UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

# SEAFLOOR FAILURES CAUSED BY THE NOVEMBER 8, 1980 EARTHQUAKE OFF NORTHERN CALIFORNIA

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# INTRODUCTION

## Background

A large earthquake measuring approximately 7.0 magnitude (ML: U.S. Berkley) on the Richter scale occurred offshore of northern California at 02:27 Pacific Standard Time on November 8, 1980. The epicenter of the earthquake was tentatively placed at 35 km west of Trinidad (J. Eaton, U.S.G.S., oral commun., Jan. 1981). Studies of the depth of the earthquake are still in progress, but the hypocenter is roughly estimated to be 10 to 20 km deep. The northern California continental margin is seismically active, with large magnitude (M>6) earthquakes occurring frequently (18 in the past 80 years) (Couch and others, 1974). Results of onshore investigations of ground effects and structural damage caused by the Nov. 8, 1980, earthquake are reported by Keefer and Lajoie (1981) and by Kilbourne and Saucedo (1981). In the weeks following the earthquake, commercial fishermen in Crescent City noted changes in the seafloor in several areas where they had been working for many years. These observations were reported to Dr. Gary Carver at Humboldt State University in Arcata, who in turn alerted the Geological Survey. A trip was made on Nov. 24 to talk with Mssrs. Wes Rook and Wes Wallace and to view their charts and depth recordings. The area just offshore the mouth of the Klamath River was the best documented (at least 3 independent observations) of the reports on seafloor changes. This area was selected for immediate study because the site is in shallow water (i.e. 30 to 80 m) where small perturbations in the seafloor are subject to obliteration by winter storms and large pulses of sedimentation. Not only was there a high probability of locating reported changes in this area, but previous U.S.G.S. cruises to the area provided high resolution seismic profiles from which a comparison with post-earthquake data could be made.

This report contains a description of the data and preliminary findings from the post-earthquake seismic reflection cruise offshore of the Klamath River and a comparison with pre-earthquake data. Copies of high resolution geophysical records obtained on the Dec. 1981 cruise are available in U.S. Geological Survey Open-File Report 81-394, "High resolution seismic reflection profiles collected from offshore northern California after the Nov. 8, 1980 earthquake" (Field and others, 1981).

## Techniques

A brief survey of the area offshore of the Klamath River was made on December 17, 1980, aboard the U.S.G.S. research vessel S.P. LEE. A total of 185 line km were profiled at an average speed of 4.9 kts using a 3.5 kHz transducer system and a E.G.& G. Uniboom high resolution seismic system. Tracklines were established to delineate the trend and continuity of offset in the seafloor; in general the tracklines were perpendicular to the orientation of the regional and local structural fabric. Positions of the S.P. LEE were continuously plotted using LORAN-C and satellite navigation; accuracy of positioning is estimated to be about 1.0 km. Corrections to the navigation data were made underway using radar fixes. Records obtained from both seismic systems were printed on Raytheon LSR-1811 analog recorders. The Uniboom system employs four hull-mounted plates that operate at a combined power output of about 1200 Joules. The return signal was received on two 20-element Del Norte hydrophones and passed through Kronhite band-pass filters to eliminate frequencies less than 200 Hz and greater than 1800 Hz. The source

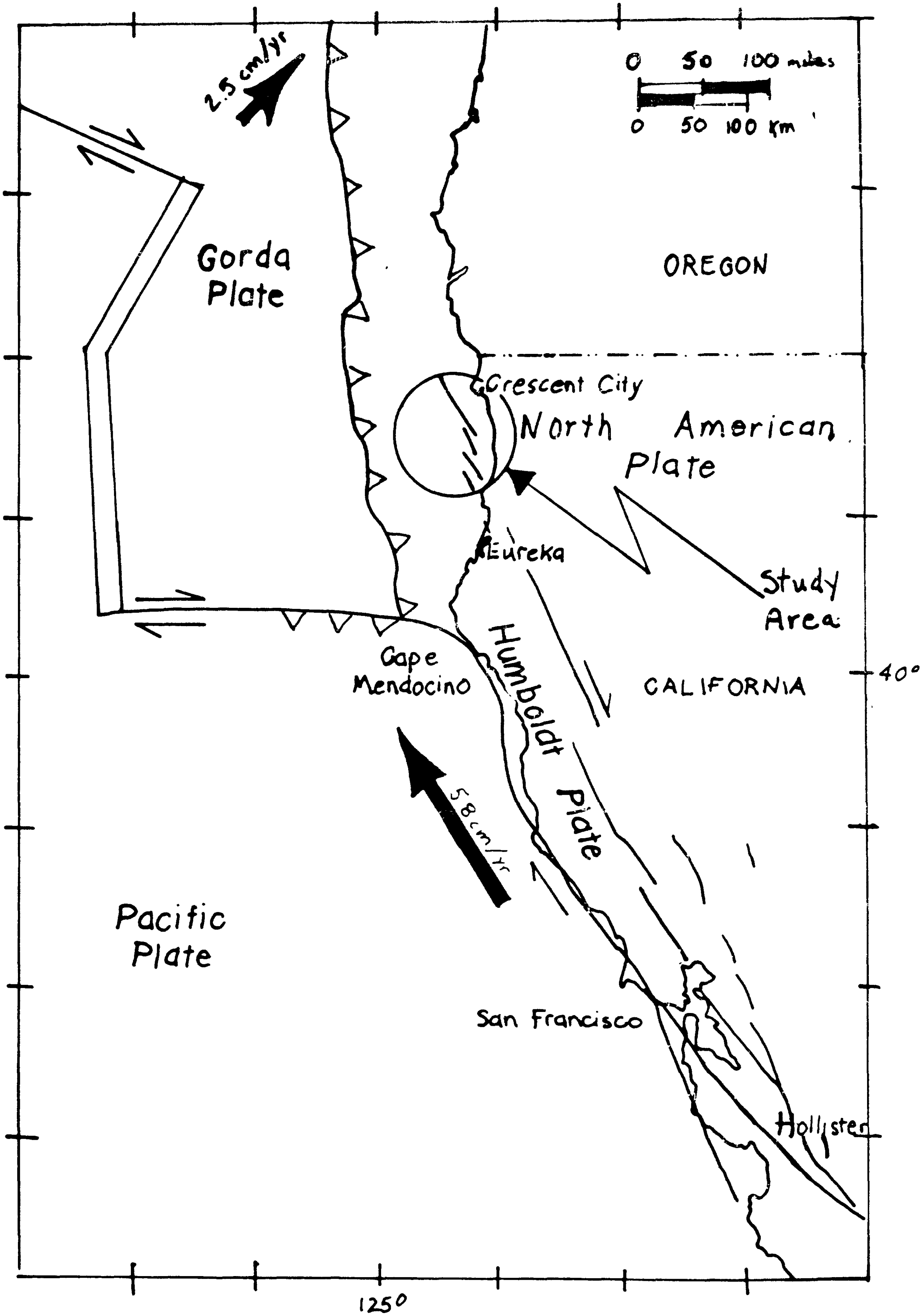



Figure 1. Map of California-Oregon continental margin showing the study area south of Crescent City. Modified from Herd, (1978).

was fired and data printed at one-half second intervals. Depth scales shown in figures of both Uniboom and 3.5 kHz records are based on an assumed velocity of sound in seawater of 1464 m/sec. Seismic signals from the 3.5 kHz hull-mounted transducers were emitted and received at one-quarter second intervals. Incoming signals from the 3.5 kHz tranducer source were both directly printed on an analog recorder and were simultaneously passed through a TSS swell filter (to eliminate variation in the signal due to ship motion) and printed on a slave recorder.

## Geologic Setting

The primary area of investigation is between the 30 and 80 m isobaths on the continental shelf offshore of the mouth of the Klamath River. The area lies along the eastern margin of the Eel River Basin, a thick sequence of Neogene sediment that extends from Eureka California to Cape Sebastian, Oregon (Fig. 1). Regional geology of the continental margin of northern California has been discussed by Silver (1969), Hoskins and Griffiths (1971), McCulloch and others (1977) and Field and others (1980). Details of sediment thickness and lithology, and local structural trends near the mouth of the Klamath River are presented by Moore and Silver (1968), Welday and Williams (1975) and Field and others (1980).

The continental shelf south of Crescent City is characterized by a series of major, northwest-striking faults. The faults generally are west-side down, and although Bolt and others (1968) resolved a right-lateral strike slip component from first motion studies, the dominant style and total offset along the faults is not known. Rocks of the Franciscan Formation are exposed on land and on the seafloor east of the fault zone. West of the fault zone

Franciscan rocks lie beneath Neogene and lower Quaternary strata which are tightly folded and faulted. The surface of this unit is marked by a major erosional unconformity of Pleistocene (?) age that is overlain by flat-lying upper Quaternary sediment. Quaternary-age surficial sediment ranges from 20 to 40 m thick on the shelf adjacent to the Klamath River and varies from silt-bearing sand nearshore to clayey silt offshore (Field and others, 1980).

## RESULTS OF THE POST-EARTHQUAKE SURVEY

### Twenty-km-long Scarp and Terrace

Reports by commercial fishermen indicated the presence of an offset in the seafloor of several meters high and several kilometers long. Orientation was reported both as west-east and northwest-southeast. Survey lines from the December post-earthquake cruise are shown in Figure 2. No evidence of a scarp was detected along the southernmost line (T-1), the northernmost line (T-10), or the shore-parallel lines (T-3, T-6). On all other lines however at least one, and commonly several, distinct scarps were recognized. The most prominent of these scarps is an apparently continuous linear scarp that forms the seaward side of a terrace and that is mappable for a distance of about 20 km (Fig. 2). The continuity of the scarp and terrace is inferred from its presence on eight lines always at a water depth of almost precisely 61 m. Spacing between the seismic lines at that depth varied from one to five km (avg: 2.5 km), and it may be that the feature is discontinuous in places.

The dominant pattern is a single, nearly-flat terrace averaging about 700 m in width, with an abrupt scarp, approximately 1.5 m high, on its seaward side and a change-of-slope that marks its landward edge. This pattern is best

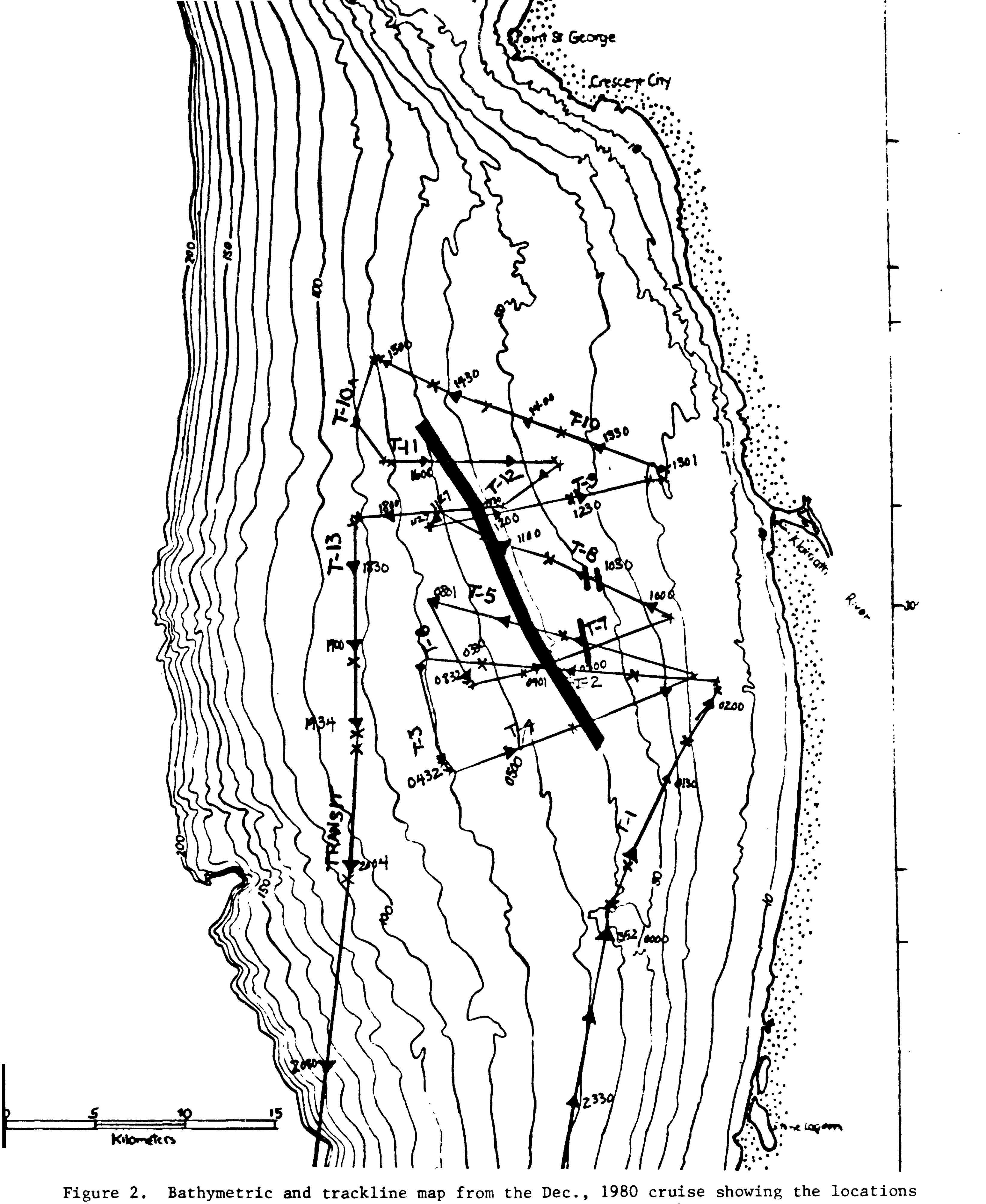



Figure 2. Bathymetric and trackline map from the Dec., 1980 cruise showing the locations of the scarp and terrace couplets, (heavy black lines).

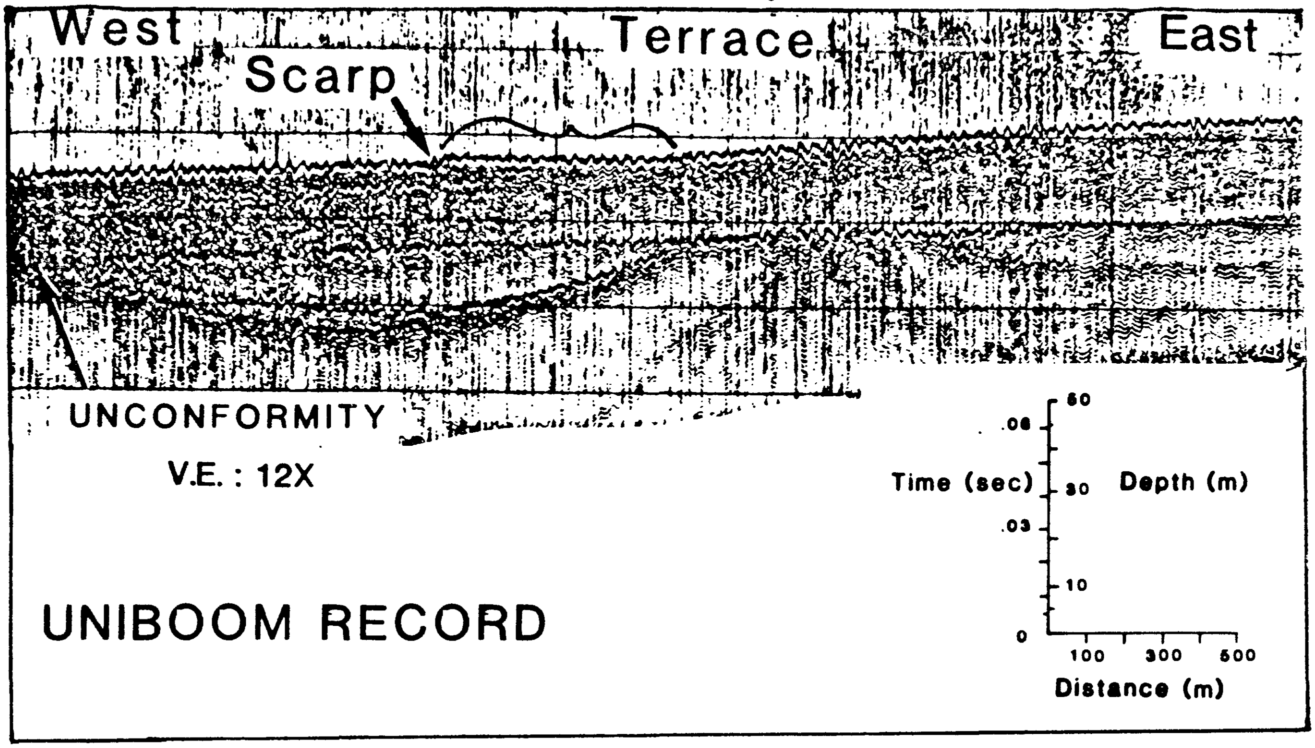
exemplified by profiles taken along line T-4 (Fig. 3). Measurements of scarp height, terrace width, and seafloor slope are given in Table 1. Values for terrace width and slope are corrected for orientation of the profile line. Slopes were calculated from measurements on the 3.5 kHz records, and imprecision in these measurements may have introduced errors of as much as 50% of the given values. There is a significant (factor of 2 to 30) difference between the slope of the terrace and the slope of the adjacent landward and seaward seafloor. Differences in slopes measured on different lines can be accounted for by real differences in the slope of the shelf in the vicinity of the Klamath River delta. For a test of the true dip calculations, measurements made from NOAA bathymetric chart 1308-N12 (scale 1:250,000) yield slope values of 0.15° to 0.25° for the shelf between 30 to 70 meters, versus slope values calculated from the 3.5 kHz profiles of 0.13° to 0.27°.

The seaward edge of the terrace on nearly all lines is delineated by a single scarp 1.0 to 1.5 m high. In two cases, however, the seaward edge is marked by two or more scarps. There are four distinct scarps composing the boundary on line T-5 (Fig. 4). The maximum single offset is about 1.5 m, and the aggregate offset of all four scarps is approximately 3.5 m.

The measured width of the terrace varies from 635 m (line T-12) to 1060 m (line T-9; Fig. 5); most values range from 650 to 780 m. The landward edge on most profiles is marked by a change in slope that is difficult to define locally. This inflection point, or hinge line, is marked by a net change in slope of only several hundredths of a degree. Vertical exaggeration of 12X on the 3.5 kHz records exaggerate this slope change and facilitate locating the landward edge of the terrace.

Sediments of the upper 5 m of the seafloor are offset along the scarp

# LINE T-4



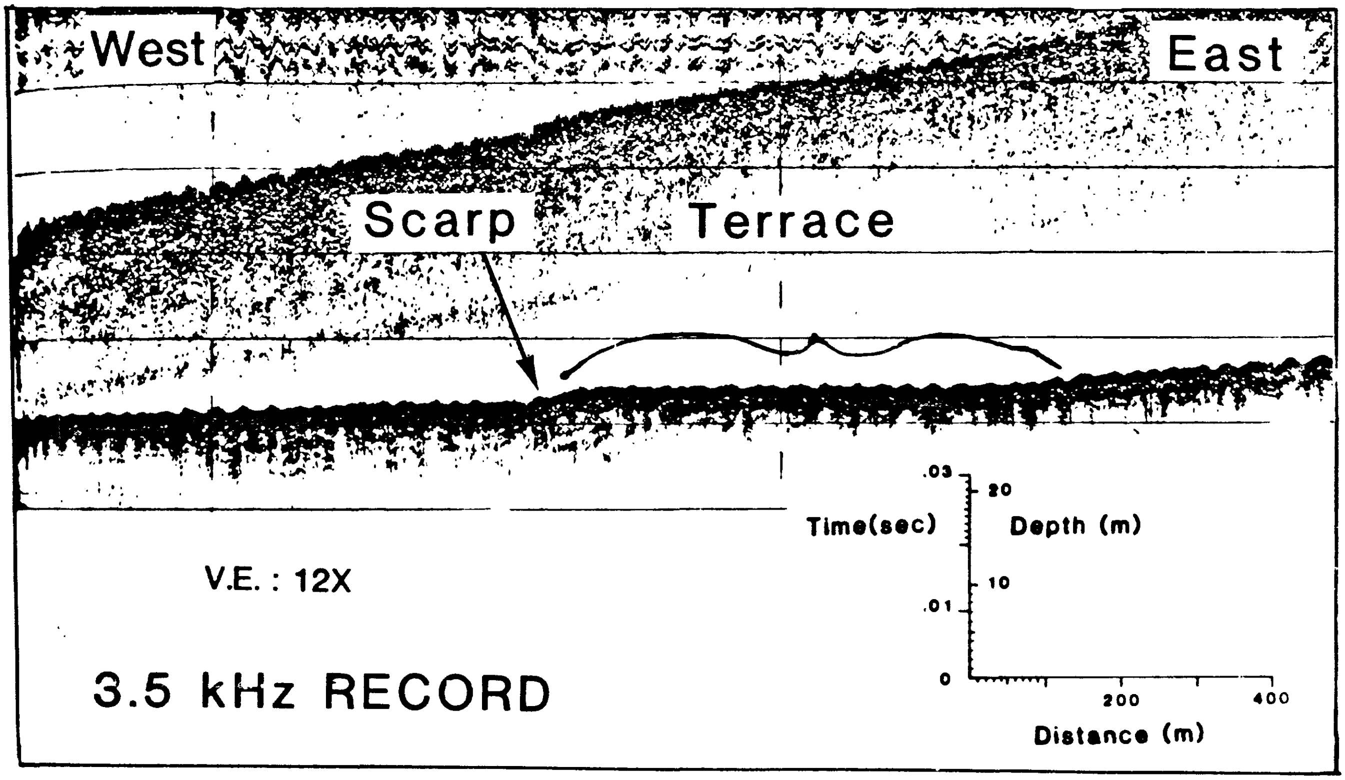
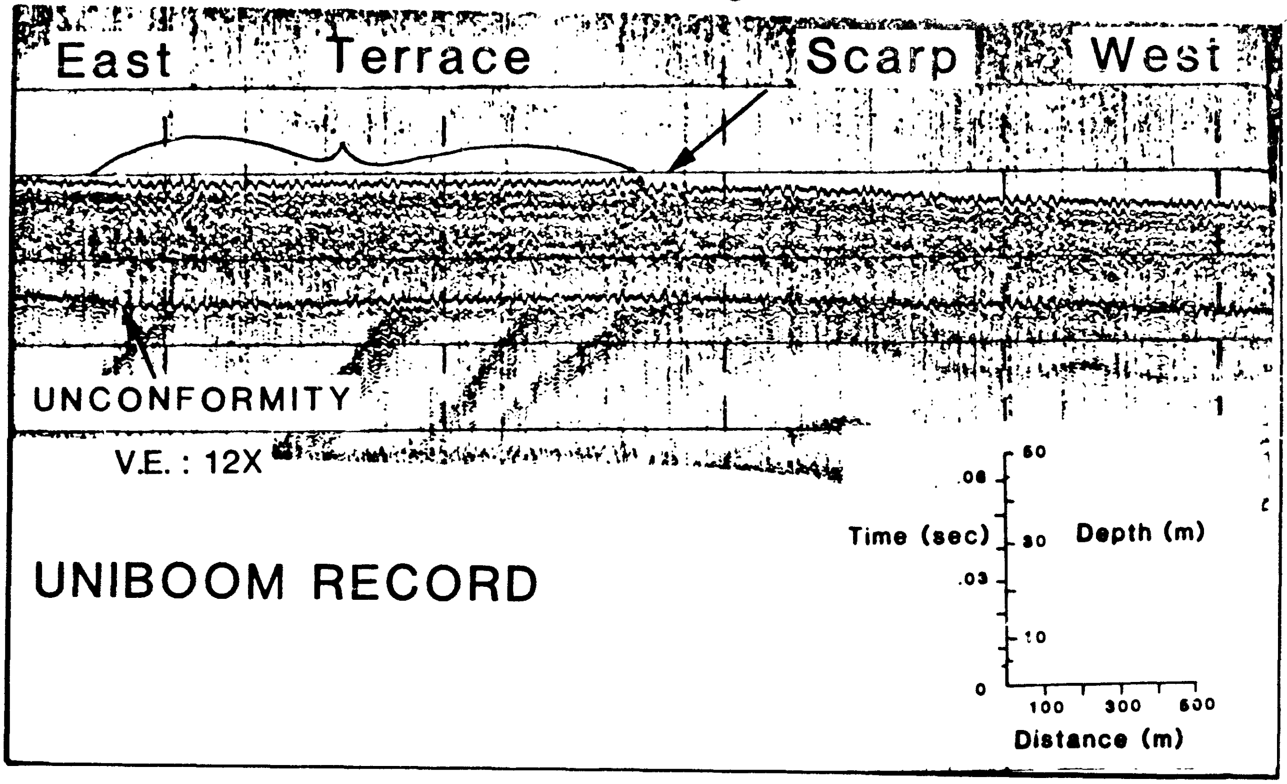




Figure 3. Uniboom (top) and 3.5 kHz (bottom) profiles taken along line T-4 illustrating the dominant pattern of the main scarp and terrace.

# LINE T-5



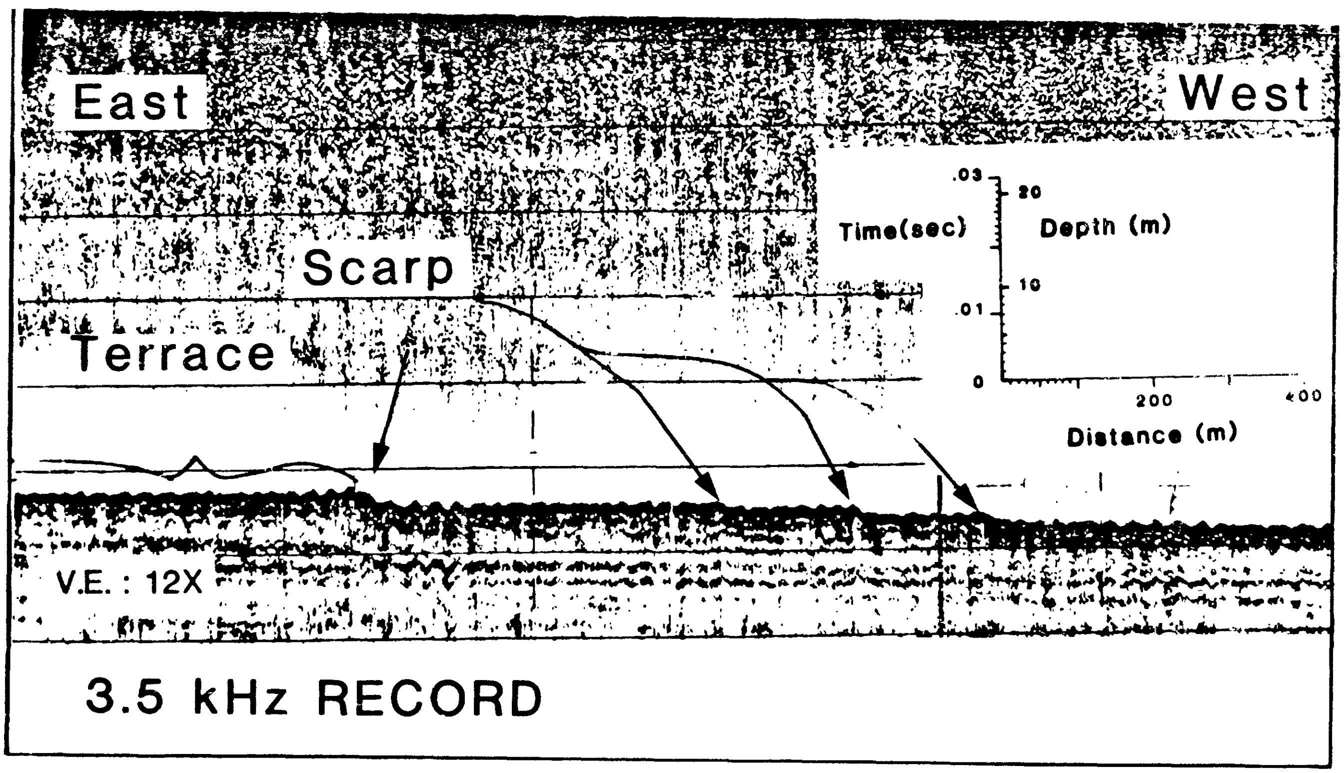
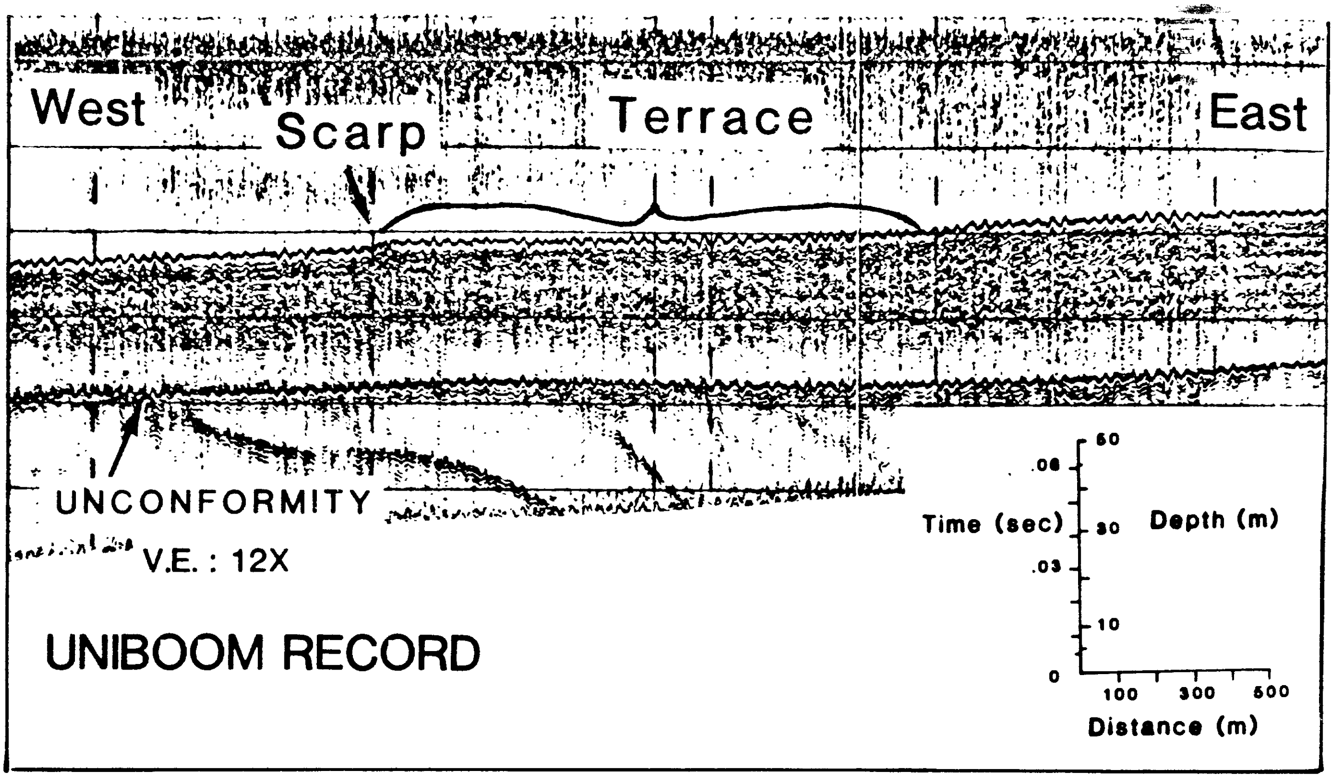




Figure 4. Uniboom (top) and 3.5 kHz (bottom) profiles taken on line T-5 showing multiple scarps with a total offset of 3.5 m.

## LINE T-9



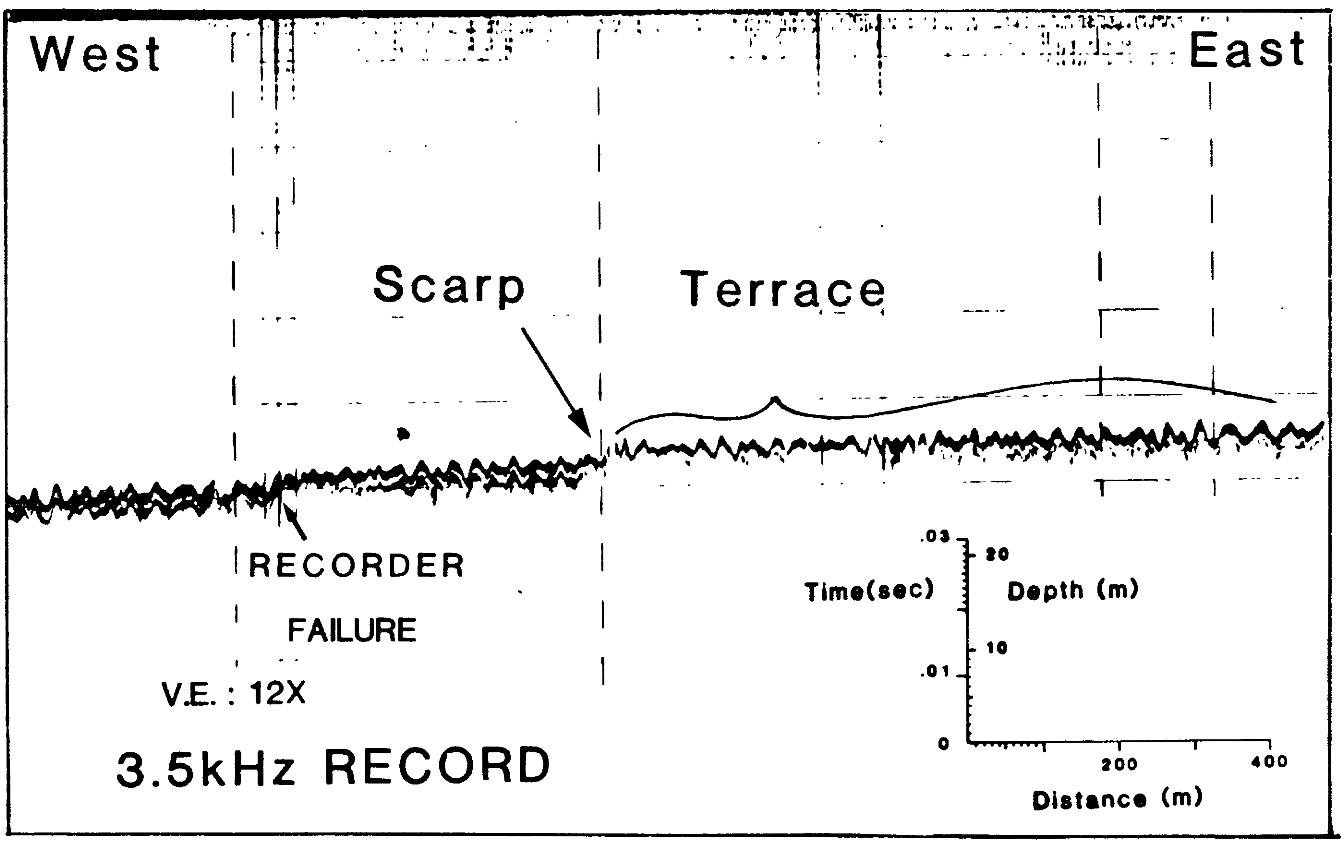




Figure 5. Uniboom (top) and 3.5 kHz (bottom) profiles illustrate that the terrace where crossed by line T-9 is at its greatest width along the feature.

CHARACTERISTICS OF THE MAIN SCARP AND TERRACE

| LINE NUMBER | WATER DEPTH (base of Scarp) | NUMBER OF OFFSETS | SCARP HEIGHT (composite) | WIDTH OF TERRACE | SEAFLOOR SLOPES Seaward of Terrace | Terrace | Landward Terrace |
|---|---|---|---|---|---|---|---|
| T-11 | 67m | 1 | 1.0m | 765m | .29° (.31°) | .01° (.01°) | .22° (.24°) |
| T-12 | 64m | 1 | 1.0m | 635m | .26° (.27°) | .01° (.01) | .20° (.20°) |
| T-9 | 62m | 1 | 1.25m | 1060m | .14° (.14) | .06° (.06) | .10° (.10) |
| T-8 | 61m | 1 | 1.5m | 720m | .14° (.21) | .05° (.05) | .11° (.17) |
| T-5 | 64m | 4 | 1.5m (3.5m) | 920m | .14° (.18) | .01° (.01) | .12° (.15) |
| T-7 | 61.5m | 1 | 1.0m | 700m | .15° (.15) | .12° (.12) | .18° (.18) |
| T-2 | 63m | 3 | 0.8m (1.5m) | 780m | .14° (.16) | .01° (.01) | .19° (.22) |
| T-4 | 64m | 1 | (1.5m) | 650m | .13° (.13) | .02° (.02) | .23° (.23) |
| AVG | 63.3 | | 1.1 (2.2) | 778.8 | (.19) | (.04°) | (.18°) |

Top No. is apparent value
Bottom No. is True value

line. However, the transparent and diffuse acoustic character of the late Quaternary sediment makes it difficult to resolve offsets deeper in the section. Despite the fact that there is clear evidence for vertical offset (separation) of the upper 5 m of seafloor sediment, the underlying unconformity does not appear to be offset. Thus the displacement was restricted to the geologically young surface and near-surface strata.

## Other Scarps and Ridges

Several other scarps were observed in addition to the scarps associated with the terrace. A distinct one-meter-high scarp was identified on line T-2 at a water depth of 70 m (Fig. 6a), but there was no evidence for continuation of the scarp on adjacent line T-7 (not shown). A well-defined scarp was identified inshore of the main scarp and terrace on lines T-5, 7 and 8. This scarp is 1.0 to 1.5 m high and is continuous for approximately five km. It marks the seaward edge of a 700 m wide terrace not associated with the main terrace (Fig. 6b).

High resolution 3.5 kHz profiles along lines T-11 (not shown) and T-12 (Fig. 6c) reveal a 3.5 km wide zone where the seafloor is marked by a series of small, nearly-symmetrical ridges (Fig. 6c). The ridges are as high as four meters, are about 70 m wide and are similar in shape and size to ridges identified by commercial fishermen from high-frequency fathometer records collected immediately following the November 8, 1980, earthquake. These fishermen had not previously found such ridges in the area.

## Pre-Earthquake High Resolution Geophysical Data

Deep penetration and high resolution seismic reflection profiles were

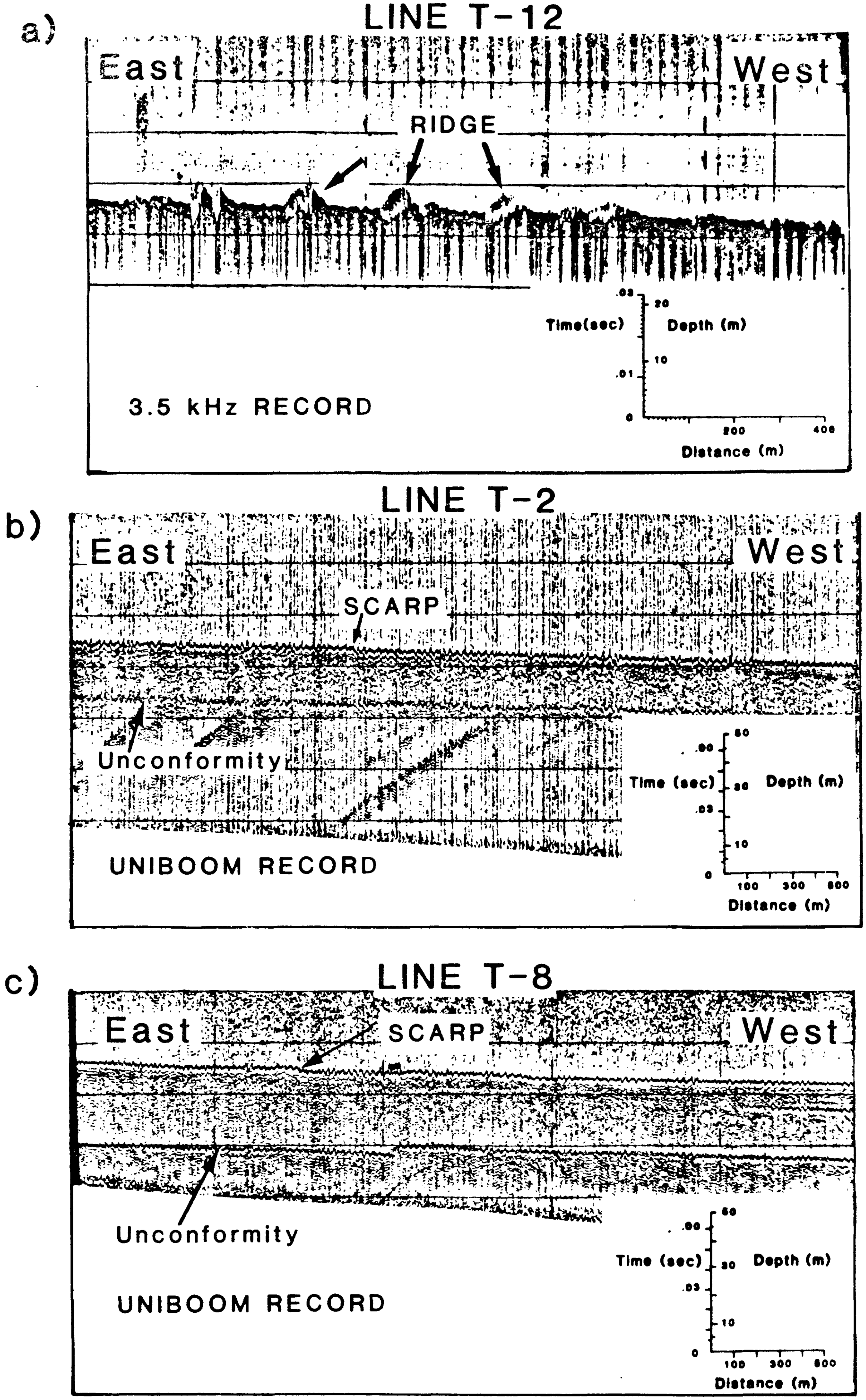



Figure 6. a) Uniboom record from Line T-2 showing small scarp at 70 m. b) Uniboom record from Line T-8 showing small scarp at 50 m. c) 3.5 kHz record showing small nearly symmetrical ridges that appear on Lines T-11 and T-12.

obtained from the northern California continental margin in 1977, 1978 and 1979 as part of a general geologic and geohazards study of the northern California continental margin. Vessel location was determined on these cruises by use of LORAN-C, satellite navigation and high resolution microwave (Miniranger) navigation. Location accuracy with the Miniranger system was about ±50 m. Some of these profiles (1977, 1979) lie in this area and provide a basis for evaluating changes in the seafloor after the earthquake (Fig. 7). These records show that no scarps or terraces were present in either Nov., 1977 or Nov., 1979 but rather, the seafloor was smooth and gently sloping (Figs. 8, 9). Changes in slope on these earlier records are smooth and probably attributable to recent sediment deposition. Uniboom and 3.5 kHz profiles obtained along Line 134, which lies between post-earthquake lines T-5 and T-2 show a flat seafloor (Fig. 8). The relative location of these lines can be established by comparison of the fold limbs beneath the unconformities in the Uniboom records (Fig. 4 and 8). Similarly, pre-earthquake Line E12 (Fig. 9, top) lies between post-earthquake lines T-5 and T-8, yet shows no evidence of offsets. Similarly, line 133 (Fig. 9, bottom) lies parallel to line T-4 (Fig. 3), and shows no evidence of offsets; these lines can be correlated by comparison of fold structures beneath the unconformity.

## DISCUSSION

### Relation of Failure Location to Local Geologic Patterns

The 20-km-long scarp and terrace couplet lies sub-parallel to major structural trends in the area (Fig. 10). Fault and fold axes strike north-northwest (Field and others, 1980) and the strike of the scarp follows the

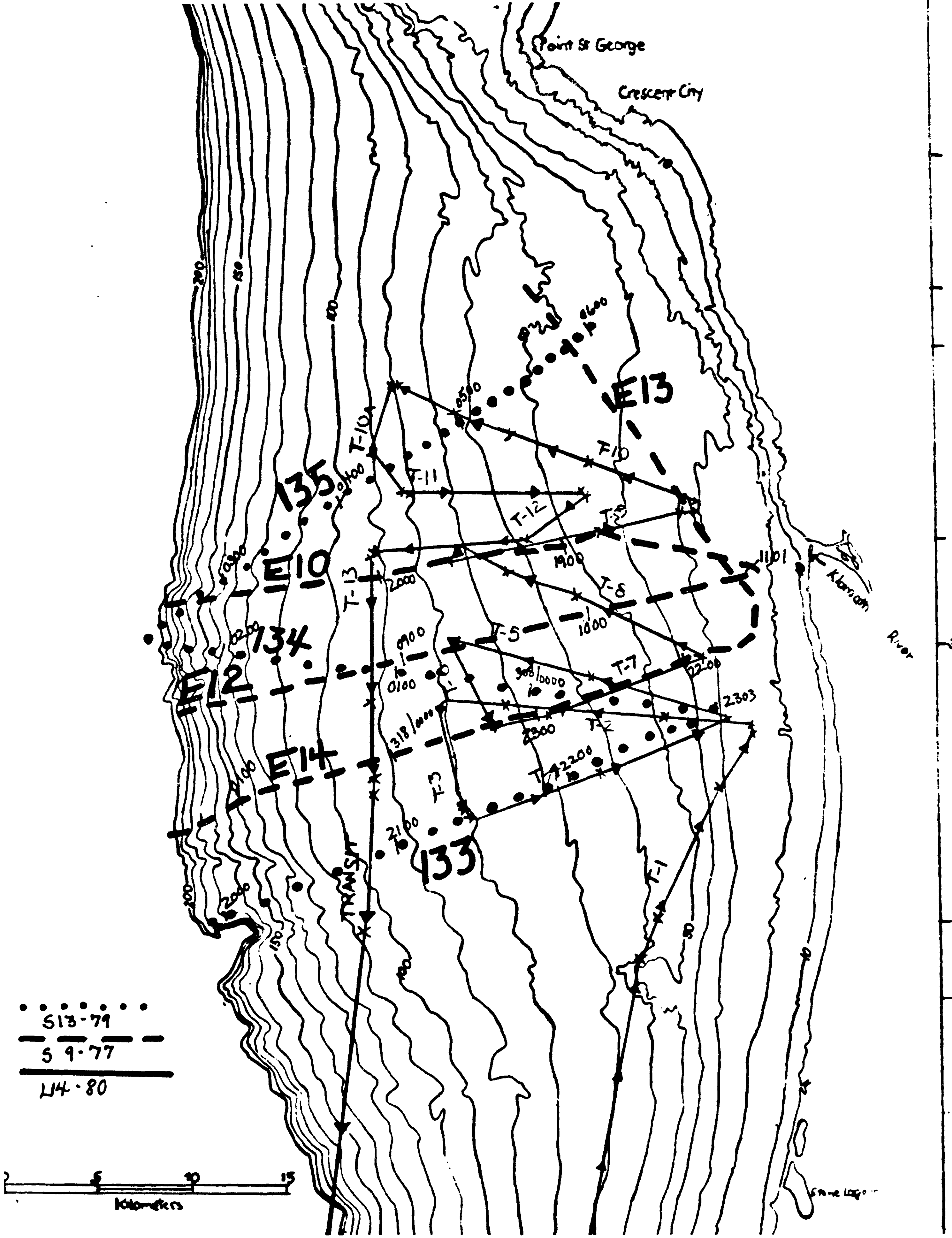



Figure 7. Tracklines from pre-earthquake cruises (1977, 1979) analyzed for comparison with the post-earthquake data.

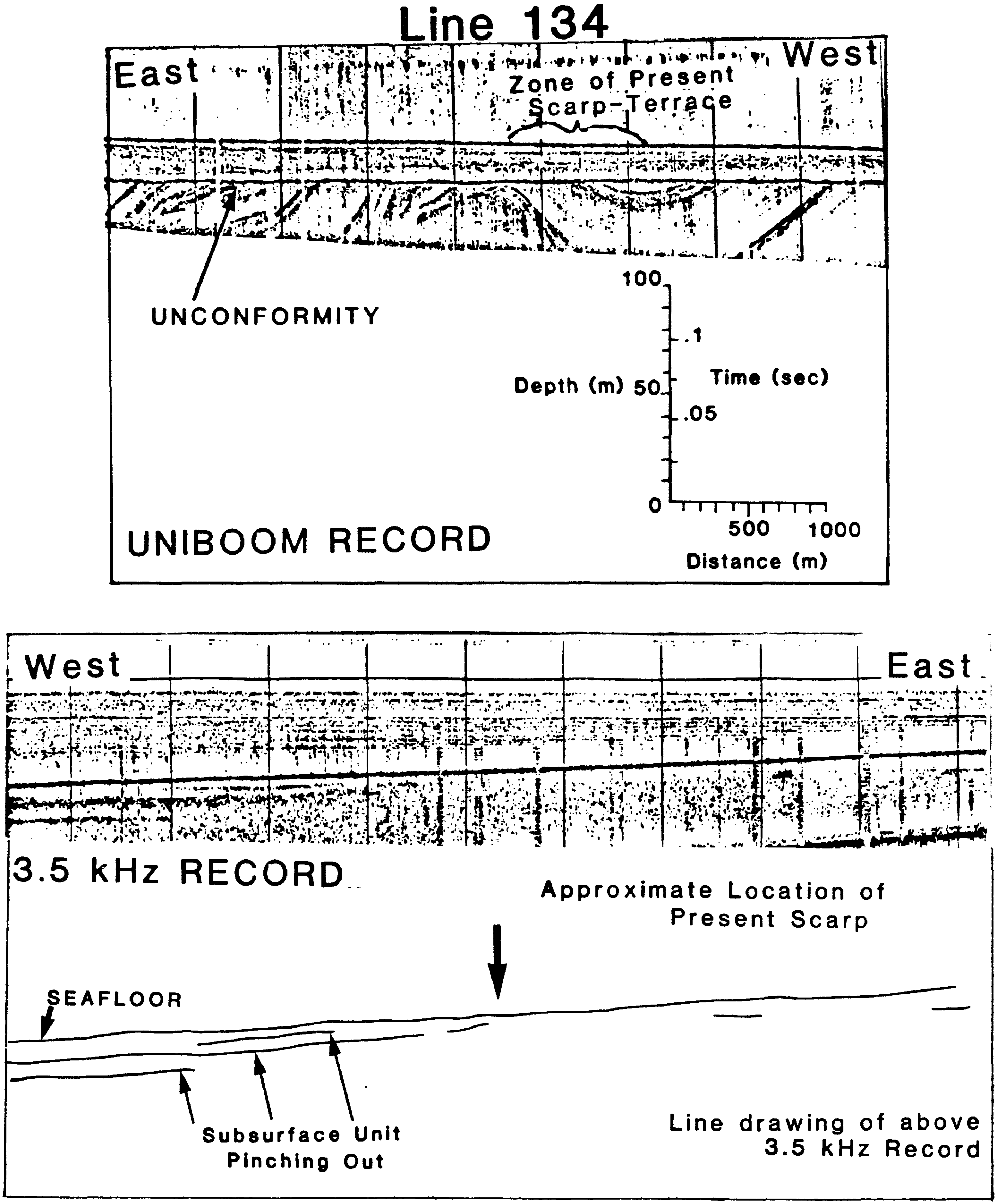
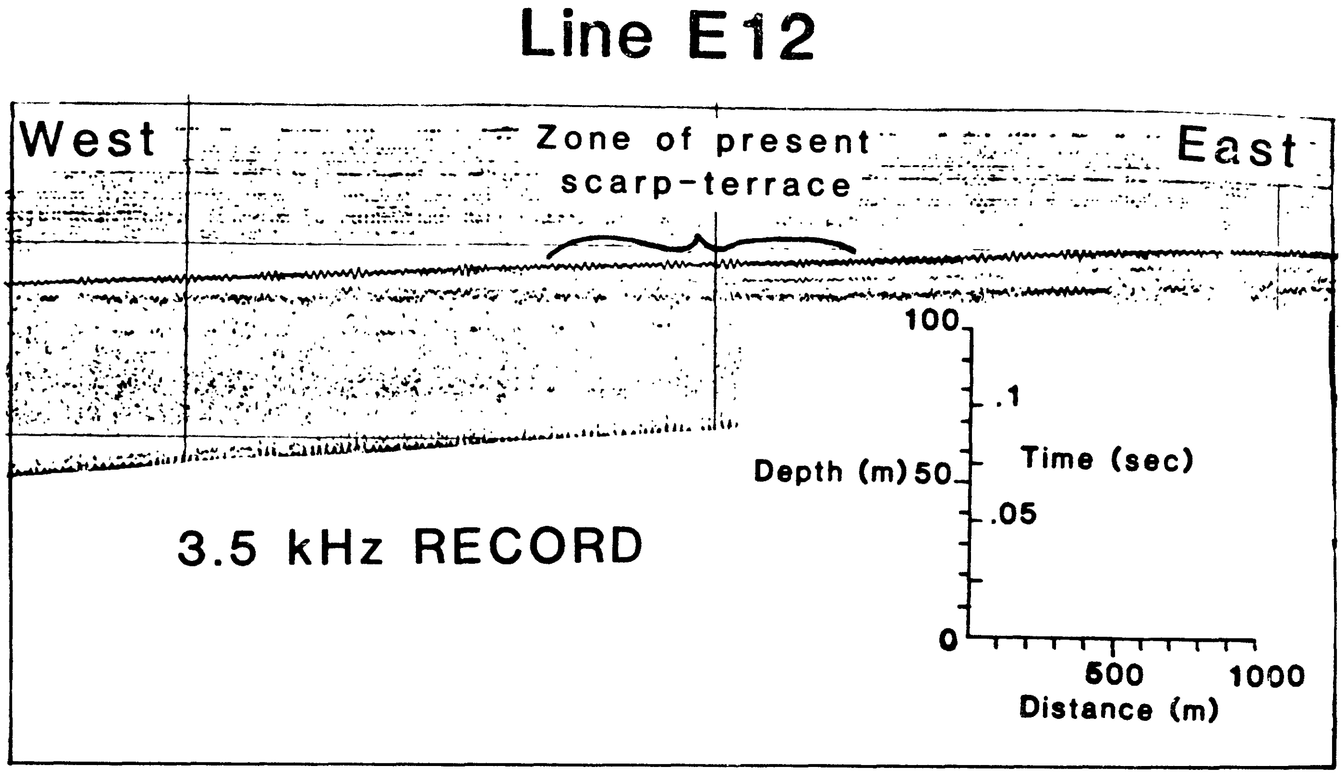



Figure 8. Uniboom (top) and 3.5 kHz (bottom) records collected along Line 134 in 1979. Note the absence of either a scarp or a terrace. The scale above applies to both records.

a)




b)

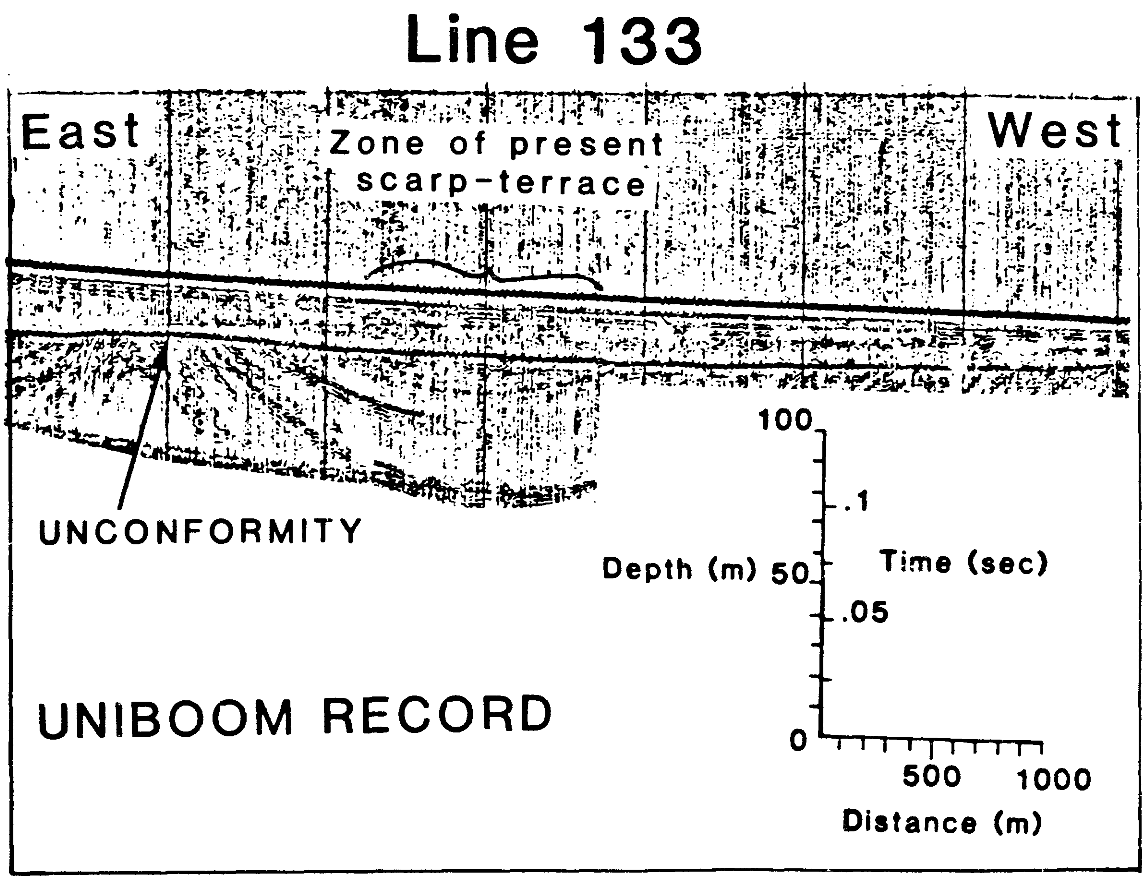



Figure 9. a) Line E12, of the 1977 survey shows that the seafloor was smooth and gently sloping in the zone of the present scarp-terrace couplet. b) Line 133 from the 1979 survey is parallel to Line T-4 from the 1980 post earthquake cruise but the seafloor is featureless in the zone of the present scarp.

same general trend. The folds mapped by Field and others (1980) shown in Figure 10 can be seen in cross-section in Uniboom profiles in Figures 3, 4, 5, 8, and 9. The absence of a rupture in subsurface sediment, particularly sediment underlying the Pleistocene unconformity, suggests that the scarp is not a fault rupture. More likely, the scarp and terrace represent near-surface sediment failure and rotation induced by ground shaking.

The scarp zone is located on a thick lens-shaped sediment unit lying northwest of the Klamath River (Fig. 11). Field and others (1980) showed the thickness of Quaternary sediment in this area to range from 20 to 50 m. The scarp crosses an area where unconsolidated sediment is about 20 to 30 m thick. This thick sediment unit probably resulted from late Quaternary fluvial deposition onto the shelf. High-resolution seismic-reflection profiles indicate that the sediment unit above the unconformity is not uniform and that, in the vicinity of the scarp, several shallow, gently dipping acoustic horizons climb toward the seafloor (Fig. 9). These acoustic units probably indicate a contrast of lithologic units that resulted from different patterns of sedimentation. The grain size of surficial sediment in the area was mapped by Welday and Williams (1975), and based on their generalized map, the newly formed scarp nearly coincides with the contact between sand and mud (Fig. 12). The approximate coincidence of the sand-mud contact with the scarp (Fig. 12) suggests that the failure may have been controlled by the character of the seafloor sediment.

## Style of Failure

The appearance of the scarp following the Nov. 8, 1980, earthquake indicates that it was triggered by that event and its location suggests that

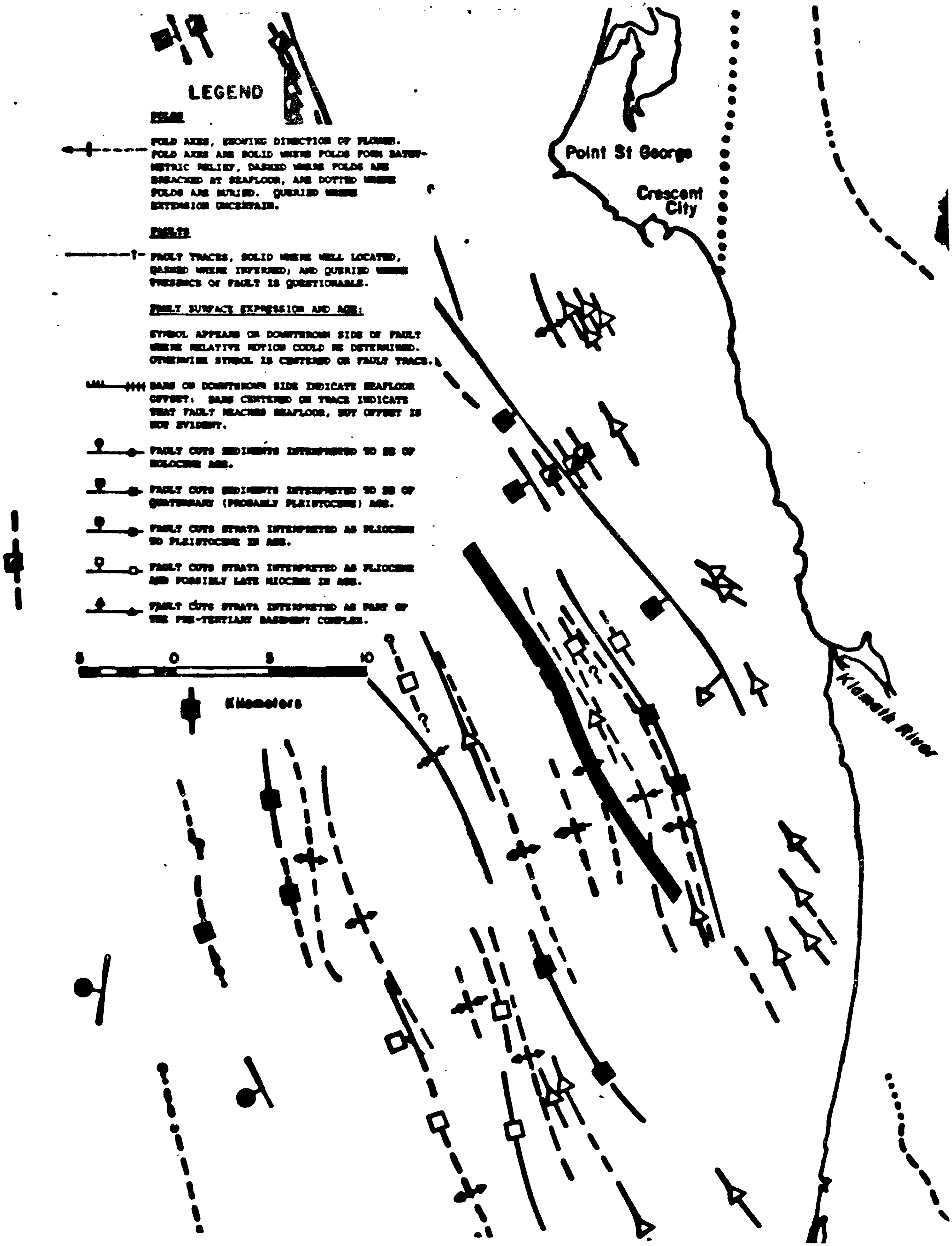



Figure 10. Position of scarp and terrace (heavy black line) in relation to the local structural trends offshore northern California. From Field and others (1980).

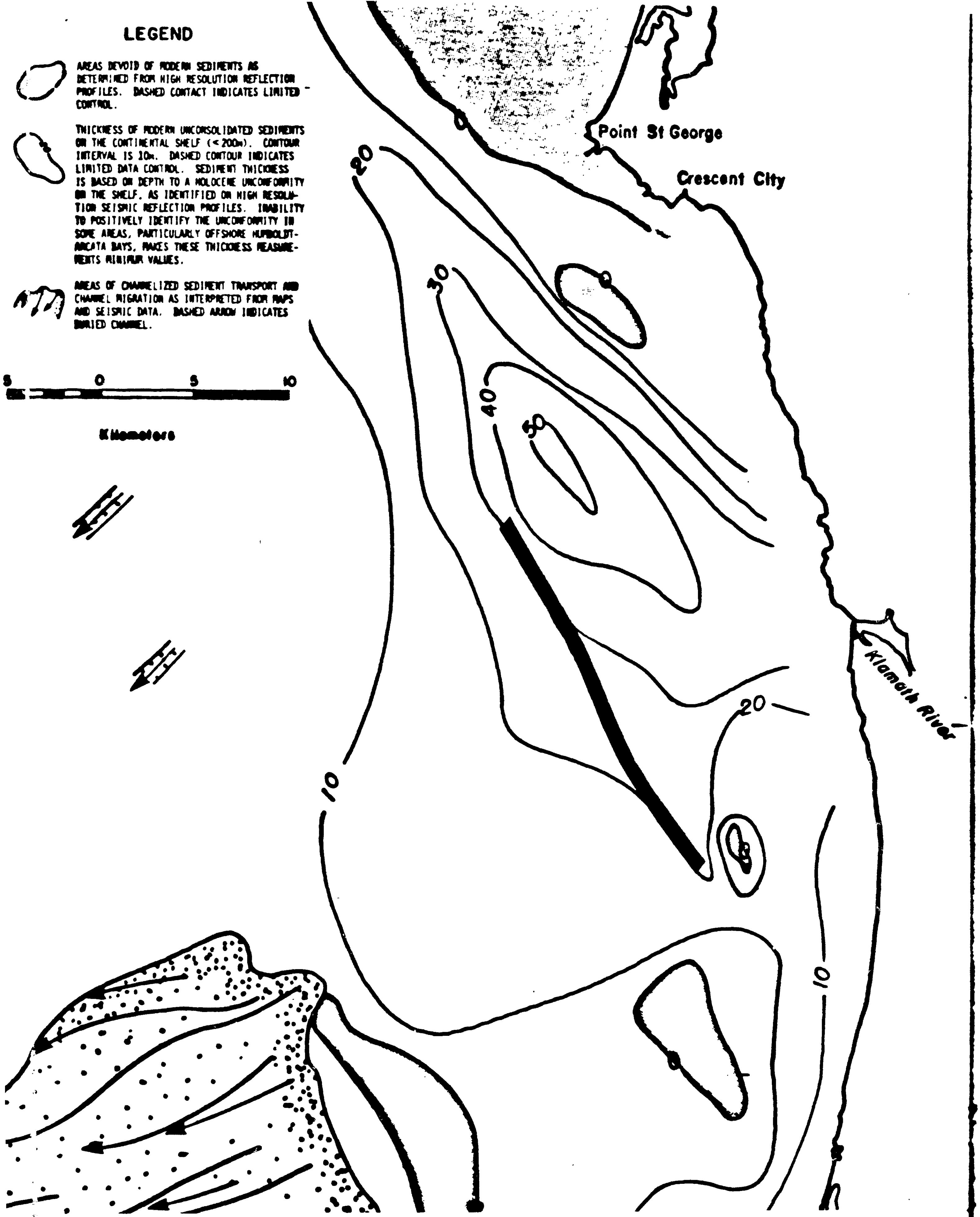



Figure 11. Position of scarp and terrace (heavy black line) relative to sediment thickness in the study area offshore northern California. From Field and others (1980).

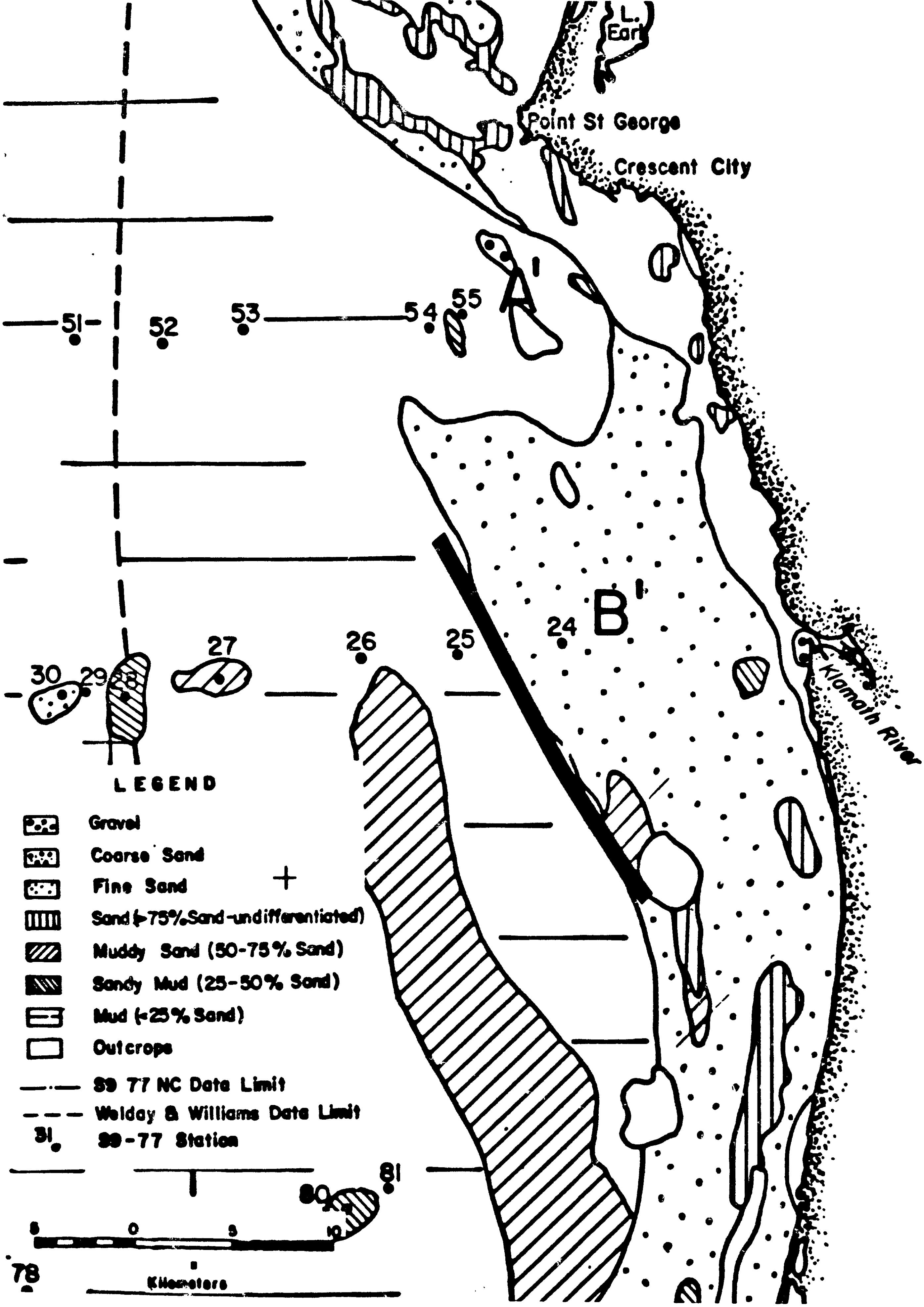



Figure 12. Surficial sediment texture map showing the position of the scarp and terrace (heavy black line). Note the coincidence of the scarp and the textural contact between sand and mud. From Field and others (1980).

its orientation and presence were controlled by the contact of dissimilar surface-sediment units. The failure mechanism is unknown.

The geometry of the scarp and terrace suggests that the failure occurred by simple rotation (Fig. 13). This rotation may have been preceded by translation of a thin slab of surface sediment across the shelf, which would eliminate some resistance at the decoupling point and facilitate simple rotation. The ridges identified west of the scarp on Lines T-11 and T-12 (Fig. 9) may be compressional features which would support a translation-followed-by-rotation mechanism. The extent and character of the ridges is unknown, however, and there are other processes which may have produced them.

Rotational failure as shown in Figure 13 accounts for rotation of the terrace surface from a very low slope ($\tilde{}0.2^\circ$) to a nearly flat surface ($.01^\circ$). This style of failure also would account for the noted variation in the width and attitude of the terrace surface. There are, however, several observations not explained satisfactorily by simple rotation or other styles of failure. These are: 1) the linearity of the scarp over a very large distance (20 km); 2) the length of the scarp-terrace (20 km) relative to its narrow width (<1 km); 3) the absence of an identifiable failure plane; and 4) the relative thinness (~5 m) of the failed section relative to its width and length. Some of these characteristics may have been controlled in part by the lithologic character and orientation of shallow Quaternary sediment units, as shown in figures 9 and 12.

Regardless of the exact mechanism of failure, it is clear that an extensive (20 km) zone of failure occurred off the Klamath River as a result of the Nov. 1980, earthquake. The failure occurred in shallow, unconsolidated sediments on a nearly flat seafloor at a distance of over 50 km from the

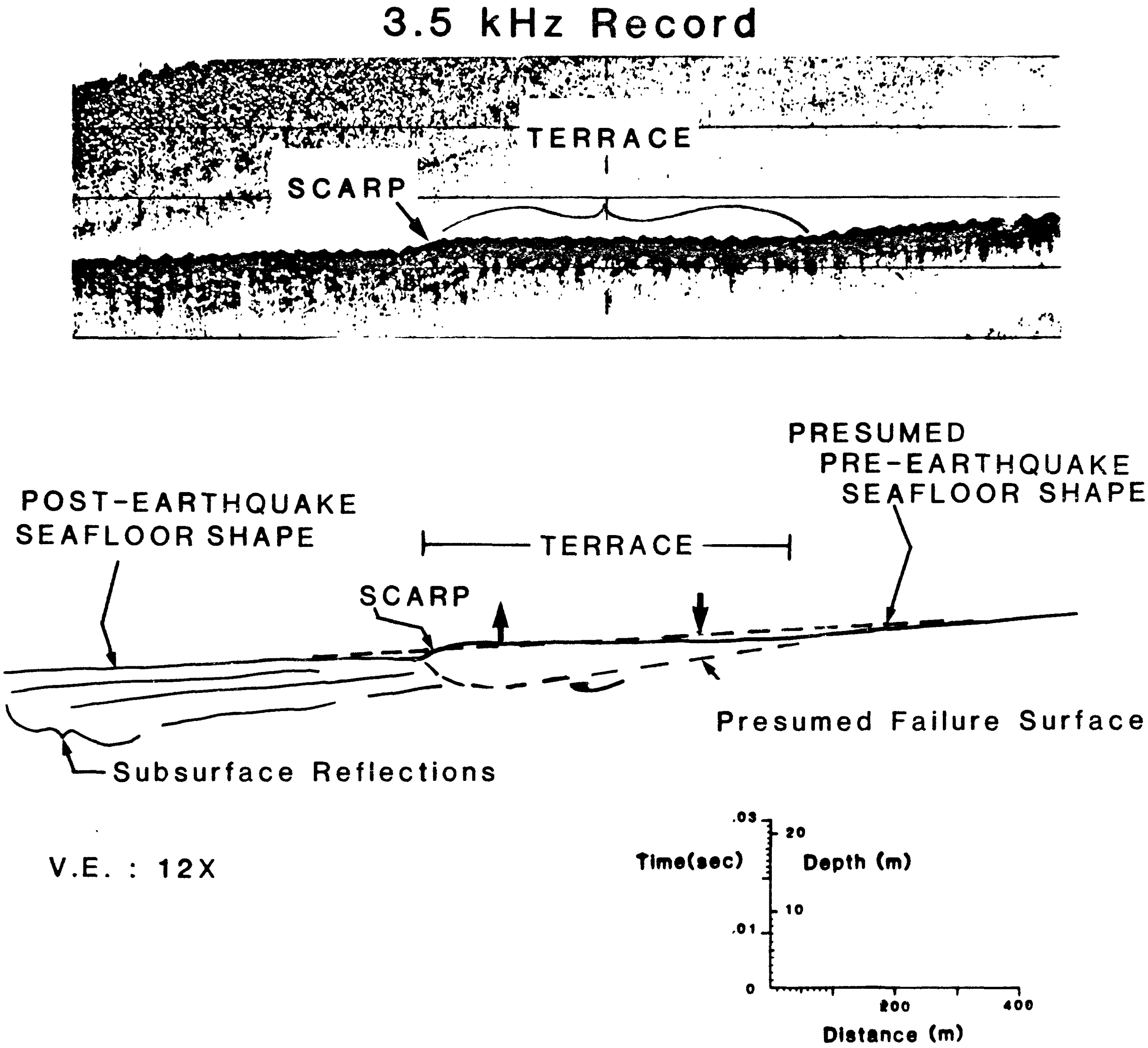



Figure 13. Profile of scarp and terrace on Line T-4 (top) with interpreted line drawing show possible rotational failure (bottom). The thin dashed line indicates the presumed attitude of the seafloor prior to the earthquake. Small black arrows over terrace show relative movement of the terrace surface.

epicenter. The availability of pre-earthquake profiles and the observations by fishermen were crucial to our findings. The geometry, orientation, and water depth of the terrace are such that had it been identified on a routine cruise not associated with investigating earthquake effects, it very likely would have been mapped as a Holocene shoreline terrace formed at a time of lower sealevel.

ACKNOWLEDGEMENTS

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