UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY AND GEOLOGIC HAZARDS OF OFFSHORE EEL RIVER BASIN, NORTHERN CALIFORNIA CONTINENTAL MARGIN

by

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Open-File Report

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This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature

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PREFACE

This report summarizes aspects of the offshore and onshore geology of the Eel River Basin, California, that are of importance in assessing the potential geological hazards to offshore petroleum exploration and development. Although these investigations focus on the identification and characterization of potential hazards in specific offshore basins, they should be considered regional in scope. They are designed to provide broad geological perspective in these areas, to be used as an adjunct to site-specific geohazards studies. The geologic phenomena investigated include faulting, seismicity, seafloor instability (e.g., submarine slides and flows), seafloor erosion and deposition, hydrocarbon seepage, hydrocarbon gases and hydrates in seafloor sediments, and diapirism.

Recently collected data from the offshore Eel River Basin that were not analyzed for this report indicate that final maps of unstable sediment zones and fault patterns will differ, but not substantially, from those presented here. However the maps and text that follow define the major, and many of the minor, sedimentary and structural patterns and processes that characterize the offshore Eel River Basin of northern California.

ACKNOWLEDGEMENTS

We are indebted to many colleagues who provided us assistance in collecting and analyzing the data used in this report. In particular we thank Florence Lee-Wong, Brian D. Edwards, Terry Hallinan, William C. Richmond, James V. Gardner, and Neal Barnes. Dave McCulloch shared his ideas and data with us, and greatly improved this report with his review.

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GEOLOGIC FRAMEWORK

Setting

The offshore Eel River Basin extends northward from near Cape Mendocino (40°30' N) for 200 km to Cape Sebastian, Oregon (42°20' N), and from the coastline seaward to the upper continental slope, an average distance of about 70 km (Hoskins and Griffiths, 1971; McCulloch and others, 1977). The area of this study includes the offshore basin and the adjacent terrane from Cape Mendocino north to the California-Oregon border (42°00' N) and seaward to the base of the continental slope (see trackline map in figure 1). The continental slope off northern California marks the approximate eastern boundary of the Gorda (also called Juan de Fuca) crustal plate where it is being subducted beneath the North American crustal plate. The Pacific-Gorda crustal plate boundary is defined approximately by the Mendocino Escarpment and the Juan de Fuca Rise, and the Pacific-North American plate boundary is defined approximately by the San Andreas Fault (fig. 2; Atwater, 1970; Silver, 1971a; Morgan, 1968).

The continental margin off northern California has a young and complex morphology developed in response to late Tertiary and Quaternary plate motion. North of Cape Mendocino the margin is composed of a continental shelf (0-200 m), plateau slope (200-500 m), marginal plateaus (500-1000 m) and continental slope (1000-3000 m) (fig. 3). The Eel River Basin extends from 50 km inland in the lower Eel River and Humboldt-Arcata Bays area offshore across the shelf, plateau slope, and plateaus (named the Eel and Klamath plateaus by Silver, 1969; fig. 3). The plateau and plateau slope are incised by two large submarine canyons, Eel and Trinity (fig. 3). Eel Canyon is a

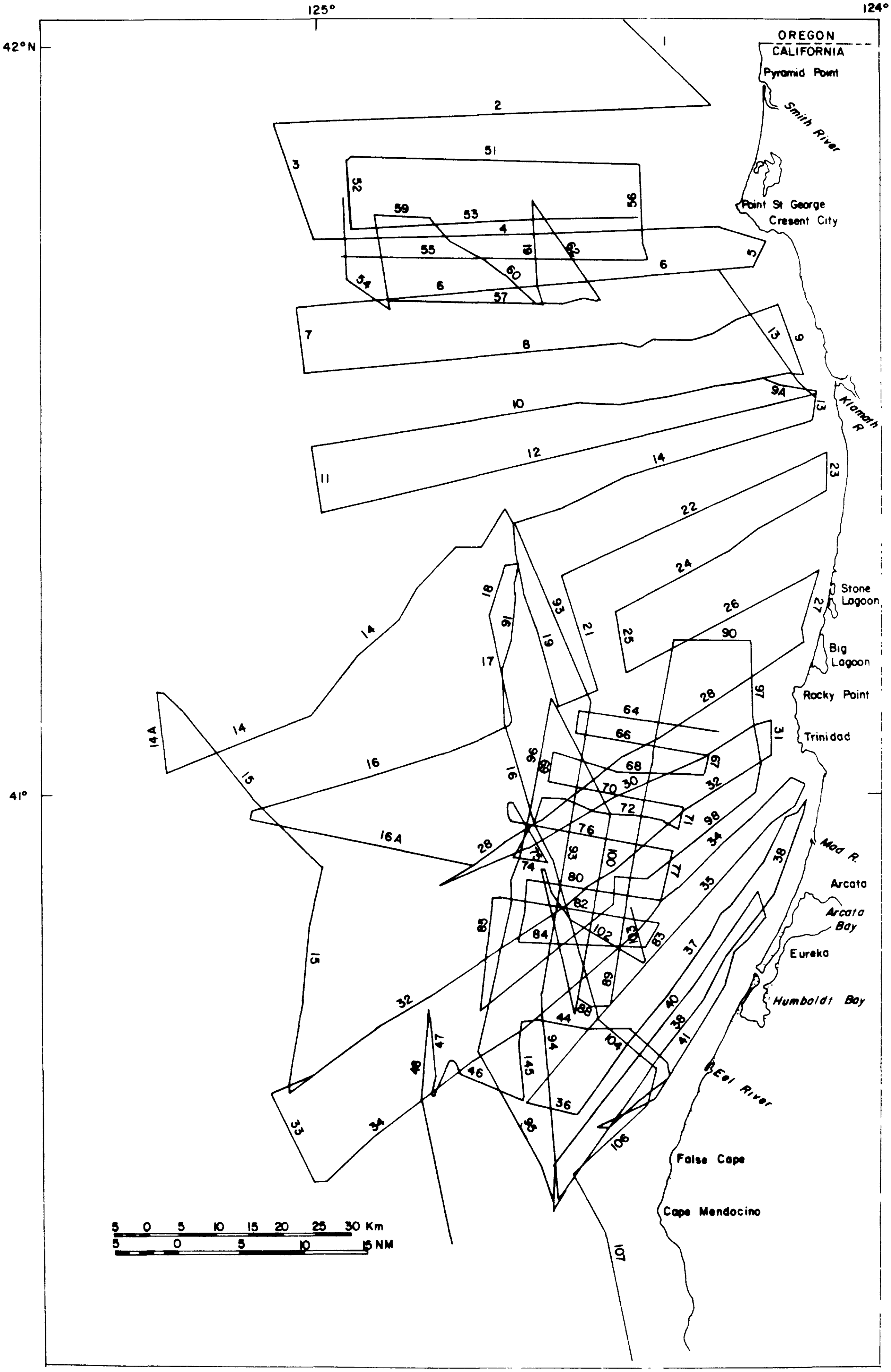

Figure 1. Geophysical tracklines from 1977 and 1978 cruises of the R.V. SEA SOUNDER on the northern California continental margin.

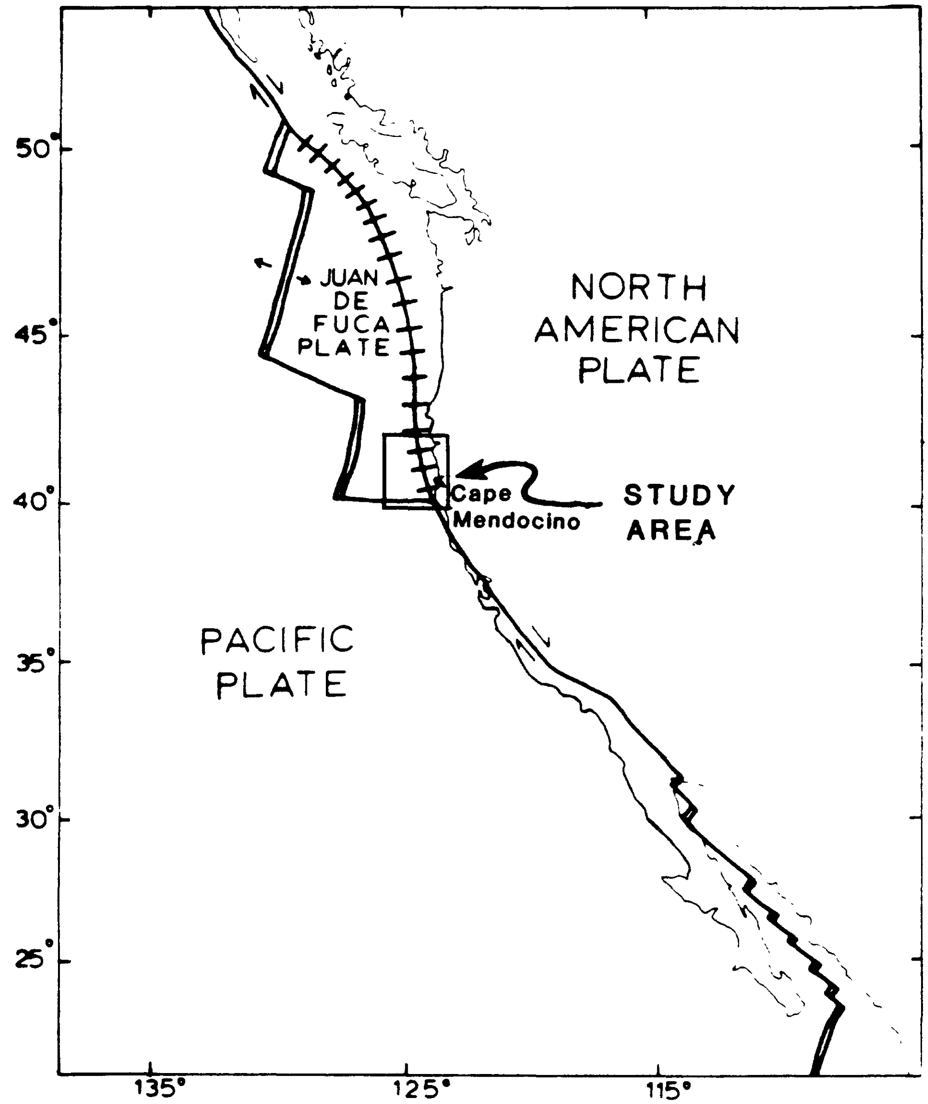

Figure 2. Map of the northeastern Pacific Ocean showing major crustal plate boundaries, from Atwater (1970). Northern California study area is shown in light gray.

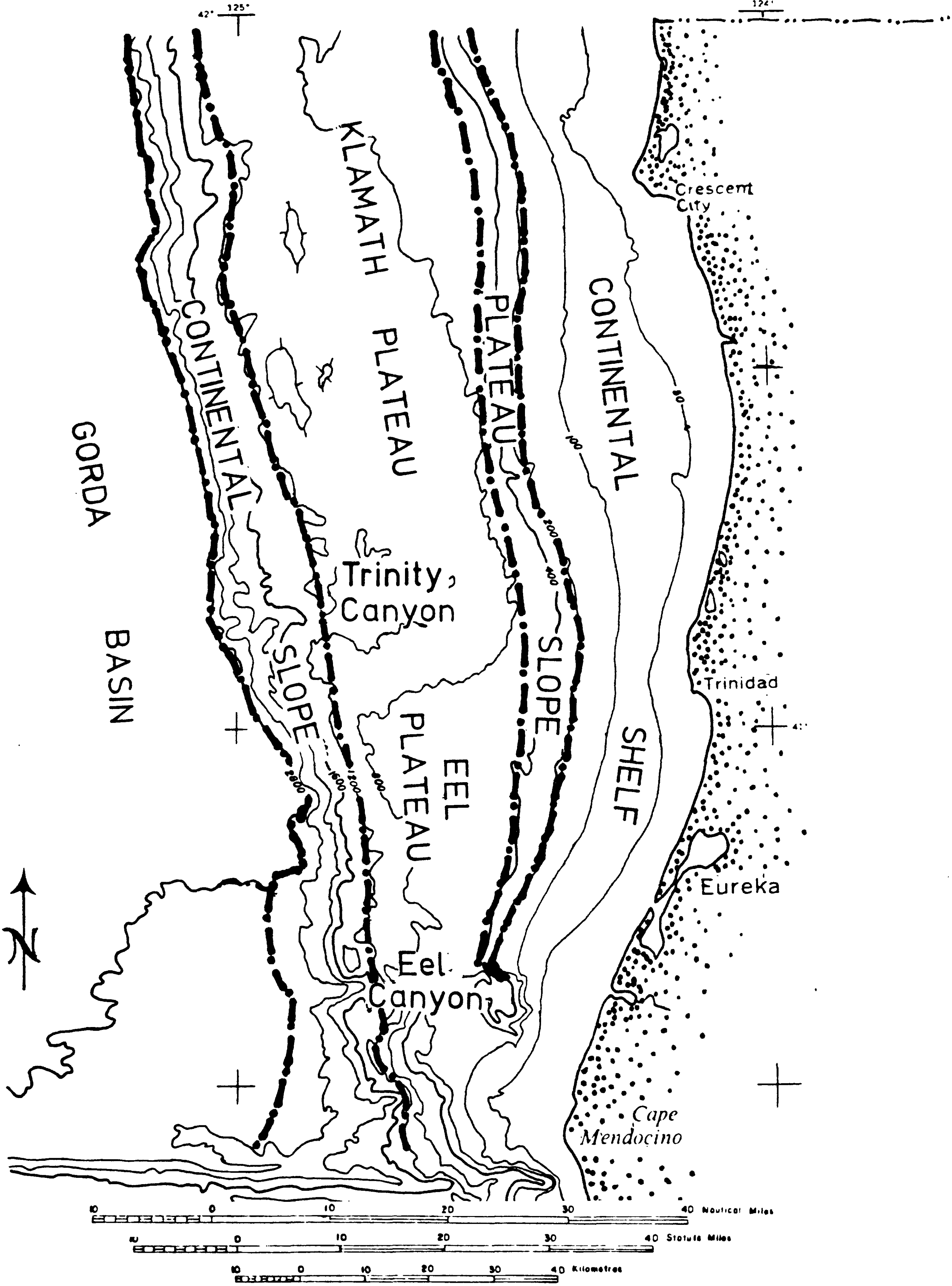

Figure 3. Bathymetry of the northern California continental margin showing major physiographic features, after Silver (1971). Contours are in meters.

steep, narrow meandering canyon that contrasts markedly in morphology with the broad, bowl-shaped tributary network that forms Trinity Canyon.

Regional Geology

Information on structure, ages and lithologic character of surface and subsurface rocks of the offshore Eel River Basin is limited to results from this study and published studies by Hoskins and Griffiths (1971) and Silver (1969, 1971a, 1971b). The geology of the onshore Eel River Basin and adjacent terranes is best known from the studies of Ogle (1953), Strand (1962, 1963), Irwin (1960) and Bailey and others (1964). A synthesis of the stratigraphy and geologic history of the onshore Eel River Basin, based on the above references, appears in McCulloch and others (1977). Appropriate parts of that synthesis are reproduced below.

Basement rocks in the onshore Eel River Basin are mostly massive graywacke with some chert, basalt-greenstone, shale, limestone and schist assigned to the coastal and central belts of the Franciscan complex of Berkland and others (1972) of Late Jurassic to Eocene age (fig.4). This eugeosynclinal assemblage probably underlies the basin offshore as well. The Yager Formation, Eocene in age (Evitt and Pierce, 1975), is in fault contact with Franciscan basement rocks of the central belt in the lower Eel River area, but depositionally overlies relatively young (upper Cretaceous-Eocene) rocks of the coastal belt a short distance to the southwest (Ogle, 1953; Irwin, 1960). It is at least 765 m and perhaps as much as 3060 m thick, and consists of dense, well-indurated mudstone, siltstone, and shale, with lesser graywacke and conglomerate containing locally-derived Franciscan detritus (Ogle, 1953).

EEL RIVER BASIN

STRATIGRAPHIC COLUMN

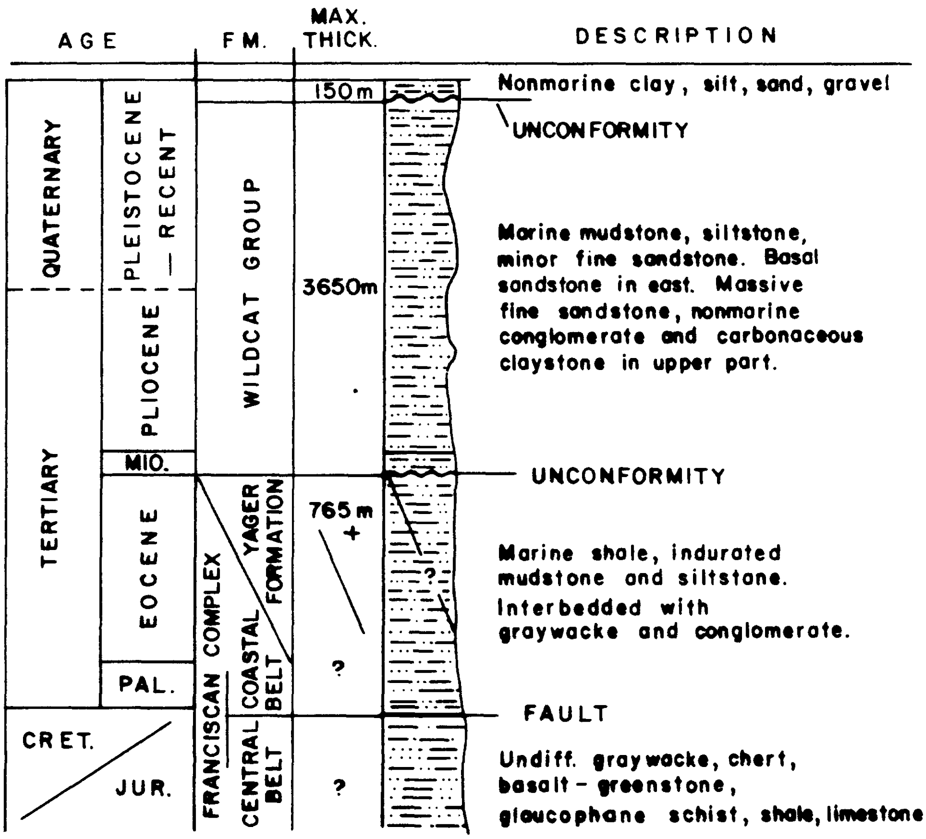

Figure 4. Stratigraphic column of the Eel River Basin, from McCulloch and others (1977) as modified from Ogle (1953) and Hoskins and Griffiths (1971).

Regional deformation occurred between Eocene and middle Miocene time, and Neogene strata unconformably overlie Eocene and older rocks in the Eel River basin both onshore and offshore (Ogle, 1953; Hoskins and Griffiths, 1971). The Wildcat Group comprises an essentially conformable sequence of mostly marine late Miocene to Pleistocene strata about 3670 m thick (Ogle, 1953; Ingle, 1976). Predominant lithologies are weakly consolidated mudstone, siltstone and claystone, with subordinate amounts of sandstone and conglomerate, and minor lignite and tuff. Units of this group appear to record a northward transgression over basement during late Miocene, followed by alternate deepening and shallowing of the basin, a marine regression during late Pliocene, and finally by emergence and marginal marine and non-marine deposition in late Pliocene and Pleistocene time. Episodic marginal uplifts are indicated by coarse Franciscan debris and conglomerates of Pliocene mudstone fragments in some units, and by local unconformities within the group (Ogle, 1953). The section coarsens upward, reflecting late Pliocene regression, and eastward, reflecting the presence of a landmass nearby. Similar, predominantly shallow-marine strata that are approximately correlative with the Wildcat Group are preserved in a graben located about 16 km to the north (Manning and Ogle, 1950), and in the Crescent City area (Back, 1957).

The close of Wildcat deposition was marked by basin margin warping and uplift that continued into Pleistocene time, culminating in basin-wide deformation that followed older structural trends (Ogle, 1953). Pleistocene and Holocene clays, sands, silts and gravels unconformably overlie Wildcat strata in onshore parts of the basin. These deposits have an aggregate thickness of about 150 m and were deposited in shallow-marine and coastal plain environments. As in the Wildcat Group, the marine section becomes finer grained northwestward, suggesting that the basin deepened in that direction.

The distribution and age of onshore rocks has been compiled by Strand (1962, 1963). This information, portrayed in Figure 5, distinguishes the later Tertiary sediments in the onshore Eel River Basin from older Franciscan rocks. Offshore, age and character are less well-known. Shallow, rocky shelf areas adjacent to large capes or headlands are assumed to be extensions of the onshore rocks (fig. 5), but ages of isolated outcrops farther out on the shelf and on the plateau are not well established; these outcrops are identified as undifferentiated Pliocene mudstones, based on analyses of forams from selected cores and from interpretation of seismic reflection stratigraphy. The ages of benthic forams obtained from cores on or near the outcrops are shown in figure 5. The bracketed age is the one assigned the highest probability of being correct. With the exception of the breached anticline 20 km northwest of Rocky Point and the large outcrop located due west of Eel River, Pliocene sediments shown in Figure 5 are all associated with large anticlinal ridges interpreted to be piercement structures. The material exposed on the crest and flanks is a compact clayey silt that appears to be undergoing diapiric emplacement from a position stratigraphically lower than the present uppermost plateau sediment sequence.

STRUCTURE

Folds

Fold axes in the offshore Eel River Basin follow the general north-northwest trend of the main axis of the basin. Folds range from broad and gentle to narrow and tight; most are symmetrical or nearly so, and no

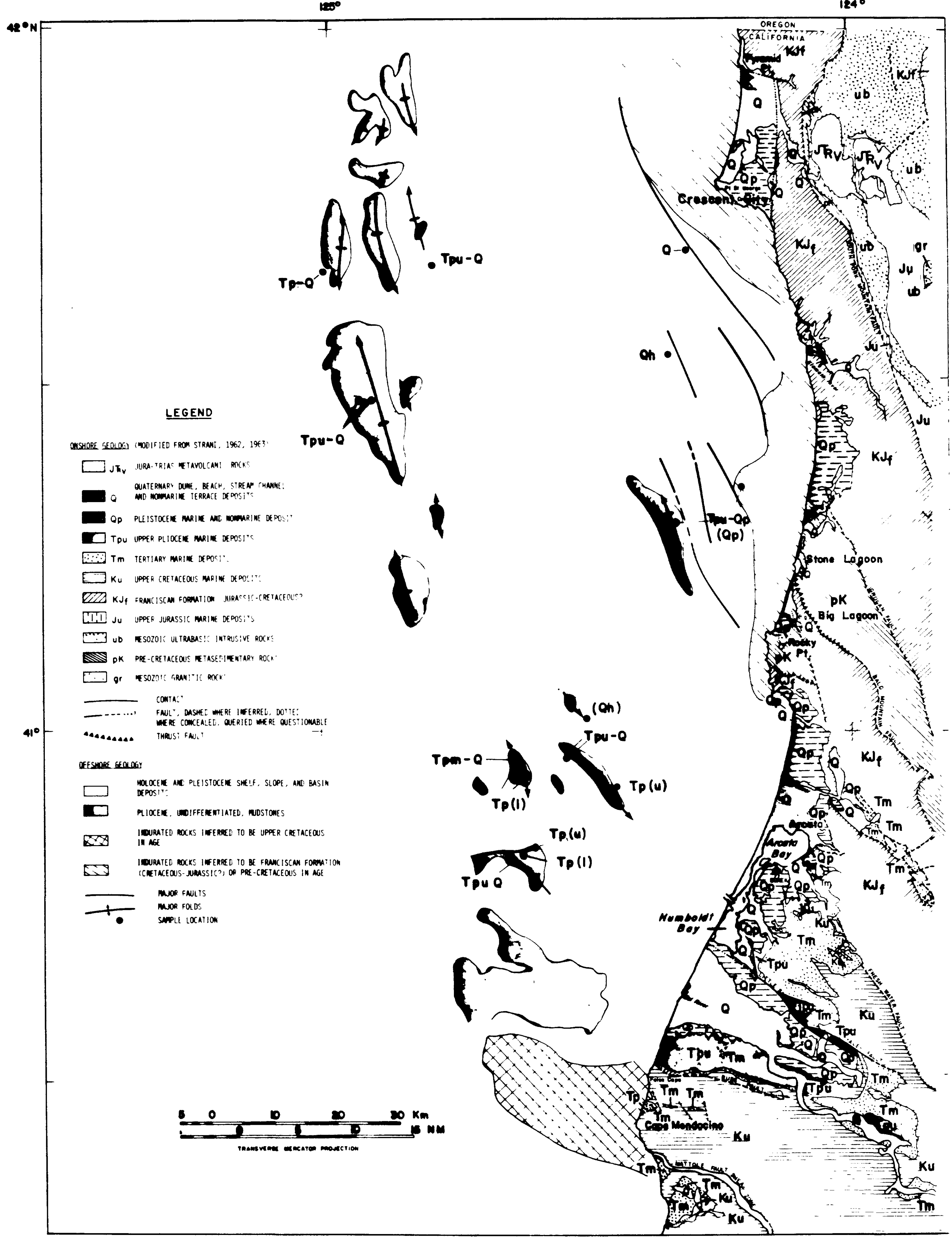

Figure 5. Preliminary geologic map of the northern California continental shelf and slope. Onshore geology is from Strand (1962, 1963).

overturned folds were noted. Many folds are mappable for 10 to 15 km, and a few are traceable for more than 25 km. Numerous folds could not be traced beyond one trackline, and they are shown as short axial lines with an orientation that is presumed to parallel the regional structural trend. Three types of folds have been distinguished, and each has implications regarding structural evolution of the basin and age of folding (fig. 6). Anticlines which have resulted in seafloor bulges, knolls, and ridges on the plateau on the order of 10's to 100's of meters high, represent the most recent phase of folding. These structures (solid lines on fig. 7) are usually double-plunging anticlines that are presently undergoing uplift and/or piercement by deeply-lying shale beds (see below). Fold axes represented by dashed lines on figure 7 indicate folds that extend to the seafloor but have been truncated by an episode of erosion subsequent to folding. These breached structures lie in shallow water (<200 m) and are pre-Holocene in age; most are Tertiary or pre-Tertiary in age. Folds that lie deep in the section and are buried by undeformed sediments are indicated by a dotted line in figure 7.

It is evident from the amount of seafloor relief (up to 200 m) created by folding and the amount of deformation of Holocene sediments that the basin has been affected by compression, at least locally, throughout the Quaternary, and perhaps longer. Although deformation may be episodic, there is clear evidence that it is a continuing process affecting the present sedimentary sequence. The major force causing the basin deformation probably is underthrusting of the continental margin by the Gorda Plate, although locally it may be caused more directly by shearing or diapirism.

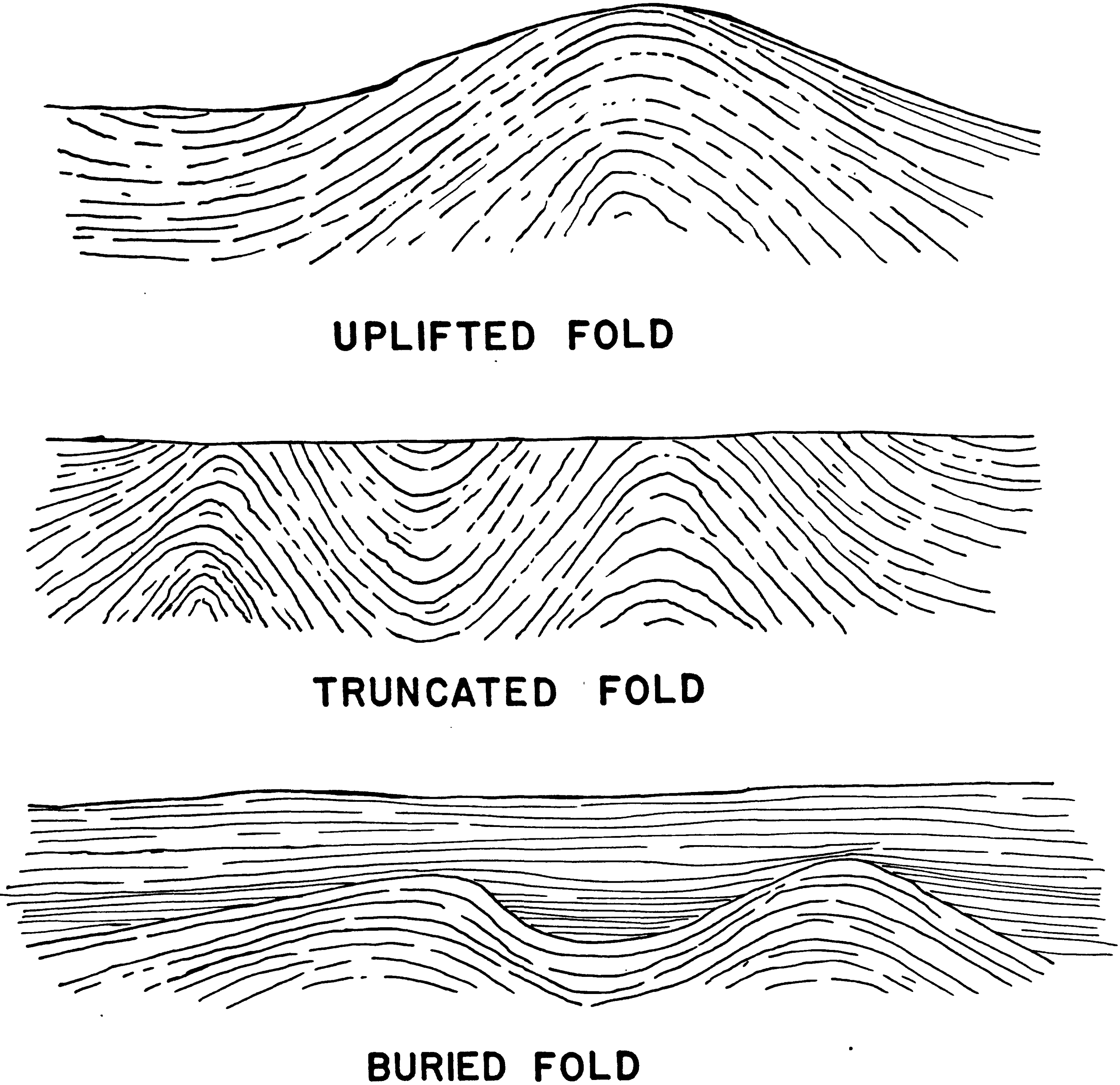

Figure 6. Types of folds present on the northern California continental margin. Raised folds are located predominately on the outer and south central plateau, truncated folds on the shelf, and buried folds on the shelf and central plateau.

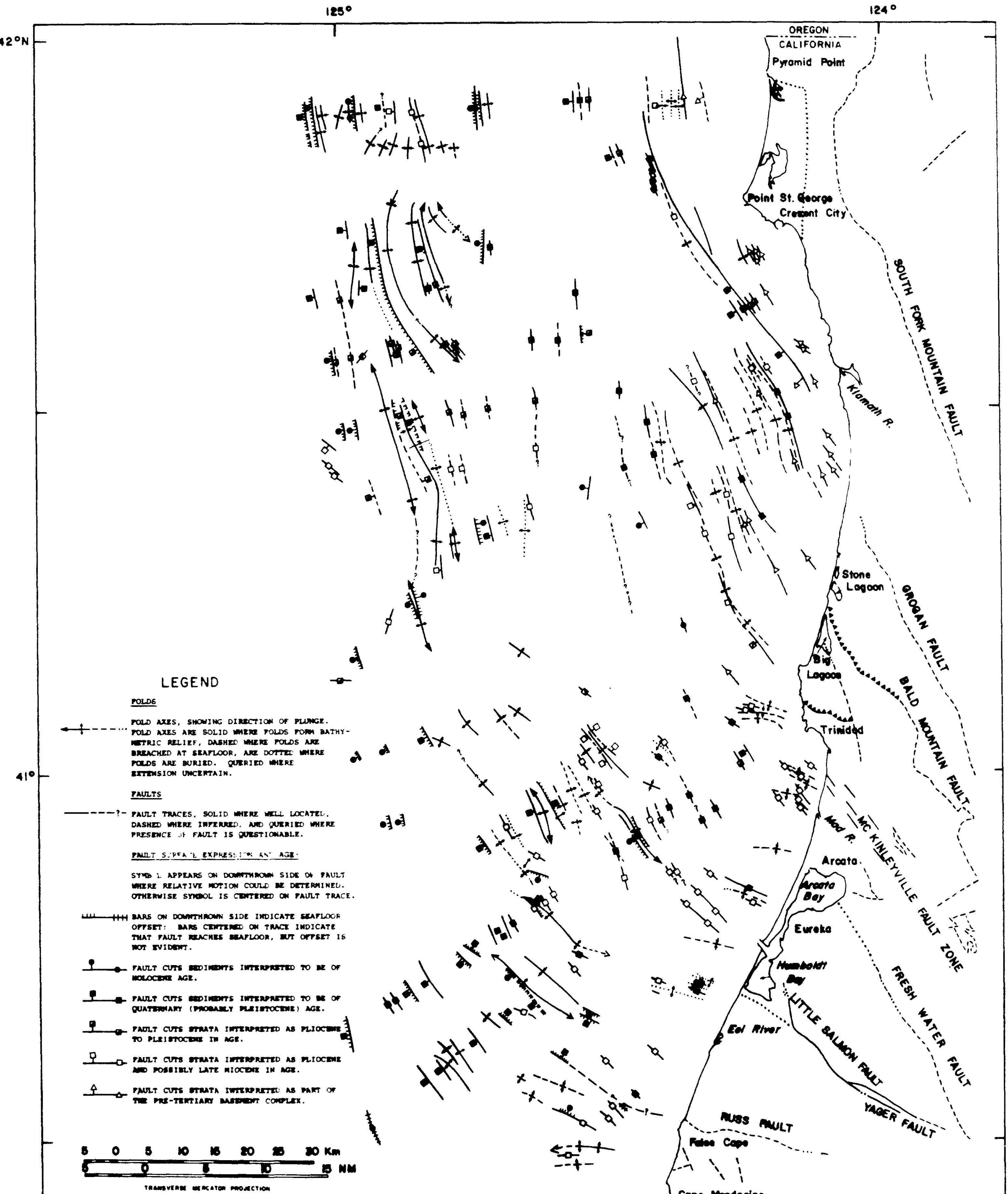

Figure 7. Preliminary structural map of the northern California continental margin showing location and trend of folds and location, trend, age, and seafloor rupture of faults.

Piercement Structures

Hoskins and Griffiths (1971) suggested that shale flowage and diapirism may occur on the northern California continental margin, as they do on the Oregon-Washington continental shelf to the north (Rau and Grocock, 1974). Our data indicate that many ridges and knolls on the Eel and Klamath Plateau are diapiric in nature. Younger sediments overlying and flanking these features , have been bowed upward by diapiric activity, hence they are mapped as anticlines exhibiting seafloor relief (fig. 7). Evidence that these features are shale diapirs in various stages of emplacement includes their:

1) Lack of internal structure - Within the core of the ridges there is no evidence of bedding, in marked contrast to the rest of the basin (figs. 8,9).
2) Lack of sediment cover - The rate of deposition offshore of northern California is estimated to be quite high, yet many ridges have no sediment cover (figs. 8,9).
3) Irregular surface topography - The surface of many ridges is extremely irregular, possibly indicating recent flowage (fig. 8).
4) Age and lithology - Sediments recovered from exposed ridge tops are cohesive muds of Pliocene age.
5) Sediment deformation - Young flat-lying sediments on the plateaus are stretched and turned upwards at the base of diapiric ridges (fig. 9).

If diapirism is presently active, as suggested by the seismic reflection data, it may pose a geologic hazard to development (see section Seafloor and Coastal Instability). The rate of diapiric uplift is not yet known, but the disruption of Holocene sediments indicates ongoing or very recent activity. Diapiric ridges are commonly faulted on their crests and along one or both

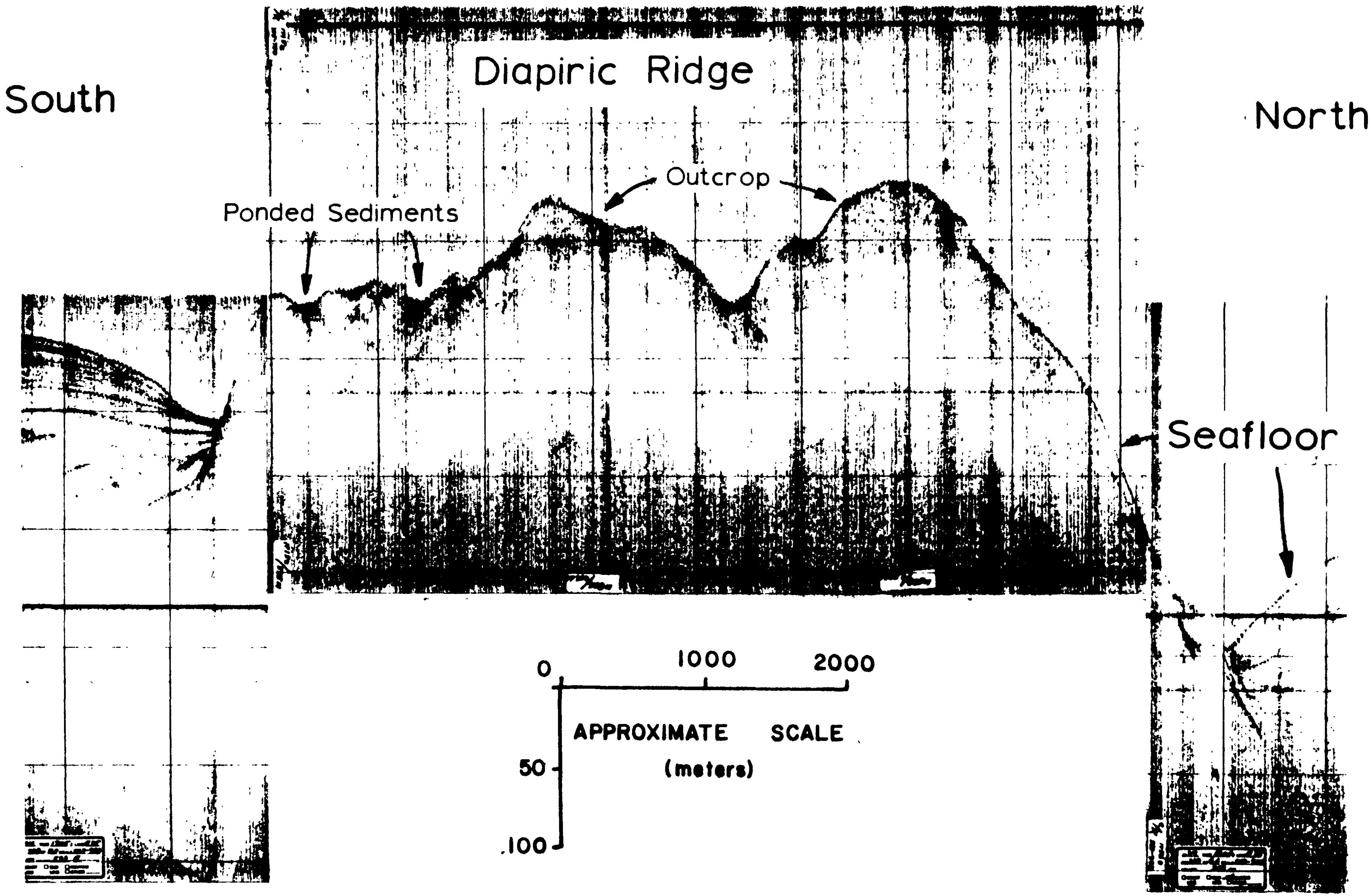

Figure 8. High resolution seismic reflection record from line 75 across diapiric structure on the Eel Plateau. Note termination of sediment reflectors against south flank, lack of internal structure, and irregular, sediment-free character of diapir surface.

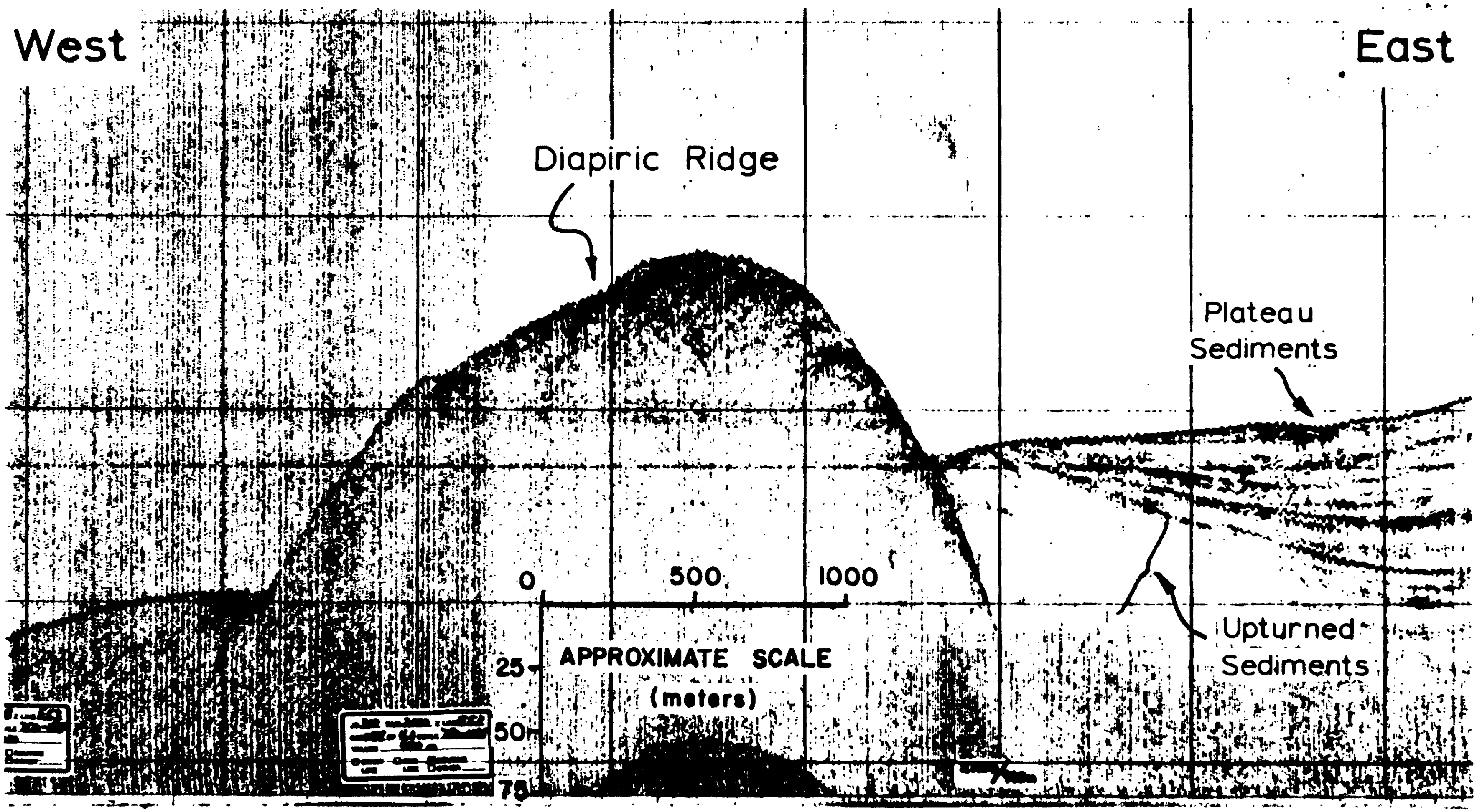

Figure 9. High resolution seismic reflection record from line 53 across diapir on Klamath Plateau. Note up-bowing of adjacent strata and lack of sediment on surface of diapir.

flanks. Strata upbowed by piercement activity fail elastically by slumping and by faulting.

Faults

Herd (1978) recently proposed that the northern California continental margin encompassing Eel River Basin lies within the Humboldt Plate, an intracrustal block of the North American plate. Part of the basis for identification by Herd of an intracrustal plate is the evidence of strike-slip motion on a northwest-trending fault along the east margin of the basin southwest of Crescent City (Bolt and others, 1968), and the alignment of this fault with a series of onshore en echelon faults composing the McKinleyville fault zone (Herd, 1978).

Numerous faults cut the rocks and sediments of Eel River Basin and adjacent terranes. Many of these faults create offsets in the seafloor and uppermost sediments, indicating a young age and a potential for continued activity. Because of the limited core and seismic velocity data in the Eel River Basin, it is difficult to establish the ages of seismic units and, consequently, the ages of faulting. However, an estimate was made of the age of sediment units based on degree of deformation, unconformities, stratigraphic position, and a limited amount of age data from benthic forams, and this was used as a basis for assignment of ages to faults. The tentative ages assigned to faults are shown on figure 7. With the exception of a small number of outcrops, surface sediments throughout the northern California continental margin are Holocene, and faults cutting the surficial layer are identified as Holocene in age (figs. 10,11). Throughout most of the basin Holocene sediments conformably overlie Pleistocene sediments and, as seen on

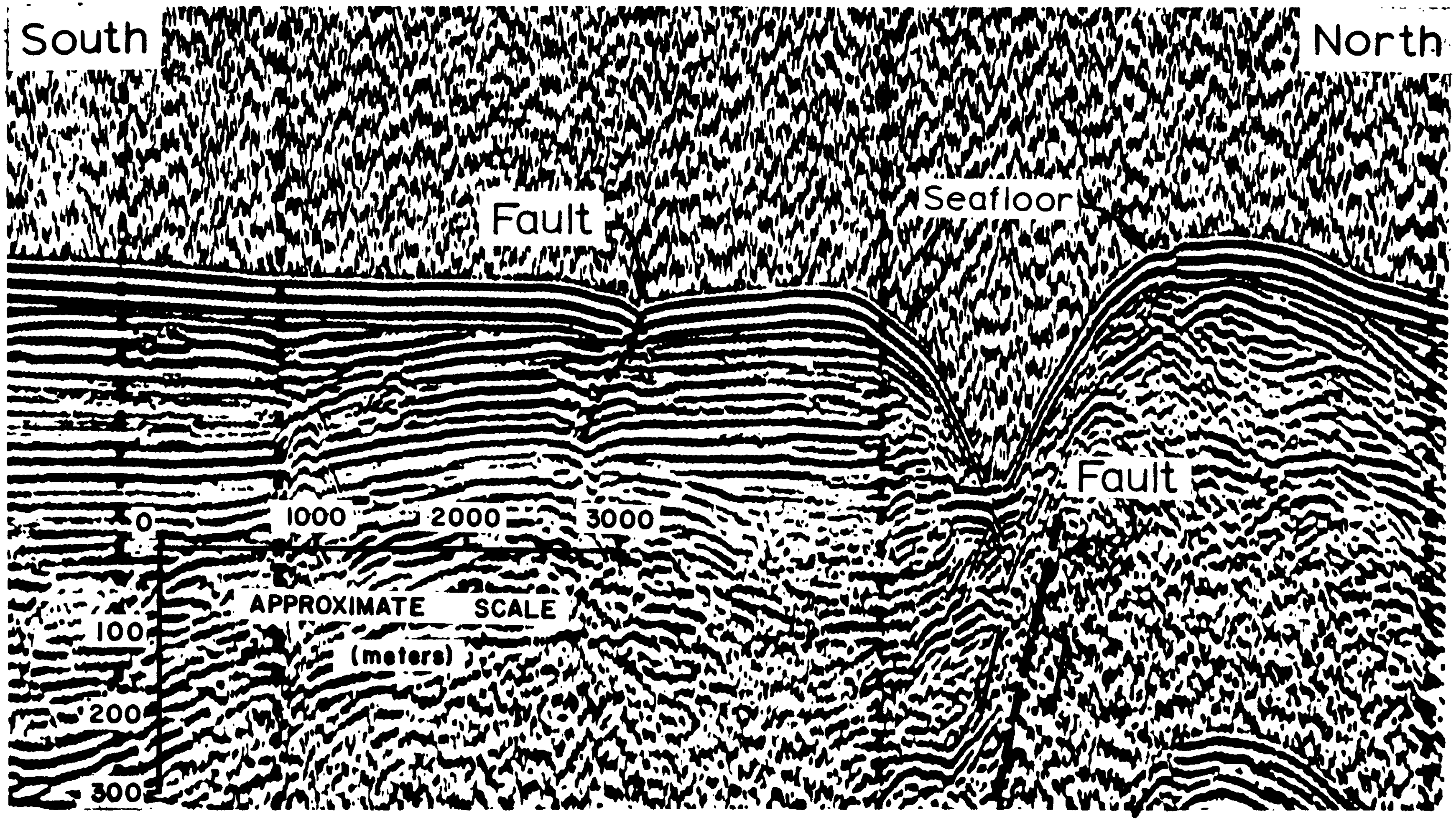

Figure 10. Deep-penetration seismic reflection (160 KJ) record from line 81 showing surface and subsurface faults.

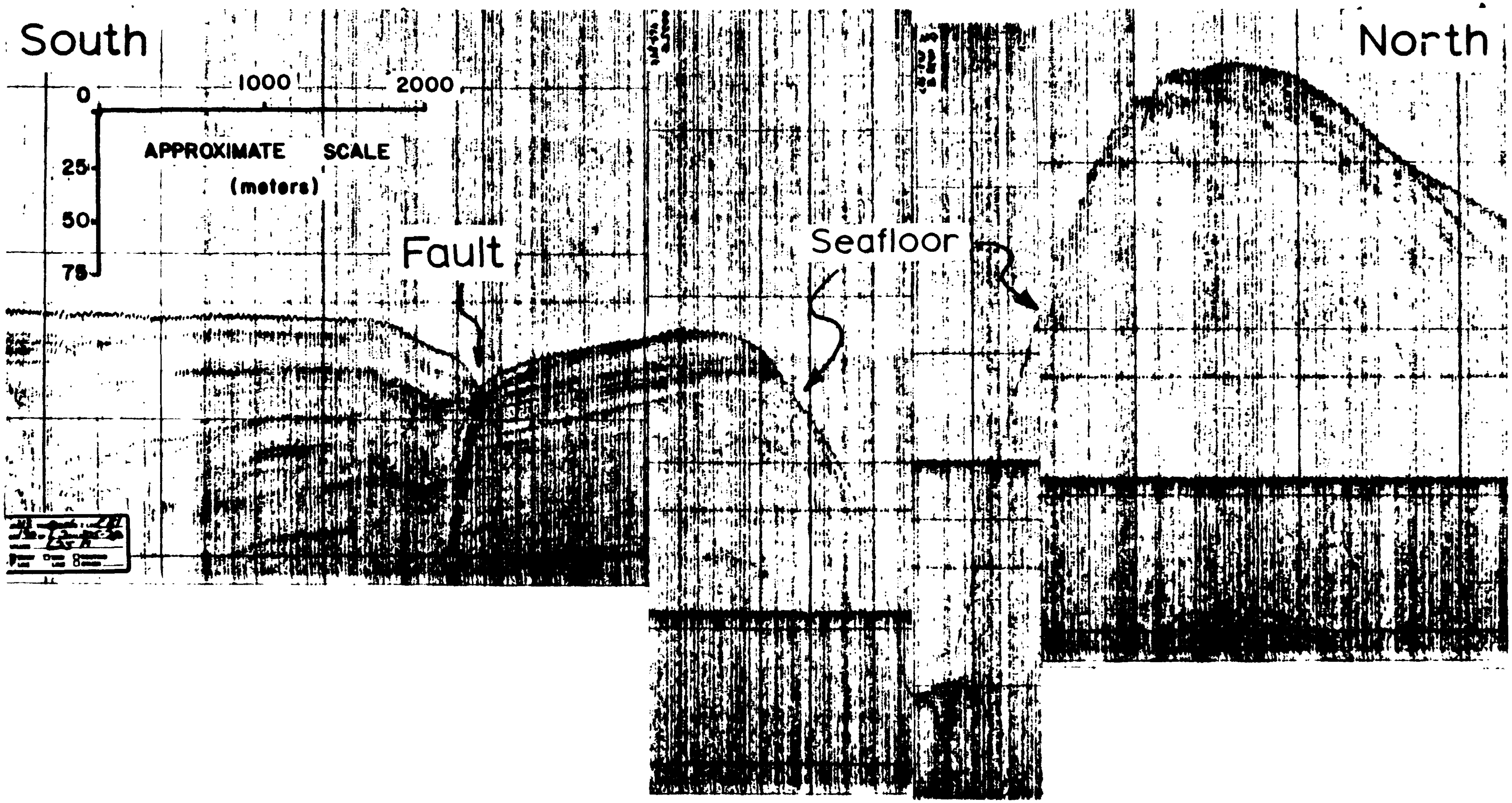

Figure 11. High resolution (uniboom) record along line 81, showing details of surface faulting shown in Figure 7.

subbottom acoustic profiles, the distinction between the two is not clear. Faults terminating below the surface unit are identified as Quaternary, but may be as young as Holocene. Pleistocene deposits conformably overlie Pliocene sediments on the marginal plateaus, and faults cutting sediments in that area are shown with symbols that reflect the possible age range. On the plateaus in particular, many faults are designated as offsetting sediments of Pliocene to Pleistocene age. Faults designated as Pliocene are those cutting the lowermost rocks of the conformable sequence thought to be Pliocene and Quaternary in age; some of these faults may be as old as late Miocene, however. On the eastern margin of the Eel River Basin lie Mesozoic and younger rocks of the Franciscan complex. Faults displacing these rocks, here and at depth beneath the basin, are designated as cutting the basement complex.

Faults that displace the seafloor, regardless of the estimated age of the rocks, are indicated on Figure 7 by hachures on the downthrown side. These faults are noteworthy because they indicate possible movement within Quaternary time and a potential for movement in the future. The northern California continental margin is an area of rapid sedimentation, and any scarp or displacement of the seafloor is presumed to be of recent origin. The mapped distribution of faults is controlled to a degree by the spacing and quality of seismic reflection tracklines. Nevertheless fault patterns are evident, and these patterns are useful in interpreting structural character of the basin. The central parts of the Eel and Klamath Plateaus have fewer faults than do either the outer plateaus or continental shelf. On the shelf, most faults show little evidence of vertical displacement subsequent to the Holocene erosional event. First motion studies by Bolt and others (1968) have shown a right lateral, strike-slip component of motion to be associated with earthquakes beneath the shelf southwest of Crescent City. If such motions are characteristic of the large faults on the shelf (fig. 7), the absence of vertical separation does not imply a lack of activity.

Faults occurring on the central part of plateaus are generally widely separated, do not offset the seafloor, and range in age from Pliocene to Quaternary. Faults are most common on the outer plateaus and upper slope, and appear to be associated with diapirism. The outer slope is characterized by westside-down faults that extend for many kilometers.

Major faults in and bordering the onshore Eel River Basin, compiled by Strand (1962, 1963) and Herd (1978), are shown on figure 7. Most of these cannot be correlated with offshore faults due to the spacing of tracklines in this study and the inherent difficulties in collecting deep-penetration seismic reflection data in shallow water. There are, however, exceptions; in particular, a major fault south of Eel Canyon (fig. 12) appears to be an extension of the Russ Fault, a group of faults south of Trinidad Head is aligned with the McKinleyville fault zone (Herd, 1978; fig. 7), and the fault zone comprising a series of faults southwest of Crescent City appear to include extensions of the Bald Mountain and Grogan Faults (fig. 7).

SEISMICITY

The northern California continental margin is tectonically active characterized by large and frequent earthquakes. The major forces generating earthquakes are right-lateral slip along the Mendocino Escarpment and underthrusting of the Gorda Plate beneath the northern California and Oregon

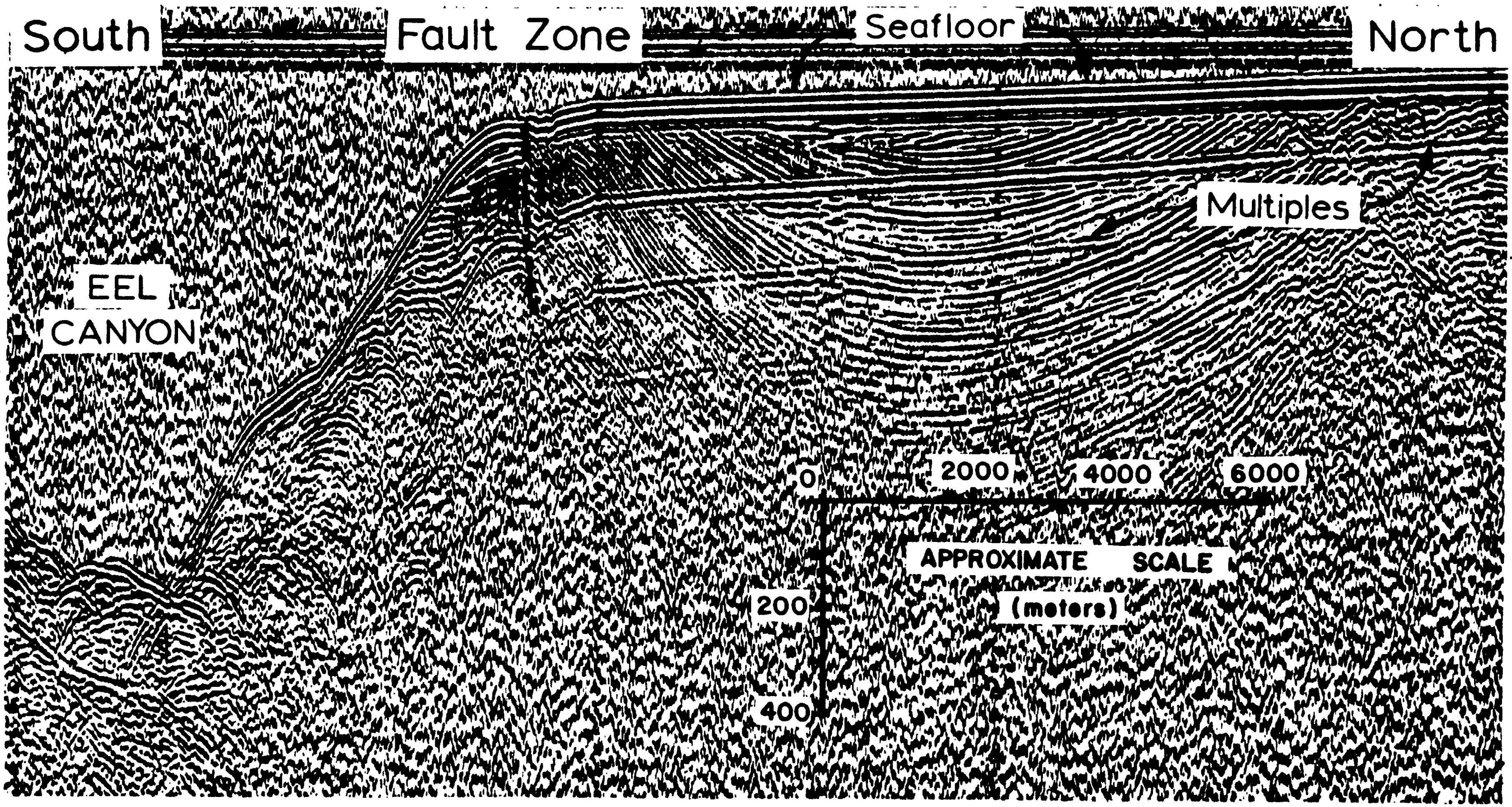

Figure 12. Deep-penetration seismic reflection record on line 94 south of Eel Canyon showing seafloor displacement along a major break in rock types. This fault may be an extension of the onshore Russ Fault.

continental margin (Atwater, 1970; Silver, 1971). The type of motion associated with major earthquakes in the area is largely unknown, with the exception of the study by Bolt and others (1968). Their first motion studies of earthquakes occurring 1962 to 1965 showed that right lateral motion occurred along prominent northwest trending faults on the shallow shelf southwest of Crescent City (fig. 7).

Locations of significant earthquakes occurring between 1853 and 1979 within the area delimitated by 40° to 42° N latitude and 124° to 126° W longitude are plotted in figure 13. The major pattern displayed on the map is the high density of epicenters in the southern part of the region in the vicinity of the Mendocino Escarpment.

The apparent lack of correlation between epicenter locations (fig. 13) and mapped faults (fig. 7) is a result of several factors. First, many of the earthquakes were in the Cape Mendocino and Mendocino Escarpment area, an area not surveyed in detail for this study. Second, location of offshore epicenters is not precise and actual locations are assumed to be only within 5 to 10 km, or greater, of their plotted locations. The apparent rectilinear alignment of epicenters results from the location of epicenters to the nearest one half degree latitude or longitude. Hypocenter depths range from 10 to 61 kilometers, based on estimates from 25 earthquakes (Couch and others, 1974). Sixteen of these earthquakes occurred at a depth of 33 km and five were shallower than 17 km; only one was deeper than 33 km.

During the 120 year period from 1853 to 1979 a total of 1,193 significant earthquakes (those detected without instruments or recorded at M>2) have been documented (Table 1). This total probably represents only a fraction of those that occurred, as the number of earthquakes recorded increased steadily as

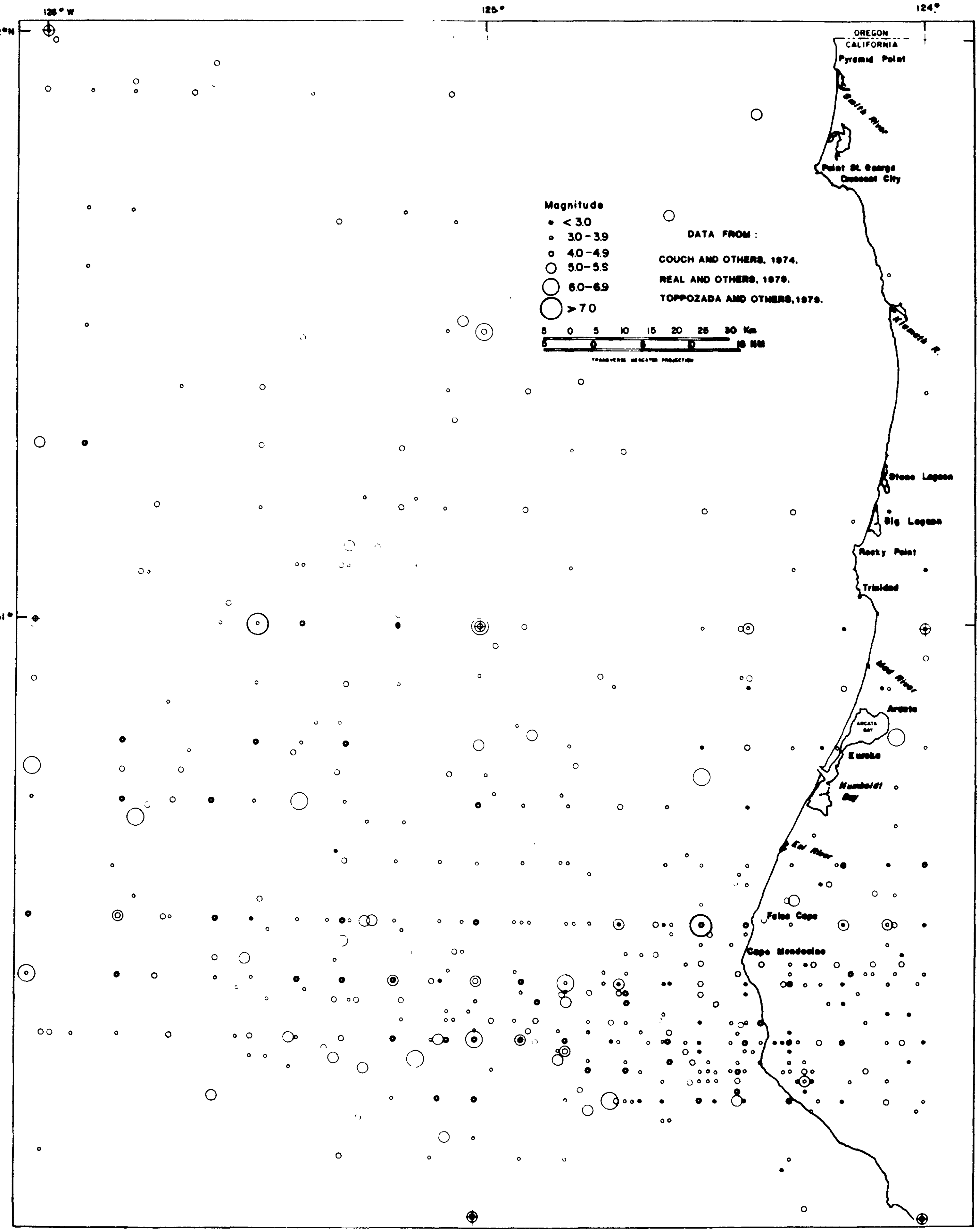

Figure 13. Seismicity of the northern California continental margin. Data from Couch and others (1974), Real and others (1978) and Toppozada and others (1979).

TABLE 1 -- NUMBER OF EARTHQUAKES PER DECADE, BY MAGNITUDE, FOR THE STUDY AREA SHOWN ON PLATE 10. DATA FROM COUCH AND OTHERS (1974), REAL AND OTHERS (1978) AND TOPPOZADA AND OTHERS (1979).

	MAGNITUDE							
DECADE	<3	3.0-3.9	4.0-4.9	5.0-5.9	6.0-6.9	>7	UNKNOWN	TOTAL
1850's							12	12
1860's							5	5
1870's							6	6
1880's							12	12
1890's							48	48
1900's				1	1		106	108
1910's					3	0	49	52
1920's				2	3	2	73	80
1930's			5	14	2	0	78	99
1940's		8	30	14	4	0	41	97
1950's	34	138	53	6	3	0	25	259
1960's	11	177	57	10	0	0	27	282
1970-3	4	75	44	6	0	0	4	133
TOTALS	49	398	189	53	16	2	486	1193

techniques for monitoring and locating epicenters were improved, until the 1950's when efficient seismic networks were established (Table 1). The increase in reports of earthquakes in the early 1900's is probably attributable to an increased awareness to tremors as a result of the catastrophic earthquake of 1906 (Couch and others, 1974).

The long-term record of seismicity compiled by Couch and others (1974) is useful for establishing trends over the past several decades. For instance, the information in Table 1 shows that there has been an average of at least one earthquake having a magnitude greater than 5.0 per year since 1920, and at least one earthquake having a magnitude greater than 6.0 per decade. Because of the proximity of the area to the subducting margin of the Gorda Plate, an earthquake of 7.0 to 7.5 magnitude can be expected to occur offshore northern California at a depth of 40 to 50 km (Smith, 1975). Two earthquakes in this magnitude range are reported by Real and others (1978).

A great deal of damage occurred along the northern California coast as a result of the 1906 San Francisco earthquake (Youd and Hoose, 1978). Consequently, any consideration of offshore hazards due to seismic shaking should include an assessment of the potential for very large earthquakes not only in coastal northern California, but in Oregon and central California as well.

SEAFLOOR INSTABILITY

Seafloor instability refers to the potential for areas of the seafloor to undergo changes in configuration, commonly abrupt, as a result of uplift, dislocation, translation, or subsidence of surface and shallow subsurface sediment units. On the northern California continental margin five types or causes of seafloor instability have been identified and mapped from examination of high resolution and deep penetration seismic reflection data (fig. 14):

1) Slumps
2) Unstable sediment masses
3) Areas of uplift (diapirism)
4) Possible accumulations of shallow gas
5) Gas hydrates

The characteristics, as well as the criteria for recognition of each of these unstable conditions, are complex, and each is discussed separately below.

Slumps and Slides

Sediments that fail and move as discrete units with little or no internal deformation (some permanent deformation occurs along the base and at the toe) are generally classified as slides (Dott, 1963). Slides can be subgrouped according to whether movement was translational along a planar surface (glides) or rotational along a curved surface (slumps). Slumps are common to many modern shelves, slopes, and rises around the world. Their size varies from 10's to 1000's of meters on side, and they have been documented on slopes of less than 1° to slopes exceeding 8° (Lewis, 1971; Haner and Gorsline, 1978; Carlson and Molnia, 1978; Hampton and Bouma, 1977; Heezen and Drake, 1964; Field and Clarke, 1979; Moore, 1961). The main criteria for recognition of slumps include: evidence of dislocation and movement of a bed or group of beds; rotation and reorientation of the bed; lack of internal formation of the bed; presence of a gently-dipping curved surface of failure. Some deposits of

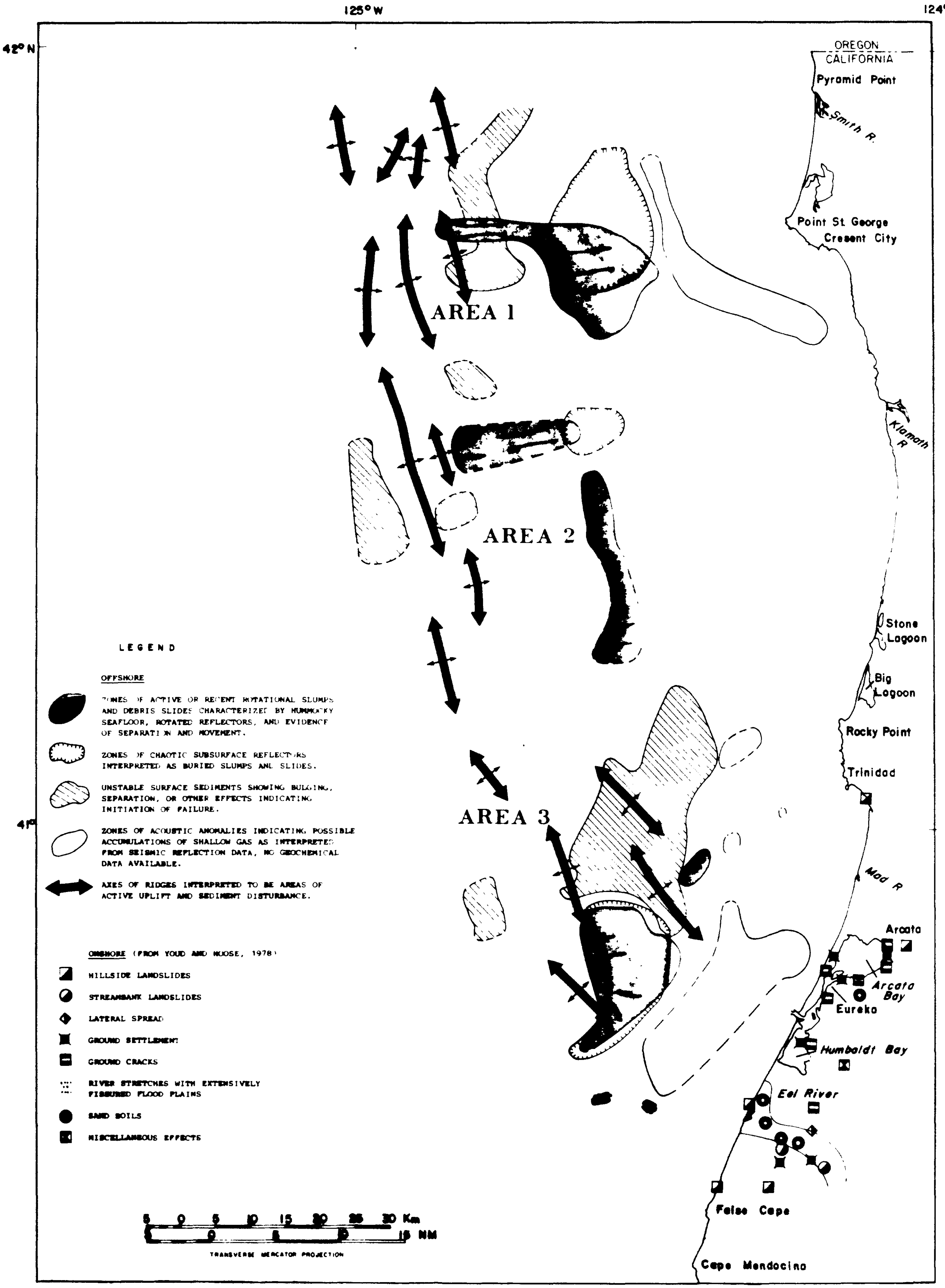

Figure 14. Areas of seafloor and coastal instability on the northern California continental margin.

mass movement that do not fit into the general classification of rock falls or slides as defined by Varnes (1978) and Dott (1963) have been recognized on modern slopes. These deposits have a hummocky upper surface and are deformed internally, and may represent the result of a series of slides, (for more discussion see Cook and others, in press). The term debris slide is used to describe such features.

Slumps covering large areas and showing seafloor expression are the dominant form of instability in northern California. Zones of slumping vary in size from major proportions (10's of kms on a side) to as small as 1000 m on a side, and they are present at water depths from 200 m to over 750 m on the shelf edge, plateau slope, and Eel and Klamath Plateaus (fig.14).

Three major zones of slumping are present within the area of this study (fig 14). These areas are west of Crescent City (Area I), west of the Mad River (Area II) and west of Eureka (Area III). The large slump zones in Areas I, II, and III are composed of a continuous series of rotated and translated sediment units (fig. 15) that start below the shelf edge and extend out onto the marginal plateau. Off Crescent City the zone of slumps extends westward for over 30 km and covers an estimated area of over 250 km^2. The irregular, hummocky topography (fig. 15) indicates that slumps extend up to the surface, and the lack of undisturbed sediment overlying the slumps indicates a very young age. The slump zone is 20 to 30 m thick and overlies well-bedded undisturbed sediment, which in turn overlies deformed sediments of an earlier slump event. Here, as in the slump zone in Area III, the direction of movement is westward. In Area II, however, there is evidence that transport is both westward, toward the center of the plateau from the plateau slope, and eastward, from the ridges on the marginal plateau (fig. 16). This zone was

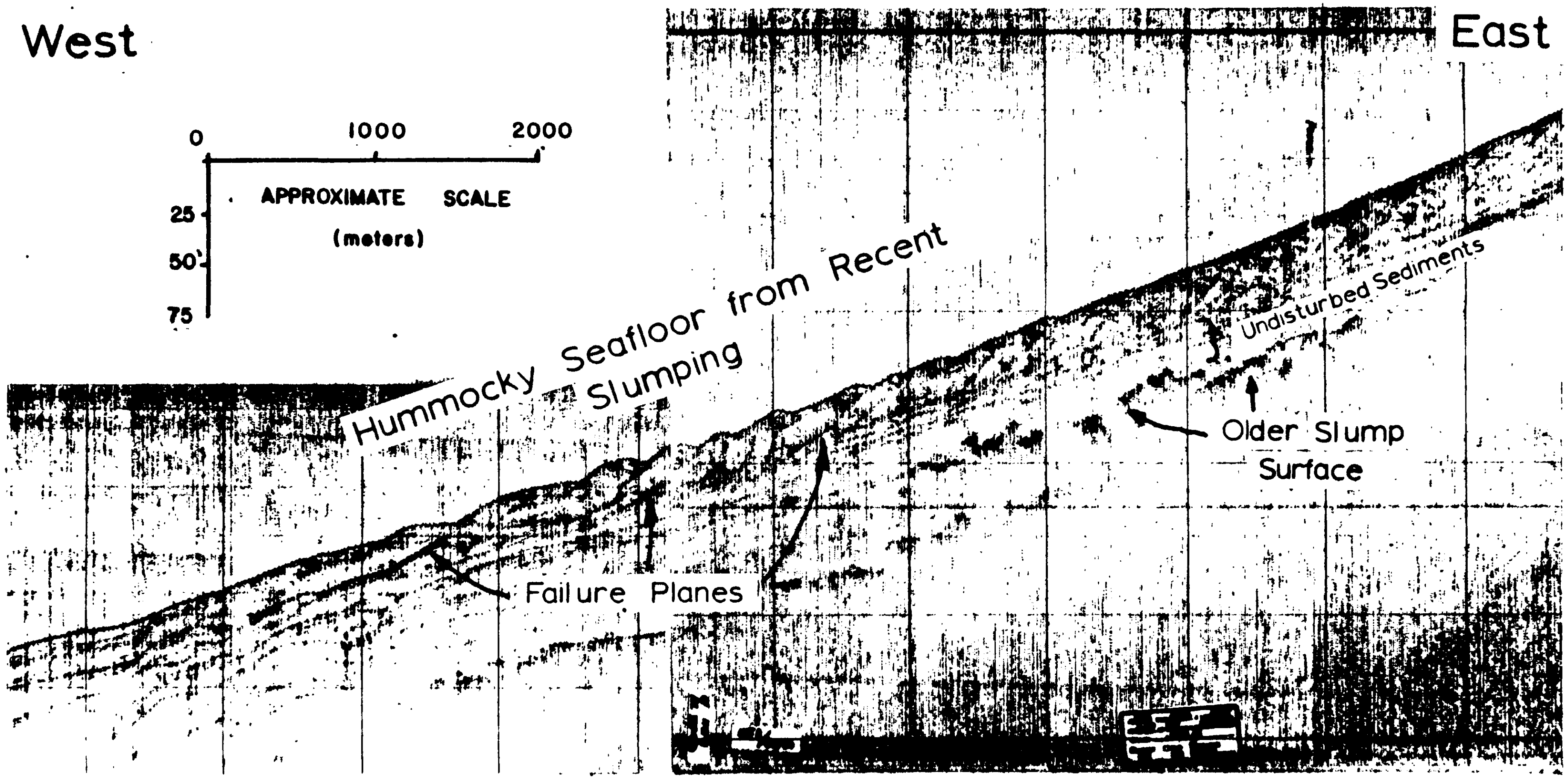

Figure 15. High resolution seismic reflection record on line 55 showing slumping on the plateau slope off Crescent City. Note the hummocky seafloor and curved failure planes of individual slumps.

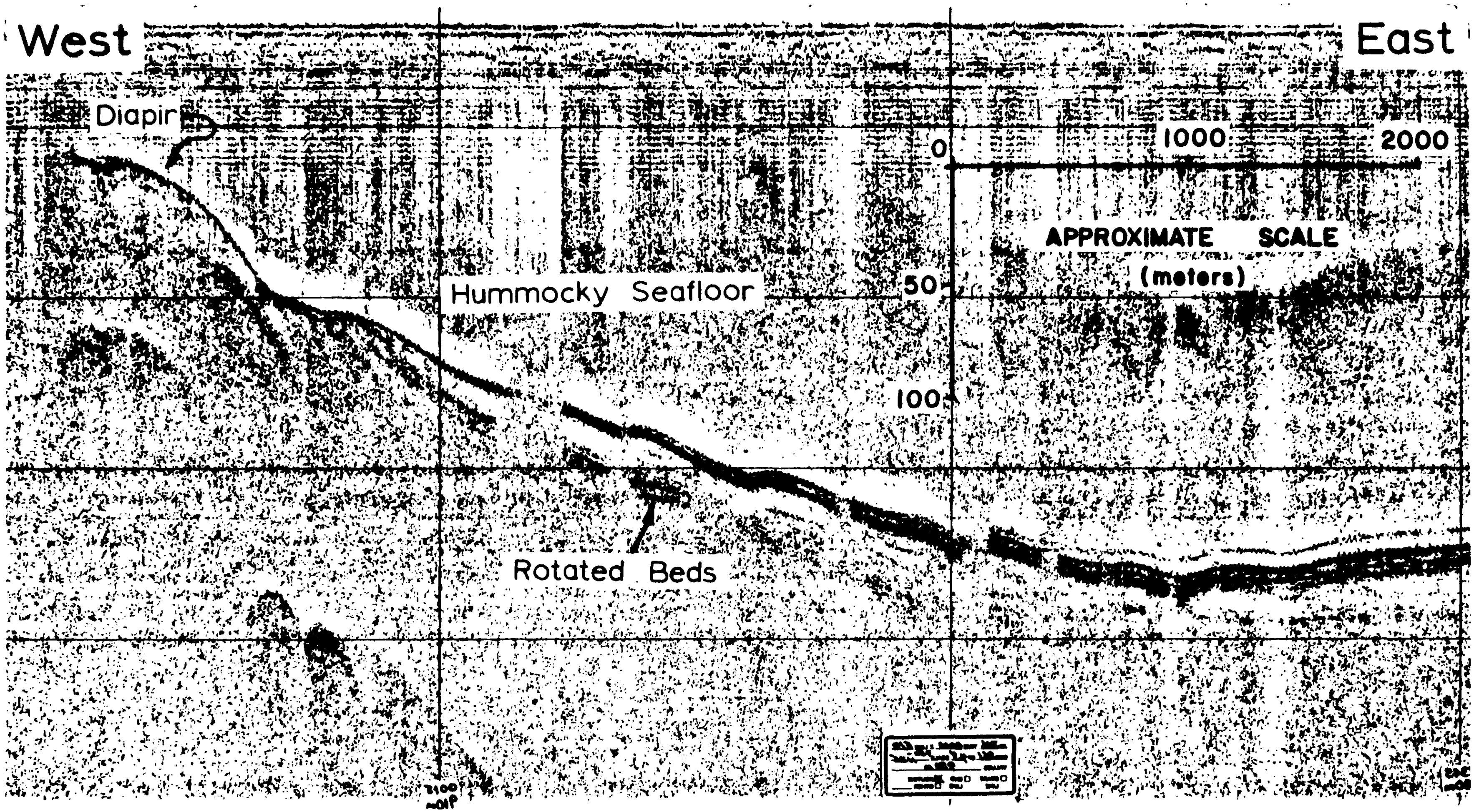

Figure 16. High resolution (3.5 KHZ) profile of eastward moving slumps along line 10 on the flank of a diapir structure.

observed only along one profile line, but assuming a minimum width of 4 km, the zone covers an area of over 70 km^2.

The large zone of slumping west of Eureka in Area III covers an area greater than 185 km^2 and extends from the surface down to at least 65 m and possibly as deep as 200 m below the seafloor. Individual slumps are about 300 to 575 m wide (fig. 17); their length and continuity along slope are unknown.

Buried slumps are also present in the same areas as the surface slump zones (fig. 14). These features are identifiable in deep penetration seismic reflection records by broken and rotated reflectors (figs. 13, 14, 18, 19). Subbottom depth and thickness of buried slumps are variable, but they are commonly at least 50 m thick and extend as deep as 370 m below the seafloor. Other types of failure include a long north-south trending debris slide at the base of the plateau slope in Area II, a discrete shelf edge slump block in Area III, and small slumps in Eel Canyon in Area III. The slide zone in Area II consists of an irregular mound of debris at the base of a relatively steep slope (Fig. 20). There is no evidence of a failure plane. This zone is defined on the basis of two crossings of the northern half by the authors and two earlier crossings of the southern half by Silver (1971a). It is possible that each of these crossings represents a discrete slide mass, or as shown in Figure 14, these features may be connected. In either case, their presence suggests that the entire slope is prone to failure.

Slides in Eel Canyon are difficult to identify because of the steep slopes and rock outcrops,and it is likely that failures in addition to those mapped on Figure 14 are present in the canyon.

A large discrete slump block was noted on the shelf edge west of Eureka (fig. 21). This block is over 1200 m wide and the upper edge lies at a depth

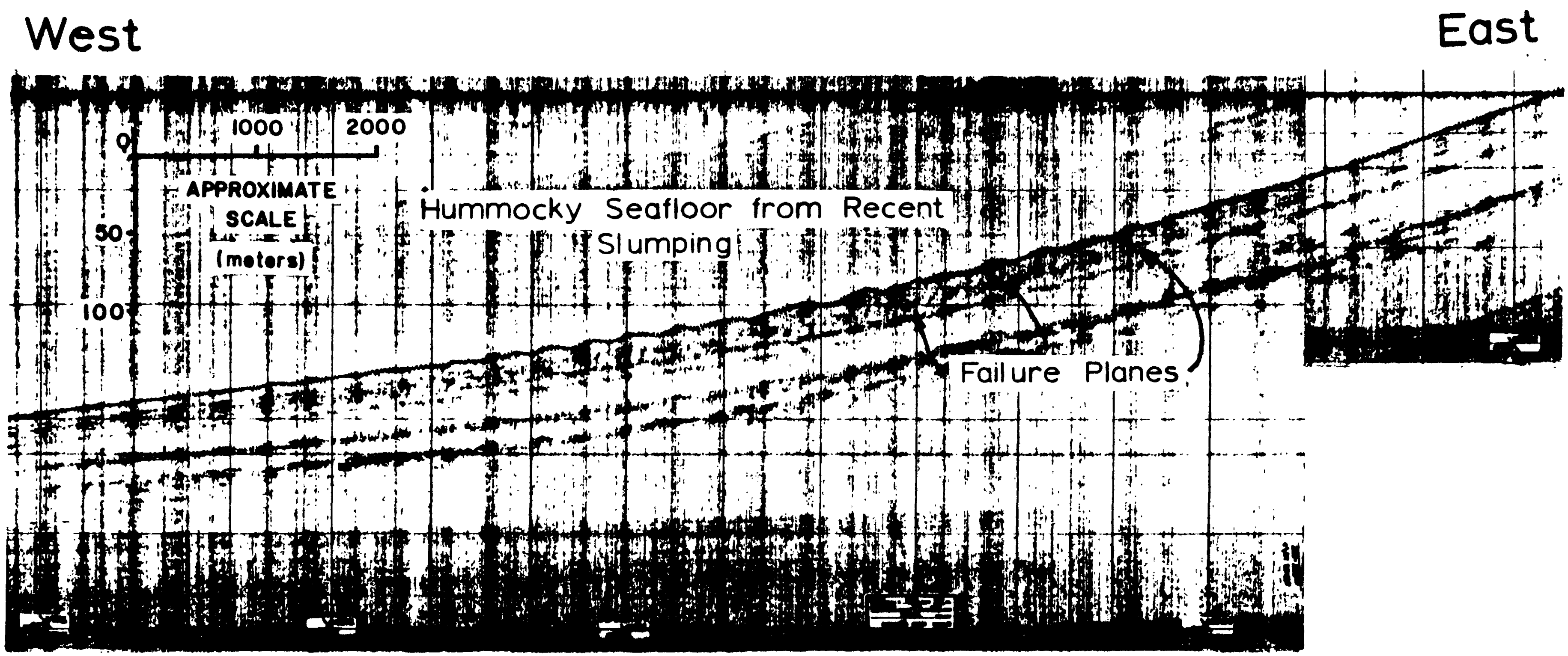

Figure 17. High resolution seismic reflection record along line 80 showing characteristics of slump zone off Eureka.

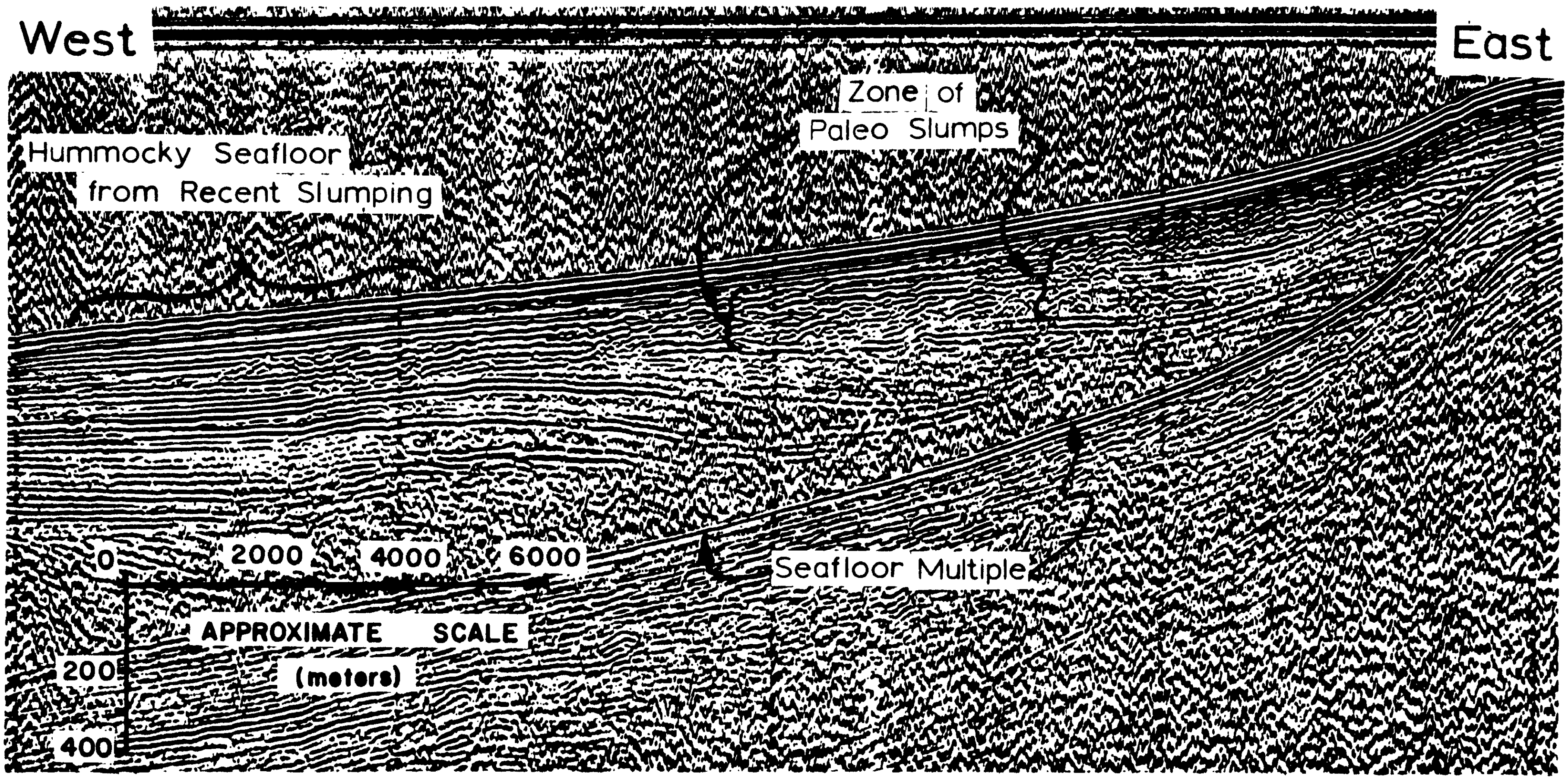

Figure 18. Deep-penetration seismic reflection record from line 53 off Crescent City showing a zone of buried slumps. Hummocky surface on western portion of line is zone of surface slumps shown in detail in Figure 15.

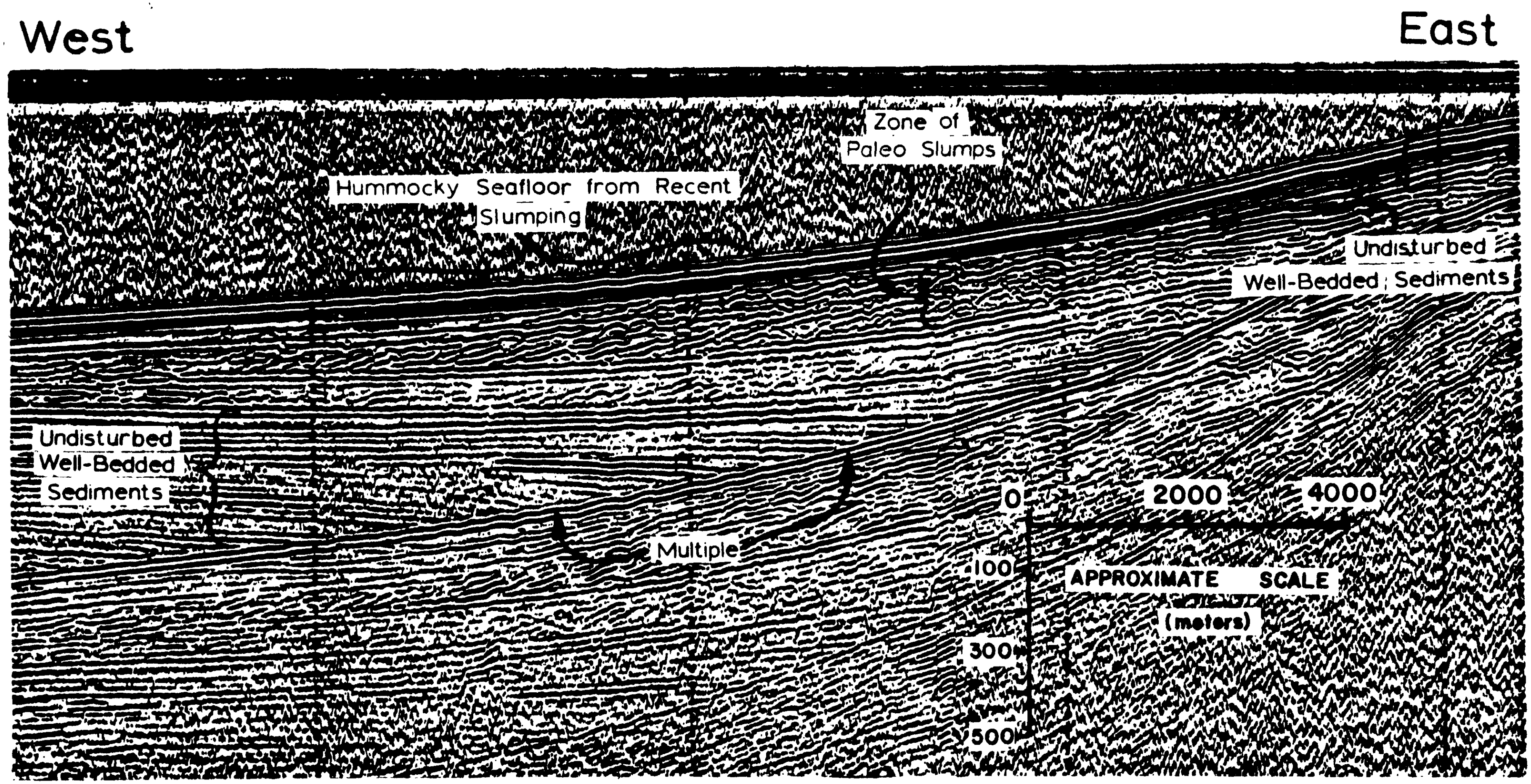

Figure 19. Deep-penetration seismic reflection record from line 80 off Eureka showing a zone of buried slumps. Hummocky surface is zone of surface slumps shown in detail in Figure 17.

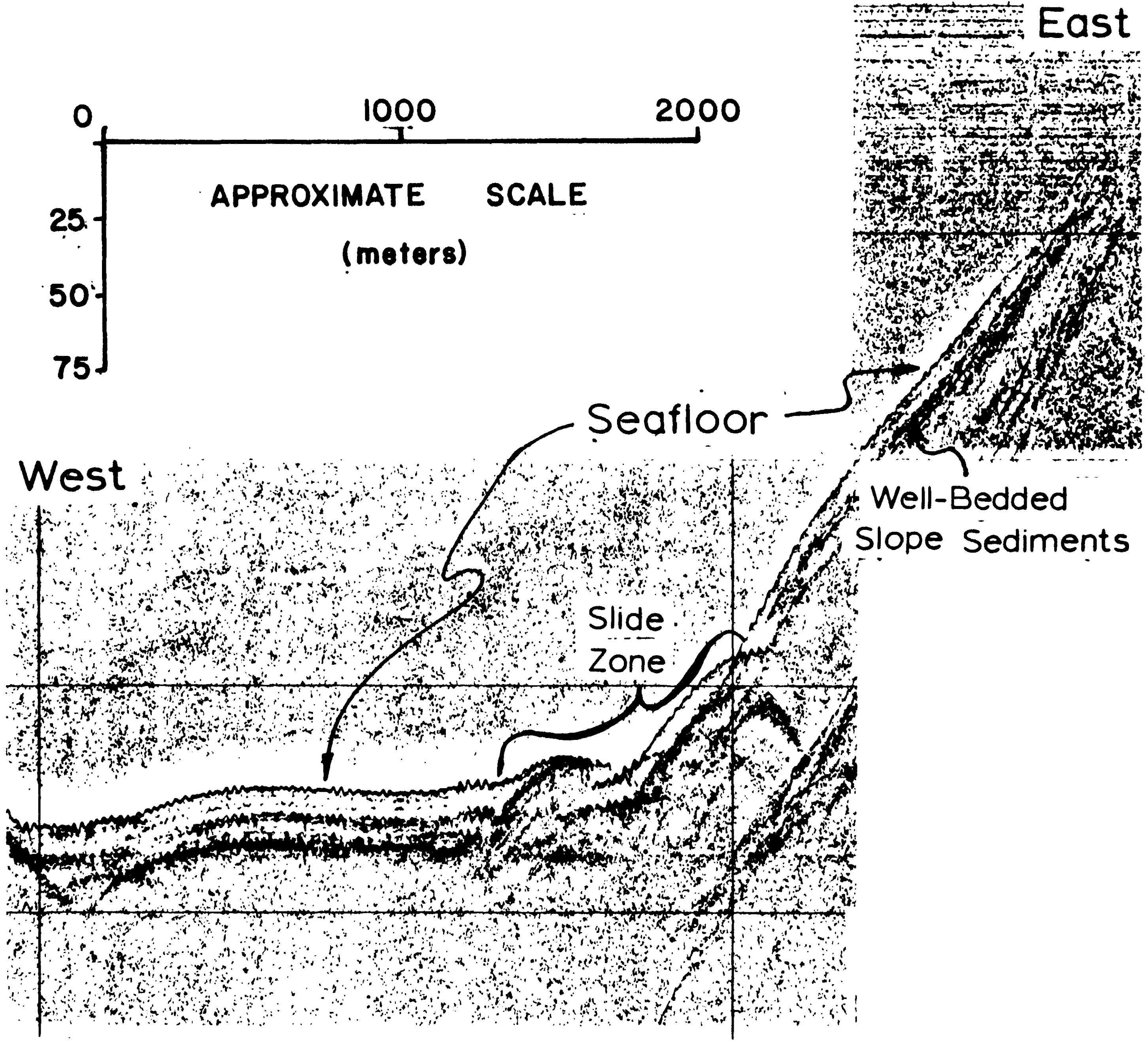

Figure 20. High resolution seismic reflection profile along line 12 showing large slide zone at the base of the plateau slope.

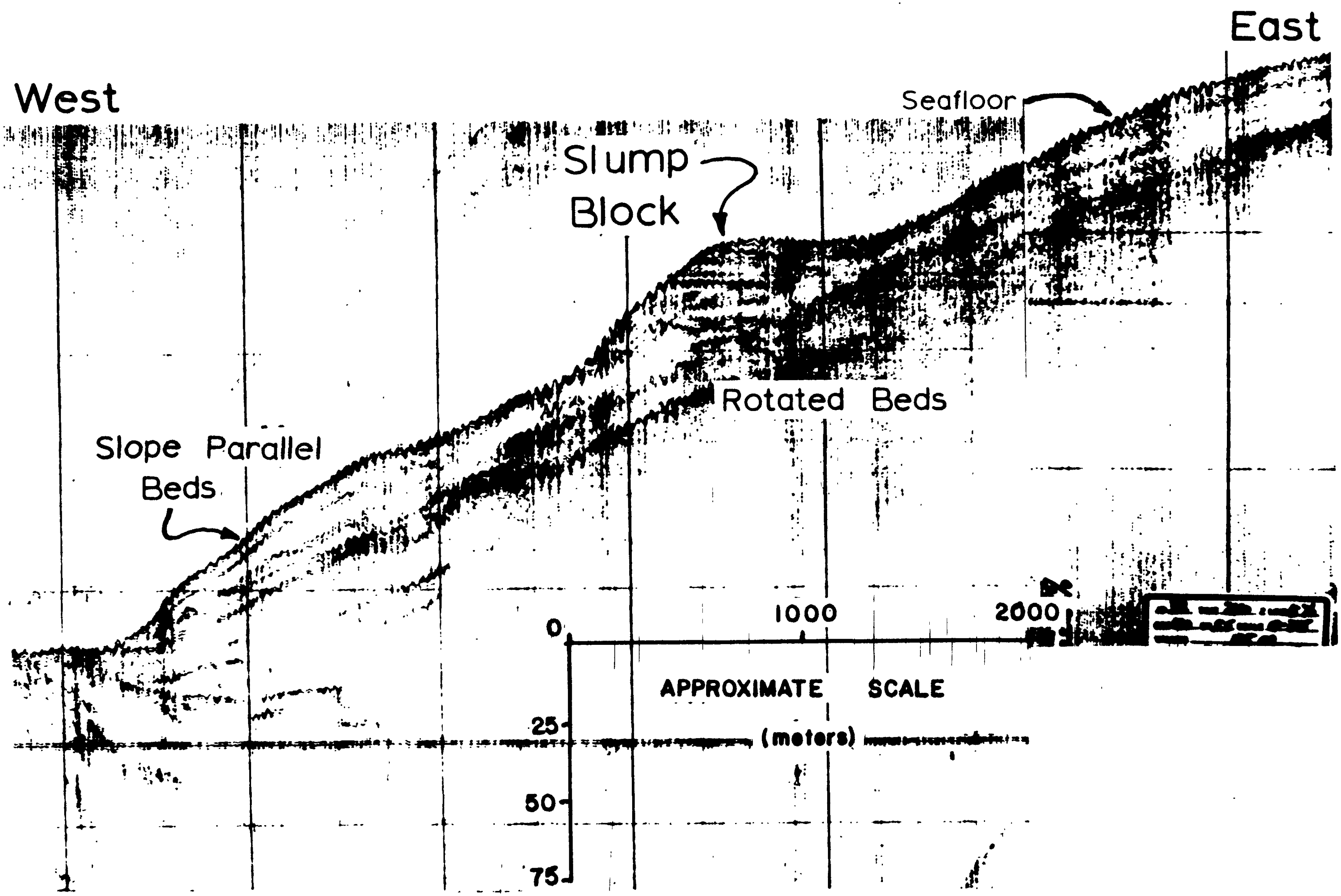

Figure 21. High resolution seismic reflection record from line 76 showing a large single-block slump on the shelf edge off Eureka.

of about 185 m. Two separate slump features, each approximately 20 m thick, compose the block; the upper of these features is shown in fig. 21. The location of the block coincides with a perturbation of the 200 m contour C&GS chart 1308N-12; comparable pertubations in the shelf edge contours may indicate additional slumps.

Clearly, slumping is a common in the marine sediments of this area, which is one of high sedimentation and high tectonism. Moreover, slope failures are common in the geologic history of the region. Large slumps are evident in pre-Holocene strata in the deep penetration records, and slumps are common in the Tertiary rocks exposed along the coast (Piper and others, 1976) and in the Mesozoic and Cenozoic rocks of the Franciscan complex (O'Day, 1974).

Unstable Sediment Masses

Associated with the large slump zones are areas identified as unstable sediment masses (fig. 14). These areas are characterized by sequences of unconsolidated sediment lying on steep (>8°) slopes and prone to failure or by sediment that shows the effects of initiation of movement, such as rupture or bulging (figs. 22, 23, 24). Although evidence of failure, in these sediments is common, they do not appear to have been transported over significant distances. Major failure planes are not evident, although internal reflectors appear to be slightly rotated or deformed, and the surface is commonly hummocky. These sediment units appear to be undergoing or to have recently undergone downslope movement, and it seems possible that they will fail, perhaps in the near future, in the form of slumps and slides.

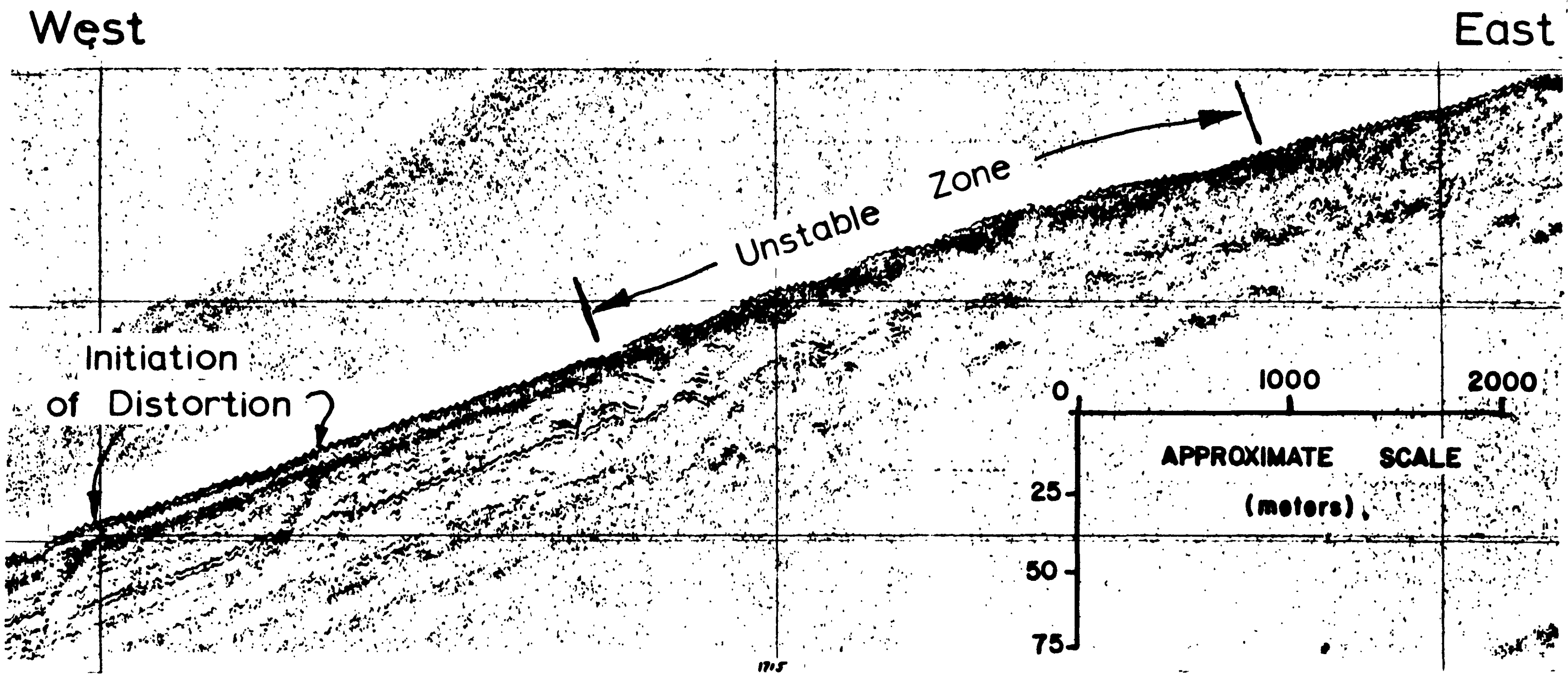

Figure 22. Unstable sediments on line 4, as shown by the hummocky surface and disturbed subsurface reflectors. Sediments in this zone are beginning to fail by slumping.

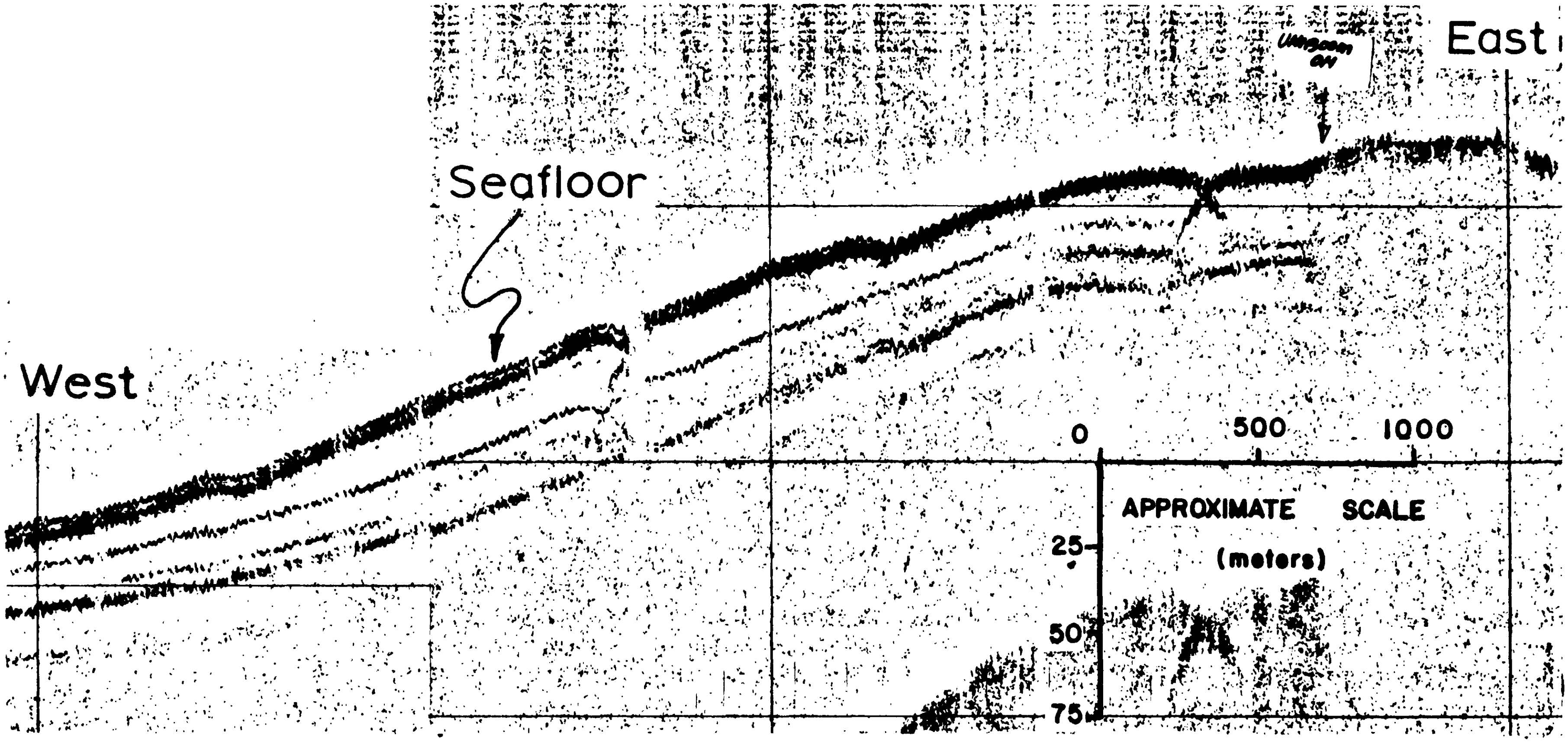

Figure 23. Unstable sediments on line 8 recorded with high resolution seismic reflection data. Irregularities in the subsurface parallel those in the surface, and sediments along those breaks or discontinuities will probably fail eventually.

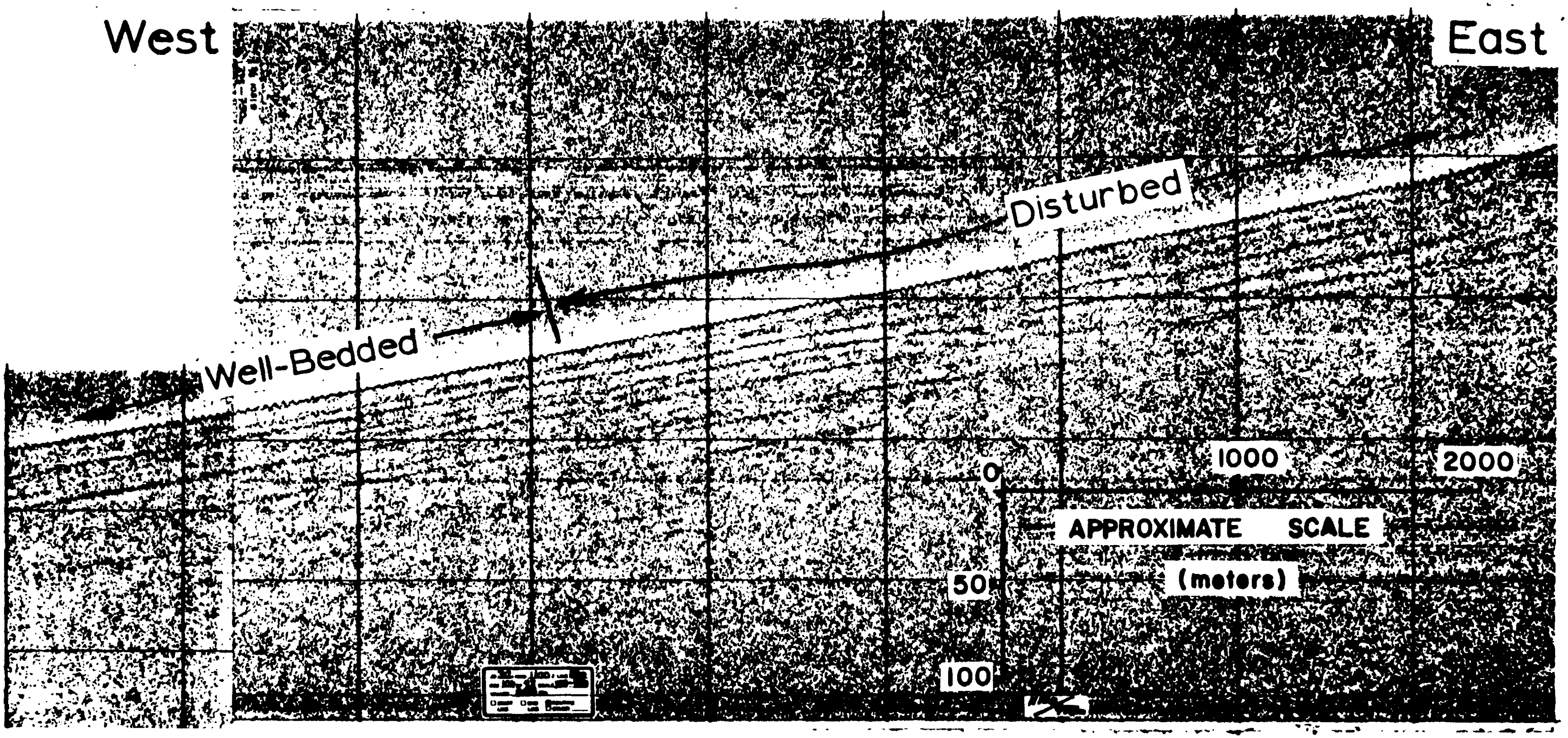

Figure 24. High resolution seismic reflection profile along line 70 showing regular, well-bedded slope sediments with distortion indicating initiation of failure.

Areas of Uplift

The Eel and Klamath Plateaus are characterized by a series of ridges and knolls that are belived to be diapiric in nature (fig. 5, 14). Several lines of evidence indicate that these ridges are undergoing uplift at present and are areas in which sediment failure is possible. Indicators of active uplift are as follows: 1) where ridges are capped by well-bedded sediment, the youngest sediments are bowed upward; 2) many of the ridges have no sediment cover, suggesting that sediment may have been lost concurrently with uplift; 3) uplifted surface sediments are locally deformed and broken; and 4) off Crescent City recent slumps have been back-rotated from seafloor uplift. The immediate zone of uplift is the ridge itself, from axis to the base of slope, but because uplift may trigger deformation and failure at some distance from the ridge, it is difficult to accurately define the areas over which seafloor failures could occur. The rate of uplift is not known. As uplift occurs, the surface gradient becomes steeper, thus increasing the potential for sediment failure. Additionally, the process of uplift, which may be episodic in nature, may itself trigger failure in unconsolidated sediment.

Shallow Gas Accumulations

Minor amounts of natural gas commonly occur in modern marine sediments, usually in a dissolved state. In shallow marine deposits gas may be derived from thermogenic or biologic sources. Thermogenic gasses are large-molecule complexes formed as part of the petroleum formation process, and their presence at shallow depth may indicate migration along a fault plane or up-dip in tilted strata. Biogenic gasses are dominated by the simple methane molecule and are derived from the bacterial alteration of organic-rich sediments. Thermogenic gasses pose a potential hazard in that they may be over-pressured (i.e. in excess of hydrostatic pressure) in consolidated sediments. Accumulations of either type of gas decrease the strength of the host sediment and may increase the liklihood of slump or liquifaction failure in unconsolidated sediments. Accumulations of gas in lithified and unlithified sediments are identifiable on high resolution geophysical records by any one or combination of the following characteristics: random displacement of subbottom reflectors; "pull-downs" or velocity decreases that delay the arrival of acoustic reflections; complete masking of subbottom reflectors; or indications of gas bubbles in the water column. Identification of accumulations of shallow gas by seismic reflection techniques is not reliable and requires direct measurement of gas content from sediment cores to verify interpretation. Seismic reflection data is useful, however, for indicating the location and extent of areas of possible gas.

Two large areas having possible accumulations of shallow gas were indentified (fig. 14). One area, on the shelf west of Crescent City, parallels a major fault and lies off the mouth of the Klamath River (fig. 25). The evidence for gas accumulation in this area is based on the masking of subbottom reflectors. Alternatively, this reflection pattern may result from facies changes associated with river discharge or displacement of reflectors along faults. Off Eureka several high resolution records and one deep penetration record have similar characteristics that may indicate accumulations of shallow gas (fig. 26).

Chromatographic analyses of gas content were performed on samples from one core (59G) collected in 1977 in the vicinity of a diapir on the outer plateau. Results of the analyses showed no substantial accumulations of gas

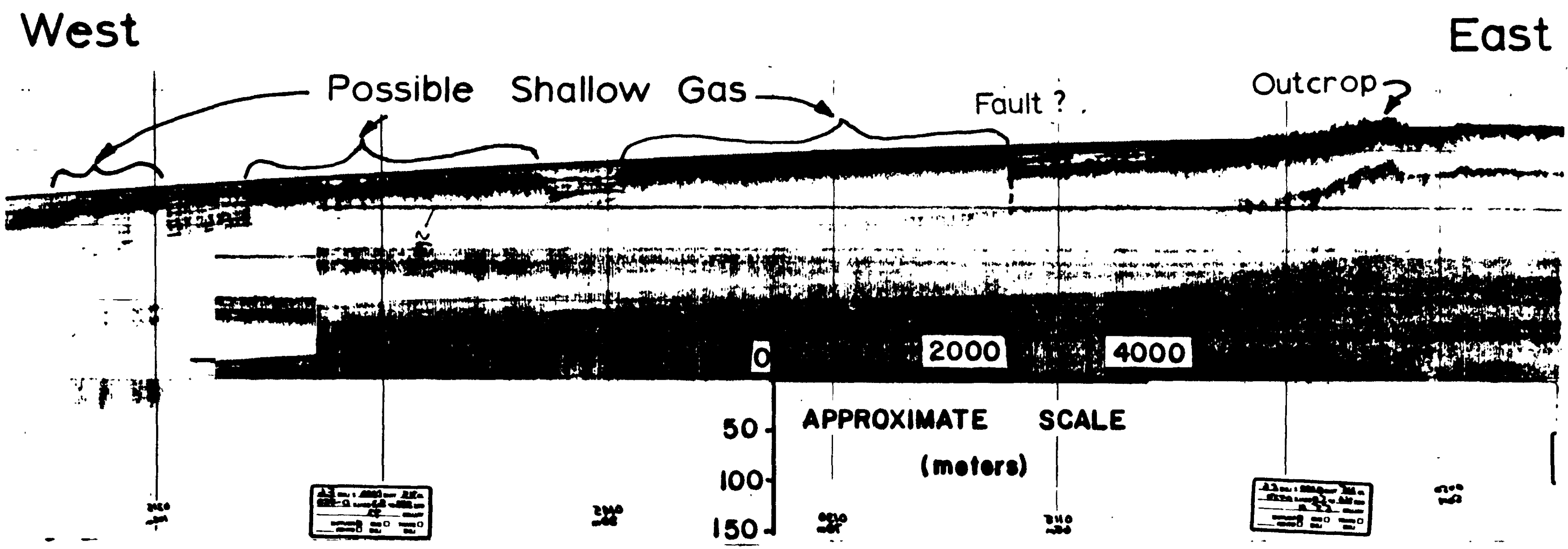

Figure 25. High resolution seismic reflection record on line 6 showing possible gas concentrations in the shallow subsurface. The characteristics indicating possible shallow gas are abrupt displacement and masking of subsurface reflectors.

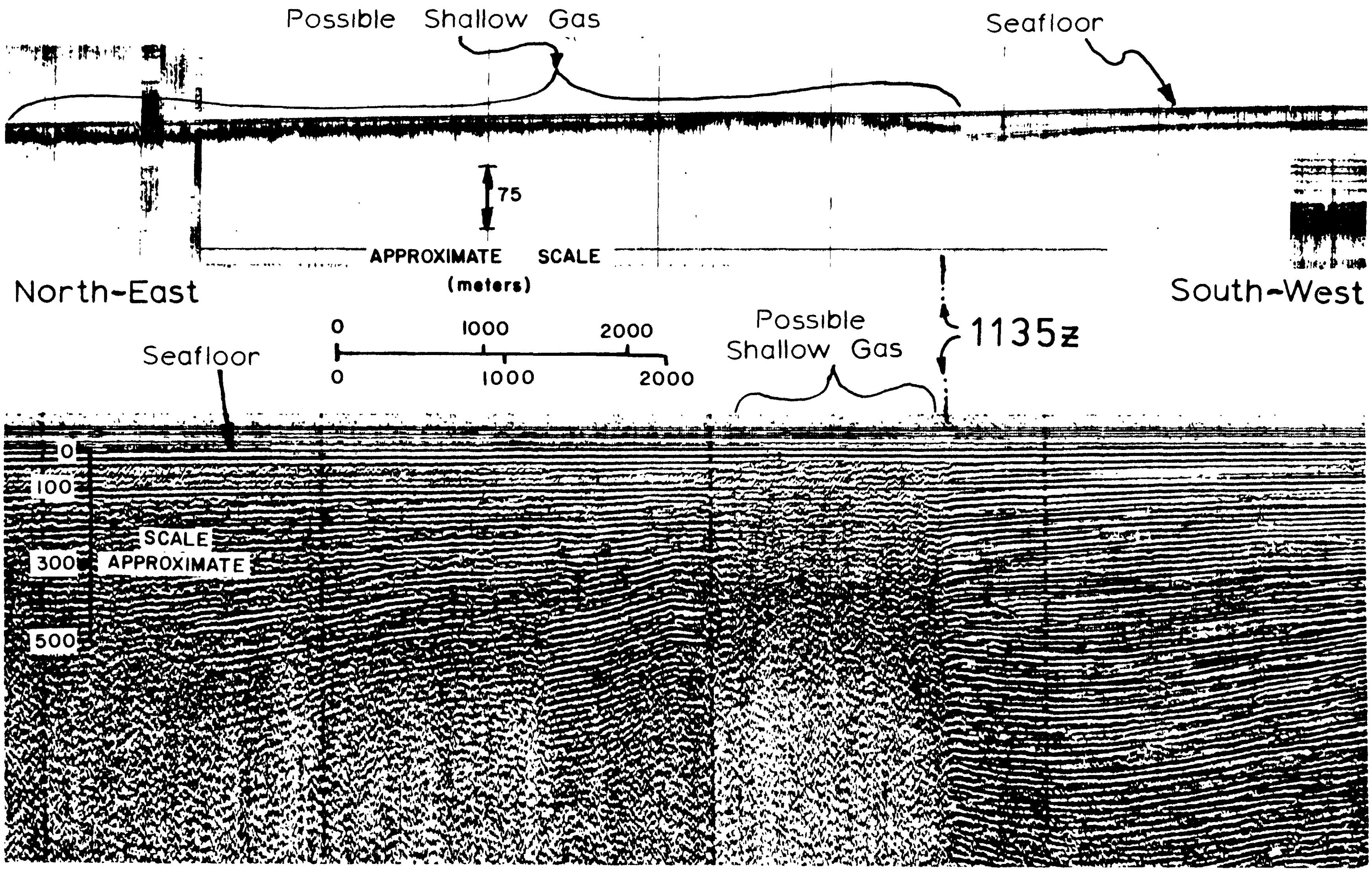

Figure 26. High resolution (top) and deep-penetration (bottom) records on line 35 along the shelf off Humboldt Bay. Note the "wipe-out" zone in the deep-penetration records where no subsurface reflectors are completely eliminated. On the top record this zone is also indicative of probable shallow gas, but the zone appears more extensive.

and no down-core gradient in gas content (Kvenvolden and Rapp, written communication, 1978).

Subsequent studies of gas content have shown relatively high concentrations of methane gas (probably biogenic in origin) in plateau sediments. One core collected from a sediment pond on a diapir (location shown in figure 7) revealed high concentrations of methane, ethane, propane, n-butane, isobutane, and gases in the gasoline range, suggesting a thermogenic origin (Field and others, 1979).

Possible Gas Hydrates

Many of the deep-penetration seismic reflection records collected along the outer plateau and upper continental slope show a distinct subbottom reflector that parallels the seafloor and cuts across bedding planes of subbottom strata. Such reflectors have been identified elsewhere and are termed Bottom Simulating Reflectors or BSR's (Scholl and Creager, 1973). BSR's are thought to be caused by a diagenetic change, and in some instances may delineate the surface of frozen gas hydrate, chiefly methane (Milton, 1976; Dillon, Grow and others, 1980; Kvenvolden and McMenamin,1980). Off northern California BSR's are found beneath the marginal plateaus and outer slope at water depths of 800 to 3000 m; they commonly lie 150 to 200 m below the seafloor. If the BSR's are gas hydrates, they indicate a possible gas resource as the hydrate or BSR (fig. 27) and may provide a membrane for trapping hydrocarbons (oil and gas) (Dillon and Grow, 1980). Because they may provide a surface beneath which natural gas, in an overpressured state, may exist, they also may pose a potential hazard to development.

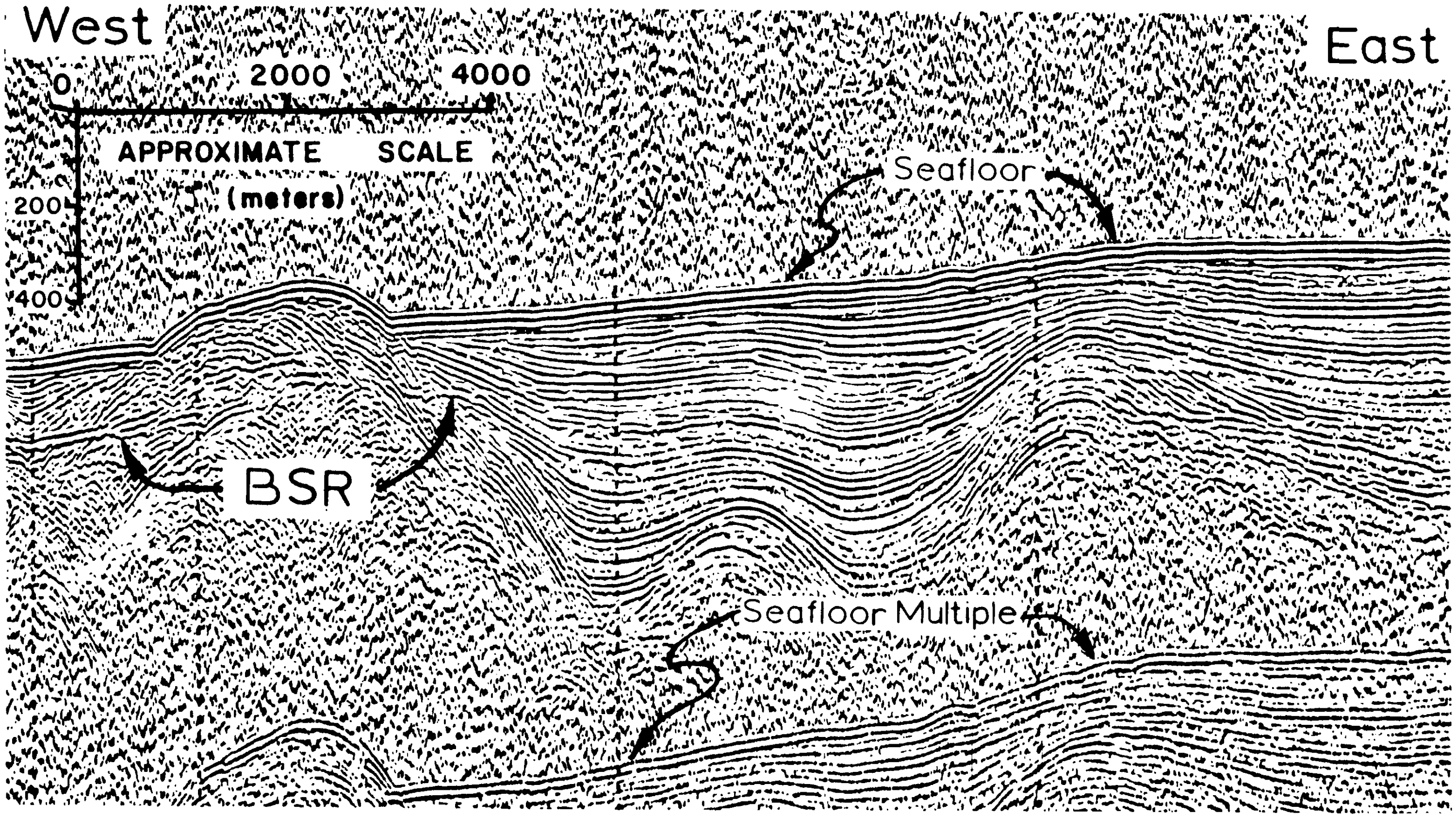

Figure 27. Sparker record from the outer Klamath Plateau along line 53 showing the presence of a Bottom Simulating Reflector (BSR) beneath the seafloor. The BSR may indicate the presence of gas at shallow depths in a hydrate or gaseous state.

Coastal Instability

A large number and variety of failures have occurred in the coastal zone of northern California as a result of earthquakes. Youd and Hoose (1978) compiled a record of the location of landslides, ground settlement, lateral spreading, ground cracks, fissured flood planes, sand boils, and miscellaneous other effects (fig. 14). Most of these failures occurred as a result of the 1906 earthquake, which had an intensity in the study area of VIII to IX on the modified Rossi-Ford scale (Youd and Hoose, 1978), and the 1954 Bridgeville earthquake of magnitude 6.1. Observations of structural damage and geologic effects were also reported for earthquakes occurring in 1853, 1865, 1927, and 1932. Evidence presented by Ogle (1953) indicates that older Tertiary deposits of the onshore Eel River Basin are prone to failure and the same may be true of their offshore equivalents. Slumps and debris slides are common in interbedded sandstones and mudstones of the Rio Del and Pullen Formations and other units of the Wildcat Group, as well as in deposits of the Yager Formation.

CHARACTERISTICS OF SURFACE SEDIMENTS

Lithology

Few investigations of the characteristics of surface sediments have been conducted along the northern California continental margin. Welday and Williams (1975) published a map showing lithology of surface sediments along the entire California coast, but aside from this study, little is known of the type, areal extent, variation, and thickness of surface sediments off northern California. In 1977, samples were collected at 63 stations to characterize surface sediments and obtain stratigraphic information for this study. Location, water depth and core length of these samples are reported in Appendix 1.

<u>Texture:</u> Sediment from the upper 10 cm of each core was analyzed for grain size. The grain size determinations are displayed graphically in Figure 28; tabulations of the results appear in Appendix 4. Textural populations are grouped by sand, silt and clay content in pie diagrams on figure 28. This diagram shows the general predominance of silt-size particles in surface sediments. Silt usually accounts for 50 to 75% of the sediment, while clay normally is less than 25% and always less than 40%. The areal distribution of sand is bi-modal. Sand-size particles usually account for less that 10% of the sediment; locally, however, it may exceed 75% in abundance. Cores having high sand content in the surface layer are clustered, and the anomolous textural distribution can be related to specific bathymetric features or to outcrops.

Textural data from surface sediments were used to modify and extend the boundaries of the lithologic map of Welday and Williams (1975). The modified map, shown in figure 29, shows the areal distribution of the entire range of sediment from gravel to mud. Samples having textural characteristics differing from those mapped by Welday and Williams (1975) are shown as discrete patches around the sample location; the lateral limits of the patches are arbitrary. Outcrops shown on this map are those plotted by Welday and Williams (1975) solely from sample data and, in general, are restricted to coastal areas around Cape Mendocino, Trinidad, and Point St. George. Our seismic data suggest that outcrops are more extensive, than mapped by Welday

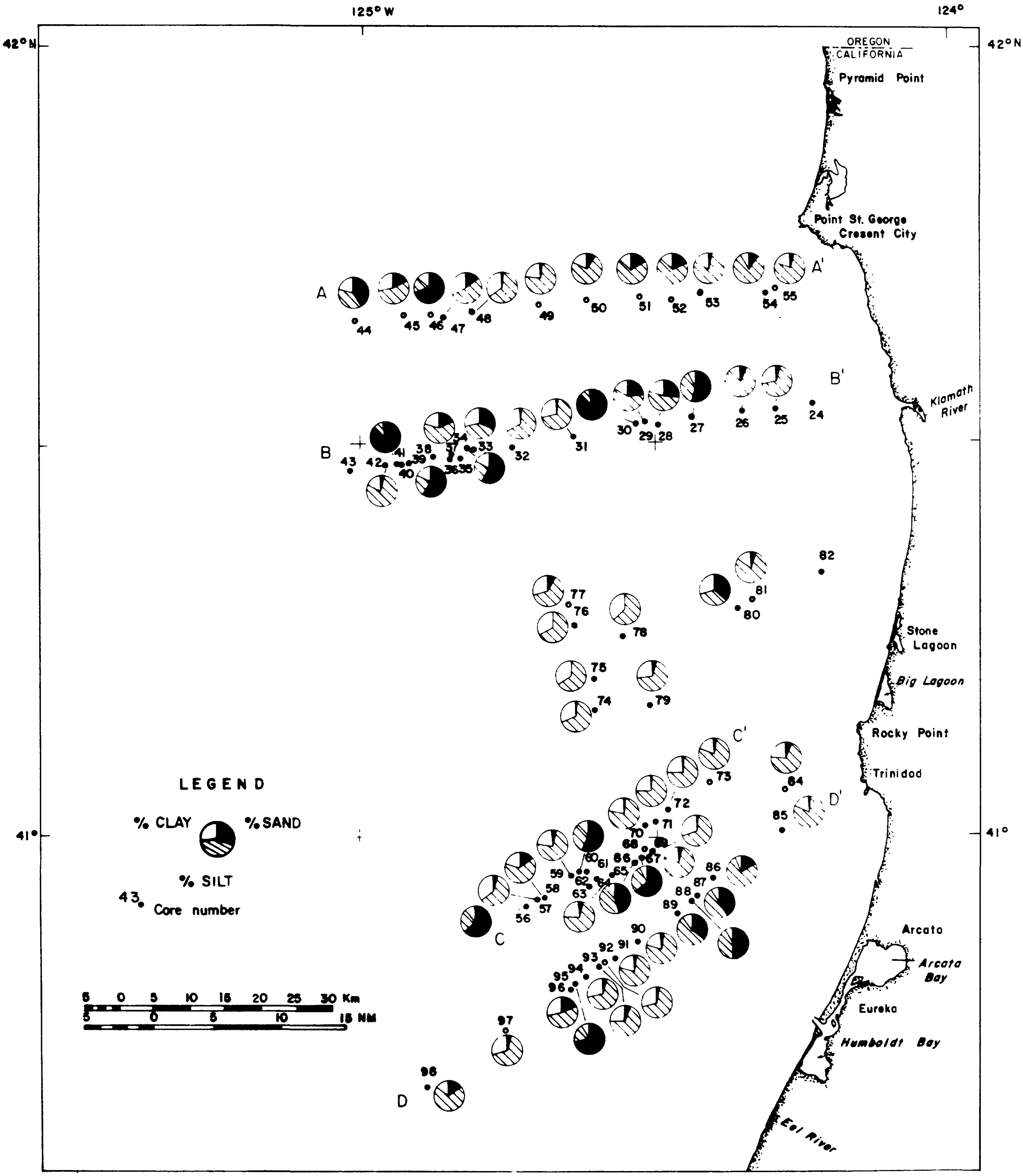

Figure 28. Sand, silt, clay ratios for surface sediments, northern California continental margin.

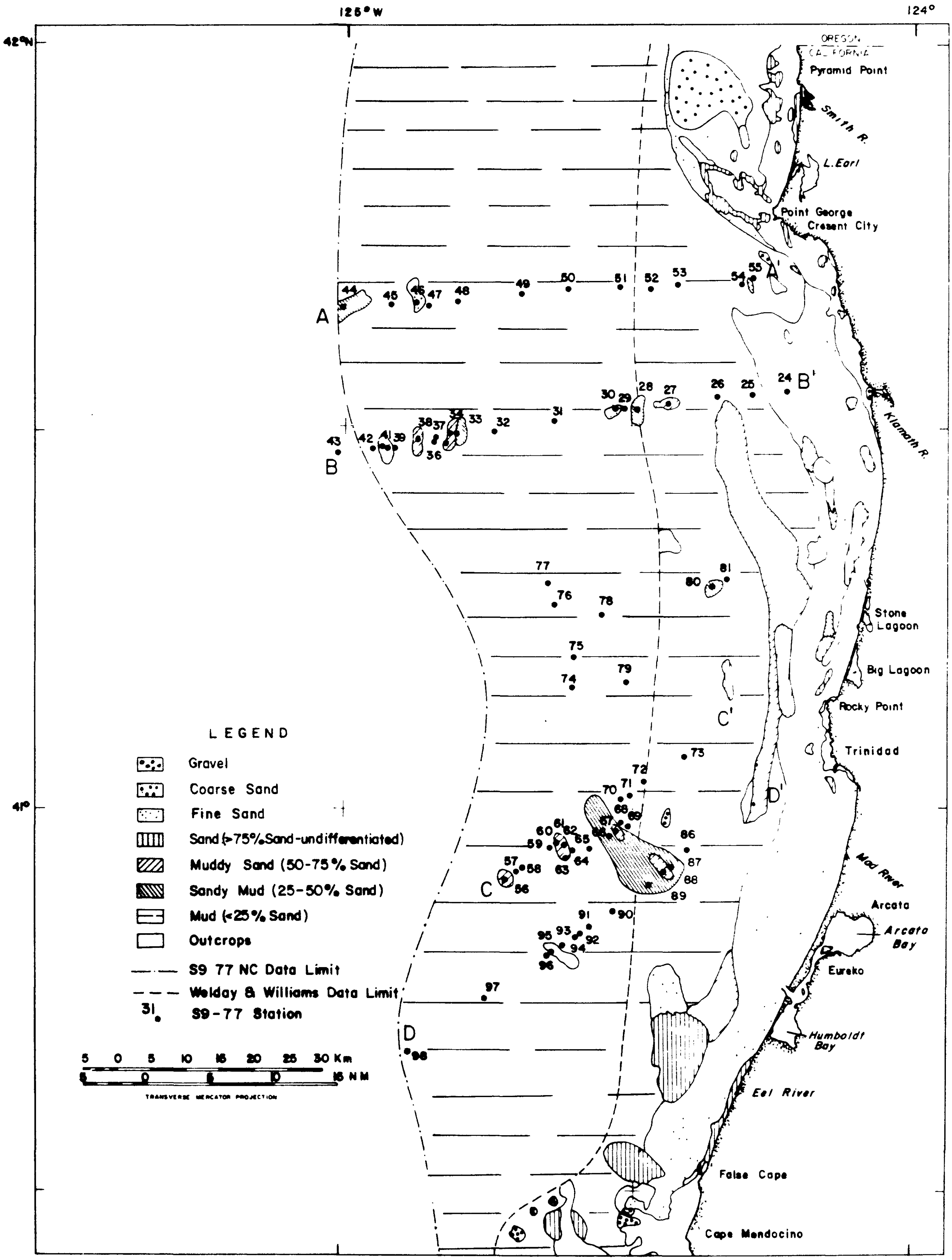

Figure 29. Lithology of surface sediments, northern California continental margin. Modified from Welday and Williams (1975).

and Williams (1975) particularly in the zone of diapirs. Otherwise, our sampling transects verified much of the information published by Welday and Williams (1975) and showed that variations occur from their maps are local in nature and occur most commonly in the vicinity of diapirs and outcropping strata. Mud is the dominant sediment type across the entire margin, with the exception of a coast parallel belt of fine sand about 10 km wide, and a narrow belt of muddy sand on the center of the shelf.

Figure 30 shows a series of four transects across the continental margin showing mud content, grain size, calcium carbonate content and organic carbon content in relation to bathymetry. Locations of transects are shown on figure 29. Note that on transects A-A', B-B', and D-D' large decreases in mud content and increases in grain size (indicated by decrease in number in fig. 30) usually correspond to the location of ridges on the marginal plateau. In profile C-C' this relationship is also evident, but other significant changes in texture occur which are not clearly related to seafloor morphology. The decrease in mud content in the vicinity of the ridges is probably caused by an influx of coarser sediment from nearby outcrops.

Composition and Mineralogy: Surface sediment offshore of northern California are dominantly terrigenous in origin, with minor amounts of biogenous and authigenic grains. The principal source terrane for sediments lies in the granitic and metamorphic rocks of the adjacent Klamath Mountains and Franciscan rocks in the northern California Coast Ranges, which are drained by the Eel, Mad, Klamath and Smith Rivers; all of these rivers carry substantial sediment loads (Griggs and Hein, in press). The terriginous fraction of sand- and silt-size particles is dominated by quartz and feldspars, with lesser

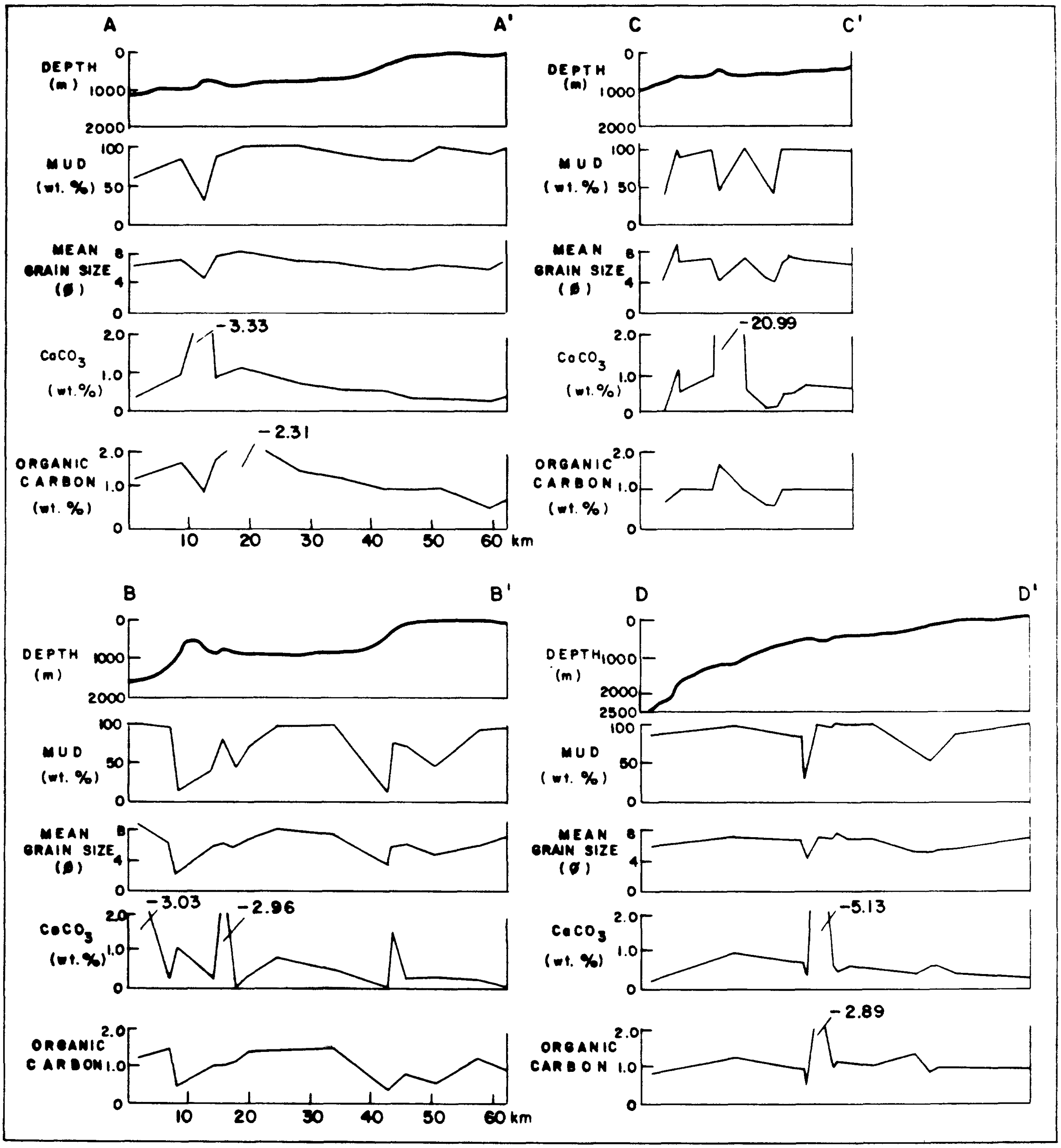

Figure 30. Mean grain size and percentage mud, calcium carbonate and organic carbon of surface sediments on the northern California continental margin.

amounts of heavy (S.G. > 3.0) minerals. The heavy mineral suite is dominated by amphiboles, epidotes, opaque minerals, altered rock fragments, and pyroxenes; other minerals compose less than 7% of the heavy mineral fraction (F. L. Wong, pers. commun., 1979). This suite suggests derivation from the adjacent metamorphic terrane.

Analysis of smear-slides prepared from surface samples shows that diatoms range in abundance from rare (1-5%) to abundant (25-75%) and are generally common (5-25%). Sponge spicules are rare to common in concentrations. Foraminifera, calcareous nannofossils, radiolarians, fish remains, volcanic glass, and glauconite grains are also present in trace (1%) to common (5-25%) quantities.

Griggs and Hein (in press) analyzed the clay mineralogy of surface sediment samples from selected cores as part of a study of the source and distribution of clay minerals off California. Their results from northern California show a distinct clay mineralogic province extending from Oregon to Cape Mendocino that is characterized by a high (50%) chlorite and kaolinite content, a moderate (30-40%) illite content, and a low to moderate (10-35%) smectite and vermiculite content. This clay mineral suite is indicative of the rocks of the drainage basins (Klamath Mountains and northern Coast Ranges) and the humid weathering conditions in the basins.

<u>Organic Carbon Content</u>: Results from analyses to determine organic carbon and calcium carbonate content of surface sediments are tabulated in Appendix 2 and are displayed graphically in Figure 30. Organic carbon content ranges from about 0.5 to about 1.5% by weight (only two samples exceed 2.0%); most samples have a value of about 1.0% ± 0.2%. No strong trends emerge from the graphical

display in Figure 29, but several subtle patterns relating organic carbon content to grain size and location are evident. As shown on profiles A-A' and B-B', plateau sediments tend to be slightly finer and slightly enriched in carbon relative to shelf sediments. Coarse sediments on the outer plateau ridges are accompanied by a corresponding decrease in organic carbon content. In profiles A-A, C-C', and D-D' the carbon content also roughly reflects the change in grain size, with slightly higher carbon values accompanying the finer-grained sediments.

Calcium Carbonate Content: Calcium carbonate content is low in northern California shelf and plateau sediments, reflecting the large influx of terrigenous material. Most samples show less than 2% $CaCO_3$ by weight. Most of the calcium carbonate is derived from tests of Foraminifera and calcareous nannofossils, with lesser amounts from fragments of molluscs and echinoderms. Samples with high $CaCO_3$ (20% on transect C-C') contain more shell fragments then typical samples. Calcium carbonate content along transects A-A', B-B', and D-D' shows a subtle increase with increasing distance offshore, probably reflecting a progressive decrease in the amount of terrigenous material present. Increases in carbonate content accompany both increases and decreases in grain size.

Geometry

Late Holocene sediment on the northern California continental shelf unconformably overlies a Quaternary (probably Holocene) erosional surface. High resolution seismic reflection records show this surficial sediment unit as transparent to well-bedded acoustically. It can be traced by its presence above the unconformity (fig. 31) and is mappable along most of the shelf area. Thickness and areal extent on the shelf of this surface acoustic unit are mapped in figure 32. Because identification of the unconformity is difficult off Humboldt and Arcata Bays, thickness values for the surface sediment unit are less reliable in that area. This unit is assumed to be unconsolidated because of its transparent nature of the unit, its relative thinness, and the lack of well-defined internal reflectors. However, the exact age and the degree of consolidation can be determined with any degree of assurance only by bore-hole studies.

Modern unconsolidated sediments on the shelf range from less that 10 to greater than 50 m in thickness, and most of the shelf is covered by at least 10 m of sediment. Two depocenters have been mapped; one off Humboldt Bay and the other southwest of Crescent City. The sediments off Humboldt Bay are more than 50 m thick. The limits of this depocenter, particularly the seaward boundary, are tenuous due to the quality of seismic reflection data, and actual thickness and extent of modern, unconsolidated sediments may differ slightly from that shown on figure 32. Southwest of Crescent City, a second large depocenter trends northwest from the mouth of the Klamath River. This sediment body, also reported by Moore and Silver (1968), appears related to the discharge of the Klamath River, but its shape may also be influenced by a major northwest trending fault that displaces Quaternary sediments (see fig. 7). The depocenter lies west of and on the down thrown side of the fault. Holocene sediments seaward of the shelf lie conformably on older Pleistocene and Pliocene deposits, and it is difficult to ascertain its thickness.

Areas devoid of modern sediment are found off rocky headlands, in canyons, on the innermost shelf, and on ridge crests on the outer plateau

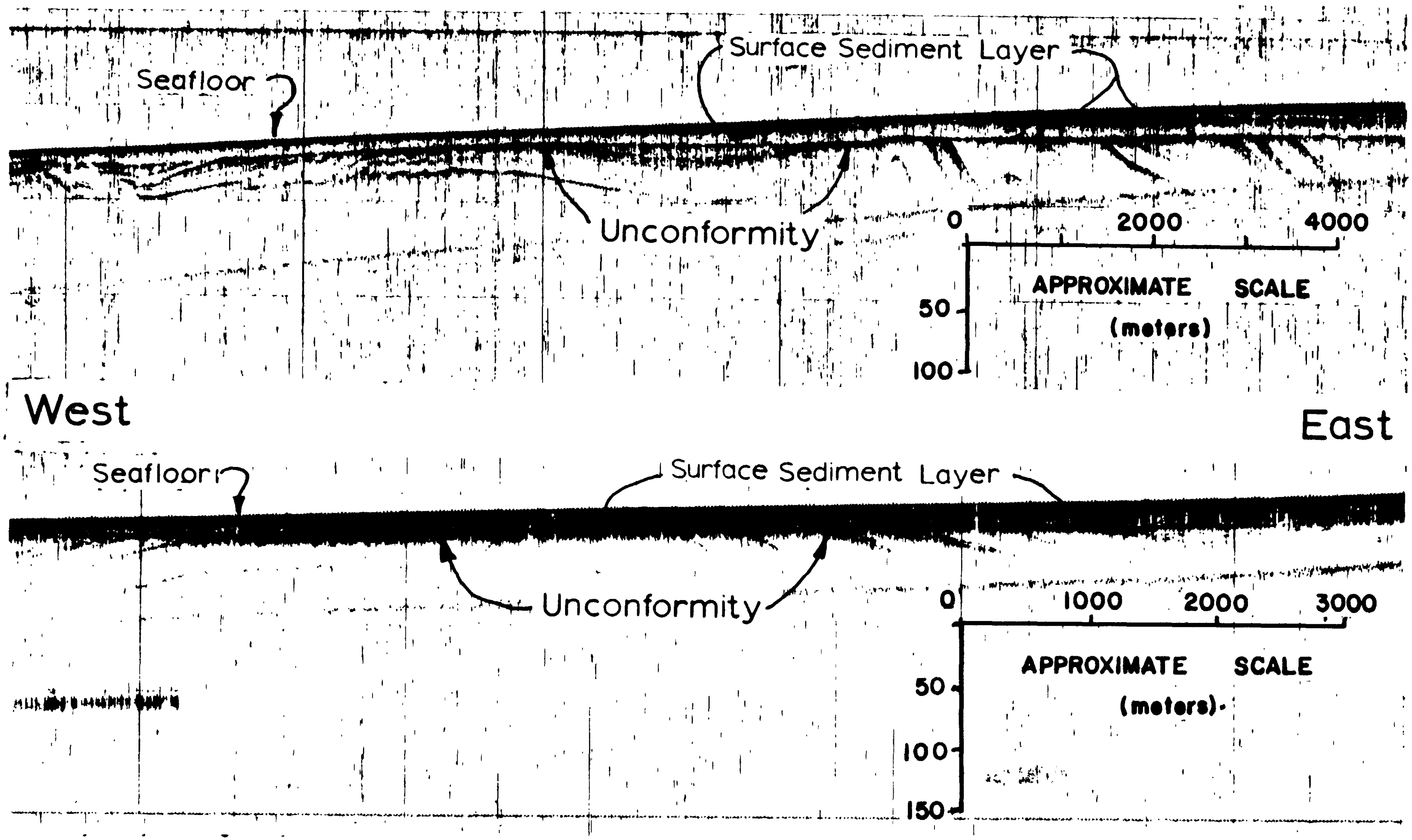

Figure 31. High resolution seismic reflection records along lines 12 (top) and 22 (bottom) showing the nature of the surface sediment layer. The layer is bedded in some places and transparent in others, and its base is well-defined by an unconformity. The surface sediments are probably unconsolidated and late Holocene in age.

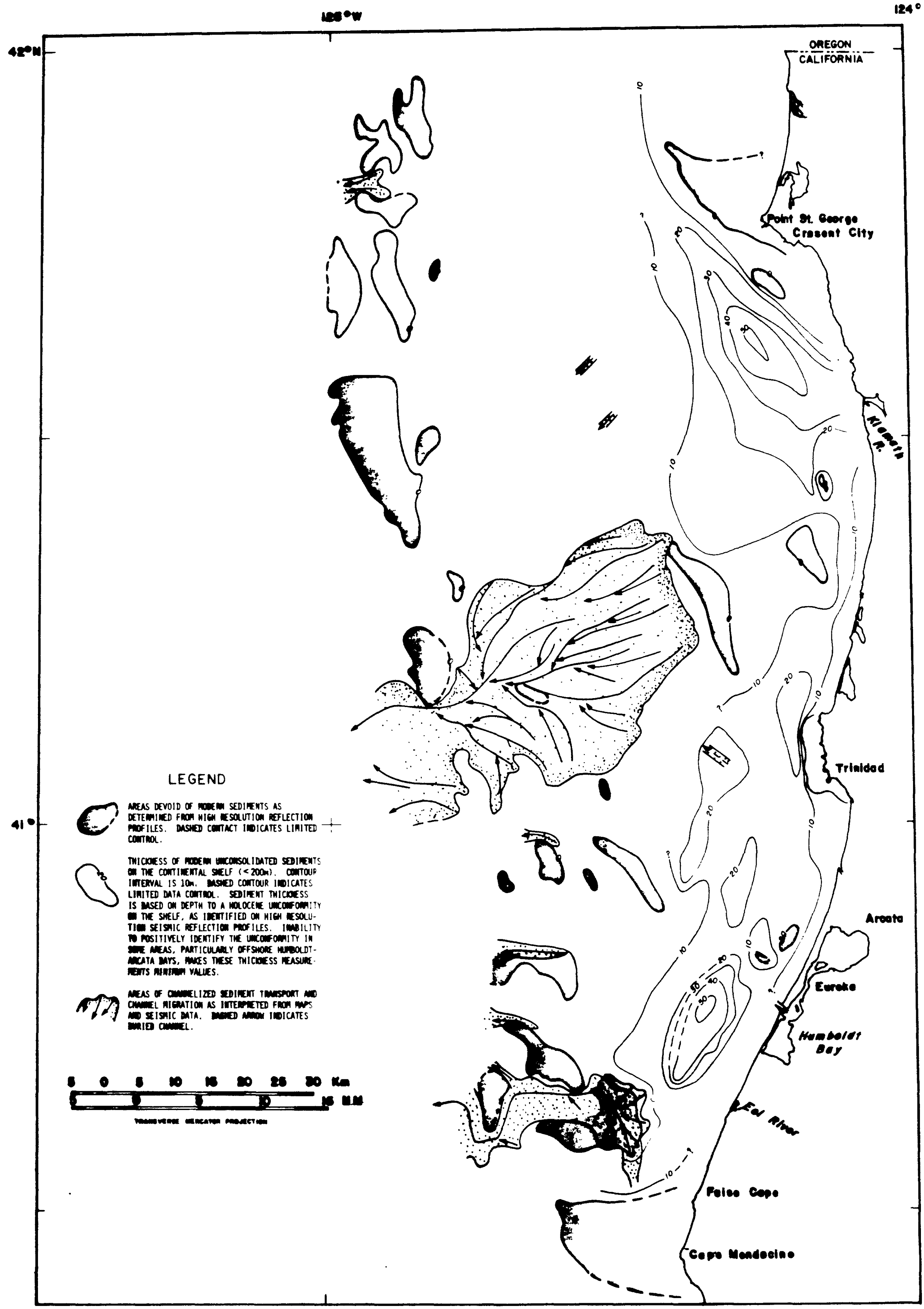

Figure 32. Areas of erosion, transport, and deposition of sediments, northern California continental margin. Isopach contours of Holocene sediment on the shelf are in meters.

(fig. 32). The exposure of strata in these areas results from a complex set of processes including uplift, sediment shedding by sliding, and wave and current erosion.

Active Sediment Processes

The continental margin off northern California is an active depositional regime. Although coastal erosion and bluff retreat play an unknown role in contributing sediment to the offshore, the major rivers are the dominant source of sediment. The Smith, Klamath-Trinity, Mad, and Eel Rivers and Redwood Creek supply over 46 metric tons of suspended load per year to the offshore (Griggs and Hein, in press). The Eel River alone has a suspended sediment yield of 3202 tons/km^2/yr, the highest yield per km^2 of drainage area for any river in the United States (Brown and Ritter, 1971). LANDSAT studies of northern California show large sediment plumes extending offshore, with the plume one off the Eel River extending as much as 100 km from shore (Griggs and Hein, in press). Based on the thickness of Holocene sediment on the continental shelf (fig. 32), sands and muds have accumulated at a rate of 0.5 to 1.0 cm/yr (5 to 10 m/10^3 yr). The average rate of sedimentation must be significantly higher, taking into consideration the high loss of sediment from the shelf that must occur from slumping, current winnowing, and down-canyon transport. Silver (1969) estimated a sedimentation rate of 20 x 10^6 m^3/yr for the past 3.5 million years to produce the estimated present sediment volume of 70 x 10^{12} m^3. This equates to a sedimentation rate of roughly 1 cm/yr (10 m/10^3 yr). Griggs and Hein (in press) estimate a rate of 1.04 cm/yr, based on the average annual sediment yield of major streams. These estimated sedimentation rates are higher than those calculated for other marine environments along the Pacific Coast of the United States.

In spite of the estimated high rate of sedimentation offshore of northern California, outcrops representing areas of erosion or non-deposition are abundant. Outcrops adjacent to rocky headlands are high energy areas where currents and shoaling waves exert forces strong enough to erode and transport materials away from the shallow shelf. Outcrops on canyon walls occur where sediments cannot accumulate in significant quantity because of the steepness and perhaps because of water/sediment flows through the canyon. Outcrops on the marginal plateaus are Pliocene shales that have been extruded upward through the over-lying Quaternary sediments.

Sediment transport is at present a very active process off northern California. Large blocks of sediment are slumping off the marginal ridges and plateau slope onto the central plateau. Cores in the slumps and out on central part of the plateau contain graded sand layers, indicating off-shelf transport by sediment-laden turbidity flows. Large plumes of suspended sediment that extend across the entire margin are clearly visible on satellite photos. Seismic reflection data showing well-developed thalwegs and channel levees indicate that many channels are still active (fig. 32). Many of the areas, especially Trinity Canyon, are characterized by a continuous series of migrating channels, and the entire area is interpreted as part of a transport zone. Cores taken from the levees of an active channel show uniform homogeneous silty clay; those from the channel show a repeating sequence of turbidite sands and silts.

SUMMARY OF HAZARDS

Tectonic forces and dynamic sedimentologic processes combine to produce a variety of conditions and phenomena that may pose hazards to engineering activities associated with petroleum development on the northern California continental margin. The motion of crustal plates, especially the underthrusting of the North American Plate by the Gorda Plate, results in high seismicity throughout the region. On the average, an earthquake of greater than 6.0 magnitude can be expected to occur an average of once a decade; major earthquakes of 7.0 to 7.5 magnitude have occurred in the past, and presumbably can be expected to recur. The shelf and plateau areas are cut by numerous faults, many of which displace the seafloor or Quaternary sediments. The potential for repeated movement along these faults appears to be high. A series of ridges on the central and outer plateaus that are interpreted as diapiric in origin appear to be undergoing uplift at present, perhaps producing concurrent ground shaking.

Streams draining northern California discharge large loads of fine-grained sediments into the offshore, resulting in an average rate of deposition of about 1.0 m/1000 yr throughout the area and much higher rates nearshore. Depocenters of sediment exceeding 50 m in thickness lie offshore from Humboldt Bay and the Klamath River. Thick sequences of sediment deposited on the slope and inner plateau, have given rise to sediment slumps and slides measuring 100's of km^2 and large areas of unstable sediment, which may be caused to fail by seismic loading. Onshore areas have also experienced failure from ground-shaking associated with major earthquakes. Large areas on the shelf show acoustic characteristics that may indicate zones of gas accumulation. On the outer plateau the seafloor is underlain by a Bottom Simulating Reflector that may mark the level of gas hydrates and possible underlying gas concentrates that may be overpressured. The northern

California coast is vulnerable to tsunamis generated in the northeastern Pacific. In 1964, Crescent City was inundated by a tsunami generated from the Alaska earthquake that produced waves as high as 6.3 m and caused eleven deaths and about nine million dollars of damages (Iida and others, 1967).

In summary, the geologic conditions and phenomena that may pose hazards to development, and that require additional understanding and consideration in engineering plans, include:

1. High seismicity (ground-shaking, earthquake-related soil failures)
2. Faults showing evidence of recent displacement
3. Diapirism and active seafloor uplift
4. Active sediment slumps and slides
5. Unstable sediments or incipient slumps
6. Possible accumulations of shallow gas
7. Bottom simulating reflectors indicating possible gas hydrates.
8. Coastal landslides and other ground failures
9. Coastal storm and tsunami damage
10. High sedimentation rates of fine-grained sediment
11. Turbidity flows across the plateau and in canyons

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APPENDICES

APPENDIX 1 - PROCEDURES

Data were obtained for this report during two cruises to the northern California and southern-central Oregon OCS. The first cruise (S9-77-NC), of approximately 19 days duration and funded jointly by the U.S. Geological Survey and Bureau of Land Management, was carried out aboard the R/V SEA SOUNDER during November, 1977. Objectives of this cruise were to provide a reconnaissance of the regional distribution of potentially hazardous processes and to delineate specific hazards for future study. Because of the impending oil and gas lease sale 53, priority was given to data collection in the offshore Eel River Basin, with approximately 11 days of the cruise spent in this area. The second cruise (S12-78-NC) of 11 days duration and funded by the U.S. Geological Survey, was completed during November, 1978. This cruise was directed toward obtaining additional data from critical areas in both basins, and making a detailed study of submarine mass movement in the offshore Eel River Basin. Data from both cruises are incorporated in this report.

NAVIGATION

Positioning data were obtained at sea using satellite navigation and Loran C systems, and a shipborne electronic ranging system employing shore-based transponders. Radar was used infrequently for positioning where terrain masking or equipment malfunctions were encountered. Data from the satellite and Loran C systems were integrated by means of a Dead Reckoning Computer (DRC). Positions derived from the DRC and electronic ranging systems initially were plotted separately and weighted according to their relative accuracy; subsequently these data were corrected and merged to produce maps of position location for geophysical tracklines and sampling stations. Estimated position accuracy ranges from $\pm$ 50 m where positions were determined principally by electronic ranging (approximately 90 percent of the cruise) to an average of about ± 500 m where DRC or radar positions were used exclusively (approximately 10 percent of the cruise).

GEOPHYSICAL PROFILING

A variety of profiling equipment were used to obtain a spectrum of data ranging from relatively high resolution, shallow penetration to low resolution, intermediate to deep-penetration seismic reflection records. Precision bathymetric and shallow subbottom records were obtained using 12 kHz and 3.5 kHz profiling systems employing hull-mounted transducers and hydrophones; during the 1977 cruise, approximately 1775 line km of 12 kHz profiles and 4235 km of 3.5 kHz profiles were collected.

A boomer system was used to obtain approximately 2180 line km of high resolution, shallow-penetration subbottom profiles. This system employed 4 hull-mounted transducers and a hydrophone streamer towed 3 m off the starboard beam approximately 0.3 m below the sea surface. Power output ranged from 800 to 1200 J and the incoming signal was filtered between 400-500 Hz (low cut) and 1200-1500 Hz (high cut). Fire and sweep rates of 0.5 second and 1 second were used depending on the geological conditions encountered and the character of the records.

A sparker system operated at 80-140 kJ was used to obtain 3165 line km of low resolution, intermediate to deep-penetration records. This system has a fundamental frequency of approximately 80 Hz, and was filtered between 50 Hz and 98-125 Hz; fire and sweep rates were 4 seconds. Four sparker ladders were towed astern at a depth of 3 m; two ladders were located approximately 3 m outboard from the ship and 45 m astern, and two were towed approximately 6 m outboard from the ship and 60 m astern. The hydrophone streamer consisted of a 45 m-long active section containing 100 elements; the streamer was towed at a depth of 3 m directly astern, with the lead hydrophone approximately 60 m aft of the ship.

In addition to the primary geophysical equipment noted above, additional data were obtained using a La Coste-Romberg 3-axis gravimeter (4700 line km) and a proton precession marine magnetometer (655 line km). Side-scanning sonar records were obtained from the shallow shelf off Humboldt Bay.

Additional geophysical profiles were run in the fall, 1978 to fill gaps in existing coverage, and to address specific geologic problems revealed during interpretation of records collected in 1977. Trackline coverage off central Oregon and northern California from this cruise totalled approximately 1975 km of sparker, 1315 km of boomer, 2130 km of 3.5 kHz profiler and 624 km of magnetometer data. A preliminary interpretation was made of these seismic reflection data and the results from northern California are included in this report.

SAMPLING AND SHIPBOARD SAMPLE PROCESSING

Bedrock outcrops and sediments were sampled on the continental shelf and plateau using dart and gravity coring equipment. The dart coring device consists of a thick-walled steel pipe approximately 5 cm ID x 0.6 m long attached to a heavy weight (680-900 kg), and is dropped onto the seafloor at velocities of 100-150 m/min; it is employed principally in areas of hard bedrock outcrop. The gravity corer employs the same weight, but the coring device consists of a thick-walled steel barrel containing a clear plastic liner approximately 7.6 cm ID x 3 m long. A core retainer and cutter are employed, and the device is dropped onto the seafloor at velocities of 100-150 m/min. It is used to collect samples from areas of sediment cover and relatively poorly indurated bedrock.

Seventy-four sampling stations were attempted in the study area during 1977, and sample was recovered from 71 of these stations. Samples were collected to provide stratigraphic, sedimentologic, and geochemical information. Location, water depth and recovery results at each sampling station are listed in Appendix 2; station locations are shown in Figure 29. Twenty-one samples were collected in the study area by gravity coring in 1978, and visual core descriptions of these samples have been included in this report.

Dart and gravity cores were removed from the core barrels and taken to the sedimentology laboratory aboard ship. There they were split, with one half being designated for archive purposes and the other for various analytical procedures. The half designated for analysis was subsampled at top (the uppermost sediment layer not disturbed by coring), bottom, and appropriate intermediate levels for microfaunal, lithologic and geochemical data; the core half designated for archive was photographed, X-radiographed (if appropriate), subsampled for smear slides and described. Smear slides from selected cores were studied to obtain detailed information concerning sediment texture and composition. Both core halves and all subsamples were placed in a refrigerated ($40^{\circ}F$) core storage area for the duration of the cruise; they are presently stored in the refrigerated core storage at the Deer Creek office of the U.S. Geological Survey in Palo Alto, CA.

LABORATORY ANALYSIS

Subsamples from the surface of 63 gravity cores were analyzed for grain size distribution. About 5 grams of each sample were placed in individual 1000 ml beakers and diluted with about 100 ml of 10% hydrogen peroxide to remove particulate organic material. Remaining sediment was wet sieved through a 0.063 mm sieve to separate the sand and mud fractions. The sand fraction (>0.063 mm) was oven-dried and split into 0.5 gram fractions for size analysis with a rapid sediment analyzer (RSA) settling tube. Duplicates were run for every tenth machine run. Mud fractions (<0.063 mm) were diluted to 1000 ml, dispersed with sodium hexametaphosphate, and a 10 to 25 ml split was taken for grain size analysis using light transmission techniques on a hydrophotometer (Jordan and others, 1971; Tilly, 1977). Replicate analyses show high reproducibility using this technique. Particle size distribution and modal, median and mean size, sorting, skewness and kurtosis were calculated using both the methods of moments and graphical statistics. Duplicate analyses show no major discrepancies.

Subsamples from these same 63 cores were analyzed for total, inorganic (carbonate) and organic carbon. Approximately 1-2 grams of sediment from each subsample was washed twice with distilled water by centrifuging and decanting to remove fluoride and chloride salts that might affect the results of carbon analysis. Washed sediment was oven-dried, ground to fine powder with mortar and pestle, and stored in airtight glass vials at room temperature. Total carbon content was determined by combustion of 0.02 gram samples for 55 seconds in a LECO tube-induction furnace. Evolved carbon dioxide gas was measured in a LECO model WR 12 carbon determinator modified after Kolpack and Bell (1968). Inorganic carbon was determined gasometrically by measuring the amount of carbon dioxide generated from sediment (0.1 gm) treated with 2 N HCl (Kolpack and Bell, 1968). Carbon content was determined by averaging three analytical runs for each between total carbon and inorganic carbon. Calcium carbonate content was derived from the analyses by multiplying the amount of inorganic carbon by the ratio of molecular weight of $CaCO_3$ (=100) to the atomic weight of carbon (12). Thus, a value of 0.25% inorganic carbon equates to a value of 0.25 x 100/12 or 2.08% calcium carbonate.

APPENDIX 2

Location, Depth, and Length of Gravity Cores

Collected from northern California on Cruise S9-77-NC

STA.	SAMPLE NUMBER	LATITUDE (N)	LONGITUDE (W)	WATER DEPTH(M)	SAMPLE LENGTH(M)
24	No Recovery	41.5471	124.2269	050	-
25	25G	41.5416	124.2937	069	1.50
26	26G	41.5403	124.3507	090	1.46
27	27G	41.5323	124.4342	120	0.50
28	28G	41.5420	124.4935	208	0.64
29	29G	41.5254	124.5157	315	0.82
30	30G	41.5244	124.5299	385	0.48
31	31G	41.5099	124.6368	920	3.00
32	32G	41.4947	124.7389	980	3.32
33	33G	41.4921	124.8036	960	0.45
33	33G2	41.4926	124.8080	955	0.20
34	34G	41.4927	124.8154	945	2.10
35	35G	41.4803	124.8274	862	Core Catcher
36	36G	41.4828	124.8381	780	0.30
37	37G	41.4834	124.8419	770	Core Catcher
38	38G	41.4841	124.8725	910	2.47
39	39G	41.4747	124.9131	610	Core Catcher
39	39G2	41.4748	124.9094	600	Core Catcher
40	40G	41.4701	124.9287	660	Core Catcher
41	41G	41.4727	124.9349	700	0.92
42	42G	41.4697	124.9500	990	1.92
43	43G	41.4655	125.0117	1515	3.07
44	44G	41.6557	125.0039	1075	3.28
45	45G	41.6599	124.9195	968	3.53
46	46G	41.6614	124.8736	757	2.10
47	47G	41.6600	124.8529	900	3.00
48	48G	41.6638	124.8029	870	2.13
49	49G	41.6765	124.6937	817	2.76
50	50G	41.6810	124.6116	695	Core Catcher
50	50G2	41.6829	124.6095	690	2.58
51	51G	41.6819	124.5225	455	1.73
52	52G	41.6811	124.4713	212	1.34
53	53G	41.6858	124.4180	122	2.01

STA.	SAMPLE NUMBER	LATITUDE (N)	LONGITUDE (W)	WATER DEPTH(M)	SAMPLE LENGTH(M)
54	54G	41.6879	124.3104	068	1.25
55	55G	41.6921	124.2895	062	1.70
56	56G	40.9152	124.7238	770	0.20
57	57G	40.9245	124.7005	720	2.27
58	58G	40.9245	124.6896	700	2.14
59	59G	40.9511	124.6458	650	2.16
59	59G2	40.9520	124.6434	650	2.37
60	60G	40.9568	124.6316	470	Core Catcher
61	61G	40.9562	124.6286	472	0.30
62	No Recovery	40.9517	124.6215	560	-
63	63G	40.9355	124.6173	510	Core Catcher
63	63D	40.9361	124.6190	505	0.18
64	64G	40.9464	124.6023	630	Core Catcher
65	65G	40.9546	124.5777	580	1.74
66	66G	40.9697	124.5418	530	2.41
67	67G	40.9780	124.5297	525	1.77
68	68G	40.9853	124.5167	535	2.30
69	69G	40.9807	124.5084	520	2.21
70	70G	41.0172	124.5222	600	2.67
71	71G	41.0219	124.5070	580	2.77
72	72G	41.0376	124.4835	570	2.43
73	73G	41.0722	124.4110	408	2.39
74	74G	41.1611	124.6044	1160	2.93
75	75G	41.2020	124.6031	1178	2.98
76	76G	41.2694	124.6363	1120	2.62
77	77G	41.2969	124.6461	1125	1.90
78	78G	41.2558	124.5523	1040	2.74
79	79G	41.1690	124.5114	990	3.00
80	80G	41.2923	124.3615	130	1.50
81	81G	41.3026	124.3353	110	1.74
82	82G	41.3346	124.2175	055	Core Catcher
83	No Recovery	41.2757	124.1728	059	-
84	84G	41.0734	124.2805	095	Core Catcher
84	84G2	41.0592	124.2858	095	2.13

STA.	SAMPLE NUMBER	LATITUDE (N)	LONGITUDE (W)	WATER DEPTH(M)	SAMPLE LENGTH(M)
85	85G	41.0085	124.2907	090	2.17
86	86G	40.9488	124.4068	215	1.96
87	87G	40.9272	124.4342	270	2.16
88	88G	40.9228	124.4464	300	1.83
89	89G	40.9055	124.4706	382	1.66
90	90G	40.8708	124.5368	525	2.31
91	91G	40.8489	124.5747	570	2.50
92	92G	40.8412	124.5920	590	2.61
93	93G	40.8364	124.6013	660	2.45
94	94G	40.8244	124.6215	585	0.25
95	95G	40.8159	124.6415	598	2.00
96	96G	40.8109	124.6479	645	2.06
97	97G	40.7572	124.7557	1221	2.37
98	98G	40.6870	124.8861	2467	2.08

APPENDIX 3

Textural Parameters of Selected Sediment

Samples from Cruise S9-77-NC

STA.	SAMPLE NUMBER	DEPTH IN SAMPLE (CM)	(GRAVEL) PERCENT SAND	PERCENT MUD	Phi MEAN (INMAN)	Phi MEDIAN (INMAN)	Phi SORTING (INMAN)	SKEWNESS 16/84 (INMAN)	KURTOSIS (INMAN)
25	25G	07.5	04	96	7.11	6.89	2.48	0.09	0.66
26	26G	07.5	07	93	6.05	5.58	1.57	0.30	1.28
27	27G	07.5	54	46	4.93	3.65	1.88	0.68	0.82
28	28G	07.5	27	73	6.13	5.52	2.75	0.22	0.62
29	29G	07.5	24	76	5.82	5.35	2.34	0.20	0.80
30	30G	07.5	87	13	3.27	3.13	0.35	0.38	4.95
31	31G	07.5	01	99	7.46	6.81	2.45	0.26	0.70
32	32G	07.5	01	99	7.98	7.42	2.39	0.23	0.78
33	33G	01.0	31	69	6.53	6.39	3.26	0.05	0.45
34	34G	01.5	55	45	5.57	3.59	2.56	0.75	1.08
36	36G	06.0	18	82	6.12	6.49	2.48	-0.15	0.97
38	38G	04.0	59	41	5.68	3.40	2.67	0.85	0.80
41	41G	07.5	86	14	2.12	1.83	0.83	0.34	4.28
42	42G	07.5	03	97	6.41	6.02	1.93	0.20	0.91
44	44G	03.0	41	59	6.04	5.90	2.92	0.05	0.59
45	45G	06.0	17	83	6.80	6.41	2.95	0.13	0.56
46	46G	06.0	32 (53)	15	0.95	-1.01	2.13	0.92	1.34
47	47G	14.0	15	85	7.19	6.77	3.13	0.13	0.50
48	48G	03.0	01	99	7.96	7.26	2.47	0.28	0.73
49	49G	02.0	02	98	6.76	6.51	2.33	0.11	0.72
50	50G2	02.0	09	91	6.43	6.03	1.83	0.22	1.20
51	51G	01.0	17	83	5.81	5.76	1.98	0.02	0.94
52	52G	07.5	19	81	5.75	5.58	2.00	0.09	0.92
53	53G	07.5	03	97	6.45	6.14	1.84	0.17	1.05
54	54G	07.5	10	90	5.87	5.29	1.48	0.39	1.17
55	55G	07.5	04	96	6.55	6.14	1.84	0.22	1.07
56	56G	02.0	63	37	4.18	2.02	2.93	0.74	0.60
57	57G	03.0	04	96	8.03	7.22	2.60	0.31	0.61
58	58G	05.0	15	85	6.45	6.00	2.41	0.19	0.78
59	59G2	16.0	04	96	6.97	6.49	2.31	0.21	0.73
61	61G	06.0	57	43	4.32	3.12	3.09	0.39	0.68
65	65G	12.0	04	96	7.16	6.90	2.33	0.11	0.74
66	66G	07.0	46	54	4.57	4.51	2.88	0.02	0.61
67	67G	01.0	62	38	4.20	2.47	2.76	0.63	0.56
68	68G	07.5	04	96	6.47	6.15	2.04	0.16	0.88

STA.	SAMPLE NUMBER	DEPTH IN SAMPLE (CM)	(GRAVEL) PERCENT SAND	PERCENT MUD	Phi MEAN (INMAN)	Phi MEDIAN (INMAN)	Phi SORTING (INMAN)	SKEWNESS 16/84 (INMAN)	KURTOSIS (INMAN)
69	69G	07.5	01	99	7.46	6.97	2.46	0.20	0.70
70	70G	07.5	01	99	7.01	6.44	2.11	0.27	0.86
71	71G	07.5	01	99	7.43	6.70	1.99	0.37	0.87
72	72G	07.5	01	99	7.13	6.77	2.22	0.16	0.79
73	73G	07.5	02	98	6.66	6.08	1.84	0.32	1.04
74	74G	07.5	01	99	7.68	7.09	2.45	0.24	0.71
75	75G	07.5	00	100	7.80	7.03	2.61	0.30	0.63
76	76G2	07.5	00	100	7.52	7.20	2.66	0.12	0.59
77	77G	07.5	08	92	7.17	6.98	2.67	0.07	0.71
78	78G	07.5	00	100	8.22	7.30	2.35	0.39	0.63
79	79G	04.0	04	96	7.23	6.85	2.37	0.16	0.70
80	80G	03.0	37	63	5.77	6.61	4.11	-0.20	0.47
81	81G	03.0	05	95	6.28	5.57	1.72	0.41	1.13
84	84G2	06.0	06	94	6.92	6.41	2.34	0.22	0.81
85	85G	09.0	01	99	6.61	6.19	1.68	0.25	1.17
86	86G	07.5	15	85	5.59	4.78	1.51	0.54	1.32
87	87G	07.5	41	59	5.15	4.52	1.85	0.34	0.96
88	88G	07.5	50	50	5.05	4.02	1.75	0.59	1.04
89	89G	07.5	36	64	5.27	4.72	1.93	0.28	0.90
90	90G	07.5	02	98	6.90	6.13	2.16	0.36	0.84
91	91G	07.5	02	98	6.91	6.21	2.14	0.32	0.85
92	92G	07.5	02	98	7.45	7.16	2.49	0.12	0.67
93	93G	07.5	05	95	7.06	6.56	2.36	0.21	0.76
94	94G	07.5	04	95	7.19	6.50	2.64	0.26	0.66
95	95G	02.5	(01) 71	29	4.16	2.80	2.42	0.56	0.73
96	96G	13.0	19	81	6.83	6.84	3.22	-0.00	0.46
97	97G	07.5	04	96	7.30	6.87	2.67	0.16	0.57
98	98G	07.5	15	85	6.04	5.33	1.96	0.36	1.04