and brine circulation. The methods of fluid expulsion are similar for both active and passive margins, and the overall slopes may also be similar. Both environments display diffusive fluid flow and diapirism, as well as focused fluid flow due to fracture permeability and stratigraphic conduits. In addition, the distinctive biological communities surrounding the surface manifestations of focused venting are found in both settings. In both environments, headless submarine canyons form by the feedback between fluid-flow and slope-failure processes. This feedback leads to a self-organized morphology where the competition between initial slope failures results in the regular spacing of mature canyon systems.

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