EVOLUTION OF CONTINENTAL SLOPE GULLIES ON THE NORTHERN CALIFORNIA MARGIN

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ABSTRACT: **A series of subparallel, downslope-trending gullies on the northern California continental slope is revealed on high-resolution seismic reflection profiles imaging the uppermost 50 m of sediment. The gullies are typically 100 m wide and have 1 to 3 m of relief. They extend for 10 to 15 km down the slope and merge into larger channels that feed the Trinity Canyon. In the lower half of the 50 m stratigraphic section, the gullies increase in both relief and number up section, to maxima at a surface 5 to 10 m below the last glacial maximum lowstand surface. Gully relief increased as interfluves aggraded more rapidly than thalwegs. Erosion is not evident in the gully bottoms, therefore gully growth was probably due to reduced sediment deposition within the gullies relative to that on interfluves. As the gullies increased in relief, their heads extended upslope toward the shelfbreak. At all times, a minimum of 10 km of non-gullied upper slope and shelf stretched between the heads of the gullies and the paleo-shoreline; the gullies did not connect with a subaerial drainage network at any time. Gully growth occurred when the gully heads were in relatively shallow water (~ 200 m paleo-water depth) and were closest to potential sediment sources. We suggest that prior to the last glacial maximum, the Mad River, then within 10 km of the gully heads, supplied sediment to the upper slope, which fed downslope-eroding sediment flows. These flows removed sediment from nearly parallel gullies at a rate slightly slower than sediment accumulation from the Eel River, 40 km to the south. The process or processes responsible for gully growth and maintenance prior to the last glacial maximum effectively ceased following the lowstand, when sea level rose and gully heads lay in deeper water (~ 300 m water depth), farther from potential sediment sources. During sea-level highstand, the Mad River is separated from the gully heads by a shelf 30 km wide and no longer feeds sediment flows down the gullies, which fill with sediment from the distal Eel River. Approximately one-half of the subsurface gullies have no expression on the seafloor, because they have completely filled with sediment following the last glacial maximum lowstand of sea level.**

INTRODUCTION

Slope gullies are shallow channels that are becoming increasingly recognized as major morphological features on continental slopes. Their newly observed abundance is largely a result of greatly improved high-resolution multibeam mapping systems (Hughes-Clarke et al. 1996). The occurrence of slope gullies on many distinct continental margins suggests that they are important in terms of sediment movement.

We have examined the evolution of a network of subparallel gullies that trend down the upper continental slope of northern California, north of Cape Mendocino (Fig. 1). Surface gullies occur from approximately 220 to 700 m water depth. Their relief and width increase downslope (Field et al. 1999), and they appear to coalesce into channels that feed into the Trinity Canyon. Surface gullies typically have 1 to 3 m of relief (referring to the relief from the gully thalweg to the ridge immediately outside of the gully) and are approximately 100 m wide (Field et al. 1999). The spacing between individual gullies varies from approximately 100 m to greater than 1 km, reflecting a variable gully density along the slope (Fig. 2).

Slope gullies similar in size to the gullies in our study area have been observed on the seafloor and in the subsurface on the Tyrrhenian margin (Chiocci and Normark 1992) and on the southwestern Japan forearc (Blum and Okamura 1992). In both areas the processes that shaped the gully systems are not well understood. Slope gullies have also been noted on the seafloor on the Middle Atlantic continental slope of the United States (McGregor et al. 1982; Twichell and Roberts 1982). Larger gullies, with 5 to 25 m of relief, have been documented in shallow water (< 50 to 250 m) in the Gulf of Corinth (Piper et al. 1990). Furrows with relief similar to the gullies in our study area, 1 to 2 m, but which are considerably narrower (~ 5 m wide), have been described on the slope offshore New Jersey (Robb et al. 1983), in the Gulf of Mexico (Coleman et al. 1981), and on the Blake Outer Ridge (Tucholke 1979). Recent studies of multibeam bathymetry offshore San Diego, Los Angeles, and Eureka, California have revealed that drainage-system types (i.e., small gullies, larger channels, or submarine canyons) are dependent on water depth, seafloor gradient, and proximity to a terrestrial sediment source (P. Dartnell, personal communication). Gullies have been documented in the rock record in a rift basin (Surlyk 1987) and in the vicinity of a shelfbreak (Ricketts and Evenchick 1999), but small slope gullies have been infrequently noted in the rock record, presumably because of their low relief (1 to 3 m of relief over 100 to 500 m laterally).

Several hypotheses have been suggested to account for the creation and maintenance of continental-slope gullies, but their low relief and occurrence in relatively deep water has limited their discovery and study. As a result, the role of gullies in transporting sediment downslope from the continental shelf is largely based on conjecture. Reynolds and Gorsline (1988) suggest several agents that may form erosional gullies on the slope off southern California, including liquefaction and downslope mass movement, and the formation of currents (analogous to rip currents) caused by the breaking of internal waves. Piper et al. (1990) suggest that large gullies (5 to 25 m in relief) in the Gulf of Corinth may have formed as a result of rip currents generated by offshore winds.

Field et al. (1999) developed a general model for the evolution of slope gullies, on the basis of the gullies on the northern California slope. In their model, gullies are: (1) formed during sea-level lowstands by downslope, near-bottom transport, (2) draped with sediment from distal sources and partially filled with sediment by local transport during sea-level rise and fall, and (3) draped with sediment from distal sources during sea-level highstand. We have mapped several coherent reflectors on the Huntec lines across the continental shelf and slope. These reflectors, which include the lowstand surface associated with the last glacial maximum, provide age control for the gully evolution model that was not available to Field et al. (1999). This results in a new gully evolution model, in which gullies form and grow *before* the sea-level lowstand and fill immediately following the lowstand. In addition, we map the network of gullies on four surfaces, in order to determine how they evolve in map view in relation to shoreline position and the proximity of potential sediment sources.

DATA ACQUISITION

A high-resolution (~ 30 cm vertical resolution) image of the seafloor was generated from the results of a multibeam bathymetry survey conducted by L. Mayer and J. Hughes-Clarke in 1995 (see description in Goff et al. 1999; Fig. 2). In addition, a grid of high-quality, digital, high-resolution seismic-reflection data was also obtained during 1995 and 1996 using the Canadian Geological Survey's Huntec deep-towed seismic (DTS) sys-

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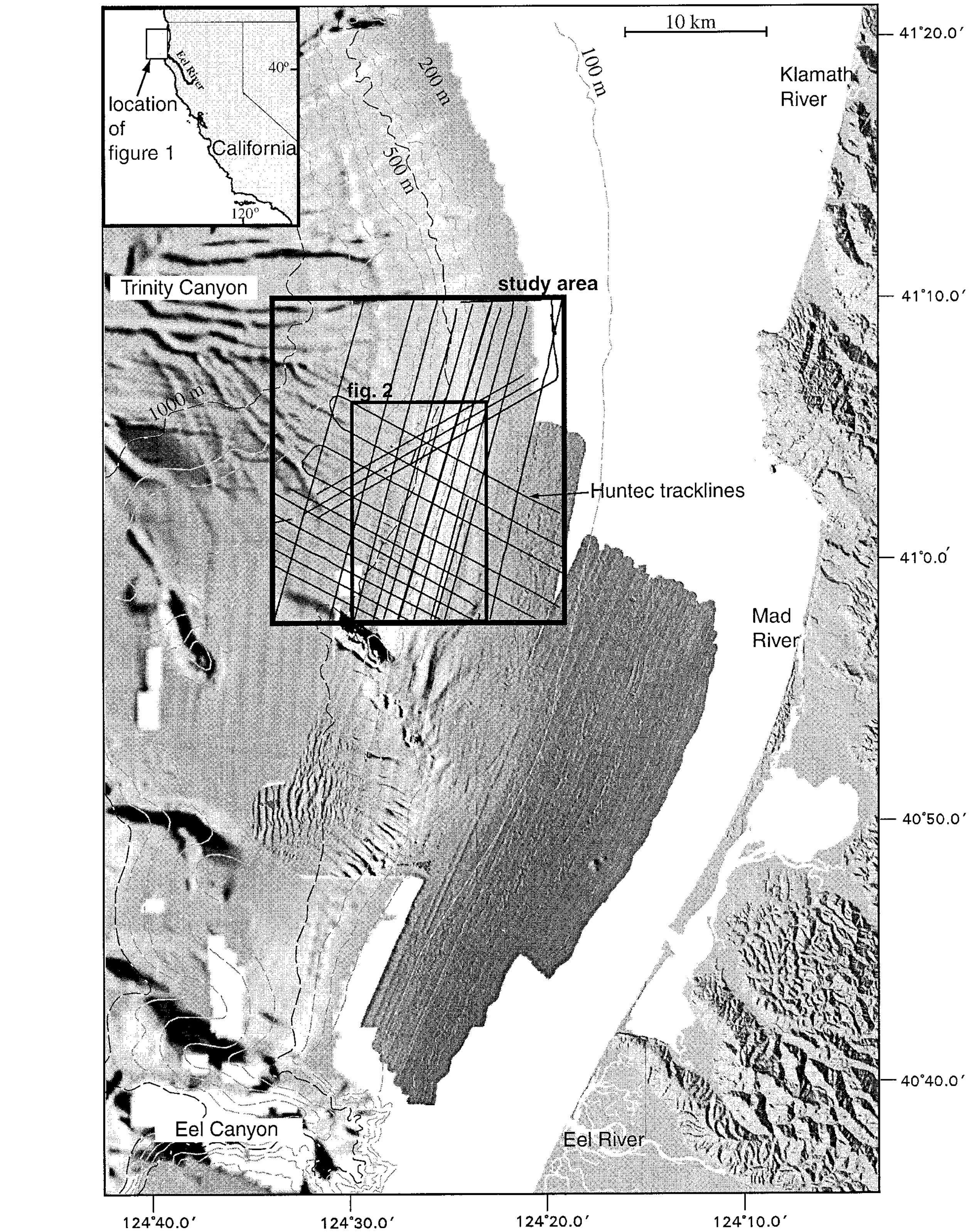


FIG. 1.—Shaded-relief map of the continental shelf and slope on the northern California margin. Shaded-relief bathymetry was produced from EM1000 multibeam mapping (Goff et al. 1999) and NOAA bathymetry data. The study area is outlined with a bold black rectangle. The location of Fig. 2 is outlined with a smaller black rectangle. The thin black lines show the tracklines of the Huntec high-resolution seismic-reflection lines used in this study. The gullies examined in this study lead into the larger channels that feed the Trinity Canyon system.

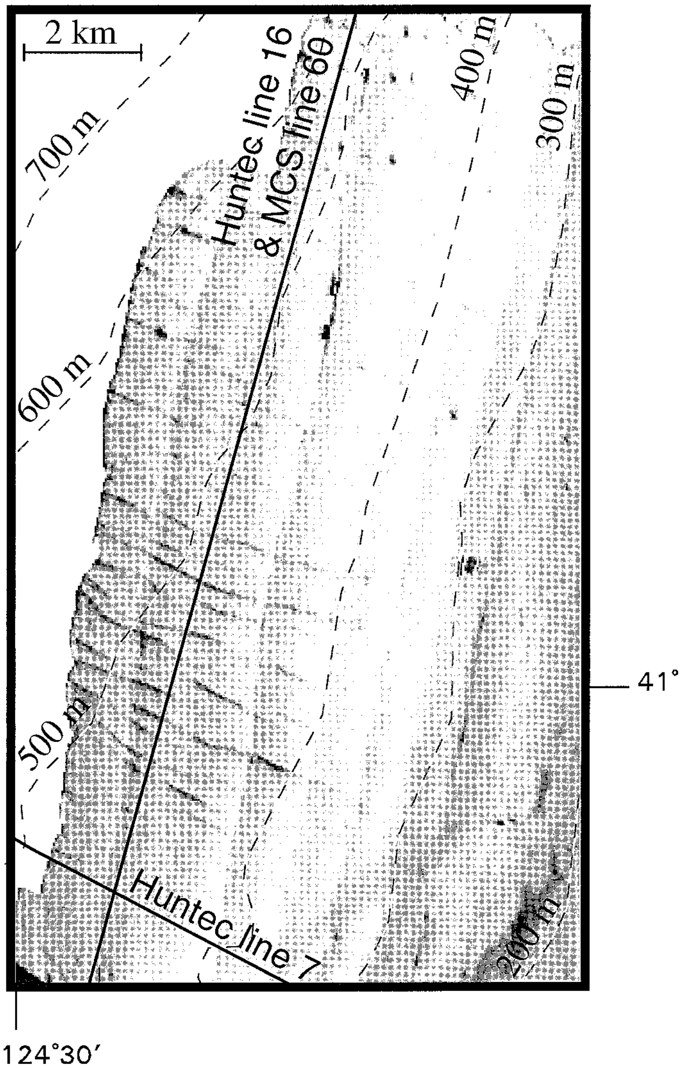


FIG. 2.—Shaded-relief multibeam image of the outer shelf and slope, showing the network of slope gullies. The solid black lines indicate the tracklines of a multichannel seismic line (shown in Fig. 3) and two Huntec high-resolution seismic lines (Figs. 4, 5).

tem (McKeown 1975). The Huntec DTS system is a boomer source, towed 25 to 100 m below the sea surface. The system comprises two receivers, an internal hydrophone, and an external 10-element, 5-m-long hydrophone streamer. The maximum energy is 550 J, which produces a source bandwidth of ~ 0.6 to 6 kHz centered around 3.5 kHz. A Rockwell P-code GPS receiver provided positions with ± 5 m accuracy with 1 s fixes throughout both surveys.

GULLY EVOLUTION

Our analysis of slope gullies, based on the Huntec seismic-reflection data, is limited to the uppermost 50 to 60 m of sediment, although an examination of a multichannel seismic line indicates that the gullied section of the slope is as much as 100 m thick (Fig. 3). Thus, we have not examined the entire thickness of the gullied section on the slope, only the upper half of the gullied strata. To evaluate the evolution of the gully network, we mapped three subbottom gullied surfaces throughout the study area. The shallowest surface, the lowstand surface, is associated with the lowstand of sea level during the last glacial maximum. An intermediate surface, the MGS (maximal gullied surface), is the surface at which the number, relief, and areal extent of the gullies are at a maximum. The deepest surface, LGS (lowest mappable gullied surface), is the lowest surface that can be mapped throughout the study area (Fig. 4).

We identify the lowstand surface on the continental slope as the surface that is correlated to the lowstand surface of erosion on the continental shelf. On the shelf, this surface is interpreted to be the lowstand surface of erosion on the basis of bedding geometry, including erosional truncation (Fig. 5) and onlap (Spinelli et al. 1998). The lowstand surface occurs 10 to 20 m below the seafloor.

Pre-LGS

On Huntec lines from the mid-slope (~ 480 m water depth), gully initiation is observed below the LGS (Fig. 4). As shown by Field et al. (1999), gullies are initiated by incision and erosion, indicated by the truncation of reflectors and the irregularity of gully floors. Individual gullies do not change size or shape greatly below the LGS.

LGS to MGS

The gullies on the LGS are irregularly spaced and have low relief (mean relief = 1.5 m, standard deviation σ = 1.5 m, number n = 91). Most gullies on the LGS head between 400 and 500 m water depth; very few gullies extend upslope as shallow as 300 m water depth (Fig. 6). We use the number of gullies underlying the modern 500 m isobath (across the 25-km-wide study area) as a measure of the number of gullies present on each surface. The number of gullies underlying the 500 m isobath increases from 55 on the LGS to 58 on the MGS. Upward through this interval, the gullies also increase in relief and extend upslope, with greater sediment accumulation on the interfluves than in thalwegs. Individual gullies all increase in relief from the LGS to the MGS. On the MGS, the heads of the gullies lie upslope from their positions on the LGS, in 300 to 450 m water depth, with a few gullies heading at approximately 200 m water depth (Fig. 6). At the resolution of the Huntec data (vertical resolution ~ 50 cm), erosional features (e.g., truncated reflectors or irregular gully floors) were not present within the gullies during this period of gully growth.

MGS to Lowstand Surface

The gullies on the MGS are at their maximum relief (mean relief = 2.1 m, σ = 1.8 m, n = 236). There are almost no differences between the morphologies of the gullies on the MGS and on the lowstand surface. A few of the gullies gradually lose relief, with greater sediment accumulation in thalwegs than on interfluves. However, uniform sediment drape of gullies and interfluves dominates this interval. On the lowstand surface, 60 gullies underlie the 500 m isobath, a slight increase from the 58 on the MGS. On the lowstand surface, many of the heads of the gullies are downslope of their location on the MGS. A few gullies extend up to 200 m water depth, with most heading at about 400 m water depth. Gully relief on the lowstand surface (mean relief = 1.8 m, σ = 2.2 m, n = 235) is similar to relief on the MGS.

Lowstand Surface to Seafloor

From the lowstand surface to the seafloor, sediment accumulation is greater in thalwegs than on interfluves. Gully relief on the seafloor is reduced (mean relief = 1.4 m, σ = 1.5 m, n = 130) relative to relief at the lowstand surface. Between the last glacial maximum (lowstand surface) and the present (seafloor), many gullies were completely filled with sediment. Individual gullies all decrease in relief from the lowstand surface to the seafloor. Gullies on the seafloor head farther down the slope than those on the lowstand surface. For example, some gullies present on the MGS and the lowstand surface in Figure 4 are not present on the seafloor. The

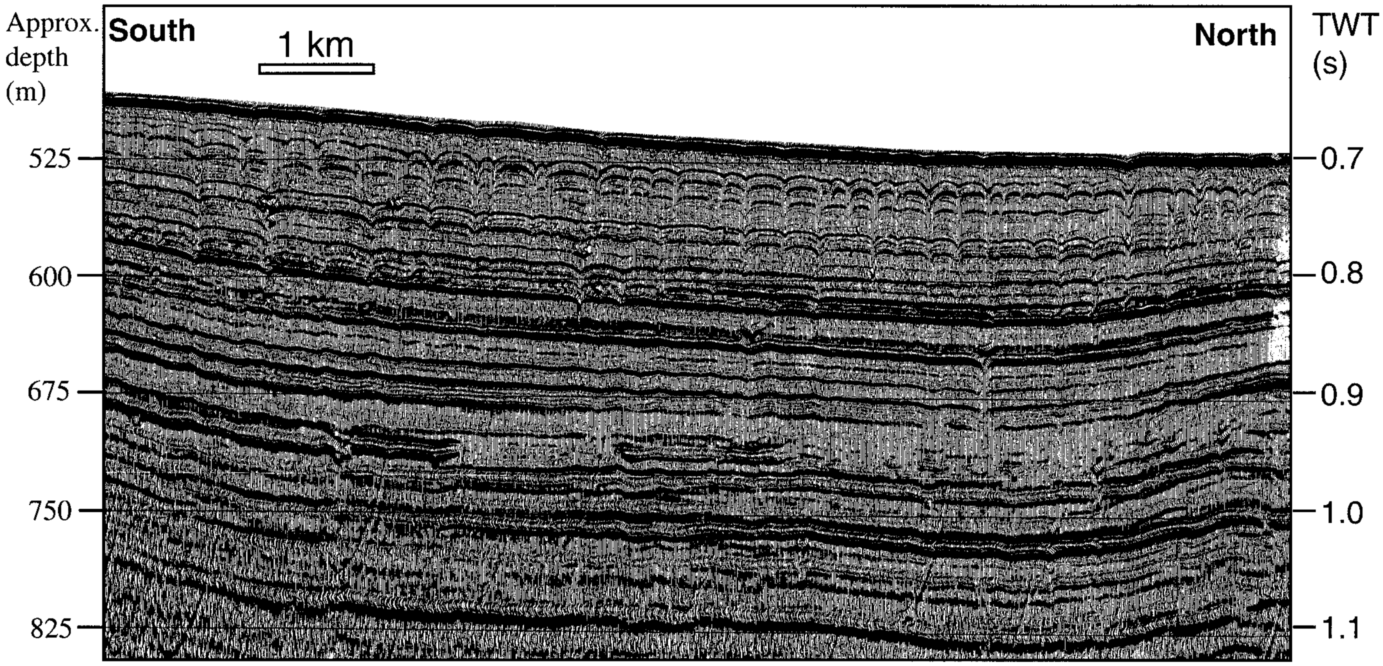


FIG. 3.—Multi-channel seismic line (# 60), which trends north-south across the mid-slope. The upper 100 m of section are gullied, with gully relief increasing up section. Gullies imaged in the subsurface are mostly filled at the seafloor.

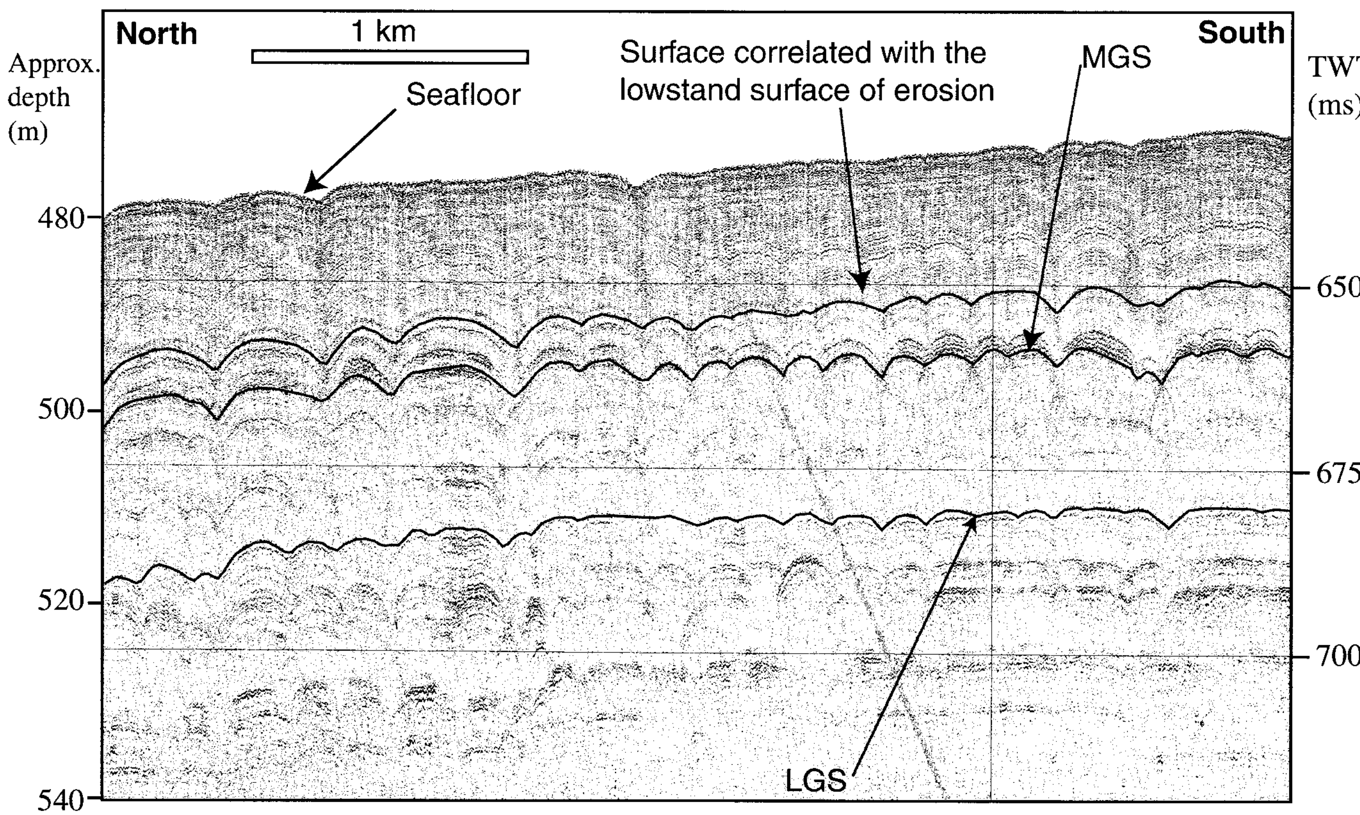


FIG. 4.—High-resolution Huntec DTS line (#16) along-slope profile (coincident with the multi-channel seismic line shown in Figure 3) showing small, shallow, evenly spaced gullies. Gullies are initiated ~ 20 m below the lowest mappable gullied surface (LGS; note, the LGS is not the surface where gullies are initiated; it is the lowest gullied surface that can be mapped throughout the study area). The gullies increase in relief to a maximum at the maximal gullied surface. The gullies are draped uniformly with sediment, preserving their relief, from the maximal gullied surface to the lowstand surface, then filled with sediment from the lowstand surface to the seafloor.

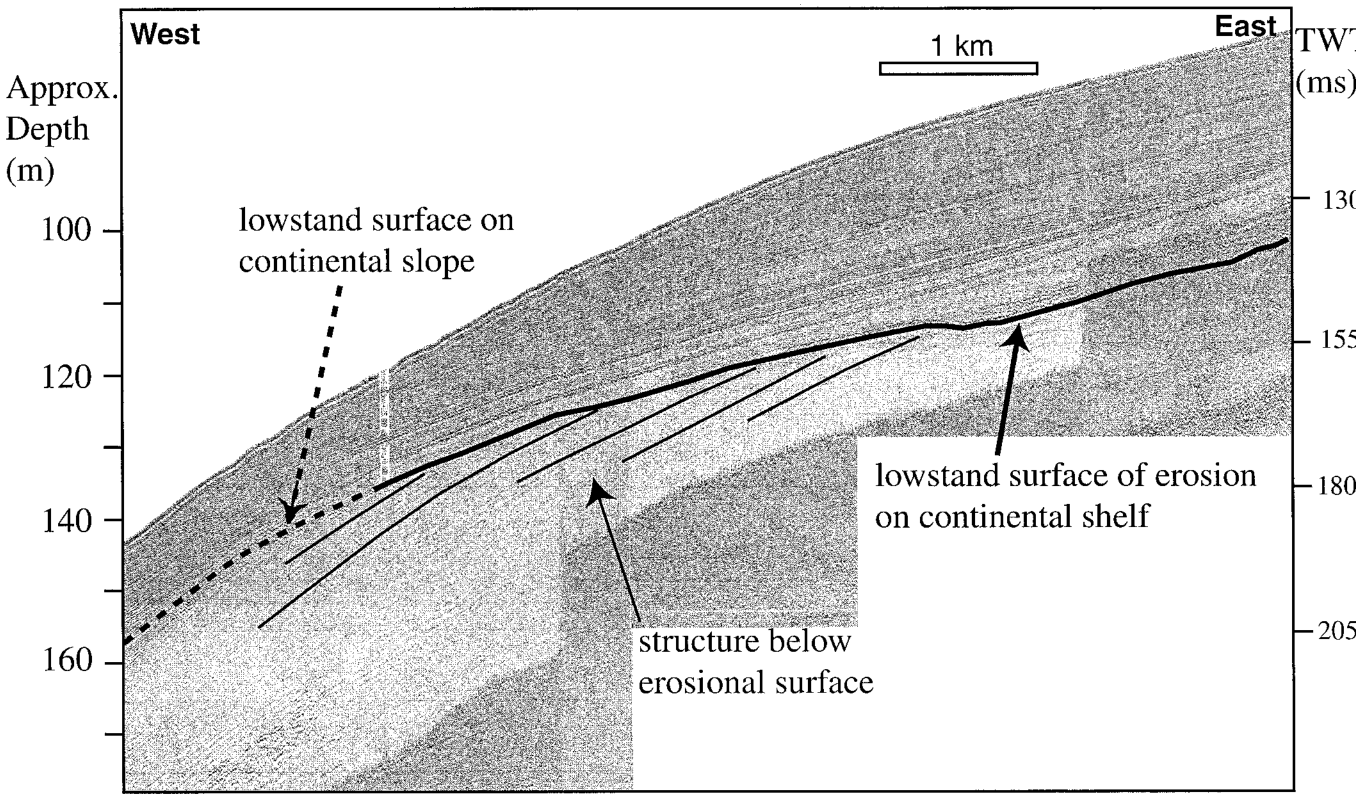


FIG. 5.—High-resolution Huntec DTS line (# 7), which trends east–west from the shelf to the slope. The lowstand surface of erosion on the continental shelf is identified as an erosional unconformity. Reflectors underlying the lowstand surface of erosion are truncated at this surface. This surface is correlated to a lowstand surface on the continental slope.

heads of most gullies on the seafloor are at 400 m water depth, with a few gullies extending up to 300 m water depth and one gully extending up to approximately 220 m water depth (Fig 6). Only 46 seafloor gullies cross the 500 m isobath, whereas 60 on the lowstand surface cross this isobath.

The decrease in gully relief from the lowstand surface to the seafloor is made apparent by the difference in sediment thickness between mapped layers in the gully thalwegs and on the interfluves. Between the MGS and the lowstand surface on the upper and lower slope, more sediment accumulated in the gully thalwegs than on the gully interfluves (Fig. 7). On the mid-slope, the gullies and interfluves accumulated sediment uniformly. From the lowstand surface to the seafloor, gully relief is reduced across the entire slope, by 1 to 3 m, as more sediment accumulated in the thalwegs than on the interfluves.

DISCUSSION

LGS to MGS

Slope gullies between the LGS and the MGS increase in relief and extend headward toward the shelfbreak. The relief of the gullies increases because the interfluves aggrade more rapidly than gully thalwegs. This disparity between sediment accumulation inside and outside of the gullies could have resulted from: (1) uniform sedimentation on the slope (both inside and outside of the gullies), followed by removal of sediment from the gullies by episodic events; (2) preferential sedimentation on the gully interfluves (or a lack of sediment accumulation within the gullies); or (3) some combination of processes between these two end members. Inasmuch as erosional features are not resolved within the gullies during the period of gully growth, episodic events (e.g., liquefaction and flow of sediment) must not have eroded more than 50 cm (the vertical resolution of the Huntec profiles) into the bed. Therefore, we prefer the ‘‘steady’’ end of the sedimentation spectrum, in which some processes inhibited sedimentation in the gully bottoms, or enhanced sedimentation on interfluves, or both.

The average sedimentation rate on the slope from the lowstand surface to the seafloor is 1 m/kyr (based on an average of 15–20 m of sediment overlying the lowstand surface, associated with the last glacial maximum, 18 kyr before present; Spinelli et al. 1998). At present, we do not have information on the ages of surfaces or sedimentation rates below the lowstand surface. We can use the sedimentation rate of 1 m/kyr, however, to estimate ages of the LGS and MGS, and hence locate the approximate positions of the coastline relative to the gully network. We do not, however, suggest that the sedimentation rate in this location has been constant. Our estimates of paleo-shoreline position do not account for tectonic deformation or the accumulation of sediment on the shelf. Removing the effects of uplift or sediment accumulation would shift paleo-shoreline locations landward. Removing the effect of subsidence would shift paleo-shoreline locations seaward. Orange (1999) notes that sediment accumulation rates on the shelf in this area are 2 to 10 times larger than rates of tectonic deformation. Thus, correcting for tectonic deformation and sediment accumulation would shift our paleo-shoreline locations landward.

When the MGS was exposed at the seafloor, the gullies headed $\sim$ 10 km offshore from the mouth of the Mad River, between 100 to 250 m below paleo-sea level (Fig. 8). The Klamath River may have contributed additional sediment to the gully network, depending on the course it followed across the subaerially exposed continental shelf. At this time, the gullies increased in relief as the interfluves aggraded more rapidly than the gully thalwegs.

MGS to Lowstand Surface

At the last glacial maximum, when the lowstand surface was exposed at the seafloor, the gully heads remained $\sim$ 10 km offshore, between 100 to

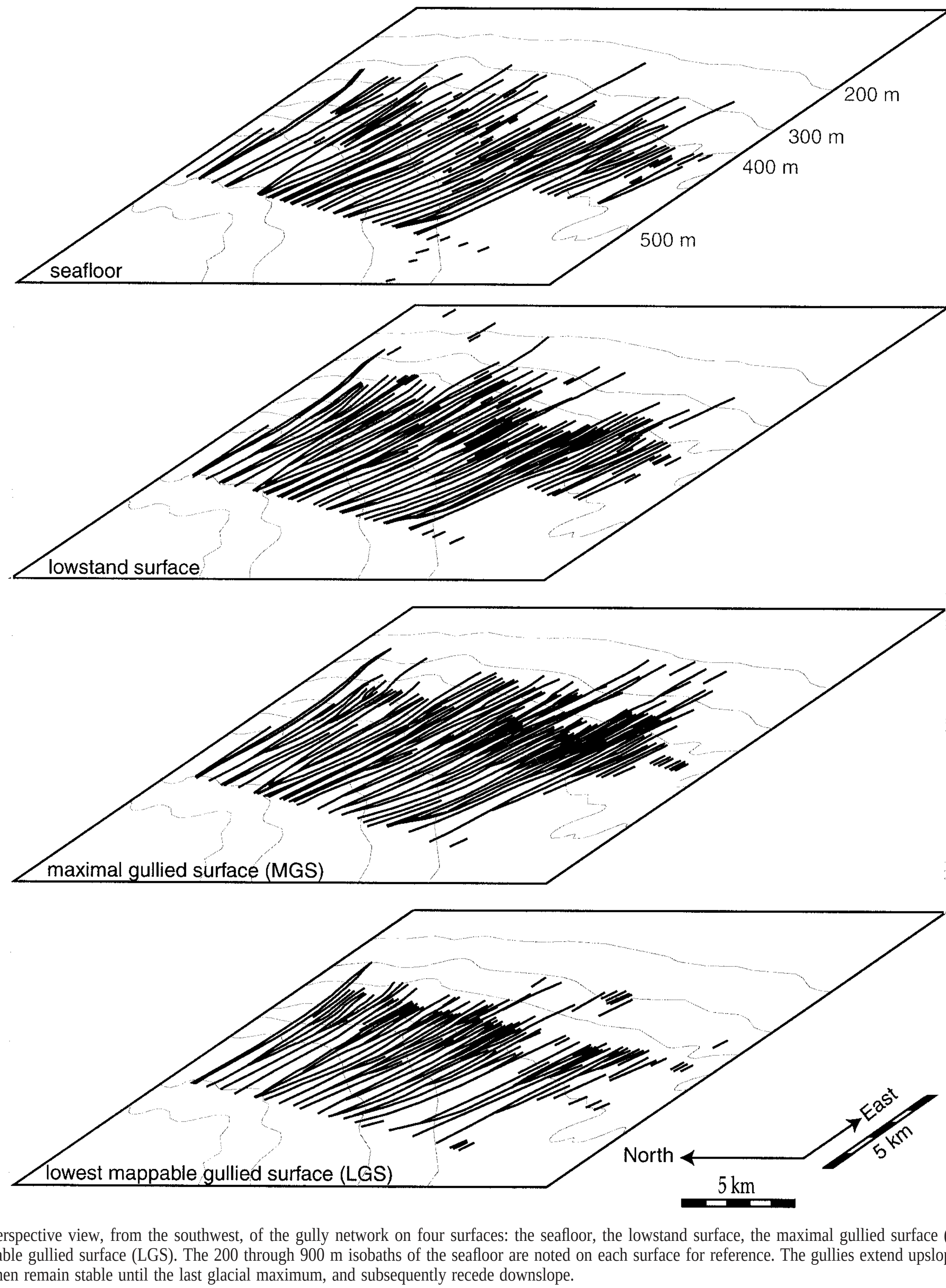


FIG. 6.—Perspective view, from the southwest, of the gully network on four surfaces: the seafloor, the lowstand surface, the maximal gullied surface (MGS), and the lowest mappable gullied surface (LGS). The 200 through 900 m isobaths of the seafloor are noted on each surface for reference. The gullies extend upslope from LGS to MGS time, then remain stable until the last glacial maximum, and subsequently recede downslope.

300 m below paleo-sea level. Between the time the MGS was exposed at the seafloor and the last glacial maximum, the slope gullies and interfluves were uniformly blanketed with sediment and their heads receded slightly downslope. This blanket of sediment could have resulted from uniform sediment deposition on the slope, or nonuniform deposition and redistribution of sediment into a uniform blanket. Whether the sediment was uniformly deposited or redistributed, processes that were enhancing sediment accumulation on the interfluves had effectively ceased.

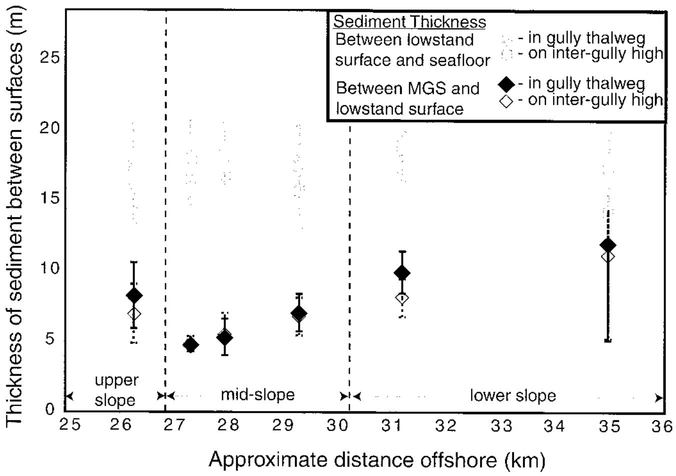


FIG. 7.—Average sediment thickness between mapped reflectors in the subsurface on six Huntec lines. Sediment thicknesses are separated into measurements made within the gullies (i.e., from gully thalweg to gully thalweg; solid symbols) and measurements made on the interfluves (open symbols). The diamonds indicate the sediment thickness from the maximal gullied surface (MGS) to the lowstand surface. The squares indicate sediment thickness between the lowstand surface and the seafloor. Error bars are ± one standard deviation. Gullies lose relief as the thalwegs fill with sediment more rapidly than the interfluves everywhere from the lowstand surface to the seafloor, and on the upper slope and lower slope from the MGS and the lowstand surface.

Lowstand Surface to Seafloor

The present coastline is ~ 30 km from the gully network, and the gullies head in 300 to 400 m water depth. Between the lowstand surface and the seafloor, the slope gullies filled with sediment and receded downslope. The most rapid infilling of gullies occurs low in the section, immediately above the lowstand surface. The gullies now head in relatively deep water, far from sediment sources. In this low-energy environment, available sediment has tended to accumulate in the gully bottoms, probably from nepheloid layers or resuspension by local physical or biological processes.

Gully-Shaping Processes

Our study, based primarily on seismic-reflection data, does not suggest definitive processes responsible for slope gully formation and maintenance. The data do, however, provide some useful information about gully-shaping processes. First, the connection of gullies into a network, including evidence of gully capture and the downslope evolution of gullies into larger channels, indicates that the gullies were a product of downslope processes, not slope-parallel transport. Second, the gullies grew prior to the last glacial maximum, when they headed closest to the coastline; they filled following the last glacial maximum, when the gullies headed in deeper water, farther from potential sediment sources. Thus, the gully-forming processes were active in shallower water or closer to sediment sources, and are not active under the current conditions on the slope. Third, the gullies increase in relief downslope. Therefore, the gully-shaping processes must be more effective at enhancing sedimentation on interfluves (or preventing sedimentation in gullies) with increasing distance downslope. Fourth, the gully-forming processes extended the gullies headward while simultaneously increasing gully relief. Finally, the lack of seismic-reflection evidence of erosional features within the gullies during their growth indicates that the gully-shaping processes cannot have eroded significant thicknesses (greater than ~ 50 cm) of sediment during individual events.

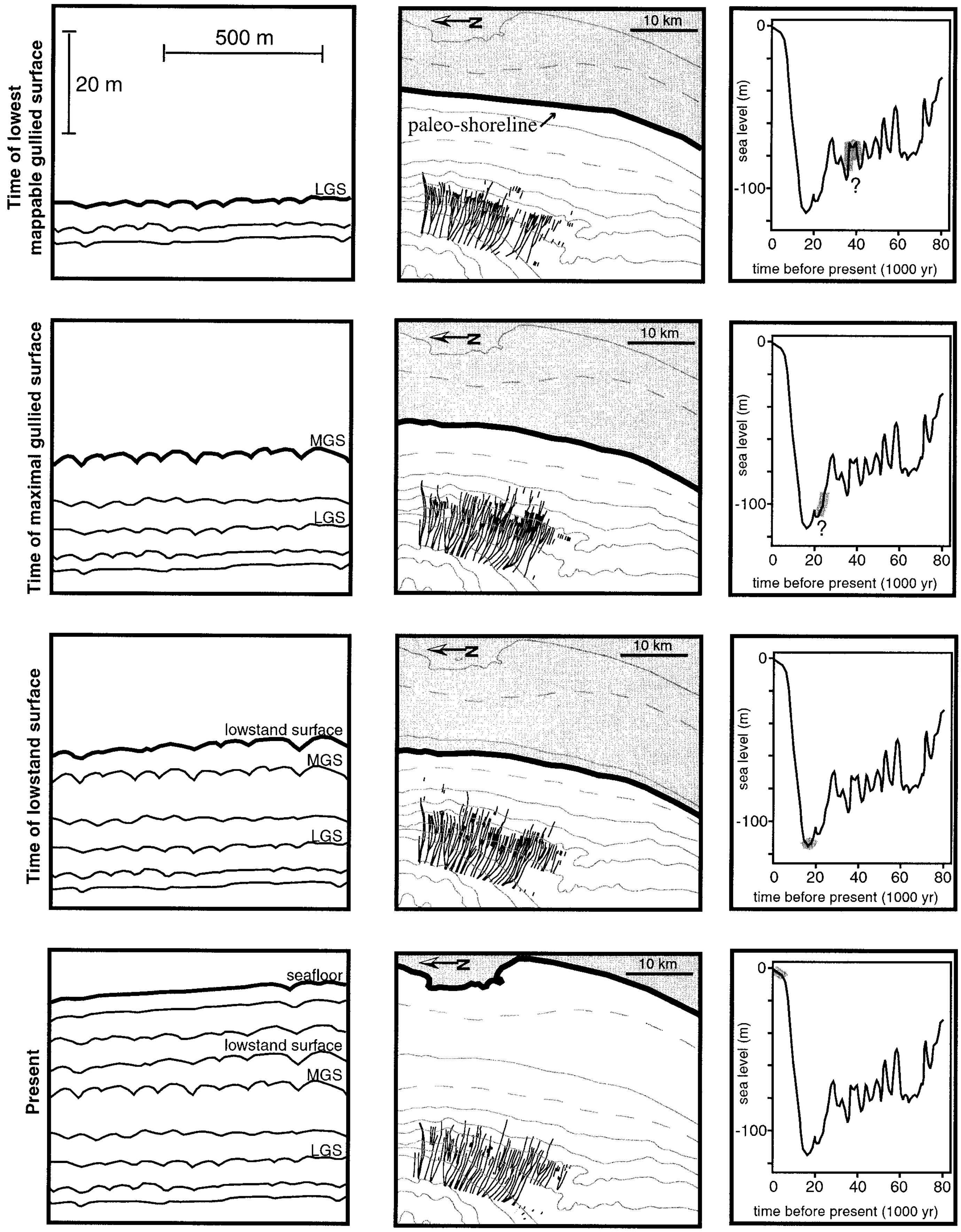
Each of the constraints noted above can be satisfied by considering downslope-eroding sediment flows on a margin that is rapidly accumulating sediment from multiple sources. Pratson and Coakley (1996) developed a numerical model to simulate development of submarine canyons in response to downslope-eroding sediment flows. In their model, spatially variable sediment accumulation leads to local slope oversteepening, which in turn causes slope failure and initiates sediment flows (Pratson and Coakley 1996). Each simulated sediment flow moves downslope, eroding sediment as it passes. Pratson and Coakley (1996) use this model to simulate the formation of submarine canyons, the first stage being the development of small, downslope trending ''rills.'' As the process continues, the sediment flows ''follow the rills to the base of the slope, eroding and deepening the rills before they are infilled by sedimentation'' (Pratson and Coakley 1996).

We suggest that a similar process is consistent with the evolution of the slope gullies recorded in the strata on the northern California margin. In this case, our study area is draped with a fairly uniform blanket of fine sediment from the distal Eel River during both highstands and lowstands of sea level. Prior to the last glacial maximum, the shoreline was near the shelfbreak. The Mad River, adjusting to lowering base level, contributed additional sediment to the upper slope, leading to small slope failures and sediment flows, which removed much of the Eel River sediment from rills or gullies. During this time, the gully thalwegs aggraded gradually, as sedimentation from the Eel River slightly exceeded removal by sediment flows. The interfluves, unaffected by the sediment flows, aggraded more rapidly. During the present sea-level highstand, Mad River sediment is largely trapped on the shelf. The number of upper-slope failures is reduced and the gullies are filling with fine sediment supplied by the Eel River.

The Eel River, located approximately 40 km south of the gullied slope (Fig. 1), supplies most sediment to the margin, an estimated 15.3×10^9 kg/yr of suspended sediment (Sommerfield and Nittrouer 1999). The Mad River has an estimated total sediment load of 2.5×10^9 kg/yr (Janda and Nolan 1979). The location of Eel River flood deposits (Wheatcroft et al. 1997; Sommerfield et al. 1999) and the determination of ^{210}Pb accumulation rates for the Eel shelf (Sommerfield and Nittrouer 1999) and slope (Alexander and Simoneau 1999) indicate that, under present conditions, Eel River sediment accumulates in a broad region to the north of the Eel River, on and around the gullied slope. Measurements of fairly continuous sedimentation rates on the slope from sediment cores (Alexander and Simoneau 1999), as well as direct measurements of nepheloid layers from ships (McPhee and Cacchione 1998) and settling traps (Walsh and Nittrouer 1999), provide evidence that nepheloid deposition is a dominant process on the modern slope. It is probable that, as inferred by Field et al. (1999), the draping of gullies and upbuilding of the slope by thin parallel reflectors result from dispersive nepheloid transport. During sea-level lowstand, coarse sediment from the Eel River may be transported down the Eel Canyon (Fig. 1), but much of the suspended sediment may be dispersed on the remaining shelf and slope north of the Eel River, providing an approximately uniform drape of sediment on the gullied slope.

Prior to the last glacial maximum, as the gullies increased in relief and extended up the slope, the Mad River may have discharged sediment within 10 km of the gully heads, providing sediment to generate slope instabilities. Following the last glacial maximum, the mouth of the Mad River has been separated from the gully heads by a wider continental shelf (~ 30 km wide), greatly reducing the amount of Mad River sediment that reaches the upper slope. For the gullies to be filling at present, near-bed processes, such as currents or bottom-impinging internal waves, must preferentially deposit more sediment in the shallow gullies than on the interfluves. The mechanism described above accounts for the development of aggradational slope gullies that grow during falling sea level, are maintained during sea-level lowstand, and fill during transgression and sea-level highstand.

The processes that shape slope gullies are slow; several meters of relief are generated, and subsequently filled, over thousands to tens of thousands of years. Identification of slope gullies on numerous continental margins (e.g., southern California, Tyrrhenian margin, southwestern Japan forearc, and northern California) suggests that the processes involved in the evolution of slope gullies may have been active in diverse oceanographic settings and at different times.


Time of lowest mappable gullied surface
20 m
500 m
LGS
10 km
paleo-shoreline
sea level (m)
time before present (1000 yr)
?
Time of maximal gullied surface
MGS
LGS
Time of lowstand surface
lowstand surface
MGS
LGS
Present
seafloor
lowstand surface
MGS
LGS

CONCLUSIONS

Slope gullies occur on the northern California margin both on the surface and in the subsurface. The network of gullies extended farthest upslope, and the gullies exhibited maximum relief, prior to the last glacial maximum lowstand of sea level, when the processes that formed the gullies were most effective. At that time, approximately 10 km of non-gullied outer shelf and upper slope separated the coastline and the gully network; thus the gullies were not connected to a subaerial or shelf drainage network. As sea level rose during the deglaciation, the gullies filled with sediment over a period of several thousand years. Gully-forming processes have been inactive, or relatively weak, since the last glacial maximum. Gully infilling presumably continues today; the number of gullies on the modern seafloor is half the number in the subsurface.

The specific processes that form, maintain, and infill the slope gullies are not understood. We recognize a distinct correlation, however, between sea-level position and gully formation and infilling. The gullies were larger and more abundant and were probably initiated prior to the most recent sea-level lowstand, a time of increased sediment delivery to the coasts and more energetic conditions at the water depth of the gullies. In contrast, the gullies decreased in size and number as sea level rose and sediment sources retreated farther landward, resulting in sedimentation that was more dispersive and a less energetic environment at the now greater water depths of the gullies.

We suggest that downslope sediment flows could have been triggered on the slope by the input of sediment from the Mad River during falling sea level prior to the last glacial maximum. These flows had to remove sediment from gullies at a rate comparable to (but not in excess of) sediment accumulation rates from the distal Eel River. Gully growth was aggradational. If gullies formed by density flows, the flows did not erode sections of sediment more than 50 cm thick. It is evident from Huntec DTS lines of the lower slope that sediment gravity flows have occurred on the slope and in the channels fed by gullies. Oceanographic currents and breaking internal waves may aid in remobilizing upper-slope sediment and moving it downslope. During the present sea-level highstand, the Mad River is no longer a significant source of sediment to the upper slope, and the gullies are filling with Eel River derived sediment. It is clear from studies of modern slope sediments and processes that dispersive nepheloid sedimentation is an important process shaping the continental slope (Walsh and Nittrouer 1999). As yet, no evidence has been obtained to document a gully-shaping mechanism.

ACKNOWLEDGMENTS

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Fig. 8.—Gully evolution in cross-sectional and plan views with changes in sea level. The rows illustrate conditions when each mapped surface was exposed at the seafloor, beginning with the oldest surface at the top. The left column is a line drawing of the major reflectors on a section of the mid-slope Huntec line shown in Fig. 5. The center column shows the network of gullies in plan view; note that north is to the left. The position of the coastline is shown in a bold black line. The solid gray lines are 100 m isobaths of the modern seafloor (the modern coastline is shown near the top of each image), and the dashed gray lines are the 50 and 150 m isobaths. The right column is a global sea-level curve from McGuire et al. (1997) with the approximate position of each surface noted by a gray box. The time of formation of the maximal gullied surface (MGS) and the lowest mappable gullied surface (LGS) are estimated, using an approximate rate of sedimentation (see text for discussion).