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A Summary of the Geology and Geologic Hazards in Proposed Lease Sale 53, Central California Outer Continental Shelf

By

D. S. McCulloch, H. G. Greene, K. S. Heston, and D. M. Rubin

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TABLE OF CONTENTS

TABLE OF CONTENTS

ILLUSTRATIONS

TABLES

APPENDICES

PLATES

INTRODUCTION

This report describes the results of studies directed toward the definition and understanding of geological features and phenomena, referred to generally as geologic hazards, that may constrain the extraction and development of possible hydrocarbon resources beneath the central California outer continental shelf. The geophysical surveys on which these studies are based were designed not only to examine the proposed lease areas, but also the adjacent areas, for some geologic hazards, such as seismic shaking and recent depositional patterns, require a more regional understanding.

The introduction and the section on Santa Maria Basin was written by D. S. McCulloch. H. G. Greene and K. S. Heston prepared the section for Outer Santa Cruz Basin, and D. M. Rubin wrote the section on Bodega and Arena Basins. Technical assistance in drafting, data research, and compilation was provided by P. Utter, J. Blank, D. Klingman, P. Swenson, and C. Utter.

Geographic Setting

The proposed lease blocks within Sale 53 lie within five nearshore geologic basins (Fig. 1). From north to south they are Eel River, Point Arena, Bodega, Outer Santa Cruz and offshore Santa Maria basins. This report describes geological hazards within all but the Eel River basin, which is reported by Field and others (1980).

The continental shelf between Point Conception on the south,

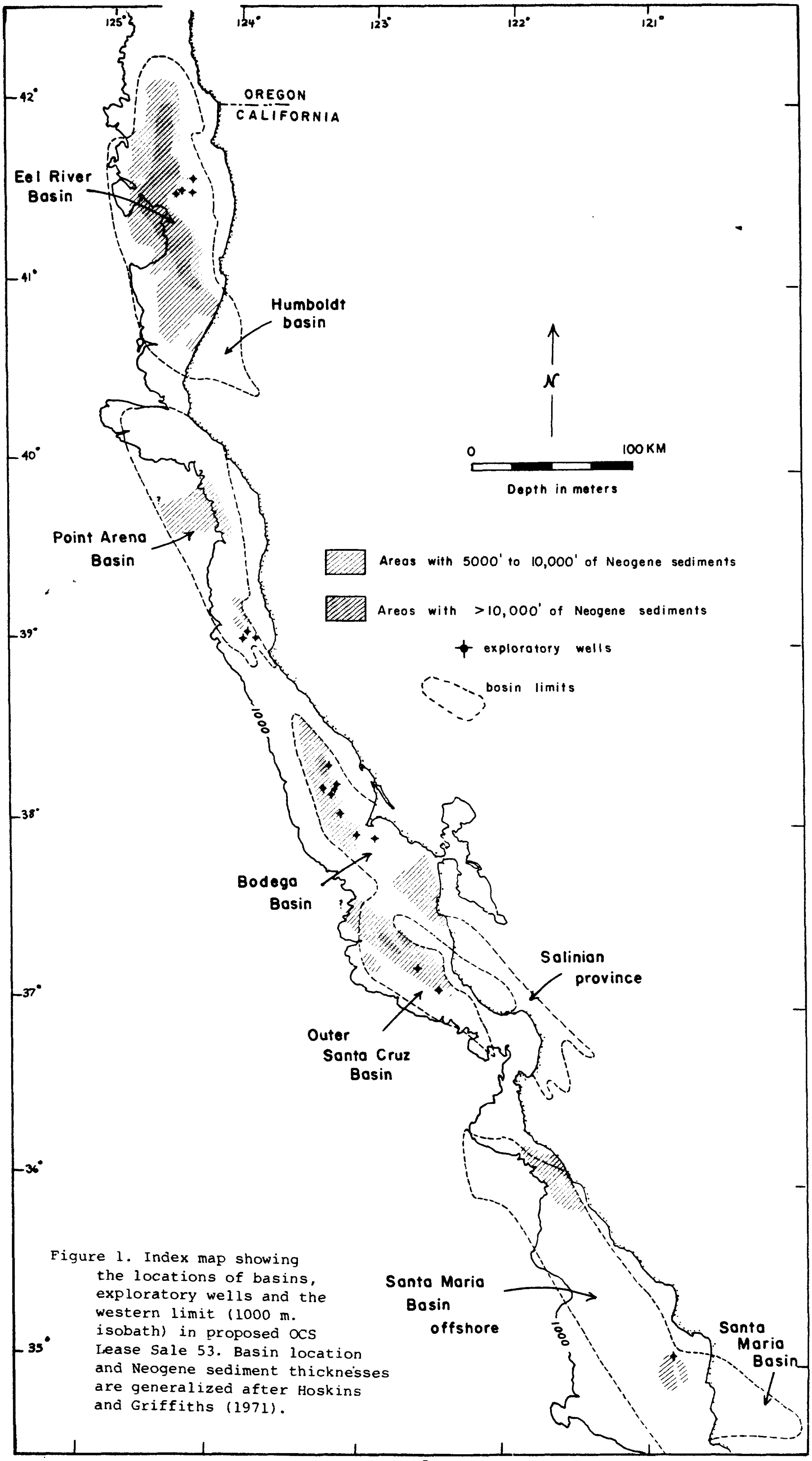


Figure 1. Index map showing the locations of basins, exploratory wells and the western limit (1000 m. isobath) in proposed OCS Lease Sale 53. Basin location and Neogene sediment thicknesses are generalized after Hoskins and Griffiths (1971).

to Cape Mendocino on the north, is approximately 700 km long (Fig. 2). The physiography of the shelf and the adjacent slope varies from north to south, with two major physiographic end members and a middle transition zone. North from Point Sur the well developed gently dipping continental shelf, which varies in width from 10 to 40 km, meets the upper edge of the continental slope at a topographic break at about the 100 fathom isobath. The continental slope merges with the ocean floor at a depth of about 1900 fathoms. From approximately 170 km south from Point Sur to the vicinity of Point Conception, there is no well developed shelf surface, and consequently no well developed topographic break between the shelf and slope. Instead, the shelf merges seaward with the shallow Santa Lucia Bank at a depth of about 300 fathoms. West of Santa Lucia Bank there is no gentle continental slope as to the north, but rather the steep Santa Lucia Bank Escarpment, along which there is about 1500 fathoms of relief. In the transition zone to the north of Santa Lucia Escarpment, there is no well developed shelf or shelf break, but the slope is long and gentle, and it merges with the ocean floor without an intervening escarpment.

To a large extent, the physiography south of the transition zone reflects the fault-bounded structural block of the Santa Lucia Bank, and the steep escarpment of the adjacent paleosubduction zone (Page and others, 1978). Similar structure and physiography is found just to the south in the California Borderland (Fig. 2) where the Patton Ridge is bounded on its

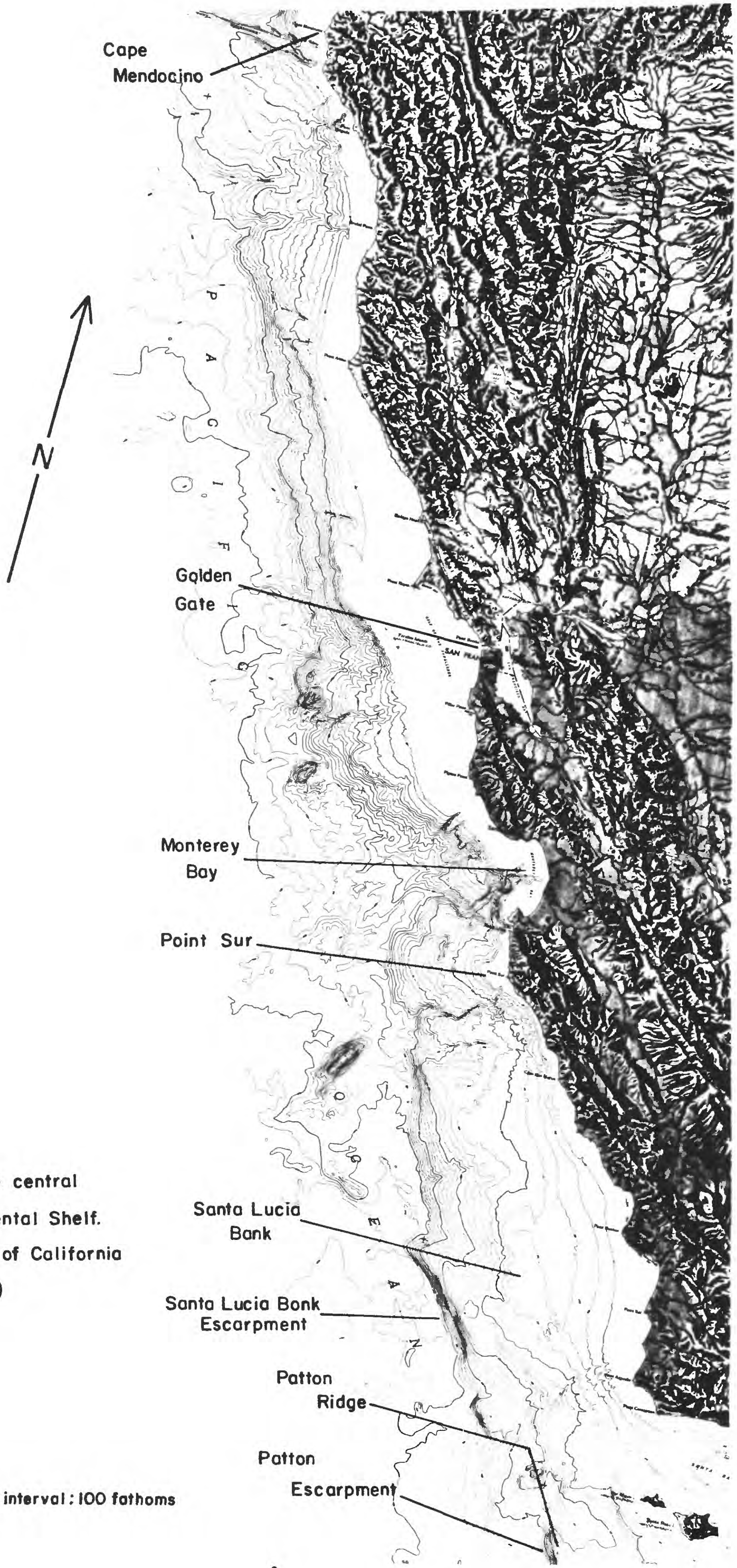


Figure 2.

Physiography of the central California Outer Continental Shelf. (Base from USGS State of California Shaded Relief Map, 1971) seaward side by the Patton Escarpment that lies adjacent to a paleosubduction zone. As noted by Vedder (1976) there is some confusion about the exact meaning of the designation California Borderland, so rather than suggest that the northern boundary of the California Borderland Physiographic Province be moved northward to include the Santa Lucia Bank area, suffice it to say that these areas share grossly similar geologic structures.

Geologic Framework

The geological framework of the central and northern California shelf has been described by Hoskins and Griffiths (1971), McCulloch and others (1977), Howell and others (1978) and additional geological cross sections across the southern part of the shelf have been developed by Page and others (1978), and Ross and McCulloch (1979). The potential resource targets in Lease Sale 53 are geologically young (late Tertiary), relatively shallow basins that have developed largely on the continental shelf. These basins are generally bounded on the west by a structural high along the outer edge of the shelf, and on the east by right lateral strike slip faults, some of which have considerable down-to-the-west vertical separation.

These basins lie along the tectonically active margin between the North American and Pacific Plates. Adjustment to the continuing relative displacement of these plates is not restricted to the San Andreas (Gawthrop, 1975) but is also occurring along faults to the west. Recent offshore geologic mapping (Hoskins and Griffiths, 1971; Greene and others, 1973, Cooper, 1971; Wagner, 1974; Leslie, in press) and seismological studies (Gawthrop, 1975; Coppersmith and Briggs, 1978; Stickney, 1979) have helped to define these faults and establish their recent seismic activity. South from the Golden Gate, seismic activity occurs along a long and as yet not fully understood offshore fault system that approximately parallels the coast line and occasionally comes ashore across coastal promontories. This system includes the Seal Cove fault and an adjacent unnamed fault in the Gulf of the Farallones, the San Gregorio Fault and its offshore extension that crosses Monterey Bay to the south, the offshore Sur Fault, the San Simeon Fault in the Point Piedras Blancas area, and the Hosgri Fault zone that extends at least as far south as Point Sal. Other poorly defined but probably seismically active faults can be found to the south as far as Point Arguello where they are stepped seaward of the Hosgri Fault zone (McCulloch and others, 1979). At the southern end of the lease area the active plate margin is not restricted to this near-shore coastal fault system, but it also includes active faulting along the western edge of the offshore Santa Maria Basin.

In a very general way the tectonic style (folding and faulting) of the shelf appears to be related to the behavior of the underlying basement rocks. Basement rocks beneath the central shelf are not well known but are thought to reflect blocks of differing bedrock terrains that have been juxtaposed by large strike-slip fault displacements. Beneath the offshore Santa Maria Basin and the Outer Santa Cruz Basin, the basement rocks are probably equivalent to the onshore Franciscan complex, composed of a melange of sedimentary and metamorphic rocks, and possibly some mafic and ultramafic rocks. The age of these rocks is conjectured to range from late Jurassic to early Tertiary (Page and others, 1978). Basement beneath the Bodega Basin is known from drill holes, coastal exposures and from rocks that comprise the Farallon Islands to be granitic. This basement block (the Salinian block of Page, 1970) which was faulted out onto the shelf appears to have since been displaced northward from corresponding rocks onshore along the major coastal fault system noted above. North of Bodega Basin, the rocks beneath the Point Arena Basin may again be equivalent to the Franciscan complex. Drill holes in the basin bottom in rocks identified as possible metasediment (Hoskins and Griffiths, 1971), and a Deep Sea Drilling Program core hole (DSDP Leg 18, site 173, Kulm and Others, 1973) bottomed in andesite on the structural high that bounds the west side of the Point Arena Basin. Folding in both the Point Arena and offshore Santa Maria Basin appears to have involved the basement rocks, whereas in Bodega Basin, as noted in a discussion below, the igneous basement rocks appear to have behaved more rigidly.

Geological Hazards

Instability of the seafloor, whether from seismic activity or sedimentary processes, is recognized as the principal hazard to emplacement of platforms and pipelines in the marine environment. Hazards related directly to seismic activity include ground shaking, fault rupture, generation of tsunamis, and earthquake-induced ground failures such as liquefaction and slumping. Faults showing displacement of either the seafloor or young (<11,000 years) sediments as well as those associated with historical earthquakes are considered active and therefore potentially hazardous to development. Instability of the sea floor can also result from dynamic (e.g. wave surge) and static (e.g. gravity) forces acting independently of seismic activity. Some areas of the sea floor are prone to mass movement (e.g. slumps, slides) or other forms of sediment transport (flows, creep, or current scour). Oil and gas seeps, while not inherently hazardous, may provide clues to the location of fractured reservoir rocks and shallow over-pressured gas pockets that can pose a danger to drilling operations. The occurrence of gas increases chances for blowouts, which are considered to be the most costly and feared operational hazards related to oil and gas operations (Danenberger, 1980).

As shown in the basin studies included in this report, all of the proposed lease block areas lie adjacent to one or more seismically active faults, and they can be expected to experience seismically induced ground motion. Slumps and slides have been mapped in the Point Arena and offshore Santa Maria basins, and evidence for shallow gas exists in, or adjacent to, all the proposed lease areas.

One mode in which shallow gas is found in several of the basins (Outer Santa Cruz, Bodega, Arena) has not previously been described. This gas occurs in strata on the upper continental slope and the adjacent edge of the shelf, where in some places it is accompanied by gas pits or craters on the sea floor and reflectors in the water column that suggest escaping gas. It is speculated that the gas is biogenic (methane) and that it is migrating up the slope where it accumulates in strata along the edge of the shelf. The name "shelf-edge gas" is suggested for this kind of occurance.

Procedures and Methods

The geologic data base for studies presented in this report consists primarily of subbottom acoustic reflection profiles run by the U.S. Geological Survey from 1972 to 1979. Most data within the prospective lease block areas were collected on cruises funded in part by the U.S. Bureau of Land Management after the lease blocks were defined in 1979. Track lines for the 1979 surveys were designed to cross each lease block at least once, and to extend sufficiently far into the adjacent shelf so as to provide a regional understanding of the geology or geologic processes that might constrain development of the lease blocks. Interpretations of these data are supplemented by acoustic profiles and interpretations from earlier investigations of the shelf by the U.S. Geological Survey.

In order to maximize the information available from these cruises, several seismic systems were run simultaneously. A precision depth sounder (12 kHz source) recorded the sea bed surface. Subbottom data, with a resolution of approximately 0.3m and a penetration depth of up to about 400 m, were collected with a multiplate uniboom (electromechanical source). Records from this system are the primary data for the geological hazards described in this report. Somewhat similar data were collected with a 3.5 kHz transducer system. Deeper subbottom information was collected using sparker or airgun array sound sources. These latter systems sacrifice resolution, but can produce reflections from more than 2000 m below the sea floor.

Primary navigation for the 1979 cruises was controlled by an electronic range-range transponder system (Motorolla Mini-ranger). Fixes were determined from ranges converted to Transverse Mercator coordinates and were plotted in real time aboard the research vessels. On some cruises this navigation system was augmented by satellite fixes and the use of Loran C. Location accuracy for the transponder navigation probably closely approached or reached the claimed system accuracy at about 15 m.

OFFSHORE SANTA MARIA BASIN

The southernmost basin in Lease Sale 53, the offshore Santa Maria Basin, is elongate in a northwest direction parallel to the coast, and it measures approximately 40 x 230 km. Data used for the description of the geologic hazards in the basin were collected on five U.S. Geological Survey cruises between 1972 and

1979. Track lines are shown on Plate 1. The 1972 USNS Bartlett cruise (Greene and others, 1975) was part of a reconnaissance exploration of the central and southern California continental shelf using a deep penetration 160 Kilojoules (kJ) sparker system and satellite controlled navigation. Two cruises, R/V KELEZ in 1973 and R/V S. P. LEE in 1975 (Wagner, 1974; McCulloch, 1976) were designed to map the near-shore geology and specifically to define near-coastal faulting. These cruises collected high resolution and deep penetration data. Interpretation of these data (Wagner, 1974a, Buchanan-Banks and others, 1978) have been incorporated in this report (Plate 2). In 1979, a short reconnaissance cruise of the R/V SEA SOUNDER ran deep penetration reflection profile lines over the southern end of Santa Lucia Bank, in an area that experienced a sequence of earthquakes in 1968-9. The principal source of data for this study of geologic hazards is a 1979 R/V S. P. LEE cruise on which the following seismic systems were used: 12 kHz transducer depth sounder; 3.5 kHz transducer and uniboom high resolution subbottom profilers; and an airgun deep penetration system which used one 30 and two 40 cubic inch airguns for most of the survey area.

The primary navigation was done with a Motorola Mini-ranger system consisting of the following components:

1. Six transponders (Universal Stations), all of which were calibrated over a known range just prior to the cruise.
2. Rotating antenna that extends the reception range of the transponders beyond the range achieved with the omni

antenna.

3. Range console that selects and queries the transponders, and indicates the ranges.

4. Microprocessor that accepts range data and drives two peripherals which are;

   a. A track indicator that visually indicates vessel position right or left of line, and percentage of line run.

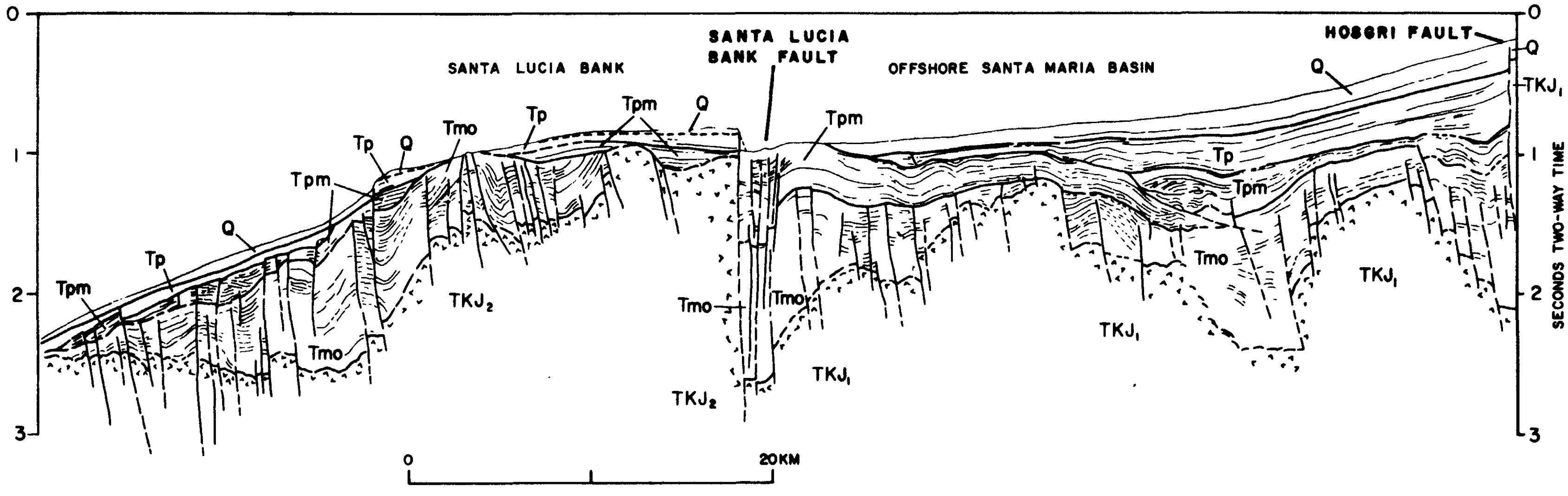
   b. An automatic track-line plotter that draws the pre-plotted track and then plots vessel position approximately every 2 minutes along the track.

5. Operator terminal (Silent 700) that controls the track indicator and track plotter through the microprocessor, and produces hard copy of ranges approximately every 2 minutes.

The navigation for this cruise shown on Plate 1 is a preliminary plot showing only half-hour fixes that were converted to Transverse Mercator coordinates and plotted in real time during the cruise. Precruise calibration tests indicate that there are variations around a mean value for ranges from any given transponder. With the automatic track line plotter it is possible to plot a course more accurately by averaging these variations than is possible by making course changes using single sets of transponder ranges.

Geology

A geological cross section based on an interpretation of a deep penetration seismic profile (Bartlett line 20) across the central part of the basin and the adjacent Santa Lucia Bank is shown on Figure 3. Ages of rock units have been carried to this section by tracing seismic reflections of units identified in an offshore well (Oceano No. 1, Plate 2) about 23 km south of the line of profile. Six geologic units were recognized. Basement rocks (TKJ_1, TKJ_2) are thought to be equivalent to rocks of the Franciscan complex, but to differ in origin; TKJ_1 rocks are possibly older in part than TKJ_2 rocks, and are an extension of similar rocks found exposed along the eastern edge of the basin; TKJ_2 basement rocks west of the Santa Lucia Bank fault may have originated as a subduction zone complex. Both TKJ_1 and TKJ_2 rocks and superjacent early Tertiary sedimentary rocks of possible Eocene and Oligocene age were deformed and eroded, leaving only small erosion remnants of the early Tertiary deposits in topographic depressions. These remnants are not identified on the cross section, but are seen on nearby reflection lines. In late Oligocene and early Miocene time (represented by the lower part of unit Tmo) volcaniclastic rocks were deposited on this erosion surface, and in the following middle and early late Miocene well-bedded silicious marine shales and cherts (upper part of unit Tmo) were deposited in relatively deep marine water over the shelf. These rocks are referred to the Monterey Formation onshore. Unit Tmo was deformed sometime in the late Miocene by folding and numerous faults. Most faults are east dipping and moderately steep. Some faults offset the basement rocks more than unit Tmo, which suggests some



Q	Well-bedded sediments of Pleistocene and Holocene age. Generally conformable on uppermost Pliocene strata, and separation from them not possible in much of area. Unfaulted, except locally along the Hosgri fault zone.
Tp	Well-bedded sedimentary rocks of middle to late Pliocene age; generally referred to Foxen Mudstone onshore. Identified in offshore Standard-Humble Oceano No. 1 well where it consists mainly of claystone. Commonly in onlap relations with older strata. Thickness ranges from wedge edge to 350 m.
Tpm	Well-bedded sediments of late Miocene and early Pliocene age; generally referred to Sisquoc and Pismo Formations onshore. Identified in Oceano well and is composed of calcareous siltstone and silty claystone. Commonly thins against structural highs and rests unconformably upon underlying folded and eroded strata.
Tmo	Well-bedded sedimentary rocks that data from the Oceano well indicate are cherty, calcareous, siliceous shales of the onshore Monterey Shale of middle and early late Miocene age in the upper part and poorly bedded volcaniclastic rocks of the onshore Lospe and Obispo Formations of late Oligocene and early Miocene age in the lower part. Moderately folded and thrust faulted; strata truncated by an erosion surface that commonly forms the upper limit of the faults. Seaward of the Santa Lucia Bank the faults generally cut the erosion surface and are either regenerated or younger that those shoreward of the bank.
TKJ_2 TKJ_1	Acoustic basement. Upper surface generally recognized by strong acoustic signature and abundant hyperbolics. Commonly no recognizable bedding but locally faintly bedded. Unit TKJ_1 is probably a continuation of Franciscan Complex onshore with small bodies of mafic and ultramafic material incorpotated. Unit TKJ_2 may be an early Tertiary subduction zone complex. Thickness unknown.

Figure 3. Geologic interpretation of a deep penetration acoustic reflection profile across outer Santa Maria Basin (Bartlett line 20, Plate 1).

reactivation of older faults. The late Miocene folding and faulting is probably the result of some compressional component related to the interval of plate margin subduction during which the adjacent oceanic plate was being driven under the edge of the North American Plate along the base of what is now the Santa Lucia Escarpment. Erosion removed some of the tops of the folded Tmo rocks before the following deposition of marine silt and clay (unit Tpm) which are referred to the late Miocene and early Pliocene Sisquoc and Pico formations onshore. Folding occurred once more but this time without the faulting that accompanied the earlier deformation. Sedimentation followed the folding, and in middle to late Pliocene time marine sediment (unit Tp, referred to the Foxen Mudstone onshore) covered the basin floor. The final episode of deposition recognized on the section (unit Q) is represented by the well bedded sediment of Quaternary (Pleistocene and Holocene) age. On some high resolution records (especially on the 3.5 kHz) an acoustically transparent surface layer is thought to represent Holocene deposits. The large vertical separation on the Santa Lucia Bank fault (Fig. 3) makes it impossible to trace seismic reflectors from the basin to the Santa Lucia bank. Therefore rock ages west of the fault have been inferred by the similarities of character of the acoustic reflectors, by the degree of deformation, and by the sequence of the depositional, deformational, and erosional events (unconformities) seen in the basin.

Faults

The eastern boundary of the offshore Santa Maria Basin is the Hosgri fault or fault zone named by Wagner, (1974a) for Hoskins and Griffiths (1971), the first to publish a map of the fault. Most acoustic profiles across the fault show considerable down-to-the-west vertical separation (Fig. 3) with presumed Franciscan basement rocks elevated to near the surface on the east. Usually several faults appear on each crossing seismic line. The western most faults generally do not extend as close to the surface as those on the east, but the faults are all nearly vertical or they dip steeply to the east, suggesting some element of compression. There is considerable controversy as to the displacement history of this fault zone, and as to whether or not, or for how long, it has acted as part of the major coastal fault system that continues north, and joins or approaches the San Andreas fault in the Gulf of the Farallones. Some investigations (e.g Graham and Dickinson, 1978) advocate large right-lateral strike slip displacement of as much as 115 km which they demonstrate by offset geologic features. Others (e.g. Hamilton and Willingham, 1977) prefer less than 20 km strike slip, and argue for no direct connection with a coastal fault system. Recent mapping (Leslie, in press) has demonstrated a possible offshore connection between an eastern strand of the Hosgri fault zone and the San Simeon fault to the northwest, and this mapping supports the possibility of a through-going fault system.

Although the long term geologic history of the fault is germane to an understanding of the structural evolution of this part of the continental shelf, of more immediate relevance to geologic hazards is the capacity of the fault to produce earthquakes, to displace the seafloor, and to produce seismic shaking. Earthquake epicenters indicate that the fault is seismically active, and is undergoing right-lateral displacement with some north-south compression (Fig. 4). The largest earthquake in this area, the magnitude 7.3 Lompoc earthquake of November 4, 1927, has been located on the southern end of the Hosgri fault (Gawthrop, 1975, and Plate 3). This location is discussed more fully in the later section of seismicity. The fault has produced no unequivocal seafloor offsets in Holocene deposits; however, both Wagner (1974a) and Leslie (in press) show displacement of the base of the unconsolidated surface sediment of Quaternary age, which probably includes Holocene-age sediment. Thus, this seismically active fault must be considered as having the potential for producing surface displacement. Furthermore, the isoseismals for the apparent intensity of shaking that accompanied the 1927 Lompoc earthquake (Fig. 4) indicate that the fault is capable of producing strong ground shaking.

As mapped on Plate 2, faulting steps seaward from the Hosgri fault at the south end of the basin. The Hosgri fault, which is represented by two strands at its south end can be mapped to about 10 km south of the latitude of Point Sal, where two faults

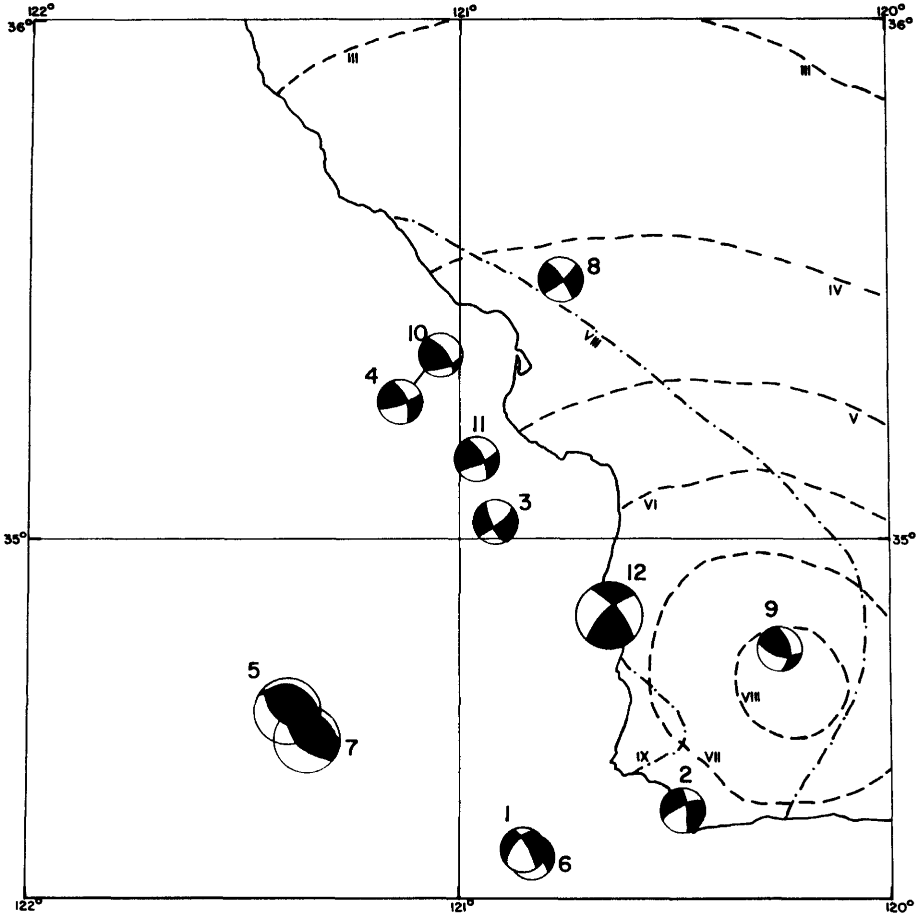


Figure 4. First motions and Rossi-Forel shaking intensities in the Santa Maria Basin area. The first motion diagrams are lower hemisphere plots, the white indicating dilation, the black, compression. Large diagrams indicate well-constrained events.

– – – – – – – 1915 Los Alamos earthquake
–·–·–·–·– 1927 Lompoc earthquake

	DATE	MAGNITUDE
1	49/06/27	4.5
2	59/10/01	4.5
3	62/02/01	3.7
4	69/09/01	3.7
5	69/10/22	5.4
6	69/10/30	3.7
7	69/11/05	5.6
8	71/01/26	3.1
9	72/09/23	3.0
10	74/06/19	2.8
11	74/09/24	3.0
12	80/05/28	4.8

References

-all focal mechanisms except events 1, 6, and 12 from Gawthrop, W. H., 1978, Seismicity and tectonics of the central California coastal zone: California Division Mines and Geology, Special Report 137, p. 45-56.

-events 1 and 6 from Gawthrop, W. H., 1975, Seismicity of the central California coastal region: U.S. Geological Survey Open-File Report 75-134, 90p.

-event 12 from Robert S. Cockerham (written commun., 1980).

-1915 Los Alamos isoseismals from Beal, C. H., 1915, The earthquake of Los Alamos, Santa Barbara, California, Jan. 11, 1915: Seismological Society of America Bulletin, v. 5, p. 14-25.

-1927 Lompoc isoseismals from Byerly, P., 1930, The California earthquake of November 4, 1927: Seismological Society of America Bulletin, v. 20, p. 53-66.

with approximately the same trend lie 3 and 10 km offshore. These more westerly faults lie within parallel northwest-trending anticlines. The crest of the western anticline is exposed in a bedrock topographic high that has been truncated by wave erosion. The western fault has been called the "offshore Lompoc fault" (Pacific Gas and Electric, 1975) because it was suggested that this fault generated the 1927 Lompoc earthquake. However, accepting the site of the 1927 earthquake as having occurred on the Hosgri fault, this name is inappropriate and is not used in this report. As seen on deep penetration records the fault associated with the western anticline lies near, but not at the western edge of the exposed bedrock. On the high resolution records there is no demonstrated fault displacement of Holocene sediment, either as seen on seismic lines run for this study or on lines run by others in this area (Payne and others, 1979).

To the southeast, off Point Arguello, the trend of the faults changes from NNW to NW and the faults are discontinuous. To the west the faults turn and parallel the northwest trend of the faults associated with the Santa Lucia Bank. About 36 km west of Point Arguello there is about 40m of seafloor relief along the trace of a steep easterly dipping reverse fault, but it is not clear if the relief is due to fault movement. Adjacent lines show no surface offset.

The Santa Lucia Bank that lies west of the basin is a fault bounded structural high. The magnetic signature of the rocks differs across the fault; to the west the total magnetic intensity is flat, at about a constant value, whereas to the east of the fault, irregularities with amplitudes of as much as 200 gammas are present (Page and others, 1979). There is also a considerable difference in the thickness of the Miocene and Pliocene aged sections across the fault. Both of the foregoing suggest that the vertical separation on the Santa Lucia Bank fault was accompanied by considerable strike-slip displacement. Northwestward transport of this structural high is consistant with the suggestion from the physiography and gross structure that this part of the shelf resembles the California Borderland to the south. As seen on acoustic reflection profiles the Santa Lucia Bank fault is two or more strands which approach but do not break the surface. The large topographic expression of the fault appears to be largely a fault line scarp, rather than a fault scarp. From the offset of unit Tp along the fault (Fig.3) there has been considerable relatively young displacement on the fault, and within the basin, sediment of probable Pleistocene age has been folded against the edge of the block, indicating young relative displacement between the Santa Lucia high and the basin. West of the Santa Lucia Bank fault there are numerous steeply dipping faults, most of which show vertical separation, and some of which have displaced the seafloor to lengths of 30 to 40 km. The general lack of young sediment on the bank makes it difficult to establish the ages of the faults; however, they cut rocks of probable late Pliocene age. Because these faults occur in a seismically active area (Plate 3) and are associated with long seafloor offsets, they must be considered candidates for future displacements.

Seismicity

As noted above, some adjustment to the motion between the North American and Pacific plates appears to be taking place west of the San Andreas fault. In this part of California movement between the plates is thought to be approximately 5.5 cm/yr (Atwater, 1970) and only about 2.5 cm/yr is occurring on the San Andreas. Thus, more than half the displacement may be involved in deformation and faulting west of the San Andreas fault (Gawthrop, 1975). Because this relative plate motion can be expected to continue, this area will continue to be seismically active. Offshore Santa Maria basin should be expected to experience seismic shaking from earthquakes that occur beneath the basin and its active fault margins and also from onshore earthquakes to the east, including those on the San Andreas fault. For example, isoseismals from the great 1906 San Francisco earthquake on the San Andreas fault (Richter, 1958) indicate that a Rossi-Forel (Appendix 1) shaking intensity of IV probably extended out into the basin. Similarly, the 10 March, 1922, earthquake in Cholame Valley, probably also on the San Andreas fault, produced liquefaction ground failures at San Luis Obispo (Appendix 1). However, more severe shaking has been produced in offshore Santa Maria Basin by local earthquakes (Fig. 4).

The earthquake history prior to instrumentally located epicenters that date from the late 1920's must be drawn from historic accounts (Townley and Allen, 1939). A summary of these accounts is given in Table 1, and in a more expanded form in Appendix 2. The earthquakes noted in the table are those that effected towns shown on Figure 5. During the pre-instrumental period of 124 years covered by these historic accounts more than 116 earthquakes were reported, most since 1900 (Fig. 6). The post-1900 increase appears to have been greater than the demographic change (Donley and others, 1979) and probably represents a real increase in seismic activity. Rossi-Forel shaking intensities assigned to 57 of the earthquakes noted in Table 1 have the following distribution:

Rossi-Forel Intensity	Number of earthquakes
X	3
VIII-IX	8
VII-VIII	5
VI-VII	4
V-VI	12
IV-V	8
III-IV	11
II-III	6

The most severe earthquake during this time, and as yet the most severe in this area, was the 4 November Lompoc earthquake of 1927 noted earlier. It was the first and the most severe shock of a

TABLE 1. Historic pre-instrumental earthquakes 1812-1927 in, and adjacent to, offshore Santa Maria Basin, California. Condensed from Appendix 2 (Townley and Allen, 1939).

YEAR	DATE	TIME (PST)	LOCALITY	INTENSITY (Rossi-Forel scale)
1812	Sept. Oct. Dec? Sunday? 8th?	7:00	S. California	IX
1812	Dec. 12	11:00	off coast of S. California	X
1830			San Luis Obispo	
1851	June 13		San Luis Obispo	V?
1852	Oct. 26		San Simeon	X?
	Nov. 26		S. California, San Simeon?	VII-IX?
	Dec. 17		San Luis Obispo	
1853	Jan.10		Captain Dana's Rancho, San Luis Obispo Co.	
	Jan.		San Luis Obispo	
	Feb. 1	13:00	San Simeon	VIII
	Feb. 14		San Luis Obispo	
	Mar. 1		San Luis Obispo	V
1855	Jan. 13	18:30	San Miguel, San Luis Obispo Co.	V
	June 25	14:00	Santa Barbara and north to the valley of Santa Maria	V
1869	Sept. 13		On the coast near San Luis Obispo	V?
	Dec. 15		San Luis Obispo	V?
1877	May 30	14:30	Paso Robles	V
1885	April 8	16:00	Cambria, San Luis Obispo Co.	
1888	Oct. 3	12:52	San Miguel	III
	Oct. 4	16:00	Paso Robles	
1889	May 1	11:55	Lompoc	
	July 10		Arroyo Grande, San Luis Obispo Co.	
1898	June 3	22:20	Los Olivos	
1900	Oct. 18		San Luis Obispo	
1901	Mar. 3		San Luis Obispo	
	Mar. 5		Paso Robles	
1901	Mar. 6		San Ardo and San Luis Obispo	
	June 3		San Luis Obispo	
	July 30	11:00	San Luis Obispo	
1902	Apr. 6		San Luis Obispo	
	July 27	20:57	Los Alamos	VIII-IX
	July 28	5:08	San Luis Obispo	
	July 31	1:20	Los Alamos	VIII-IX
	July 31	19:30	Los Alamos	VIII-IX
	Aug. 1-4		Los Alamos (several shocks)	
	Aug. 9	16:00	Los Alamos	
	Aug. 10	2:40	Los Alamos	
	Aug. 14		Los Alamos (several shocks)	
	Aug. 28		San Luis Obispo	
	Aug. 31		San Luis Obispo	
	Sept. 10		Los Alamos (2 shocks)	IV-V
	Oct. 21	14:00	Los Alamos (3 shocks)	
	Oct. 22	2:00	Los Alamos	
	Dec. 12		Los Alamos	VII-VIII
1903	Jan. 11		San Luis Obispo	

TABLE 1 continued--

YEAR	DATE	TIME (PST)	LOCALITY	INTENSITY (Rossi-Forel scale)
1903	Mar. 24		Santa Margarita	
	July 28	23:13	Point Piedras Blancas Lighthouse	IV-V
	Aug. 24		Los Olivos	
1904	Jan. 22		Los Alamos	
	Jan. 23		Los Alamos	
	Sept. 10		San Luis Obispo	
1905	May 25	21:49	San Luis Obispo	
1906	July 6		San Luis Obispo	
	July 21		San Luis Obispo	
	Aug. 1		San Luis Obispo	
	Dec. 6	22:40	San Luis Obispo	VIII?
1907	July 1	22:10	San Luis Obispo	
	July 21		San Luis Obispo	
1908	May 19		San Luis Obispo	
1909	Aug. 18		San Luis Obispo	
1911	Mar. 22	2:55	San Miguel	
1913	Oct. 20	3:25	San Luis Obispo, Paso Robles, Betteravia, Santa Maria	
1914	Nov. 23	20:25	San Luis Obispo	II
1915	Jan. 11	20:31	Los Alamos	VIII
	Jan. 15		Los Alamos	
	Jan. 20		Los Alamos	
	Jan. 26		Los Alamos	
	Jan. 27		Los Alamos	
	Apr. 21	1:58	San Luis Obispo	III-IV
1916	Feb. 27	5:26	Los Alamos	
	Mar. 1	11:15	Los Alamos	
	May 5	19:45	Los Alamos	III
	June 26	5:46	San Luis Obispo	II
	Dec. 1	14:53	Avila Beach	VII
1917	July 7	13:00	Lopez Canyon (10 miles from San Luis Obispo)	
	July 7	19:20	Santa Maria	
	July 8	3:29	Lopez Canyon	
1917	July 9		Lopez Canyon	VI-VII
	July 26	00:31	Santa Maria	V
	Dec. 4	18:38	Paso Robles	IV
	Mar. 14	23:53	San Luis Obispo	III-IV
1918	Dec. 17	23:15	Paso Robles	
1919	Mar. 19	23:04	San Luis Obispo	II
	June 28	1:01	San Luis Obispo	V
	Dec. 6		San Luis Obispo	
1922	Mar. 10	3:21	Cholame Valley	VIII-IX
	Mar. 16	15:10	Cholame Valley	V
	Mar. 19	3:00	Paso Robles	III?
	Mar. 23	2:00	Paso Robles	III?
	Mar. 25	4:00	Paso Robles	III?
	May 30	17:25	Paso Robles	III

TABLE 1 continued--

YEAR	DATE	TIME (PST)	LOCALITY	INTENSITY (Rossi-Forel scale)
1922	July 5	11:00	Los Alamos	
	July 9	4:00	Los Alamos	
	July 10	2:00	Los Alamos	
	July 11	7:30	Los Alamos	
	Aug. 17	21:12	Cholame Region	VII?
	Aug. 20	13:14	Atascadero, San Luis Obispo Co.	III
	Sept. 4	2:15	Paso Robles	IV
	Sept. 5	1:05	San Luis Obispo	V
1923	Mar. 11	22:00	Los Alamos	IV
	May 4	14:45	San Luis Obispo	V
	May 7	21:02	Cholame	II
	June 16	12:40	Paso Robles	IV
	June 25	5:21	San Luis Obispo	II
	Dec. 18	11:35	Santa Maria	II
1925	June 29	7:20	San Luis Obispo	III
1926	Apr. 29	4:18	Buellton	IV
	Oct. 22	2:10	Paso Robles	III
	Dec. 8	16:03	Paso Robles	IV
1927	Nov. 4	3:00	Pt. Arguello (foreshocks)	
	Nov. 4	5:51	West of Pt. Arguello	X
	Nov. 4	11:00	Pt. Arguello (aftershocks)	
	Nov. 5		Pt. Arguello (aftershocks)	IV
	Nov. 6		Pt. Arguello (aftershocks)	IV
	Nov. 8	2:10	Buellton	IV
	Nov. 18	19:32	Santa Maria	VII

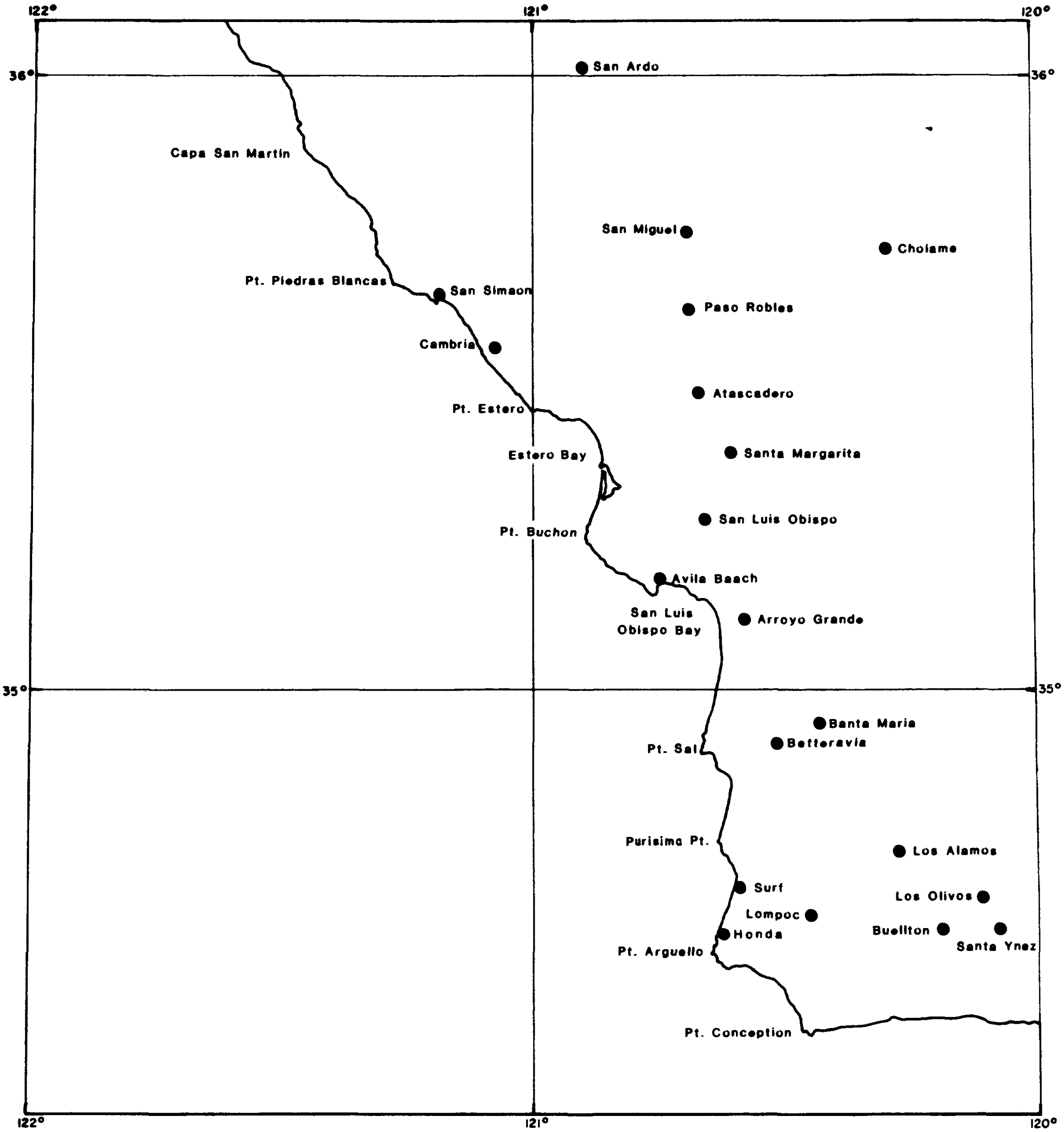


Figure 5. Locations noted in the accounts of earthquakes listed in Table 1 and Appendix 2.

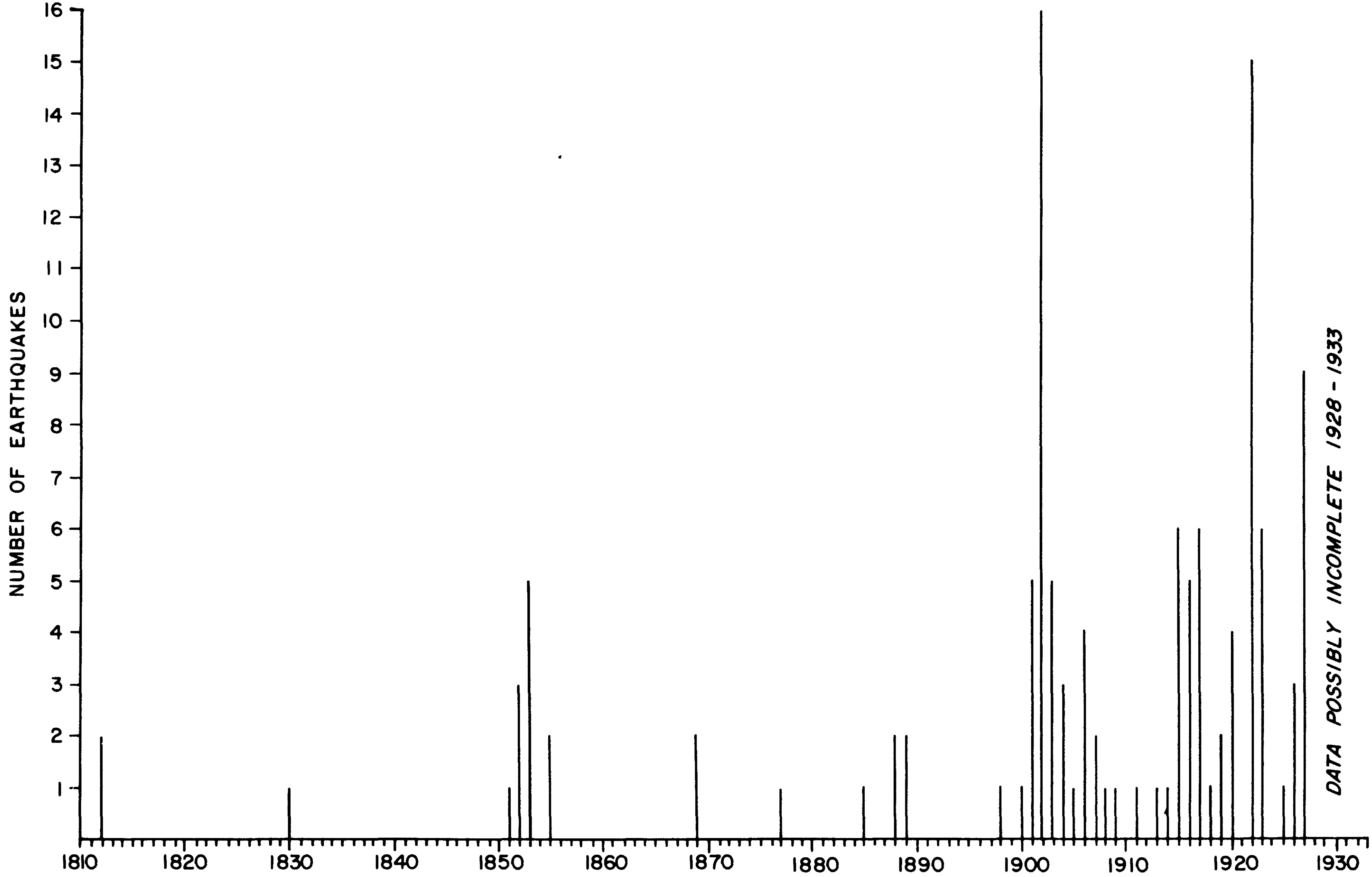


Figure 6. Earthquakes from 1810 to 1933 reported along the California coast from Cape San Martin to Lompoc. Earthquakes from 1810 to 1927 from Townley and Allen, 1939. No earthquakes from 1928 to 1933 cited in Coffman and von Hake, 1973.

long sequence of strong earthquakes that occurred on November 4, 5, 6, 8, 18, and December 5 and 13. Local accounts placed the epicenter of the main shock off Point Arguello, and some of the following shocks were reported by ships off Point Arguello and Point Conception (Table I and Appendix 2). Although there were no local seismographs, the main shock was large enough to be recorded at a distance and Byerly (1930) calculated its epicenter as lying approximately 75 km west of Point Arguello (Plate 3) and assigned it a magnitude of 7.3. Reanalysis of seismographic data by Smith (1978), Hanks (1979), Gawthrop and Engdahl (1975) and Gawthrop (1975, 1978a) have moved the epicenter progressively eastward (Plate 3), and the Gawthrop location places it very nearly on the Hosgri Fault. Evernden (oral communication, 1980) has modeled the observed onshore distribution of shaking intensity (Fig. 4) and has concluded that the epicenter was close to the mapped location of the Hosgri fault. There was probably some vertical displacement of the seafloor associated with this earthquake for it generated a tsunami that reached a height of 6 feet at Surf and 5 feet at Port San Luis. The tsumani was also recorded on tide gauges at San Francisco and San Diego, and was sufficiently large to cross the Pacific and to be recorded at Hawaii and Japan. This earthquake has received considerable scrutiny. Its possible location on the Hosgri fault, that passes approximately 7 km west of the Diablo Canyon nuclear reactor at Point Buchon, has made it the basis for the maximum credible earthquake that the reactor must be designed to withstand.

Instrumentally located epicenters and their magnitudes are shown on Plate 3. The onshore boundary of the epicenters plotted was chosen to show only earthquakes that have occurred in the immediate coastal area. The data time intervals are not uniform on the Plate; south from Lat. 34°30'N it is 1970-1976; from Lat. 34°30'N to 36°N it is 1932-1978, and north from Lat. 35°N these data are augmented by data from 1969-1979. Thus, most of the proposed lease blocks are covered by the 1932-1978 data, and comparisons within this data block are possible.

North of the latitude of Point Conception, there are 258 offshore epicenters. Of these 33 are magnitude 4.0-4.9 or greater, and of these nearly half (15) lie at the southwestern end of the Santa Lucia Bank. The largest events on the Santa Lucia Bank (m 5.4 and 5.6) have been relocated by Gawthrop (1975; Plate 3) and they lie in the area where faults break the seafloor. First motion solutions for these two events (Gawthrop, 1975; events 4 and 5 on Fig. 4) suggest either very low angle thrusting with the northeast side over, or nearly vertical steep reverse faulting with the west side up. As located, these epicenters lie a few km from a west-side-up nearly vertical fault along which the seafloor has been offset for a length of about 38 km. Most (13) of the remaining m 4.0-4.9 or greater offshore earthquakes lie within 40 km of Point Conception. First motion determinations for two of this group (Fig. 4) are poorly constrained but they allow for some component of right lateral slip on northwest trending planes that parallel the mapped folds and faults. These first motions also show northeast-southwest directed compression, normal to the structure. The remaining 4.0-4.9 or greater earthquakes lie along the coast to the northwest. First motion solutions for 4 earthquakes north from Point Sal to Morro Bay, that probably are associated with displacement on the Hosgri fault zone also indicate a component of right lateral slip.

In summary, the large offshore events in, and adjacent to, the offshore Santa Maria Basin fall into two principle groups; those that suggest high angle faulting on the Santa Lucia Bank, and those that suggest northwest striking right lateral slip with northeast-southwest directed compression that are related to the Hosgri fault and similar faults on approximately the same trend in the Point Conception area.

A recent earthquake (28 May, 1980) of magnitude 4.79 occurred approximately 8 km northwest of Point Sal (Plate 3). A first motion solution for this earthquake (Rob Cockerham, written commun. 1980; Fig. 4) allows for left lateral slip on a northwest trending fault, approximately parallel with faults mapped in the area. Approximately 40 km to the southeast, first motion on an earthquake also indicates possible left lateral motion on structures that strike northwest. Aeromagnetic data (McCulloch and Chapman, 1977) in the area of the 1980 earthquake show northwest trending anomalies, approximately parallel to the first motions of these two earthquakes. These anomalies stop abruptly at the anomaly associated with the Hosgri fault. It is possible that the left lateral slip suggested by these first motions indicates a clock-wise rotational displacement of the rocks to the east of the Hosgri fault in response to northwestward movement of the plate on the seaward side of the Hosgri fault.

The ground motion along the eastern margin of the offshore Santa Maria Basin can be expected to be strong in the event of a repeat of a 1927 earthquake on the Hosgri fault zone. In his design spectra for the Diablo Canyon reactor facility at Point Buchon, Newmark (1976) uses a maximum ground motion with the following characteristics at a distance of 5.8 km from the Hosgri Fault zone:

Acceleration (g)	Velocity(inches/sec.)	Displacement (inches)
0.75	24	8

Although this ground motion is strong, it is presently under review, in part because the unexpectedly high vertical accelerations recorded during the M 6.7 Imperial Valley earthquake of October 15, 1974 (Porcella and Matthesen, 1979) suggest the possibility for still stronger ground motion. Strong ground motion could also be produced along the western margin of the basin as the result of faulting on Santa Lucia Bank. If one of the several approximately 40 km long seafloor fault offsets is considered to have resulted from a single event, the magnitude of the earthquake can be estimated from comparisons of observed fault rupture length vs. earthquake magnitude. There is general agreement in several studies of this kind (e.g. Tocher, 1958; Iida, 1965; Albee and Smith, 1967; Bonilla, 1967, 1970) that rupture lengths of approximately 40 km are associated with earthquakes of magnitude approximately 7. Therefore, the faults that bound the offshore Santa Maria Basin are capable of producing large earthquakes that would probably be accompanied by relatively strong ground motion in the basin.

Gas

As noted above, shallow gas pockets can pose a danger to drilling operations by increasing the chances for blowouts. There is considerable evidence for shallow gas in some areas of the offshore Santa Maria Basin (Plate 4). The simple occurrence of gas does not, in itself, constitute a hazard, for the quantity or the pressure of the gas may be too small to produce a blowout, and good drilling practice reduces the risk of blowouts; however, the presence of gas indicates the possibility for blowouts. Accumulations of gas in unconsolidated sediment and sedimentary rocks produce several kinds of distinctive reflectors on seismic profiles. The velocity of the seismic signal through sediment and sedimentary rock is considerably greater than through gas. The velocity difference, or acoustic contrast, increases the amount of energy that is reflected, and a seismic recording system that is sensitive to signal amplitude responds by printing a dark signal sometimes referred to as an amplitude anomaly or bright spot. If the vertical thickness of the gas accumulation is sufficient, the slower travel time of the signal through the gas delays return signals from reflectors below the gas, and makes them appear to be displaced downward. In some cases edges of gas accumulations produce defraction tails that appear as small reflectors curving downward from the edges of the accumulations. On high resolution records the presence of gas is sometimes displayed by discontinuous, abnormally high amplitude reflections along bedding surfaces, and by grey zones in which other seismic reflections are masked.

In offshore Santa Maria Basin the tops of some of the folds in the Miocene-aged rocks produce high amplitude reflections that probably indicate the presence of gas that has migrated upward through the folded rocks (Fig. 7a). Bright spots and depressed reflectors can be traced upward from the tops of the folds, indicating that some gas is trapped, at least temporarily, as it moves upward toward the surface (Fig. 7a, b). East of the folds, and lying generally updip, the sedimentary rocks contain a myriad of small defraction tails from discontinuous reflectors, suggesting the presence of gas throughout most of the rock section (Fig. 7c, d). Although other phenomenon can cause defraction tails, such as the presence of coarse clastic sediment, the distribution of these defractions throughout the entire section of late Miocene to Quaternary sediment, which are known from the Oceano Well not to be coarse clastics, eliminates this most likely alternative. In addition, high resolution records over this dense diffraction area show numerous discrete bright reflectors indicating shallow gas.

Because the source for some of the gas appears to be the rocks of Miocene or older age, it is possible that the gas is thermogenic, and related to the formation of petroleum, rather

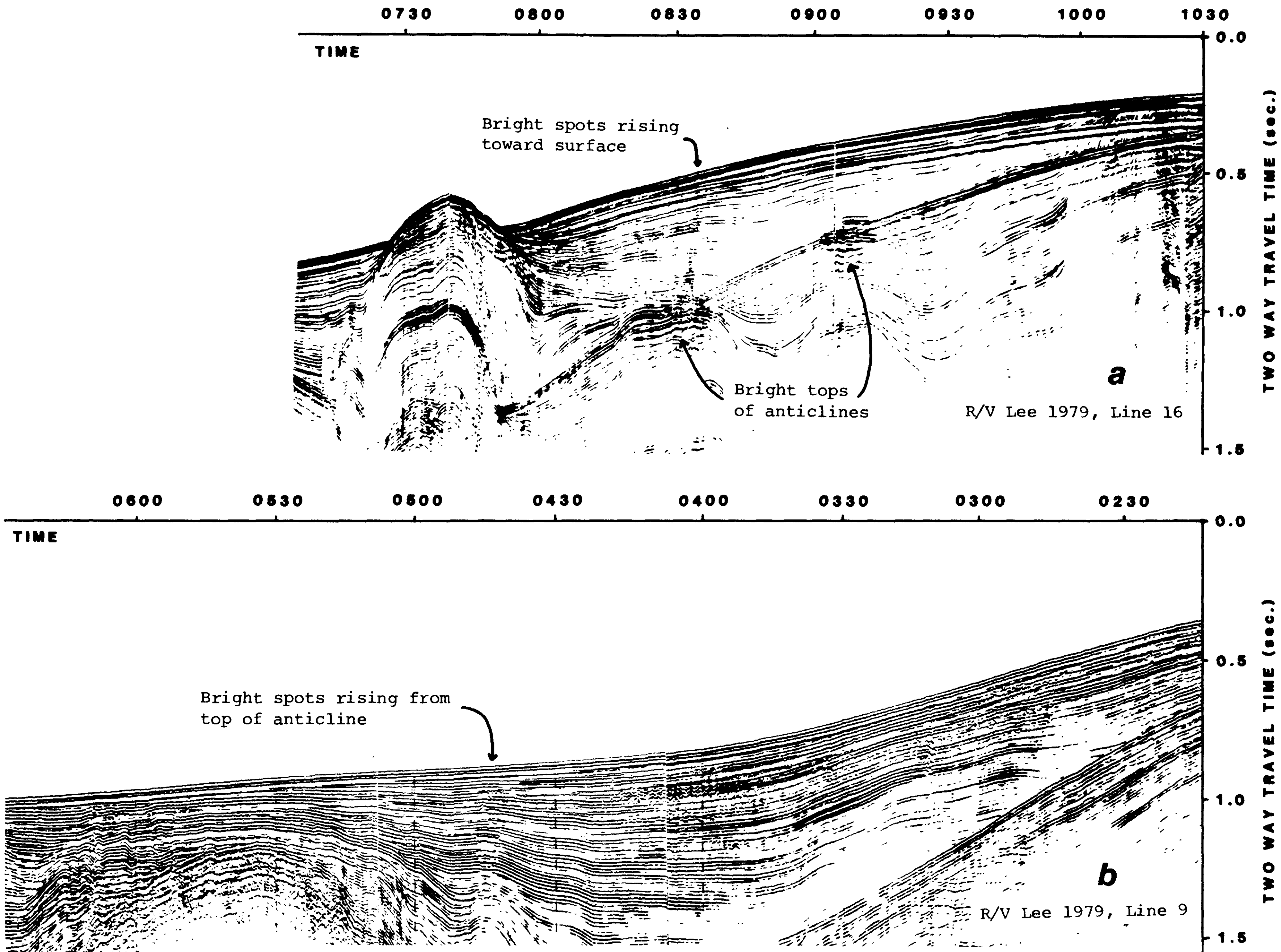
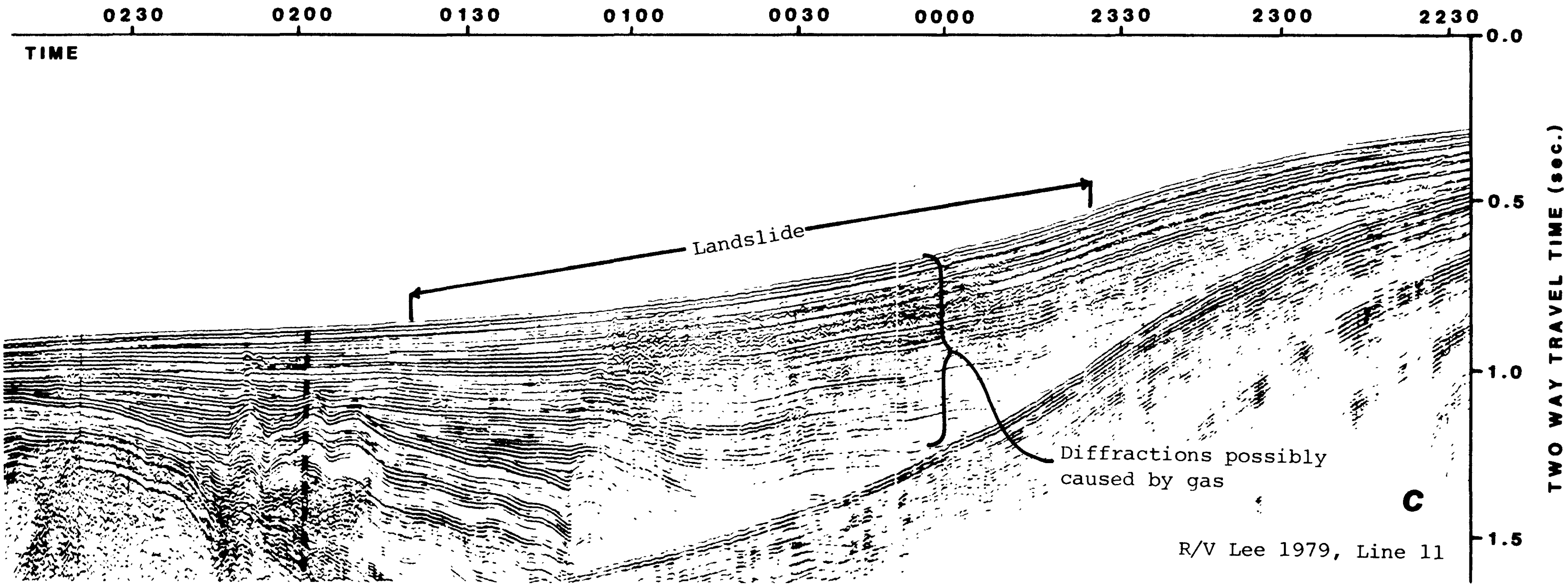


Figure 7a,b. High amplitude "bright spot" reflectors and diffractions associated with subsurface gas in Outer Santa Maria Basin. Seismic lines located on Plate 1.



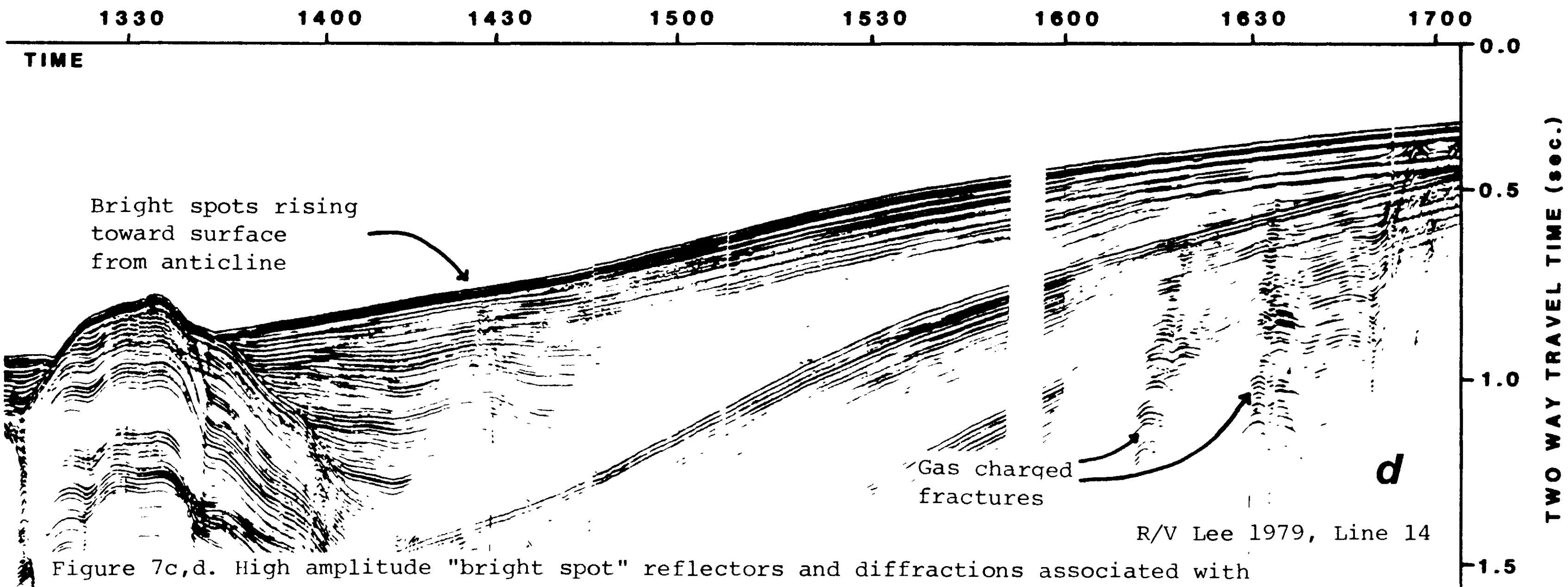


Figure 7c,d. High amplitude "bright spot" reflectors and diffractions associated with subsurface gas in Outer Santa Maria Basin. Seismic lines located on Plate 1.

than biogenic. Ethane, propane and butane accompanied by traces of petroliferous sands were recovered from rocks of possible middle to late Pliocene age at a depth of about 3355 feet in a deep stratigraphic test well (OCS-CAL 78-164 No. 1, Plate 2) approximately 29 km west of Point Conception (McCulloh, 1979). However, extrapolation to the basin from this well must be done with caution for although temperatures high enough for the generation of petroleum occur in this well, these temperatures are higher than those reported at equivalent depths in wells in the nearby Santa Barbara Channel, Ventura Basin, and large parts of the Los Angeles and San Joaquin Basin (McCulloh and Beyer, 1979). Measurements of dissolved hydrocarbons in the water over the Santa Barbara Channel and the offshore Santa Maria Basin indicate the presence of both methane (a biogenic gas) and propane. Concentrations of both are on the average higher in the Santa Barbara Channel waters, but the mean methane to propane ratio is slightly lower in the offshore Santa Maria Basin; 440:1 in Santa Barbara Channel and 350:1 in Santa Maria Basin (Mousseau and Williams, 1979). Thus, the subsurface gas is probably both thermogenic and biogenic in Santa Maria Basin.

Near-surface gas zones shown on Plate 4 were mapped from the high resolution data. The basis for the discontinuous zones is the presence of bright reflectors, or less commonly, abruptly bounded areas of no or greatly diminished subsurface reflection. The continuous zone is mapped where a reflector at the base of the Holocene (?) sediment masks all underlying reflectors, either by dispersion or by absorption of the seismic energy within the gas layer.

Gas also appears to have accumulated in faults and fractures. On Figure 7d, there are two slightly inclined dark bands of reflectors near the eastern end of the profile. These reflectors are in part convex upward. Normally a seismic signal, which has a spherical wave front, is somewhat dispersed when it encounters a convex surface, and the amplitude of the return signal is reduced. In these reflectors the convex upward surfaces are high amplitude, and are probably produced by high acoustic contrast, and thus are probably due to gas. The form of the reflectors suggests fractures or small displacement faults along which the beds have been slightly folded. On high resolution records the gas-charged mapped fault traces (Plate 4) appear as zones of shallow gas, in which the gas masks the subsurface reflections.

Slides and Possible Slides

A large landslide with a small scarp at its head covers an area of about 125 sq. km on the eastern side of the basin (Plate 4). The slide mass is composed of discrete blocks of sediment that have been rotated downward at their up-slope edges along slip surfaces. The slip surfaces appear to merge downward with unbroken seismic reflectors that parallel the general slope of the seafloor. This slide geometry suggests progressive slumping along a buried failure zone or surface. The failure zone or surface is not well defined on the seismic reflection profiles; in some places the first unbroken reflector lies at a depth of

26m below the surface, and in others at a depth of 35m.

Individual rotated slide blocks are reflected in the surface topography of the slide, thus sliding was sufficiently recent that sedimentation and/or erosion has not had time to mask the slide topography. On high resolution records that cross the slide there is a deeper horizon of disarticulated reflectors at a depth of about 100m that is separated from the overlying slide mass by unbroken reflectors (Fig. 8). The breaks in the buried reflector have about the same periodicity as the slump blocks in the overlying slide, and this deep broken layer is interpreted as evidence for previous sliding. Evidence for repeated sliding at a single locality is not unique to this basin, and is also reported by Field and others (1980) in Eel River Basin.
The slope of the failure zone or surface is about 1.2°. Slumps and slides occur on similar gentle slopes in Eel River Basin, in the California Borderland to the south, and in coastal areas adjacent to other parts of the United States and other continents (e.g. Lewis, 1970; Reimnitz, 1972; Hampton and others, 1978; Edwards and others, 1980; Carlson and others, 1980; Field and others, 1980; Field and Edwards, 1980).

The cause of the slide in the offshore Santa Maria Basin is not known. No samples of the slide material have been collected, thus the mechanical properties of the sediment are not known.
The slide lies many kilometers offshore of the seaward edge of sandy ocean floor sediment as mapped by Welday and Willians (1975), and it lies within an area they show the surface sediment to be mud (mixture of silt and clay). The bathymetric contours

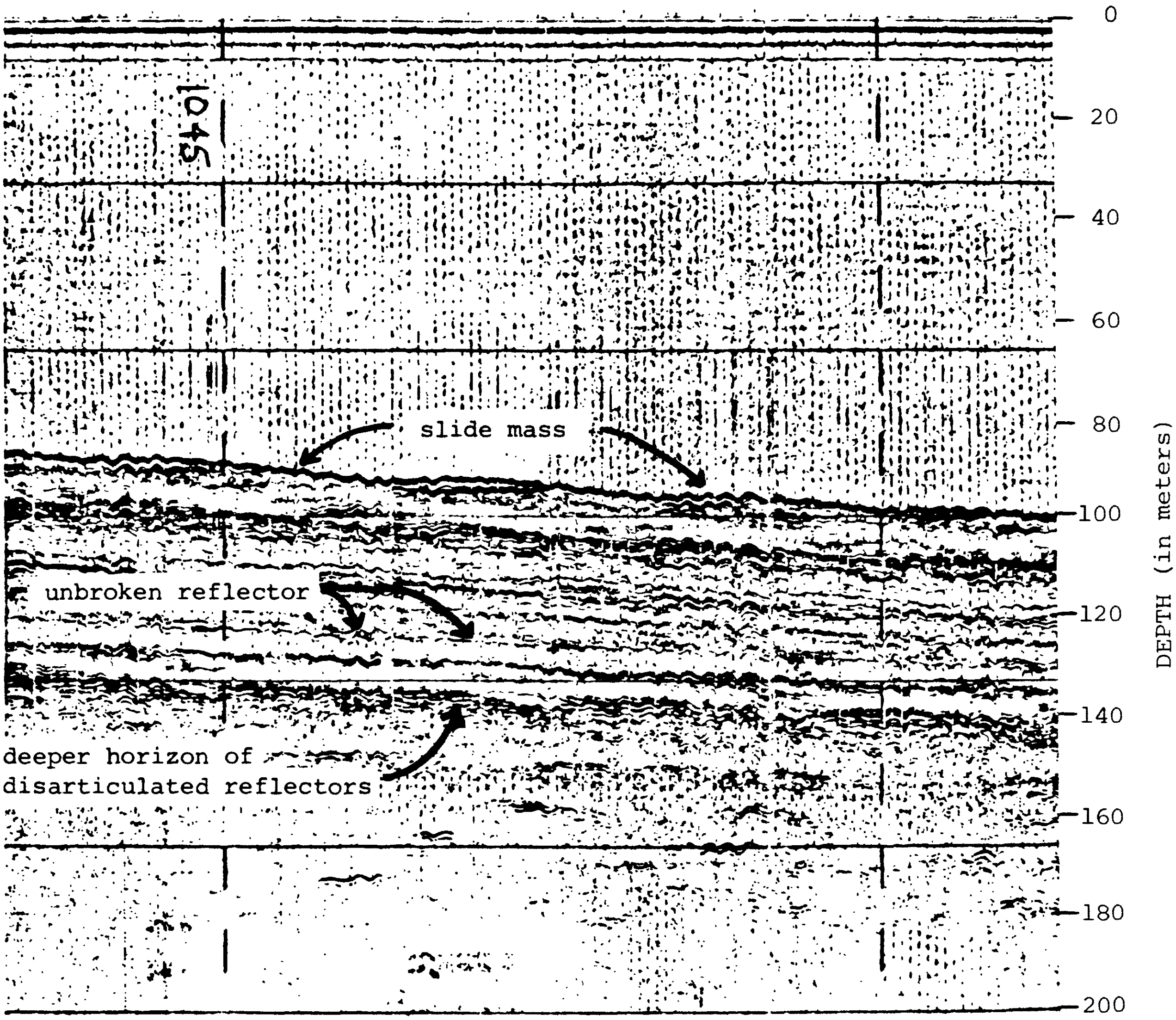


Figure 8. High resolution seismic line showing a recent slide mass and a deeper horizon of disarticulated reflectors. The two units are separated by unbroken reflectors. Please view this figure at a low oblique angle from the end.

(Plate 4) indicate no constructional seaward convexity that might indicate a local sediment accumulation on the slope, and there is no suggestion of such a constructional feature on the seismic reflection records. The lack of evidence for localized sediment accumulation over the gentle failure slope suggests that slumping did not result from the rapid accumulation of unstable sediment, to which some submarine failures are apparently attributable. Some soil failures on gentle slopes are thought to have been triggered by cyclical loading resulting from strong surface waves that increase the pore water pressure within the sediment to the point of liquefaction. The water depth over the slide in Outer Santa Maria Basin is 325m and deeper. At this depth surface storm waves have little or no detectable effect on bottom loading (Fig. 9 of Hampton and others, 1978). The gentle failure slope (1.2°) indicates that very little gravitational force contributed to the initial downslope movement of the slide as a whole, but once motion was initiated gravity could make considerably more contribution to soil failure along the more steeply dipping rotational failure surfaces that bound individual slump blocks. In this seismically active area earthquake induced ground motion remains the likely candidate to supply the initial energy necessary for failure. Gas within the sediment may have contributed to the instability of the sediment. Both the deep penetration seismic records (note the slide topography on Figure 7c) and the high resolution records indicate the presence of gas, and the upper part of the slide lies within the zone of the continuous shallow gas reflector (Plate 4). Vane shear

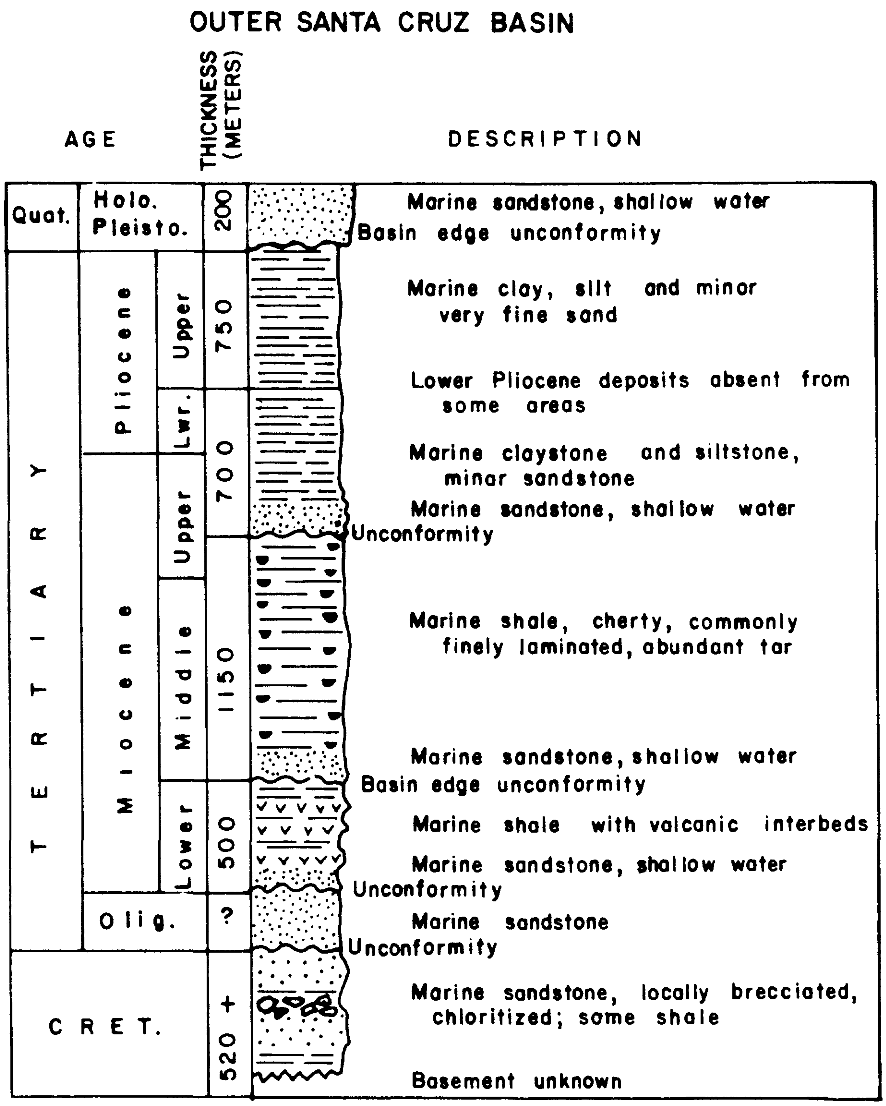


Figure 9. Generalized stratigraphic column for the Outer Santa Cruz Basin, central California. Unit thicknesses are the maximum encountered in the basin. (After Hoskins and Griffiths, 1971).

measurements indicate that gas can significantly decrease the shear strength of marine sediment; however, the mechanisms by which gas contributes to instability are conjectural (Whelan and others, 1975; 1977). These workers suggested that in a dynamic regime cyclical loading can exsolve gas during transient low pressure intervals. They also suggested that once present in bubble form, the gas decreases grain to grain contact within the sediment, which decreases its internal frictional strength and that it provides buoyancy which decreases the overburden pressure. All these factors would promote liquefaction failure, the most common type of earthquake induced soil failure in saturated sediment on gentle slopes. Evidence for repeated failure at the site of the slide in the offshore Santa Maria Basin indicates a repetition of the triggering mechanism, which is also consistent, but not unique to earthquake induced failure.

Two additional small areas are recognized as possible slides. A 40 sq. km area about 20 km southwest of Purisima Point also lies in the area of discontinuous gas. There is a small scarp at the head of the possible slide, a suggestion of disruption and rotation of reflectors within the slide mass, and a possible toe in which shoreward dipping reflectors suggest upthrusting. The possible slide mass is about 20m thick, and has only a slightly irregular surface. If this feature is a slide, it may have moved downslope nearly en mass, not by progressive slumping. The second possible slide lies about 25 km west of Point Sal and is considerably smaller (8.5 sq. km). The sea-floor is only slightly irregular over the slide, and there are some disturbed but not broken seismic reflectors down to an undisturbed reflector at a depth of about 12m. This possible slide also lies within the area of gas-charged sediment.

OUTER SANTA CRUZ BASIN

Introduction

The proposed lease sale area for the Outer Santa Cruz Basin lies almost exclusively on the broad continental shelf northwest of Santa Cruz (Figs. 1 and 2). Physiographically the area is simple and consists mainly of a very flat seafloor (average slope of 0.1-0.5%) with local topographic irregularities on bedrock outcrops. Along the southwestern boundary of the area the flat seafloor of the shelf gives way to the steeper (average slope of 2%) continental slope. Near the extreme southwest part of the lease area the shelf and slope are incised by a branch of Ascension Canyon.

The area studied for this investigation lies approximately between latitudes 37° N and 37° 45' N and longitudes 122° 10' W and 123° W. The area extends from 3 miles offshore (between Half Moon Bay and Point Santa Cruz) to the edge of the continental shelf, and the center of the area lies approximately 70 km northwest of Santa Cruz and 50 km southwest of San Francisco.

Data used in this investigation were collected in April, 1973 on the R/V Kelez, in October, 1979 on the R/V S.P. Lee and in November, 1979 from the R/V Sea Sounder (Plate 5).

A preliminary geologic map (Plate 6) was constructed principally from interpretation of high-resolution seismic reflection profiles. Deeper structures were mapped (Plate 7) in a more general manner from both intermediate penetration 160 kJ sparker and twin 40 cu.in. air-gun seismic reflection profiles. Maps depicting seismicity data and thickness of Quaternary unconsolidated sediment are shown in Plates 7 and 8 respectively.

Geology

Stratigraphy of Outer Santa Cruz basin is based largely on data from two wells (P-035-1 and P-036-1 drilled in the basin (Fig. 1). From these wells and from unspecific additional data of Outer Santa Cruz Basin Hoskins and Griffiths (1971) constructed a stratigraphic column that is reproduced on Figure 9 to show the general stratigraphic relationships that exist in the basin.

Two major bedrock acoustic units are identified in the high-resolution seismic reflection profiles (appendix 3) and are mainly distinguished by their structure. Both units exhibit well defined acoustic reflectors, however, the older unit is more deformed--contains more folds and faults. The older unit is believed to be composed of upper Tertiary strata of probable Miocene age and still older rocks that have been tightly folded, locally sheared and eroded (e.g. appendix 3, fig. 2). Lapping onto this unit is a well layered, gently folded unit that is probably Pliocene in age (e.g. appendix 3, fig. 2).

Both units become less well defined to the north and in the extreme northern part of the lease area neither unit can be identified. Seismic reflection interpretation is difficult in this area, and it is believed that the geology is tectonically complex and that an older bedrock unit may crop-out on the seafloor.

The geologic structure of the Outer Santa Cruz Basin area is dominated by the axis of the basin which trends northwest, extending from Monterey for over 120 km to the break in slope near 37° 30' N latitude (Hoskins and Griffiths, 1971). According to Hoskins and Griffiths, (1971), this structure is a shallow post-middle Miocene syncline bounded by two basement highs, the nearshore Pigeon Point High and the offshore Santa Cruz High. Both the highs and the intervening synclinal basin plunge to the northwest. As shown by McCulloch and others (1977) basin sediment thickens downslope and appears to be limited along the toe of a discontinuous volcanic ridge along which Mulberry, Guide and Pioneer seamounts form prominent topographic highs.

In the shallow subsurface, the basin axis and the Santa Cruz High are undetectable, however, the Pigeon Point High is well defined in the shallow subsurface; its overlying Tertiary and Cretaceous sedimentary rocks crop out on the seafloor. The Pigeon Point High is the most prominent structural feature in the area. It is bounded and slivered by en echelon faults that appear to have offset the entire ridge in a right lateral fashion (Plate 6). Based on offset of bedrock outcrops, displacements along some of the more continuous fault segments may be as much as 4 km, however, the spacing of the acoustic profile lines does not allow for a more accurate determination.

Delineation of the Pigeon Point High is complex because its bedrock cover is severely deformed by faults and tight folds. The late Neogene sediment of the Outer Santa Cruz Basin laps onto the high and is folded near its contact with the older Tertiary rocks. Seaward of the high the folding becomes more gentle and faults are rare. The young rocks dip homoclinally seaward from the high and they may be a progradational sequence near the shelf break (appendix 3, figure 2).

Faults

Most of the faults mapped in the proposed lease area lie along the eastern part of the area. Many of these faults are probably not active and are possibly of pre-Quaternary age. Although they extend to the seafloor, they are primarily restricted to late Tertiary or older rocks. A fault associated with the Pigeon Point High in the north-central part of the proposed lease tract, has some associated seafloor expression. It is unknown if this is a faultline scarp produced by differential erosion of the Tertiary rocks along the fault or if the scarp is the result of recent fault displacement. More recent faults are present in the Half Moon Bay area outside of the lease blocks and many appear to displace Quaternary sediment or offset the seafloor. These faults may be part of the seismicaly active offshore fault system noted earlier in the discussion of the geologic framework.

The remainder of the study area is exceptionally devoid of Quaternary faults. Few faults appear to extend upward into the probable Pliocene-aged sediment that covers much of the shelf. Locally, however, a few faults appear to displace Pliocene sediment that drapes the shelf break near the western margin of the proposed lease area.

The major structural deformation that occurs in the area of study lies adjacent to a probable northwestern offshore extension of the San Gregorio fault zone, near the coastline from Point Ano Nuevo north. This deformation increases to the northwest. This pattern of deformation supports the seismographic evidence noted below and the arguments made above in the discussion of the geologic framework that some of the displacement between the Pacific and North American Plates is being accommodated by movement along faults to the west of the San Andreas fault.

Seismicity

The seismicity of the study area is low in comparison to the number of earthquakes that occur to the south in Monterey Bay. Large earthquakes (>M4) in this area would have been recorded by distant seismographs but the offshore area lies outside the seismograph network, and if small seismic events occur they may go undetected.

Seismic events shown on Plate 7 are generally concentrated in two clusters; one near Point Ano Nuevo and the other near Pacifica where the San Andreas fault trends offshore. The most significant cluster of epicenters is located approximately 10 km north of the lease area along the San Andreas fault. Although the largest earthquake in this cluster (Plate 7) for the period of 1933 to 1979 was a magnitude 4, the San Andreas is capable of producing great earthquakes (M 8.0 or larger) such as the M 8.3 event that occurred in this region in 1906. Therefore, any structure placed on the seafloor in the northeastern part of the proposed lease area may be subjected to high intensity, high magnitude events in the future.

The cluster of earthquake epicenters that lies in the vicinity of Point Ano Nuevo (Plate 7) are all small magnitude earthquakes that are probably associated with the San Gregorio-Palo Colorado fault zone, which extends south from this point across Monterey Bay. The maximum magnitude earthquake instrumentally detected in this area is M 5.5 (Toppozada and others, 1978), however, the recorded seismic history may be deceptively low in terms of the maximum potential earthquake magnitude (Plate 7). Based on the assumption that this fault is part of a coastal fault system that extends from at least the southern edge of Monterey Bay to the Golden Gate, it has been suggested that this fault may be capable of producing a M 7.5 earthquake (Greene and others, 1973).

Very few earthquakes have been detected in the offshore outside of the two clusters just discussed. The one or two events detected between 1933 and 1979 (Plate 7) are all low magnitude events (less than M 0.9).

Seafloor Instability

Areas of potential seafloor instability usually are detected by the identification of downslope sediment creep and submarine slides and slumps on seismic reflection profiles (Plates 7 and 8; Appendix 3, Fig. 2). Although few of these features exist within the proposed lease tract, there are many just seaward of the lease area where the continental slope begins. Another determinant of seafloor stability is the potential liquefaction of bottom sediments. At present, data concerning the engineering properties of sediments in the Outer Santa Cruz Basin area are not adequate to assess liquefaction potential.

Slumps, Landslides and Downslope Sediment Movement

The only major submarine landslide mapped in the region is near the head of Pioneer Canyon, some distance (9 km) west of the northwestern boundary of the proposed lease tract. Slumping has also occurred in the heads of Ascension Canyon in the extreme southern part of the proposed lease area. Elsewhere within the study area no submarine landslides have been detected on the flat continental shelf. Areas of irregular bottom topography that are inferred to indicate downslope soil movement are found along the continental slope immediately west of the proposed lease area (appendix 3, figures 2 and 3). Irregular seafloor of this kind is especially conspicuous near the extreme southwestern margin of the lease area. Although downslope sediment movement is not observed in the proposed lease blocks, headward encroachment of

Canyon tributaries or slumping on the slope could adversely impact seafloor structures placed near the shelf break.

Channels

Presently active, inactive, and buried stream or submarine channels have been mapped in the study area (Plate 6). Most exist along the continental slope, west and well removed from the proposed lease tract. However, a fairly continuous buried channel extends across a lease block in the extreme southern part of the proposed lease tract (appendix 3, fig. 1). The channel deposits appear to be exposed along the slope just north of Ascension Canyon and immediately south of the southern boundary of the proposed lease tract. Several submarine channels head near the west-central and northwest boundaries of the proposed lease area. These channels may be actively conducting sediment away from the shelf. The channels lie either just outside or just within the southeasternmost corner of the lease area. If the sediment in these channels is granular and uncompacted, it may be subject to earthquake induced liquefication which, in turn could cause seafloor failure in this area.

Quaternary Sediment Character and Thickness

Topographically irregular exposures of bedrock, largely upper Tertiary Miocene-aged sedimentary rocks, trend northwesterly across the north-central part of the proposed lease area. Elsewhere the area is covered with younger sediment of late Tertiary and Quaternary age.

No sediment samples were taken in this study to assess sediment character, however inferences about the sediment dynamics can be drawn from its distribution. The sediment thickness of the probable upper Quaternary cover was determined by mapping the thickness of the acoustically transparent unit identified in high-resolution profiles collected during the field investigation (Plate 5). Three distinct units are identified and mapped (Plate 8) for these sediments. Unit C is a shelf edge and slope accumulation of generally unstable or potentially unstable unconsolidated sediment identified on the basis of discontinuous subbottom reflectors and surface irregularities. Unit B (Plate 8) is a layer of unconsolidated sediment of 5-10 m thickness through which shallowly dipping upper Tertiary rocks of possible Pliocene age crop out locally as elongate ridges on the seafloor. Upslope of the ridges the unconsolidated sediment is ponded to a thickness of 10 to about 20 m. Unit A forms two distinct sediment wedges which thin seaward against the Pigeon Point High. This unit locally overlies unit B and is therefore inferred to be of Holocene age.

Erosion and Deposition

No area of active sediment accumulation or erosion was identified. Nearshore currents apparently are strong enough to prevent sediment deposition on the exposed bedrock, but elsewhere within the proposed lease tract, there is no evidence of significant erosion of the seafloor.

Gas

In several localities within the study area water column anomalies and possible subsurface velocity pull downs and bright spots occur suggesting both the existence of gas in the shallow subsurface as well as in the water column. These features exist primarily in two zones; one along the exposed part of the Pigeon Point High and the other along the shelf break in the extreme southern part of the study area. Without direct sampling it is difficult to determine whether the water-column anomalies in the vicinity of the Pigeon Point High are kelp, fish or gas. However, the many anomalies that are associated with faults and subsurface velocity anomalies are probably gas seeps.

The zone of gas-charged sediment and local water-column anomalies that trends along the shelf break in the southern part of the study area (Plate 7) is characterized by subsurface velocity anomalies, which may possibly be associated with shallow faulting. The extent and type of gas within this zone is not known. It could be biogenic methane gas produced by the reduction of organic material in Quaternary sediment, or gas escaping along faults from hydrocarbon reservoirs at depth. The gas zones could be a hazard to seafloor structures for as noted above in the discussion of gas-charged sediment in Outer Santa Cruz Basin, the presence of gas weakens the sediment and may promote failure during seismic shaking.

BODEGA BASIN

Geologic Framework

This basin is approximately 180 km long and has an average width of approximately 25 km. It is bounded on the east by the San Andreas fault and down-to-basin faults along which granite basement has been elevated, and to the southwest in the Gulf of the Farallones by a structural high of deformed Neogene sediments. The basin overlies the granitic Salinian basement block. Granitic rocks on the east side of the basin crop out onshore west of the San Andreas Fault. They have also been recorded from two offshore exploratory wells south and southeast of Point Reyes (P-041-1ET, P-039-1ET, Plate 10), and from the Farallon High, a structural high that forms the southwestern basin margin. Cretaceous rocks, primarily marine sandstone, basic volcanics and sills are probably limited to scattered remnants in the southern part of the basin. Eocene marine shale and sandstone are thin and scattered over the basin, with greater thickness to the north, where they rest conformably on the underlying granite.

Neogene strata record repeated periods of uplift and erosion followed by periods of marine sedimentation. Lower Miocene rocks rest upon an erosional unconformity, and grade vertically from shallow-marine basal sandstones to deeper-marine shales and sandstones. The middle-Miocene sequence is similar, with shallow-marine basal sandstone resting on an erosional unconformity, and grading upward to finer grained rocks containing cherty shale. Uplift and erosion of the Farallon High and the Pigeon Point High, its southeastern extension, occurred in early late Mioncene time. Formation of the Bodega basin to the northeast was followed by deposition of as much as 3000 m of Neogene marine clays and silts and some sands of late Miocene and Pliocene age.

The tectonic history of this part of the shelf and the Bodega basin is similar to that of the adjacent shelf areas. Episodes of pre-middle Miocene deformation are recorded in the structure and erosional unconformities in Cretaceous and Paleogene rocks. Pre-Neogene structures are complex and may follow a different structural grain than those developed in the younger overlying strata (Hoskins and Griffiths, 1971). Subduction-related tectonics probably came to a close in late Miocene time with the uplift of the Farallon-Pigeon Point High. At about this time mid-Tertiary strata were deformed within the basin. The end of this deformation within the basin is recorded by an unconformity between the middle and upper Miocene units. Right-lateral shear and regional compression accompanied the transition to strike-slip faulting. Folds developed parallel to the long axis of the basin, and the northeastern-bounding structural high of compressed Neogene sediment underwent additional compression. Compression was accompanied by the development of high angle reverse faults, and at the same time a large displacement fault formed along the eastern basin margin west of Montara Mountain. This latest episode of deformation, which began in late Pliocene, continues today.

Faults

Faults in the Bodega Basin area are shown in Plate 10. The eastern bounding fault is a double stranded high-angle fault (Fig. 10). A fault that extends from at least as far south as Point Reyes to Point Arena has downdropped the ocean floor relative to the continental slope along the western side of a structural high that forms the western margin of the basin. Active faulting has offset the seafloor on the San Andreas fault. Other faults shown in Plate 10 may have experienced recent displacement. To accurately date the most recent movement of a fault requires dated samples of the youngest rocks offset by a fault, and dated samples of the oldest rocks overlying and not offset by the fault. Most recent movement occurred between those two dates. Where rock samples are not available for dating fault activity, as in the Bodega Basin and Arena Basin areas, most recent fault movement must be determined from the less reliable technique of inferring ages from the character and geometry of beds on seismic records. Faults (like the San Andreas) along which the sea floor is offset are inferred to have been active recently. Faults that reach, but do not offset, the sea floor may also have been active recently, but may have had horizontal (rather than vertical) displacement, or may have had seafloor

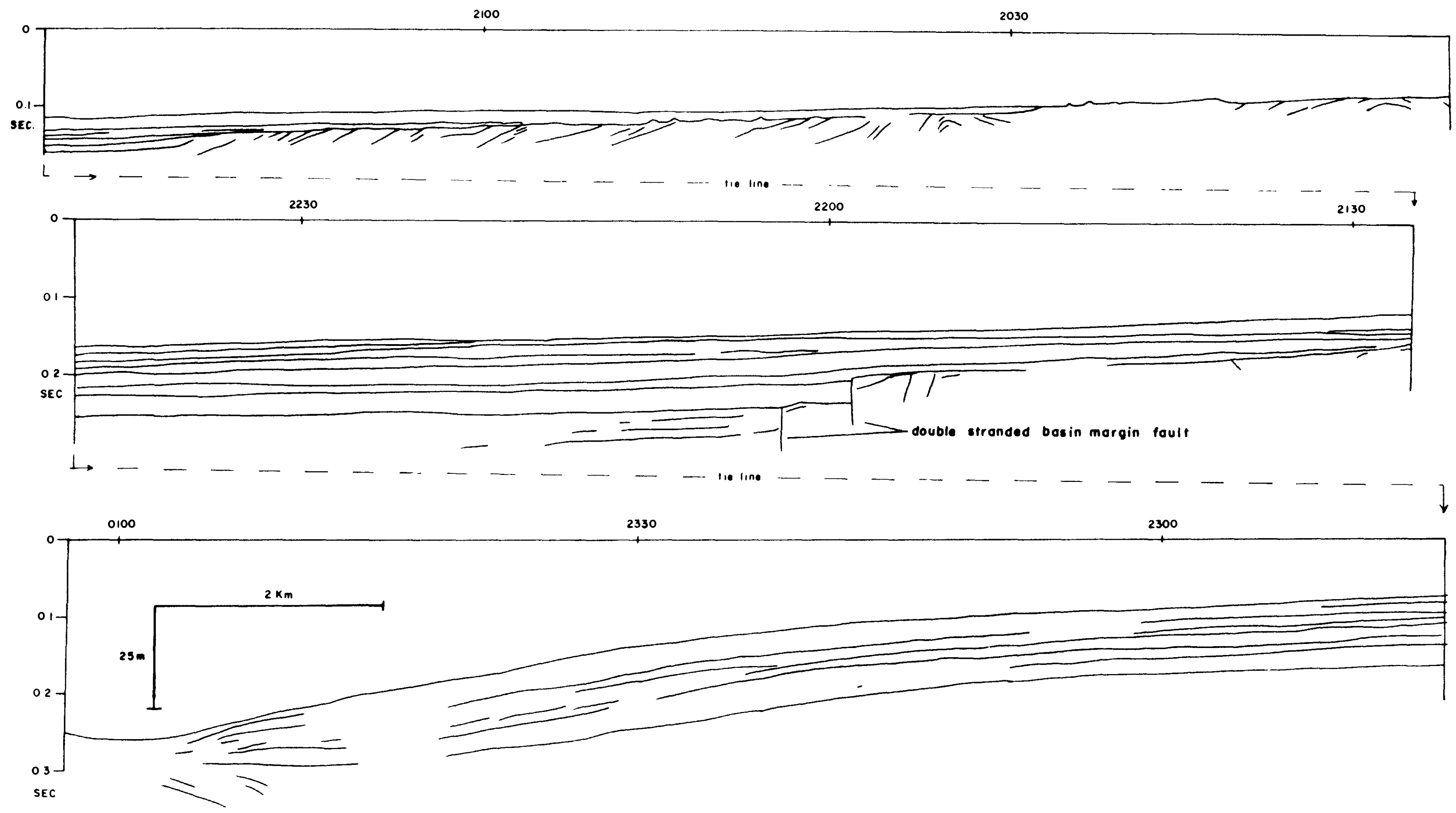


Figure 10. Tracing and interpretation of high-resolution profile line 35 in Bodega Basin. Profile shows double-stranded fault at eastern margin of basin. Location of line 35 is given in Plate 9.

offset destroyed by wave activity. At some locations faults reach the sea floor where highly folded (presumably Miocene) rocks crop out. Such faults may have been active recently, or they may not have moved since the Miocene. Details and illustrations of the system used to categorize faults in the Bodega and Arena Basin areas are given in the explanation of Plate 10. Active faulting has offset the seafloor on the San Andreas fault. Other faults shown in Plate 10 may also have experienced relatively recent displacement.

Seismicity

Seismic activity in the Bodega Basin area has been monitored by the USGS since 1970. Since then, eight earthquakes were detected offshore between Point Reyes and Point Arena (Plate 11). Seven had magnitudes between 1.0 and 2.0, and one had a magnitude of 3.3 and was followed by 60 aftershocks (Stickney, 1978).

Seismic events in the Bodega Basin area have been monitored for a time interval that is short with respect to the recurrence interval of large earthquakes. Hence, observed events are not representative of large less frequent earthquakes. For example, movement on the San Andreas fault during the 8.3 magnitude 1906 San Francisco earthquake displaced the seafloor in the Bodega Basin area. Earthquakes of similar high magnitude can be expected to reoccur on the San Andreas fault in the Bodega Basin area.

Slumping

Slumping is identifiable by surface relief and be rotated, contorted, or discontinous internal reflectors. Slumps cover most of the continental slope between Point Reyes and Point Arena, an area where slopes are commonly 1-7° (Plate 12, Fig. 14). At most locations, the entire slope is so disrupted by slumping that it is impossible to recognize the lateral or vertical extent of individual blocks. Total thickness of sediment that appears to be disrupted by slumping is commonly as much as 300-400 m.

Shallow Subsurface Gas

Shallow subsurface gas is recognizable by discontinous bright reflectors and by regions in the subsurface where reflectors are obscured in an otherwise bedded section (Fig. 11). At some locations, shown in Plate 12, gas occurs immediately below the seafloor and produces seafloor craters as it seeps into overlying seawater. More commonly, the gas occurs a few meters or tens of meters below the seafloor.

ARENA BASIN

Geologic Framework

The eastern and northern margins of the Point Arena basin are well defined by the San Andreas fault as it runs northwestward from Point Arena and swings westward along the Mendocino Escarpment. The western margin is a ridge formed by a partially

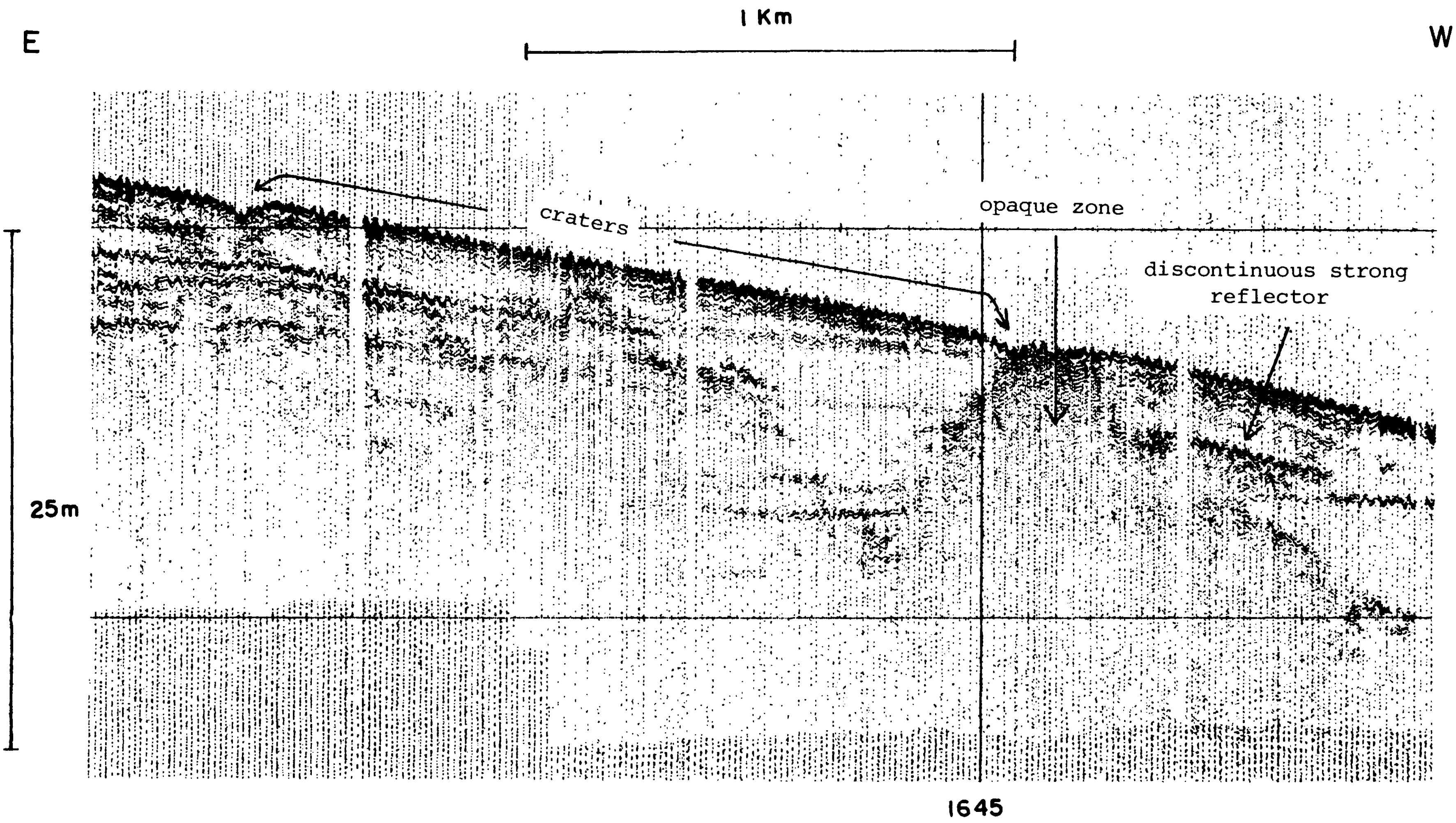


Figure 11. High-resolution profile of subsurface gas and seafloor craters. Beds containing gas appear as discontinuous strong reflectors and as acoustically opaque zones. Profile is from line 43.

buried northwest trending structural high. The ridge appears to be geologically complex. A Deep Sea Drilling Project core hole (DSDP Leg 18, Site 173, Kulm and others, 1973) drilled on the ridge bottomed in andesitic basement at a depth of 320 m. Silver (written commun., 1976) dredged graywacke of middle-Eocene to Oligocene age from this ridge about 50 km west of Fort Bragg. The basin is reported to be underlain partly be pre-Cretaceous (Jurassic ?) metasediments (Hoskins and Griffiths, 1971). Cretaceous shallow water marine shale, siltstone and fine-grained sandstones thin abruptly to the north in the basin, probably as the result of pre-Eocene erosion. Eocene sediments also thin abruptly to the north in the basin, and are also truncated by an erosional unconformity below lower Miocene strata. Lower Miocene deep water marine shales containing a thick but discontinous basal sandstone rest on the unconformity, and record a transgression and subsequent deep marine deposition. As in the basins to the south, the following middle Miocene is represented by cherty shale and over most of the basin there appears to have been no break between middle and upper Miocene sedimentation. Upper Miocene marine siltstones and claystones grade upward into upper Pliocene marine sandstones, which in turn are truncated by an unconformity at the base of the coarser Pleistocene section.

Little is know of the pre-Neogene tectonic history of the basin except that several episodes of deformation and erosion occurred during Cretaceous and Paleogene time. Judging from the degree of induration of early Eocene sediments, a considerable thickness of overlying rocks may have been removed. Likewise little is known of the history of the western boundary ridge. Seismic reflection profiles (Silver, 1971; Kulm and von Huene, 1971) across the ridge and age determinations from the DSDP core hole suggest that Miocene and younger strata are little deformed. Neogene structure is complex at the south end of the basin, but is relatively simple to the north. Deformation of the south end of the basin may have started with the uplift that produced the early late Miocene unconformity in the Point Arena area. However, the major high-angle reverse faults, some with verticle displacements of about 2000 m and the fold axes that lie parallel to the elongate basin were largely formed in upper Pliocene time. These faults and folds trend northwest, and diverge northward from the San Andreas fault.

Faults

In the Arena Basin area, recent faulting has offset the seafloor along most of the length of the San Andreas fault (Plate 10 and Fig. 12). Other faults occur in older basement rocks and along the axis of anticlines on the continental slope (Plate 10).

Seismicity

Between 1971 and 1979, one earthquake occurred in the Arena Basin area. It had a magnitude between 3.0 and 3.9, and its epicenter was located approximately on the San Andreas fault (Plate 11).

The 1906 magnitude 8.3 San Francisco earthquake occurred on

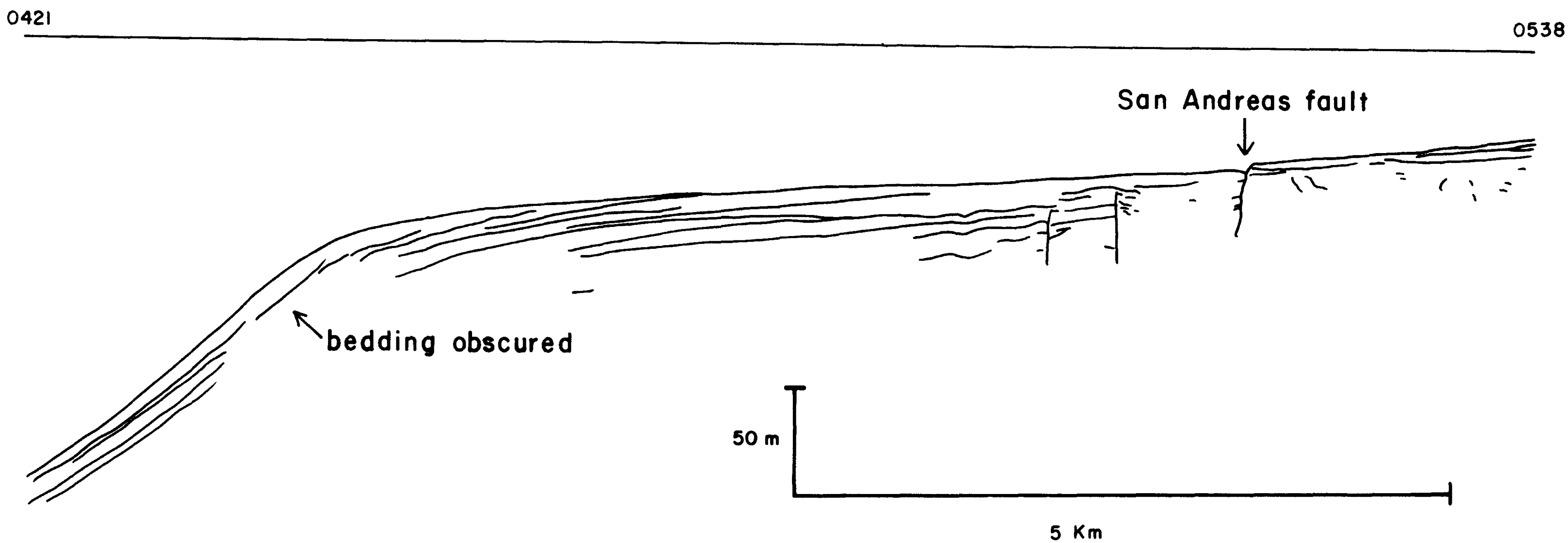


Figure 12. Tracing of high-resolution profile line 83 in Arena Basin area. Profile shows seafloor offsets on San Andreas fault and bedding obscured by gas at shelf edge. Location of line 83 is given in Plate 9.

the San Andreas fault, and similar magnitude earthquakes can be expected to occur in the future. Strong ground motion could be expected to occur over a large area in Arena Basin during such an event. Boore and Porcella (in press) have shown that in deep earthquakes on long faults (such as the San Andreas), peak ground acceleration, velocity, and displacement at a distance of 4-5 km from a fault can be as large as immediately adjacent to the fault. In the case of the 1979 Imperial Valley earthquake, ground motion 10 km from the fault was one-half as strong as several hundred meters from the fault. As illustrated in Plate 9, much of the shelf north of Point Arena is within 5 or 10 km of the San Andreas fault and could be expected to have very strong ground motion during a large earthquake.

Slumping

Locations of slumps are shown in Plate 12. Slumps in the Arena Basin area range in size from small isolated masses of sediment a few tens of meters or less in thickness and a few hundred meters in lateral extent (Fig. 13), to areas of the slope tens of kilometers in extent disrupted to depths of 300 m or more (Fig. 14).

Shallow Subsurface Shelf-edge Gas

As noted earlier in this report shallow subsurface gas occurs in a belt that lies along the shelf-edge north of Point Arena (Plate 12). The gas prevents penetration by high-

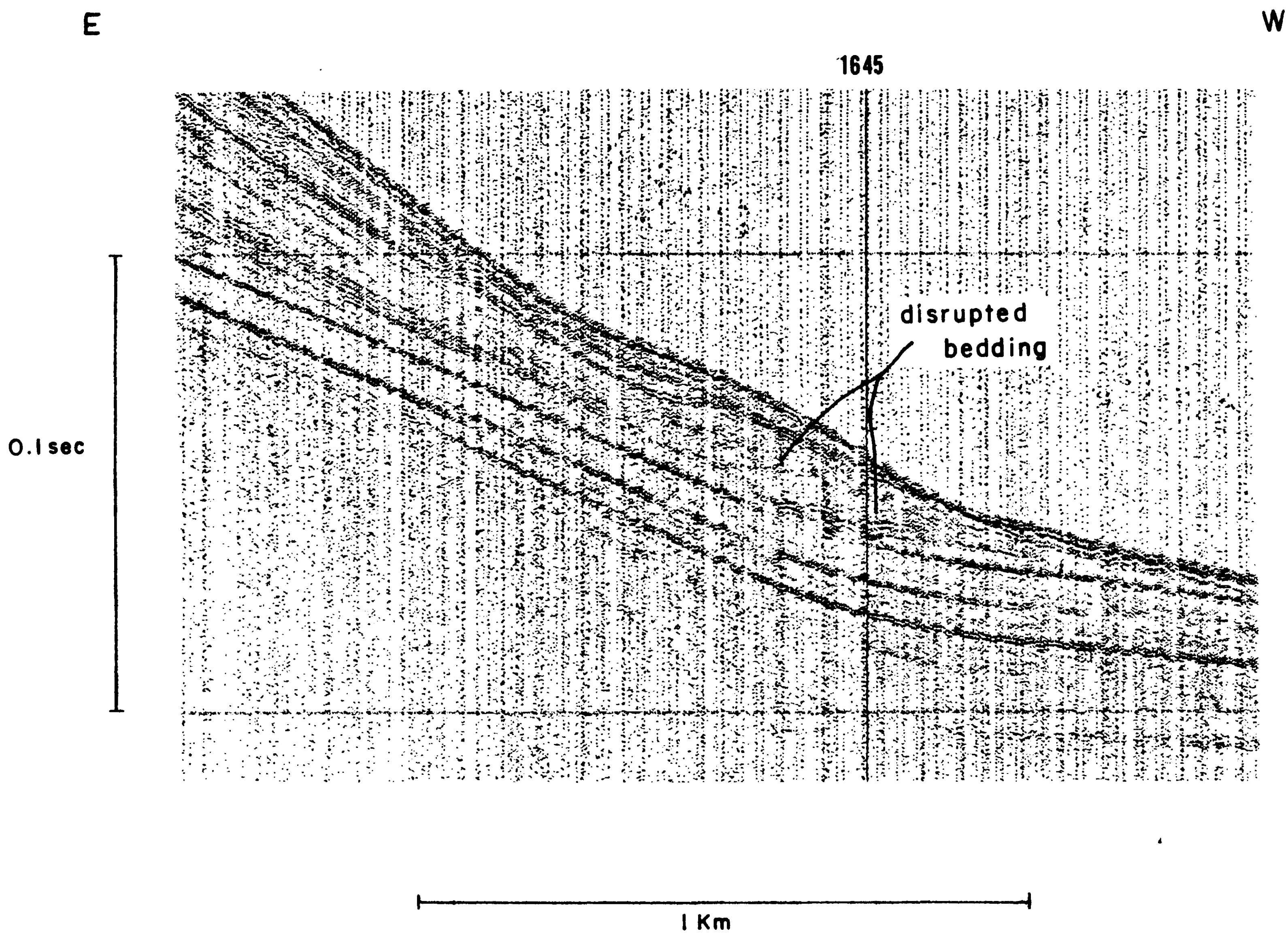


Figure 13. High-resolution profile of small slump and related downslope soil movement with surface relief and disrupted bedding; from line 81.

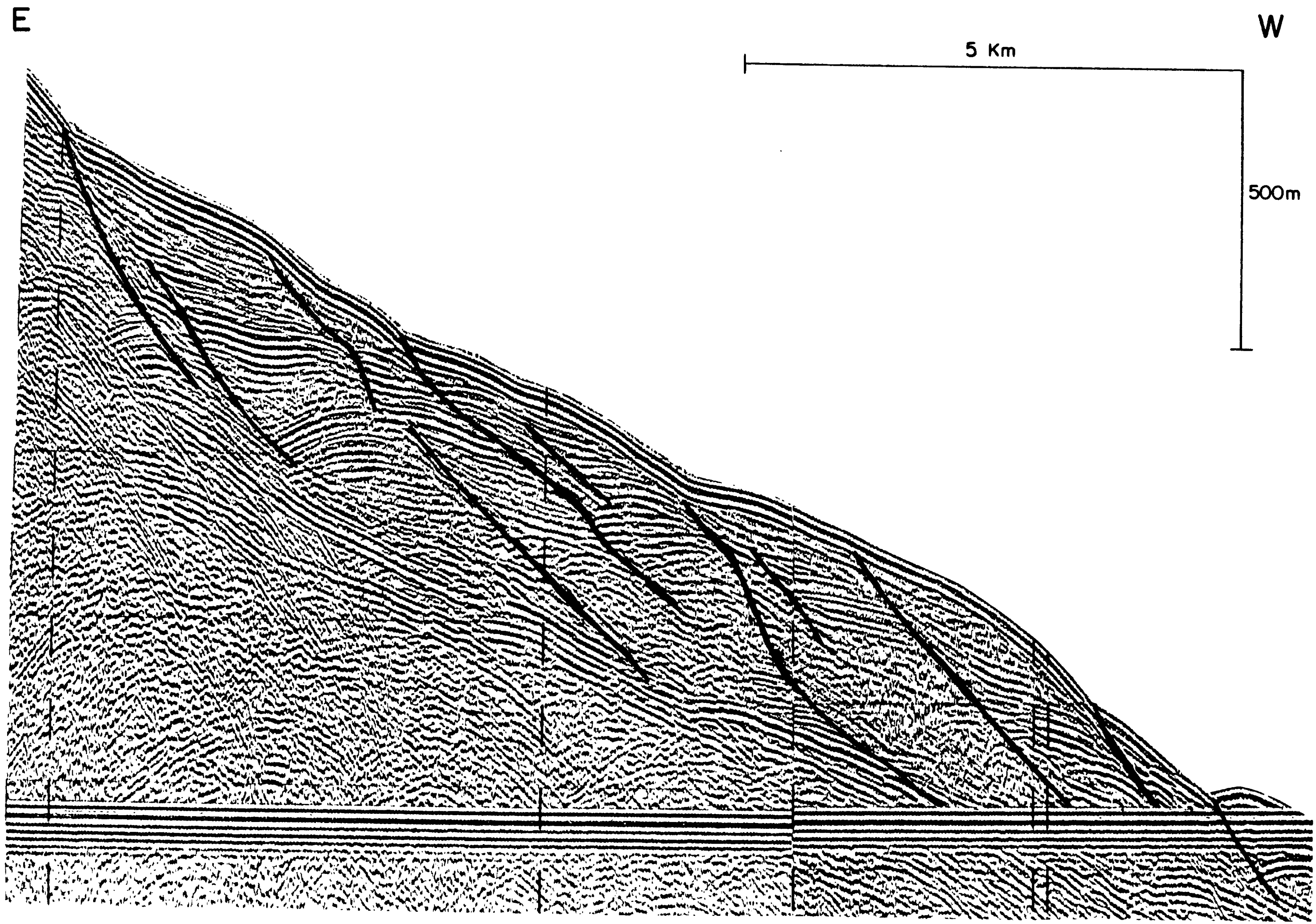


Figure 14. Sparker profile of large slump blocks from line 68. Bedding in some blocks has been rotated. Thick lines are inferred failure surfaces.

resolution seismic systems. In many locations, the gas appears to be confined by bedding, and much of the shelf-edge gas may have migrated updip through permeable beds of slope sediment.

REFERENCES

Albee, A. L., and Smith, J. L., 1967, Geologic criteria for nuclear power plant location: Society of Mining Engineers Transactions, v. 238, p. 430-434.

Atwater, Tanya, 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geological Society of America Bulletin, v. 81, p. 3513-3536.

Bonilla, M. G., 1967, Historic surface faulting in continental United States and adjacent parts of Mexico: U.S. Geological Survey Open-File Report; also U.S. Atomic Energy Commission Report TID-24124, 36 p.

______, 1970, Surface faulting and related effects, in Wiegel, R. L., ed., Earthquake Engineering, Englewood Cliffs, New Jersey, Prentice Hall, Inc., p. 47-74.

Boore, D. M., and Porcella, R. L., in press, Peak horizontal ground motions from the 1979 Imperial Valley Earthquake: comparison with data form previous earthquakes, U.S. Geological Survey Professional Paper on Imperial Valley Earthquake.

Buchanan-Banks, J. M., Pampeyan, E. H., Wagner, H. C., and McCulloch, D. S., 1978, Preliminary map showing recency of faulting in coastal south-central California: U.S. Geological Survey Miscellaneous Field Studies Map MF-910.

Byerly, Perry, 1930, The California earthquake of November 4, 1927: Seismological Society of America Bulletin, v. 20, no. 1, p. 53-66.

Carlson, P. R., Molnia, B. F., and Wheeler, M. C., 1980, Seafloor geologic hazards in OCS Lease Sale area 55, eastern Gulf of Alaska: Offshore Technology Conference OTC 3914, p. 593-598.

Coffman, J. L., and von Hake, C. A., 1973, Earthquake history of the United States: National Oceanic and Atmospheric Administration, Publication 41-1, p. 139-189.

Cooper, Alan, 1971, Structure of the continental shelf west of San Francisco, California: U.S. Geological Survey Open-File Report.

Coppersmith, K. J., and Griggs, G. B., 1978, Morphology, recent activity, and seismicity of the San Gregorio fault zone: California Division of Mines and Geology, Special Report 137, p. 33-43.

Danenberger, E. P., 1980, Outer continental shelf oil and gas blowouts: U.S. Geological Survey Open-File Report 80-101,13 p.

Donley, M. W., Allan, Stuart, Caro, Patricia, and Patton, C. P., 1979, Atlas of California: Culver City, California, Pacific Book Center, P. 26-27.

Edwards, B. D., Field, M. E., and Clukey, E. C., 1980, Geological and geotechnical analysis of a submarine slump, California Borderland: Offshore Technology Conference OTC 3726, p. 399-402.

Field, M. E., Clarke, S. H., Jr., and White, M. E., (1980) Geology and geological hazards of offshore Eel River Basin, Northern California continental Margin: U.S. Geological Survey Open-File Report 80-1080.

Gawthrop, W. H., 1975, Seismicity of the central California coastal region: U.S. Geological Survey Open-File Report 75-134, 87 p.

______, 1978a, The 1927 Lompoc California earthquake: Seismological Society of America Bulletin, v. 68, p. 1705-1716.

______, 1978b, Seismicity and tectonics of the central California coastal region: California Division of Mines and Geology, Special Report 137, p. 45-56.

Gawthrop, W. H., and Engdahl, E. R., 1975, The 1927 Lompoc earthquake and the 1969 San Luis Bank (sic) earthquake sequence, a comparative study: EOS, Transactions of the American Geophysical Union, v. 56, no. 12, p. 1028.

Graham, S. A., and Dickinson, W. R., 1978, Evidence for 115 kilometers of right-slip on the San Gregorio-Hosgri fault trend: Science, v. 199, p. 179-181.

Greene, H. G., Lee, W.H.K., McCulloch, D. S., and Brabb, E. E., 1973, Faults and earthquakes in the Monterey Bay region, California: U.S. Geological Survey, San Francisco Bay Region Environment and Resources Planning Study, Basic Data Contribution 58, 14 p.

Greene, H. G., Silver, E. A., and von Huene, Roland, 1975, Seismic reflection profiles, USNS BARTLETT, November 1972 cruise, offshore central and southern California: U.S. Geological Survey Open-File Report 75-121.

Hamilton, D. H., and Willingham, C. R., 1977, Hosgri fault zone, amount of displacement, and relationship to structures of the western Transverse Ranges: Geological Society of America Abstracts with Programs, v. 9, p. 429.

Hampton, M. A., Bouma, A. H., Carlson, P. R., Molnia, B. F., and Clukey, E. C., 1978, Quantitative study of slope instability in the Gulf of Alaska: Offshore Technology Conference OTC 3314, p. 2307-2312.

Hanks, T. C., 1979, The Lompoc, California earthquake (November 4, 1927; M-7.3) and its aftershocks: Seismological Society of America Bulletin, v. 69-2, p. 451-462.

Hoskins, E. G., and Griffiths, J. R., 1971, Hydrocarbon potential of northern and central California offshore; in Cram, I. H. (ed.), Future petroleum provinces of the U.S. - their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 212-228.

Howell, D. G., McCulloch, D. S., and Vedder, J. G., 1978, General geology, petroleum appraisal, and nature of environmental hazards, Eastern Pacific Shelf, Latitude 28° to 38° North: U.S. Geological Survey Circular 786, 29 p.

Iida, Kumizi, 1965, Earthquake magnitude, earthquake faults, and source dimensions: Nagoya University, Journal of Earth Sciences, v. 13, no. 2, p. 115-132.

Kulm, L. D., von Huene, Roland, and others, 1973, Initial reports of the Deep Sea Drilling Project, v. 18, Washington (U.S. Government Printing Office), p. 31-95.

Lee, W.H.K., Yerkes, R. F., and Simirenko, M., 1979, Recent earthquake activity and focal mechanisms in the western Transverse Ranges, California: U.S. Geological Survey Circular 799-A, p. 1-26.

Leslie, R. B., (in press), Continuity and tectonic implications of the San Simeon-Hosgri fault zone, central California: U.S. Geological Survey Open-File Report, 82 p.

Lewis, K. B., 1970, Slumping on a continental slope inclined 1°-4°: Sedimentology, v. 16, p. 97-110.

McCulloch, D. S., 1976, Acoustic reflection profiles, R/V SAMUEL P. LEE, November 1975, Carmel Bay to San Luis Bay, central California: U.S. Geological Survey Open-File Report 76-180.

McCulloch, D. S., and Chapman, R. H., 1977, Maps showing residual magnetic intensity along the California coast, Latitude 37°30'N to 34°30'N: U.S. Geological Survey Open-File Report 77-79.

McCulloch, D. S., Clarke, S. H., Jr., Field, M. E., Scott, E. W., and Utter, P. M., 1977, A summary report on the regional geology, petroleum potential, and environmental geology of the southern proposed lease sale 53, central and northern California outer continental shelf: U.S. Geological Survey Open-File Report 77-593, p. 1-57.

McCulloch, D. S., Vedder, J. G., Wagner, H. C., and Brune, R. H., 1979, Geologic setting, in Cook, H. E., ed., Geologic studies of the Point Conception Deep Stratigraphic Test Well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-1218, p. 10-25.

McCulloh, T. H., 1979, Implications for petroleum appraisal, in Cook, H. E., ed., Geologic studies of the Point Conception Deep Stratigraphic Test Well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-1218, p. 26-42.

McCulloh, T. H., and Beyer, L. A., 1979, Geologic and geophysical implications of density and sonic logs, in Cook, H. E., ed., Geologic studies of the Point Conception Deep Stratigraphic Test Well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-1218, p. 43-48.

Mousseau, R. J., and Williams, J. C., 1979, Dissolved hydrocarbons in coastal waters of North America: American Association of Petroleum Geologists Bulletin, v. 63, no. 4, p. 699-700.

Newmark, N. M., 1976, Rational for design spectra for Diablo Canyon Reactor Facility, Appendix C, in Supplement No. 5 to the Safety Evaluation of the Diablo Canyon Power Station, Units 1 and 2, p. C1-C42.

Pacific Gas and Electric, 1975, Additional geologic and seismologic studies-1975: Appendix 2.5E to Amendment No. 31, to the Diablo Canyon FSAR.

Page, B. M., 1970a, Sur-Nacimiento fault zone of California: Continental margin tectonics: Geological Society of America Bulletin, v. 81, no. 3, p. 667-690.

Page, B. M., Wagner, H. C., McCulloch, D. S., Silver, E. A., and Spotts, J. H., 1979, Geologic cross section of the continental margin off San Luis Obispo, the southern Coast Ranges, and the San Joaquin Valley, California: Geological Society of America Map and Chart Series MC-28G, 12 p.

Pampeyan, E. H., 1979, Preliminary map showing recency of faulting in coastal North-central California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1070, 1:250,000.

Payne, C. M., Swanson, O. E., and Schell, B. A., 1979, Investigations of the Hosgri fault offshore southern California, Point Sal to Point Conception: U.S. Geological Survey Open-File Report 79-1199, 22 p.

Porcella, R. L., and Matthesen, R. B., 1979, Preliminary summary of U.S. Geological Survey strong motion records for the October 15, 1979 Imperial Valley earthquake: U.S. Geological Survey Open-File Report 79-1654, 40 p.

Reimnitz, Erk, 1972, Effects in the Copper River Delta, in The Great Alaska Earthquake of 1964: Oceanography and Coastal Engineering, Washington, D.C., National Academy of Sciences, p. 290-302.

Richter, C. F., 1958, Elementary seismology: San Francisco and London, W. H. Freedman and Company, p. 477.

Ross, D. C., and McCulloch, D. S., 1979, Cross section of the Southern Coast Ranges and San Joaquin Valley from offshore Point Sur to Madera, California: Geological Society of America Map and Chart Series MC-28H, 4 p.

Smith, S. W., 1978, Seafloor expression of the 1927 Lompoc earthquake (abs.): EOS, American Geophysical Union Transactions, v. 59, no. 12, p. 1128.

Stickney, M. C., 1979, The Fort Ross earthquake sequence, March and April, 1978: Seismological Society of America Bulletin, v. 69, no. 6, p. 1841-1849.

Tocher, Don, 1958, Earthquake energy and ground breakage: Seismological Society of America Bulletin, v. 48, p. 147-153.

Toppozada, T. R., Parke, D. L., and Higgins, C. T., 1978, Seismicity of California--1900-1931: California Division of Mines and Geology, Special Report 135, 39 p.

Townley, S. D., and Allen, M. W., 1939, Descriptive catalog of earthquakes of Pacific Coast of the United States, 1769 to 1928: Seismological Society of America Bulletin, v. 29, p. 1-297.

Vedder, J. G., 1976, Precursors and evolution of the name California Continental Borderland, in Howell, D. G., ed.,Aspects of the geologic history of the California Continental Borderland: American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24, p. 6-12.

Wagner, H. C., 1974, Subbottom acoustic reflection profiles, Cape San Martin to Point Sal, south-central California offshore: U.S. Geological Survey Open-File Report (no number assigned).

______, 1974a, Marine geology between Cape San Martin and Point Sal, south-central California; U.S. Geological Survey Open-File Report 74-252.

Welday, E. E., and Williams, J. W., 1957, Offshore surficial geology of California: California Division of Mines and Geology, Map Sheet 26.

Whelan, T., III, Coleman, J. M., Suhayda, J. N., and Garrison, L. E., 1975, The geochemistry of Recent Mississippi River sediments- gas concentration and sediment stability: Offshore Technology Conference, OTC 2342, 14 p.

Whelan, T., III, Coleman, J. M., Suhayda, J. N., and Roberts, H. H., 1978, Acoustical penetration and shear strength in gas-charged sediments: Marine Geochemistry, v. 2, p. 147-159.

APPENDIX 1

Rossi-Forel intensity scale (Townley and Allen, 1939).

I. Microseismic shock--recorded by a single seismograph, or by seismographs of the same model, but not putting seismographs of different patterns in motion; reported by experienced observers only.

II. Shock recorded by several seismographs of different patterns; reported by a small number of persons who are at rest. A very light shock.

III. Shock reported by a number of persons at rest; duration or direction noted. A shock; a light shock.

IV. Shock reported by persons in motion; shaking of movable objects, doors and windows, cracking of ceilings. Moderate; sometimes strong; sharp; light.

V. Shock felt generally by everyone; furniture shaken, some bells rung, some clocks stop. Smart; strong; heavy; severe; sharp; quite violent; some sleepers waked.

VI. General awakening of sleepers; general ringing of bells; swinging of chandeliers; stopping of clocks, visible swaying of trees; some persons run out of building, window glass broken. Severe; very severe; violent.

VII. Overturning of loose objects; fall of plaster; striking of church bells; general fright, without damage to buildings; nausea. Violent; very violent.

VIII. Fall of chimneys; cracks in the walls of buildings.

IX. Partial or total destruction of some buildings.

X. Great disasters; overturning of rocks; fissures in the surface of the earth; mountain slides.

APPENDIX 2

Historical accounts of earthquakes 1812-1927, in, and adjacent to, offshore Santa Maria Basin (Townley and Allen, 1939).

1812 September, October, or December? Sunday?

IX. San Juan Capistrano. Fatal earthquake; the church was destroyed, with loss of life (thirty to forty-five persons). The Mission Church at Santa Inez, near Santa Barbara, one hundred and seventy miles from San Juan Capistrano, was completely destroyed and some lives lost.--J.B.T., "Register." [see fifth entry below.] A Spanish ship at anchor, thirty-eight miles from Santa Barbara, was injured by the shock.--J.B.T., "Register." The year 1812 was ever after known as el ano de los teblores.--H.H.B. See letter of Lieut. E. O. C. Ord, U. S. A., (November, 1849), in Tyson's Report, "Geology of California," p. 125, where, however, it is called the shock of 1814. October 8, between 7 and 8 a.m., is the day of the great earthquake which destroyed the church of San Juan Capistrano, according to a careful article in the SF Bulletin, March 5, 1864. This date is so often fixed in September or on December 8. The Sundays were: September 6, 13, 20, 27; October 4, 11, 18, 25; November 1, 8, 15, 22, 29; December 6, 13, 20, 27.

1812 December 21.

VIII? San Fernando. The church received serious damages. At San Buenaventura, three heavy shocks before January 1. At Santa Barbara, a long series of shocks beginning on the 21st and lasting several months [days?].--H. H. B.

Santa Inez; two shocks, fifteen minutes apart, beginning at 10 a.m. At Purisima (IX), at 10:30 a.m., December 21, the earth shook for four minutes so violently that it was difficult to stand. Half an hour later another more violent shock. A succession of light shocks this day and the next.--H.H.B.

P. Gil reported that there was a huge earthquake wave at sea. A stick with a pendant ball was set up at the Mission (Santa Barbara), and the ball vibrated continually for eight days, and later, at intervals for fifteen days. A ship at Refugio (IX) was carried up a canyon by the wave and returned to sea.--H.H.B.

Several asphaltum springs formed in the mountains and tulares; gaps in the Sierra; the "shore volcano" has more openings, and another is reported behind the Sierra de los Pinos.--H.H.B.(??)

[The above accounts of the shocks which occurred in Southern California in 1812 are quite unsatisfactory. Since the Holden catalog was published, Father Engelhardt's books on the California Missions have appeared. As the accounts given in these books were taken largely from reports written by the missionaries a few days after the events, they should be accurate.

It appears that there were at least two destructive shocks in 1812, both in December. On the morning of December 8, while mass was being held in the church at the San Juan Capistrano Mission, the shock came which partically destroyed the church and killed forty persons, all Indians. The church was of massive stone construction, but probably the mortar was poor, and it is difficult to assign an intensity. The shock was local.

Bancroft and others state that December 8, 1812, was Sunday, but this is an error; it was Tuesday. Perhaps he hastily concluded that it was Sunday from the fact that mass was being held, but in the Catholic Church mass is said on many special days other than Sunday. The day in question, December 8, is "consecrated to the Most Pure Conception of the Most Holy Virgin."]

The other destructive shock occurred on December 21, with disastrous results for the missions at Santa Barbara, Santa Inez, and Purisima. At Santa Barbara the church was completely wrecked and a new one was built a few years afterward. At Mission Purisima Concepcion, which was located within the limits of the present city of Lompoc, almost total destruction occurred, as will be seen from the following account in the annual report of Fathers Payeras and Ripoll, written ten days after the earthquake:

> "The extraordinary and horrible earthquake, which this Mission suffered on the memorable day of the glorious Apostle St. Thomas, entirely destroyed the church and vestry, buried under the walls the various images and paintings, and ruined the greater part of the furniture. The vestments have not suffered because they were inside the cases. Some of the work shops went down, but some more stongly built may serve as habitations if not for minor uses which require no such security. One hundred houses of neophyte Indians and the pozolera or community kitchen, the walls of which were an adobe and a half thick, and roofed with tiles, have become inserviceable. The garden walls of adobe, covered with tiles, have either collapsed or threaten to fall. The damaged portion will scarcely afford material for rebuilding. The furniture and other contents of the Mission have likewise suffered; some of the contents are entirely crushed, some are broken and all are damaged."

These buildings were all of adobe and were never rebuilt. The new Mission Purisima was built five quarter leagues to the north of the old site, on the Camino Real between Santa Inez and San Luis Obispo.

At Mission Santa Inez the destruction causes by the earthquake of December 21, 1812, was considerable, but not so great as at Santa Barbara and at the Mission Purisima. In Father Engelhardt's account there is no record of loss of life at any of these three missions on December 21.

As H. O. Wood suggests, the origin of this shock was probably on a submarine fault off shore from Santa Barbara and Lompoc, although an origin on land is quite possible. The destruction wrought is sufficient to indicate an intensity of X in the epicentral area.

References: Z. Englehardt San Juan Capistrano Mission, p. 53; Mission La Concepcion Purisima, p. 30; Mission Santa Ines, p. 25; H. H. Bancroft History of California, 2, 200, 347, 367, 368.

1830.

VIII. San Luis Obispo. The church was injured.--T.H.H.

1851 June 13.

V. [?] San Francisco, San Luis Obispo, and San Fernando. Smart shock.--J.B.T.--Perrey. [The literal meaning of this statement is that one and the same earthquake was felt in the three places mentioned, the first and third of which are separated by a distance of over 300 miles. Only destructive earthquakes are felt over such a distance as that, and this shock is described as smart, not destructive. Again the literal interpretation of Holden's statement is that this shock had an intensity of V at all three of the places mentioned, which would indeed be a remarkable occurrence.

The probable facts of the case are that there were two, perhaps three separate shocks on the date mentioned, and the meagerness of the data is such that there is no justification for assigning an intensity of V or any other intensity. There are, unfortunately, many intensities in the Holden catalog based on very slender evidence.]

1852 October 26.

San Simeon. Eleven shocks. An equal number at Los Angeles and San Gabriel. Felt also at San Luis Obispo, San Diego, and Colorado River. During the next six days all the southern part of California shaken at short intervals.--Perrey. (See November 26.) [Wood places intensity at X?]

1852 November 26.

(October 26?) Southern California. Eleven strong shocks at San Simeon, Los Angeles, and San Gabriel.--J.B.T.--Perrey says November 20 was the beginning of a series of thirty-two shocks in Southern California. [Subsequent accounts show that the shock was felt in Mexico as far as Guaymas in the state of Sonora. Amer. Jour. Sci., 2d ser., 22, 112.]

1852 December 17.

V. San Luis Obispo. Two smart shocks.--J.B.T.--Perrey. [Fractured walls of two adobe dwellings and threw down part of the walls of the house belonging to and occupied by Don Jesus Pico and family.--Amer. Jour. Sci., 2d ser., 22, 112. Intensity probably IX.]

1853 January 10.

Captain Dana's rancho, San Luis Obispo County.--B. MS. Alta, February 24, 1853.

1853 January.

San Luis Obispo. Also at Mariposa and San Francisco.--Perrey.

1853 February 1.

1 pm. VIII. San Simeon, San Luis Obispo County. Violent shocks. Houses were injured.--B. MS.--Alta, February 24, 1853.

1853 February 14.

San Luis Obispo.--J.B.T.--Perrey. [Trask says a light shock.]

1853 March 1.

V. San Francisco, San Luis Obispo, and Santa Barbara. Smart shock.--J.B.T.--Perrey. [Probably two different shocks.]

1855 January 13.

18h 30m. [6:30 m.m.]. V. San Benito and San Miguel. Smart shock. It was also felt at San Luis Obispo.--J.B.T.

1855 June 25.

14h [2 p.m.] V. Santa Barbara, and north to the valley of Santa Maria. Smart shock.--J.B.T.

1869 September 13.

California.--Fuchs. Nevada City.--B. MS. On the coast, a light shock; heavy at San Luis Obispo (V?); light at Sacramento (IV?).--Perrey.

1869 December 15.

V. [?] San Luis Obispo. Heavy shock.--Fuchs.--Perrey. [In the Sacramento Union of December 22, 1869, this shock is described as slight.]

1877 May 30.

Between 2 and 3 a.m. V. Paso Robles. Heavy shock.--C.G.R.

1855 April 8.

4 p.m. Cambria, San Luis Obispo Co.--San Luis Obispo Tribune, April 17, 1885.

1888 October 3.

12:52 p.m. III. San Miguel, S.L.O. Co. Light shock. two seconds duration, north to south. Another at same place at 1:02 p.m., quite severe, north to south, four seconds duration, no damage done (VI?). S.F. Chronicle, October 4.

1888 October 4.

p.m. Paso Robles. Slight shock.--S.F. Report, October 5.

1889 May 1.

11:55 [a.m.] Lompoc. Quite a heavy earthquake shock was felt here at 11:55 today. The vibrations were from east to west. No damage. Susanville: at 9 o'clock a sharp earthquake. The vibration was north and south. [Separate shocks.]

1889 July 10, and preceding days.

Arroyo Grande, San Luis Obispo Co. The following report if from the San Jose Times:

> The territory around Los Olivos has been troubled with an earthquake the past few days. Sunday there were six distinct shocks, one of which rattled the dishes off the shelves. The hardest shock took place at 3 o'clock this morning. The druggist at Santa Ynez has removed his bottles from the shelves to the floor. Four years ago a burning volcano was reported at Lookout Mountain, on the south side of Santa Maria valley, which was decided to be a burning asphalt bed. [Rather indefinite as to dates July 10, 1889, was Wednesday.]

1893 June 3.

10:20 p.m. Los Olivos. Felt throughout the Santa Ynez Valley. Santa Barbara. Heaviest for some years. Vibration from east to west.

1900 October 18.

San Luis Obsipo.

1901 March 3.

San Francisco, San Luis Obispo. [Probably two different shocks.]

1901 March 5.

Paso Robles, Porterville.

1901 March 6.

San Ardo, San Luis Obispo.

1901 June 3.

San Luis Obispo.--John R. Williams, U. S. Weather Bureau.

1901 July 30.

11 a.m. San Luis Obispo.--J. R. Williams.

1902 April 6.

San Luis Obispo.

1902 July 27.

10:57 p.m. [Los Alamos. VIII to IX. The shock of July 27 was quite local, being confined to the northern part of Santa Barbara County. Store buildings were damaged and goods thrown about. On the property of the Western Union Co. two tanks containing 3000 barrels of oil each were destroyed. Pipes for conducting oil and water were twisted and broken. The adobe house on the Oreana ranch, which had been a landmark for years, was a mass of ruins. At Lompoc buildings were damaged and pipes broken. One account says the greatest damage in Santa Barbara.--Reid's Scrapbook, 2, 20, 21, 22.

"A month before the earthquake distinct rumblings were heard in the yard and the ground heaved at the Rancho Los Alamos."--Letter from Walter Nordhoff.]

1902 July 28.

[5:08 a.m.] San Luis Obispo. [Many aftershocks followed the heavy shock at 10:57 p.m. on July 27. One of the most distinct of these aftershocks was that felt at 5:08 a.m., July 28. This was felt in San Luis Obispo as well as other places. The shock at Berkeley on July 28 was probably of some other origin.]

1902 July 30.

Severe shocks occurred from the 27th to the 31st at Lompoc, Los Alamos, San Luis Obispo. Santa Maria, and other places in Santa Barbara and San Luis Obispo Counties. A few buildings were thrown down, but the property loss was not great and no lives were lost.

[It is misleading to place this note under date of July 30, as there is no record of any shock on that date, although there may have been some minor ones. One account states that a total of seventy-five shocks occurred in the five day interval between July 27 and 31. No one seems to have kept a complete record.]

1902 July 31.

1:20 a.m., 7:30 p.m. VIII to IX. Los Alamos. Two more severe earthquakes occurred in Los Alamos and surrounding country on July 31, and many minor shocks were felt during the day. The shocks of July 31 completed the ruin started on July 27. Not a chimney was left standing in Los Alamos, and not a house escaped damage. During the five days of terror the people became so nervous that when the severe shocks of the 31st came, nearly the whole population left by whatever means of transportation was available. A special train of fourteen cars was sent from San Luis Obispo to take the terrified inhabitants away. The effects were worst in a strip about fifteen miles long and four miles wide. There were fissures and cracks in the ground, landslides, and a stream which was dry flowed a large volume of water. Some of these effects occurred on July 27 and others on the 31st, but as newspaper accounts are all the evidence available, it is not easy to segregate the happenings in a chronological order. That there was no loss of life was due probably to the fact that there were no brick buildings in the area most badly shaken.

1902 August 1 to 3.

Los Alamos. Severe shocks.

1902 August 4.

Los Alamos. [There were six shocks on August 4, at 2:05 a.m., 3:18 a.m., 4:15 a.m., 1:29 p.m., and 3:40 p.m., 4:55 p.m. The third and the sixth were the most severe. There was no damage, but then there was nothing much left that could be damaged.--Reid's Scrapbook, 2, 25.]

1902 August 9.

4:00 p.m. Los Alamos. Distinct earthquake detonation and tremor.--S. F. Call, August 10, 1902.

1902 August 10.

2:40 a.m. Los Alamos. Heavy detonation followed by trembling.--S. F. Call, August 10, 1902.

1902 August 14.

[2:15 a.m., 3:05 a.m., 3:20 a.m., 1:50 p.m., 3:50 p.m. Los Alamos. All slight except the one at 3:20 a.m. This one was said to have shaken the ground violently.--Reid's Scrapbook, 2, 26. A and R.]

1902 September 10.

9:30 p.m., 11 p.m. Los Alamos. [Severe. Reid estimates intensity at IV to V. Several light shocks during the past few days. A and R.]

1902 October 21.

[Between 1:45 p.m. and 2:15 p.m. Los Alamos. Three shocks; the first quite severe; duration forty seconds; no damage. Felt also in Lompoc.--Reid's Scrapbook, 2, 26. A and R.]

1902 October 22.

2 a.m. Los Alamos. Light shock.--Reid's Scrapbook, 2, 26.

1902 December 12.

Los Alamos. [VII to VIII. All the northern part of Santa Barbara County was again shaken by severe earthquakes in the afternoon of December 12. At

Los Alamos there were three shocks in five minutes, but the time was not stated. At Los Alamos dishes and glasswares were thrown from shelves and at Santa Maria the walls of a brick school were cracked and plaster fell in many houses, indicating an epicentral intensity of VII to VIII.--San Francisco Call, December 12 or 13, 1902.

Lompoc, San Luis Obispo, Santa Barbara. A and R.]

1903 January 11.

San Luis Obispo.

1903 March 24.

Gonzales, Santa Margarita [Monterey and San Luis Obispo Counties].

1903 April 24.

Santa Margarita [San Luis Obispo Co.].

1903 July 28.

11:13 p.m. IV-V. Point Piedras Blancas Lighthouse. Also a later one between 2 and 3 a.m., on July 29.--Reid's Card Catalog.

1903 August 24.

Los Olivos.

1904 January 22.

Los Alamos.

1904 January 23.

Los Alamos.

1904 September 10.

San Luis Obispo.

1905 May 25.

9:49 p.m. San Luis Obispo. Light shock, east to west. Duration three seconds.

1906 July 6.

San Luis Obispo.

1906 July 21.

San Luis Obispo.

1906 August 1.

San Luis Obispo.

1906 December 6.

10:40 p.m. San Luis Obispo. Duration thirty seconds; from north to south. A second shock half an hour later. Felt also in Santa Maria. [Reid reports that the tower at Piedras Blancas lighthouse was cracked,according to a letter from there, indicating an intensity of VII or VIII. Reid gives intensity at Cambria as V.--Reid's Card Catalog.]

1907 July 1.

10:10 p.m. San Luis Obispo.--WB Form 1030.

1907 July 21.

San Luis Obispo.--WB Form 1030.

1908 May 19.

San Luis Obispo.--WB Form 1030.

1909 August 18.

San Luis Obispo.--WB Form 1009.

1911 March 22.

2:55 a.m. San Miguel, San Luis Obispo Co. Quite severe.--WB Form 1009.

1913 October 20.

3:25 a.m. San Luis Obispo and Paso Robles, San Luis Obispo Co.; Betteravia and Santa Maria, Santa Barbara Co.--WB Form 1009; BSSUC, 1, 139, 145.

1914 November 23.

8:25 p.m. II. San Luis Obispo. Abrupt trembling felt by many, lasting twenty seconds. Direction north and south.--ERWB.

1915 January 11.

8:31 p.m. VIII. Los Alamos, Santa Barbara Co. After a field investigation Carl H. Beal concluded that the epicenter of this earthquake was two or three miles east of Los Alamos. In its epicentral region the shock was a series of hard jerks in different directions, ending with a vertical jolt. It lasted about a minute in the vicinity of the origin. Practically every chimney in Los Alamos was damaged, and some were thrown many feet. The intensities at some of the principal places in the disturbed area were: Los

Alamos VIII; Lompoc VII; Santa Maria VI to VII; Santa Barbara V; San Luis Obispo V; Paso Robles, San Luis Obispo Co., IV; Los Angeles II. There were from one to three aftershocks daily for about thirty days after the main shocks, but most of them do not seem to have been recorded.--BSSA, 5, 14.

The Weather Bureau observers reported intensities as follows: Santa Barbara V, nine shocks felt (report of Geo. W. Russell), or VI, a single shock lasting five seconds (report of C. E. Rachford); Ozena V and Nordhoff (Ojai), III, Ventura Co.; San Luis Obispo V, duration thirty seconds, and Paso Robles IV; Priest Valley II, Monterey Co.; Bakersfield, Kern Co., rapid rocking, felt by several.--ERWB.

The shock was recorded on the University of California instruments at Berkeley and Mount Hamilton, but with considerably less energy than was the equally distant Cape Mendocino earthquake of May 6, which caused no damage.--BSSUC 1, 174, 179.

The most northerly point reporting this disturbance was San Jose, about 200 miles, and the most southerly was Los Angeles, 125 miles to the southeast. The shaken area was in excess of 50,000 square miles.--Reid's Scrapbook, 3, 249, 252.

1915 January 15

Los Alamos, Santa Barbara Co.--WB Form 1009.

1915 January 20.

Los Alamos, Santa Barbara Co.--WB Form 1009.

1915 January 26.

Los Alamos, Santa Barbara Co.--WB Form 1009.

1915 January 27.

Los Alamos.--WB Form 1009.

1915 April 21.

1:58 a.m. III to IV. San Luis Obispo. A rocking motion of abrupt onset, from southeast to northwest, lasting three seconds and felt by many. Also felt by several three miles northwest of Priest Valley, Monterey Co., as a rocking of intensity II.--ERWB; BSSA, 5, 108.

1916 February 27.

5:26 a.m. Los Alamos, Santa Barbara Co.--ERWB.

1916 March 1.

11:15 a.m. Los Alamos, Santa Barbara Co.--ERWB.

1916 May 5.

7:45 p.m. III. Los Alamos, Santa Barbara Co. Abrupt bumping, northwest and southeast; felt by many at El Roblar Ranch, two miles southeast of Los Alamos.--ERWB.

1916 June 26.

5:56 a.m. II. San Luis Obispo. Felt by many. This report of the Weather Bureau probably is one day in error, since a shock was reported by the San Luis Obispo paper at this hour on June 27, at the same time that a rather strong shock was taking place about one hundred miles to the northward.--ERWB.

1916 December 1.

2:53 p.m. VII. Avila, San Luis Obispo Co. Considerable glass broken and goods in stores thrown from shelves. A landslide covered the railroad tracks two miles north of Avila, in Dairy Canyon. "Disturbance of waters in the Bay of San Luis Obispo." "The plaster in the several cottages occupied by the employees of the Union Oil Company's refinery was jarred loose . . .while some of the smokestacks on the refinery buildings were toppled over." "At 2:50 o'clock . . .four heavy shocks of earthquake were felt in this city (San Luis Obispo) . . . . There was no damage resulting in this city except that one of the bricks in the building occupied by Ray Howell fell out of the wall, which astonished some of the customers. . ." "At Port San Luis the shock was severe . . ."

The shock was reported as of intensity III, east to west, at Santa Maria, Santa Barabara Co.--San Luis Obispo Morning Tribune, San Luis Obispo Evening Telegram, ERWB;BSSUC, 1, 279, 288; BSSA, 7, 38.

1917 April 5.

11 a.m. IV. Santa Rita, Santa Barbara Co. Houses rattled and creaked and a few pans were thrown from a wall; generally felt. Also felt by a few persons in Lompoc, eight miles to the west of Santa Rita.--BSSA, 7, 72.

1917 July 7.

12:57 p.m., 1:02 p.m., 1:15 p.m. Lopez Canyon, about ten miles from San Luis Obispo. These shocks were reported by Forest Ranger Stephen J. Rhyne, stationed in Lopez Canyon, some ten miles from Arroyo Grande, and San Luis Obispo. The three shocks seem to have been nearly identical; duration of each five seconds; trembling motion which came on rapidly, followed by a roaring sound; shaking of doors and windows; violent swinging of hanging objects; felt by all. The first shock was felt at San Luis Obispo as a double shock of abrupt bumping type, felt by several. At San Luis Obispo the motion was east to west, and the two parts of the shock lasted three and four seconds, respectively.--BSSA, 7, 115; ERWB.

1917 July 7.

7:20 p.m. II. Santa Maria, San Luis Obispo Co. A very light tremble, felt by several; duration ten seconds.--ERWB.

1917 July 8.

3:29 a.m. IV. Lopez Canyon, San Luis Obispo Co. Trembling motion which began gradually; distinct swaying of buildings; rattling of doors, windows, etc.; underground sounds; felt by several persons at rest.--BSSA, 7, 116.

1917 July 9.

2:22 p.m., 2:38 p.m., 4:45 p.m. VI to VII. Lopez Canyon, San Luis Obispo Co. Violent swaying of buildings; dishes overturned; rocks rolled down hillsides; chimneys damaged; loud sounds following shocks. The first of these shocks in the only one that was recorded instrumentally at Mount Hamilton. None of them recorded at Berkeley. The first shock was felt, IV, by many at San Luis Obispo.--BSSUC, 1, 316; BSSA, 7, 115, 8, 10; ERWB.

1917 July 26.

12:31 a.m. V. Santa Maria, Santa Barbara Co. Rapid rocking, followed by two trembles; motion east to west; awakened many; considered most vigorous shock since 1906; duration about fifteen seconds; furniture moved. Reported also from Los Olivos, in the same county; duration twenty-five seconds; trembling motion; roaring sounds; intensity IV. At San Luis Obispo the shock was felt by many, which means it awakened many and was stronger than the intensity II reported by the observer there; abrupt bumping; southeast to northwest; duration two seconds.--BSSA, 7, 117; BSSUC, 1, 305, 317: ERWB.

1918 December 4.

6:38 p.m. IV. Paso Robles, San Luis Obispo Co. Abrupt rocking; northwest to southeast; four or five seconds duration; felt by many. At San Luis Obispo, a trembling motion; intensity II; felt by several.--ERWB.

1919 March 14.

11:53 p.m. III to IV. San Luis Obispo. Rocking; shaking of bed awoke observer; reported by several.--ERWB.

1919 December 17.

11:15 p.m. Paso Robles, San Luis Obispo Co. Felt by several.--WB Form 1009.

1920 March 19.

11:04 p.m. II. San Luis Obispo. Rocking; duration two seconds; felt by several.--ERWB.

1920 May 6.

5:59 p.m. IV. San Luis Obispo. Rocking; southeast to northwest; duration five seconds; felt by many. Recorded instrumentally at Mount Hamilton.--BSSUC, 1, 413; ERWB.

1920 June 28.

1:01 a.m. V. San Luis Obispo. Rocking motion lasting about ten seconds; southeast to northwest; shook buildings rather hard, but caused no damage; felt by many. Recorded instrumentally at Mount Hamilton.--BSSUC, 1, 416; ERWB.

1920 December 6.

San Luis Obispo.--BSSA, 11, 14.

1922 March 10.

3:21 a.m. VIII to IX. Cholame Valley, Monterey and San Luis Obispo Counties. Origin in region of San Andreas Fault in southern part of Cholame Valley. Aggregate damage not great, because of thinly settled nature of the epicentral region. Cracks six to twelve inches wide opened in the ground for a distance of one-fourth of a mile in Cholame Valley; new spring formed; brick chimneys destroyed; water tank collapsed; at Parkfield chimneys were toppled and some houses badly wracked; the hard shock lasted "several minutes" and was followed by at least a dozen small shakes.

Outside of the Cholame Valley the intensity was about VII to VIII at Shandon to the west, where the motion was a north to south rocking as of a ship in a heavy sea, duration ten to fifteen seconds; VI to VII at San Luis Obispo, where some telephone poles fell; VI to VII at Simmler, to the southeast, where a strong rocking motion awakened all and lasted one minute, the direction being east to west; at Paso Robles it was by far the most severe shock since 1906, motion a rocking, part east to west, part north to south.

The shock was reported as of intensity V at Los Angeles because of having stopped a few pendulum clocks. The actual intensity there probably did not exceed II to III; long vibrations from a strong shock will stop a pendulum of the proper orientation even when the intensity is quite low, while much higher intensities of quick period do not interfere with clocks. The shock was felt as of intensity IV as far northwest as Spreckels and Hollister; to the east into the Sierra at Springville, Tulare Co., where the shock awakened several and lasted thirty seconds as a "severe" trembling. People were awakened at rather uniform distances of ninety to one hundred miles in different directions, indicating an area of intensity IV to V of about 25,000 square miles. At hours better suited for perception the shock probably would have been noticed at distances outlining an area of at least 100,000 square miles. Los Angeles, where the shock was felt by some, lies on the circumference of the circle of which the area is 90,000 square miles.

This shock was recorded by forty-three seismograph stations over a large part of the earth.--Press dispatches; CE1918-1924, BAAS; ERWB; BSSA, 12, 239, 14, 169.

<u>1922 March 16.</u>

3:10 p.m. V+. Cholame Valley. Rather strong aftershock, recorded over the United States. Reported at San Luis Obispo, V, direction northeast to southwest, duration ten seconds, felt by many; Antelope Valley, Kern Co., IV, rocking motion southeast to northwest, two shocks of five seconds each; Paso Robles, San Luis Obispo Co., V, east to west, felt by many; Shandon, San Luis Obispo Co., sharp.--ERWB; CE 1918-1924, BAAS.

<u>1922 March 19.</u>

3 a.m. III? Paso Robles, San Luis Obispo Co. Felt by several; east to west.--WB Form 1009.

<u>1922 March 23.</u>

2 a.m. III? Paso Robles. East to west; felt by several.--WB Form 1009.

<u>1922 March 25.</u>

4 a.m. III? Paso Robles. East to west; felt by several.--WB Form 1009.

<u>1922 May 30.</u>

5:25 p.m. III. Pao Robles, San Luis Obispo Co. Two shocks; duration five seconds; east to west; felt by several; rocking.--ERWB.

<u>1922 July 5.</u>

11 a.m. Los Alamos, Santa Barbara Co.--WB Form 1009.

<u>1922 July 9.</u>

4 a.m. Los Alamos.--WB Form 1009.

<u>1922 July 10.</u>

9 p.m. Los Alamos.--WB Form 1009.

<u>1922 July 11.</u>

7:30 a.m. Los Alamos.--WB Form 1009.

1922 August 17.

9:12 p.m. VII? Cholame region of Monterey or San Luis Obispo County. Recorded at fifteen seismographic stations, this shock appears to have originated in the thinly settled Cholame region traversed by the San Andreas Fault. No report has come from the probable epicentral region, but intensities of V were reported at San Luis Obispo and Paso Robles, to the southwest or west; and the shock was felt to the northwest at Spreckels, Monterey Co., to the northeast at Fresno, to the southeast at Bakersfield, and to the south at Los Alamos, indicating a shaken area of some 25,000 square miles.

Two shocks with a ten second interval were shown by the seismograms at Berkeley and at Mount Hamilton. At Speckels two shocks were felt, of five and ten seconds duration. At Paso Robles several distinct vibrations, northwest to southeast, were felt by many; a second report there gave duration ten seconds and direction east to west. At San Luis Obispo two shocks, of rocking nature from northeast to southwest, were felt by many. At Lemoore, Kings Co., the duration was twenty seconds and the intensity IV.--Press Items; BSSUC, 2, 61, 66; CE 1918-1924, BAAS; ERWB; WB Form 1009.

1922 August 20.

1:14 p.m. III? Atascadero, San Luis Obispo Co.--WB Form 1009.

1922 September 4.

2:15 a.m. IV. Paso Robles, San Luis Obispo Co. Rocking; southwest to northeast; duration three seconds; felt by many.--ERWB.

1922 September 5.

1:05 a.m. V. San Luis Obispo. Two shocks, of one and five seconds duration; abrupt bumping; northeast to southwest; felt by many. Recorded instrumentally at Berkeley.--BSSUC, 2, 62; ERWB.

1923 March 11.

10 p.m. IV? Los Alamos, Santa Barbara Co. Short, quick jerk.--WB Form 1009.

1923 May 4.

2:45 p.m. V and II. San Luis Obispo. Two shocks; rocking and trembling; duration eight or ten, and two or three seconds; southeast to northwest; felt by many.--ERWB.

1923 May 7.

9:02 p.m. II. Cholame, San Luis Obispo Co. Duration a few seconds; trembling; felt by few.--ERWB.

1923 June 16.

12:40 p.m. IV. Paso Robles, San Luis Obispo Co. North to south; duration fifteen to twenty seconds. Recorded at Mount Hamilton by seismograph.--BSSUC, 2, 102; WB Form 1009.

1923 June 25.

5:21 a.m. II. San Luis Obispo. Rocking; duration two seconds; felt by several.--ERWB.

1923 December 18.

11:35 p.m. II. Santa Maria, Santa Barbara Co. Duration twenty seconds.--MWR, 51, 676.

1925 June 29.

7:20 a.m. III. San Luis Obispo. Light shock, duration ten seconds.--SRC&GS.

1926 April 29.

4:18 a.m. IV. Buellton, Santa Barbara Co. Like the blow of a hammer; sounds preceding shock awakened observer.--SRC&GS.

1926 October 22.

2:10 a.m. III. Paso Robles. Slight.--SRC&GS.

1926 December 8.

4:03 p.m. IV. Paso Robles, San Luis Obispo Co. Gradual rocking; northeast to southwest; ten seconds; felt by many. Probably a mistimed report of the shock at 4:41 p.m.--SRC&GS.

1927 November 4.

3 a.m. to 3:30 a.m. Point Arguello, Santa Barbara Co. Four shocks. Foreshocks of the strong shock at 5:51 a.m. The first shock awakened sleepers at Lompoc and Santa Maria, Santa Barbara Co., and was felt at San Luis Obispo. The other three shocks were reported only at Lompoc.--Lompoc Record, November 4, 1927; Oakland Tribune, November 4, 1927.

1927 November 4.

5:51 a.m. Probably X. At sea, west of Point Arguello, Santa Barbara Co. This was the largest earthquake in California since January 22, 1923. It was recorded over the world as a stronger shock than the destructive Santa Barbara earthquake of 1925; was reported felt to distances of two hundred miles; attained intensity of fully IX in the region of the shore near Surf, nearest the origin. The shock was investigated by Perry Byerly, whose study appears in the Bulletin of the Seismological Society of America, 20, 53.

The shock was an exception to the ordinary California submarine shocks in producing a small seawave, which was recorded on the tide gauges at San Diego and San Francisco, and observed at Surf and Port San Luis. At Surf the rise of the water was six feet; at Port San Luis it was five.

In the region nearest the origin, from Lompoc to the coast at Honda and Surf, the usual phenomena associated with severe earthquakes were reported; earth and rock slides on steep slopes, spurting of water from crevasses and formation of sand craters, changes in the flow of springs, etc. Chimneys were generally wrecked in Lompoc, the nearest point of any size, and some were damaged as far away as Arroyo Grande, San Luis Obispo Co., and at Santa Maria, Santa Barbara Co.

Byerly located the epicenter at 121°24' west longitude, 34°32' north latitude. From this point as a center the distances to points in different directions where the intensity was VI exceeded 120 miles, indicating an area of the order of 40,000 square miles shaken with intensity VI or higher. It is probable that the shock was perceptible, although because of the hour not usually felt, at distances well in excess of two hundred miles; the representative distance to which it was reported was just short of that distance, but the shock was reported at Yosemite, two hundred and fifty miles, and at a more favorable hour for perception probably would have been felt as far in other directions. Whittier, southeast of Los Angeles, was the most distant reporting point point in that direction, while Morgan Hill was the most northerly place reporting the shock as felt.--BSSA, 17, 258. 20, 53; SRC&GS; news items.

1927 November 4.

Point Arguello. Many aftershocks occurred, but few have been listed. The steamer "Floridian," at sea in the region of the epicenter off Point Arguello at about 11 a.m. experienced four shocks which made the sea appear to "shimmy." About noon the steamer "Los Angeles," then in the same region, felt two strong shocks of considerable duration. Aftershocks were reported by the press at Santa Maria at 6:12 a.m., 6:14 a.m., and 7:42 a.m., and one at San Luis Obispo at 7 a.m.--Press dispatches.

1927 November 5.

12:17 a.m., 1 a.m., 3:37 a.m., 6:25 p.m. Point Arguello. Aftershocks. The first was "mild" at Surf; the second was reported from Paso Robles to Hadley Tower, San Luis Obispo Co.; the third from Surf, Santa Barbara Co., to Hadley Tower, south of San Luis Obispo; the fourth was the strongest of the immediate aftershocks at Lompoc, where it added slightly to the damage by widening cracks opened by the greater shock. On the same date shocks were reported at Buellton, Santa Barbara Co., at 4:06 p.m., and 7:10 p.m.; both of intensity IV.--Press dispatches; SRC&GS.

1927 November 6.

2:10 p.m., 2:50 p.m., and 3:10 p.m. The first and third shocks were reported by a steamer off Point Conception; the second at Buellton, Santa Barbara Co., as a shock of intensity IV, felt by nearly all.--SRC&GS.

1927 November 8.

About 2:10 a.m. IV. Buellton, Santa Barbara Co. Sharp bumping at 2:02 a.m. aroused nearly all. At Lompoc many were awakened by a shock at 2:15 a.m.--SRC&GS; Lompoc Record, November 8, 1927.

1927 November 18.

7:32 p.m. VII. Santa Maria, Santa Barbara Co. This shock was centered, apparently, to the northwest of the origin of the larger earthquake on November 4, as while a much weaker shock it was nearly as strong as the earlier shock at Santa Maria, chimneys falling. At Betteravia, nearby, and at Bicknell, in the same region, intensity of VI was reported. The shock was reported from San Miguel, San Luis Obispo Co., and Parkfield, Monterey Co., on the north, to the Santa Barbara Channel on the south, and was recorded at nearby seismographic stations. The intensity estimates of observers as reported in the Seismological Report of the Coast and Geodetic Survey should be considered only after comparison with the descriptions accompanying them.--SRC&GS. Press dispatches.

1927 December 5.

3:45 a.m. IV +? Point Arguello. Felt at Buellton, IV; Surf, Guadelupe, and Santa Maria, Santa Barbara Co., and at Santa Margarita, San Luis Obispo Co. It awakened many and caused alarm at Santa Maria. At Buellton two shocks fifteen seconds apart awakened many.--Santa Maria Times, December 5, 1927; SRC&GS.

1927 December 31.

2:10 a.m. V? Point Arguello, Santa Barbara Co. Heavy shock felt.--BSSA, 17, 263.