FAULTS AND EARTHQUAKES IN THE MONTEREY BAY REGION, CALIFORNIA*

By H. G. Greene, W. H. K. Lee, D. S. McCulloch, and E. E. Brabb

INTRODUCTION

As urbanization of the Monterey Bay coastal region progresses, city and county planners find a growing need for up-to-date information on where geologic hazards are located and how serious a threat they present. At the same time, the public, aware of the dangers of active faulting along the California coast, is bringing pressure for development of earthquake-resistant communities and structures.

Faulting and seismic activity are being investigated by the U.S. Geological Survey along the continental shelf between Point Sur and Point Reyes, California. The Survey's work in Monterey Bay (fig. 1), the area dealt with in this report, has revealed the presence of many previously unrecognized faults. Some of the faults are active and, according to existing maps, extend onshore.

Offshore faults were mapped by geophysical methods. In 1969, detailed seismic reflection ("sparker") surveys were made in Monterey Bay and the shelf areas of Point Sur to Cypress Point and Santa Cruz to the Gulf of Farallones. In 1970, additional surveys were made across the shelves from Point Sur to Cypress Point, and northern Monterey Bay to Año Nuevo Point.

Procedures and Methods

Continuous seismic reflection profiles were obtained by a high-resolution, .6 kj sparker system, and an intermediate-penetration, 23 kj sparker system. The geophysical data were collected along approximately 2,600 km of track line. See the appendix for detailed descriptions of equipment, procedures, and methods used in this investigation.

Numerous faults mapped on the basis of interpretations of the seismic reflection records are shown on plate 1. All major faults are well defined by several seismic criteria given in the appendix.

Acknowledgements

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Previous work

Unlike the present study, previous geological and geophysical investigations of Monterey Bay have been primarily reconnaissance studies (e.g., Shepard and Emery, 1941; Shepard, 1948; Martin, 1964; Curray, 1965, 1966; Rusnak, 1966; Martin and Emery, 1967; Hoskins and Griffiths, 1971; and Silver and others, 1971). The geophysical studies discuss the general regional structure and major faulting as they relate to more extensive investigations of the central California continental shelf, but do not treat the structure of the bay in detail, as this report does.

Martin (1964) used detailed bathymetry and geologic samples as a basis for a geologic map of Monterey Bay. Dohrenwend and Ellsworth used detailed bathymetry to describe the geology of the continental shelf between Point Sur and Cypress Point (J. C. Dohrenwend, 1971, and W. L. Ellsworth, 1971).

The onland geology of the region has been studied extensively (for example, Johnson, 1855; Clark, 1930, 1970a, 1970b; Woodring, 1938; Taliaferro, 1943; Allen, 1946; Jennings and Strand, 1958; Jennings and Burnett, 1961; Baldwin, 1963; Page, 1966, 1970a, 1970b; Compton, 1966; Christensen, 1966; Bowen, 1969; Durham, 1970; Brabb, 1970), and onland faults have been the subject of studies by Fairborn (1963), Sieck (1964), Durham (1965), Burford (1971) and Gilbert (1971).

Geologic setting

Principal onland faults in this region are the seismically active San Andreas and the Sur-Nacimiento fault zones (fig. 1), which mark the northeast and southwest boundaries, respectively, of the Salinian block (Reed, 1933). The Salinian block consists of continental crust dominated by granitic rocks and is flanked on either side by oceanic crust of the Franciscan assemblage. The Sur-Nacimiento fault zone comprises faults of various kinds and ages in a belt extending southeastward from Point Sur through the central and southern Coast Ranges of California; it includes the Sur fault zone and the Nacimiento fault (Page, 1970a).

The Cretaceous granitic basement rocks of the Salinian block, and the overlying Tertiary strata, have been both horizontally and vertically offset by many faults that trend southeast from Monterey Bay through the Santa Lucia Range. Some of these faults can be traced for more than 10 km and appear to have controlled the development of major geomorphic features, such as the Salinas, Carmel, and Palo Colorado Valleys, which formed along the King City, Tularcitos, and Palo Colorado faults (pl. 1).

North of Monterey Bay, faults in the Salinian block trend generally northwest and offset the granitic basement rocks and overlying Tertiary strata (Jennings and Burnett, 1961). Several of these faults, the Butano, Ben Lomond, and Zayante faults, bend around to trend east-west as they approach the San Gregorio fault zone. Near Año Nuevo Point, the San Gregorio fault, oriented N. 25°W., extends for nearly 30 km onland and cuts across the regional structural grain.

Offshore the granitic basement of the Salinian block "imparts a rigid block-faulting structural style to the overlying sediments" (Hoskins and Griffiths, 1971, p. 212). The seaward extension of onland faults has not yet been well established. However, offshore faults have been discussed in several reports. Curray (1966, p. 342) noted that sediments on the Monterey Bay shelf have been displaced by many faults, and Martin and Emery (1967) described a northwest-trending fault across the upper axis of the submarine Monterey Canyon, and two northwest-trending faults in Carmel Canyon that they connected with the San Gregorio fault to the north and with the Palo Colorado and Sur faults to the south. Hoskins and Griffiths (1971) interpreted onshore-offshore faults southeastward from the San Gregorio fault through Carmel Canyon in a similar manner but did not map the southeast end of the fault onshore.

OFFSHORE FAULTS

Faults in the Monterey Bay region lie primarily within two major intersecting northwest-trending zones (plate 1), the Palo Colorado-San Gregorio and Monterey Bay zones. The Palo Colorado-San Gregorio fault zone, a narrow (approximately 3 km wide) zone represented in most places by one or two faults, appears to connect at the south end with the onland Serra Hill and Palo Colorado faults (Trask, 1926; Jennings and Strand, 1958; Gilbert, 1971) near Kaslar and Hurricane Points, and at the north end with the San Gregorio fault and a thrust fault on Año Nuevo Point described by Clark (1970a) and J. G. Evans and K. Lajoie (written commun., 1971). The length of this zone, including onland segments, is at least 125 km; the zone may be much longer, for it may join the faults at Half Moon Bay, which may, in turn, join the San Andreas fault northwest of the Golden Gate (Cooper, 1970). To facilitate discussion, the zone is divided into three segments: (1) Cypress Point-Point Sur shelf, (2) Monterey Bay, and (3) Año Nuevo Point-Santa Cruz shelf.

The Monterey Bay fault zone (previously called Tularcitos fault zone by Greene, 1970) in the inner bay between Monterey and Santa Cruz, is a diffuse zone 10 to 15 km wide of short en echelon northwest-trending

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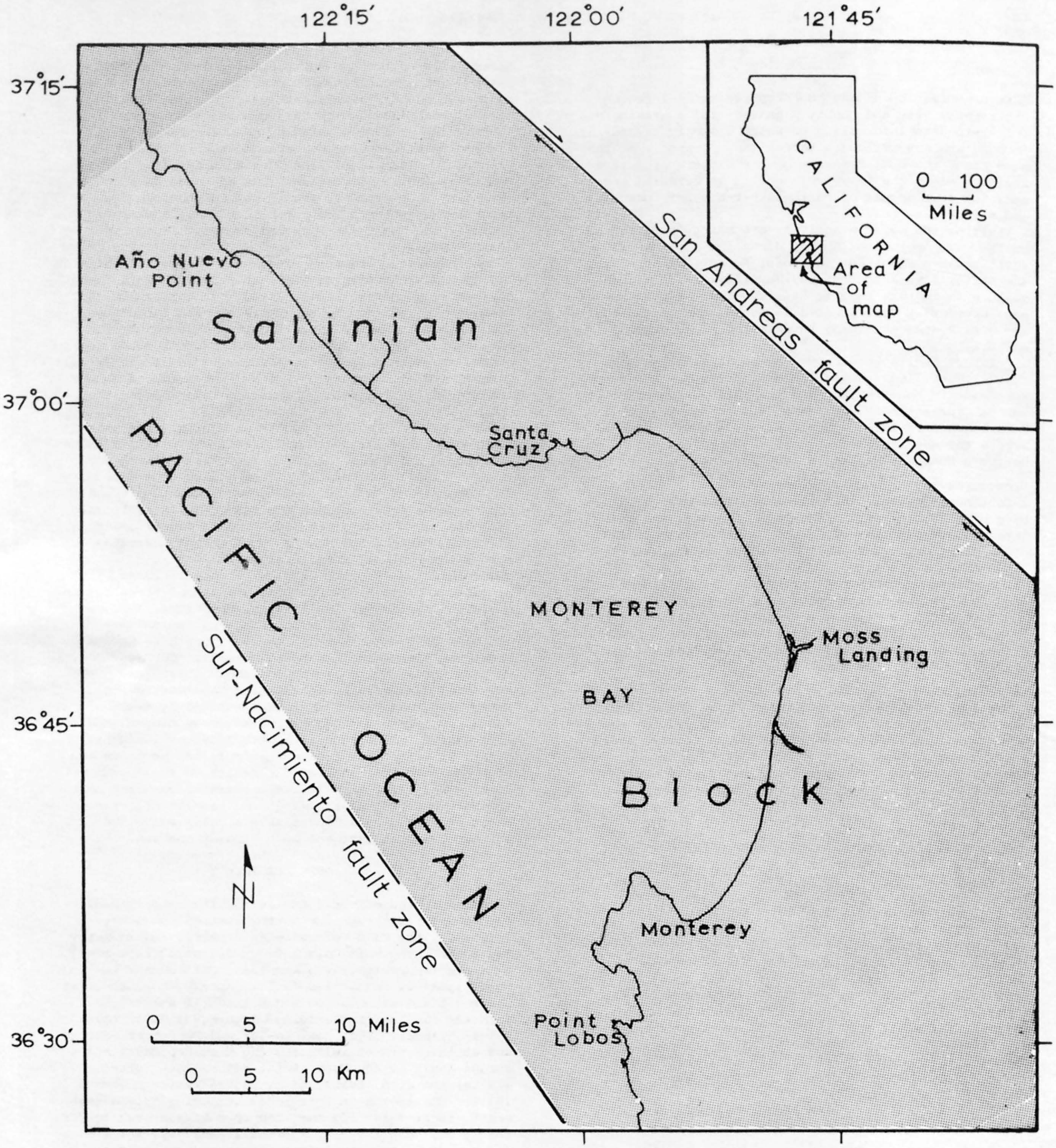

Figure 1.--Index map of central California coast showing location of study area.

faults. It may be the offshore extension of northwest-trending faults in the Salinas Valley and the Sierra de Salinas Mountains to the southeast. To the north, the zone appears to terminate against the Palo Colorado-San Gregorio fault zone.

A third major fault, the probable offshore continuation of the Sur-Nacimiento fault zone, lies parallel to, but offshore of, the Palo Colorado-San Gregorio fault zone at the southwestern edge of the Monterey Bay region.

Sur-Nacimiento fault zone

Several faults occur on the shelf between Point Sur and Cypress Point. They are alined with onland faults in the Sur-Nacimiento fault zone, a major structural feature in the southern Monterey Bay region. This zone, described as a belt of faults of various kinds and ages extending southeast from the Sur fault zone (Page, 1970a, p. 670), is approximately 300 km long and includes the Sur thrust zone, the Nacimiento fault, and other faults.

Along the shelf between Point Sur and Hurricane Point, where the offshore extension of the thrust zone should be found, seismic reflection profiles fail to reveal the subsurface bedrock structure, perhaps because the rocks are highly folded and faulted. This complex zone of poor reflectivity may be bounded on the south by faults that are assumed to parallel the northwest trend of the onshore faults (pl. 1). The two longest faults may join a fault to the northwest, and both may be part of a longer fault zone that extends southeastward, parallel to the coast.

Tightly folded and sheared rocks onshore south of Point Sur suggest the existence of such an offshore fault (W. G. Gilbert, oral commun., 1970). Another fairly continuous inferred fault strikes N. 40° W. from the zone of poor seismic reflectivity and has been projected along the continental slope to connect with a fault observed on another profile several kilometers to the north (pl. 1). The fault, buried beneath about 200 meters of late Tertiary(?) sediment, may be the offshore trace of the Sur-Nacimiento fault, or it may be a fault that Page (1970a) suggested should pass seaward of the Farallon Islands, west of the Sur fault trace, for Page believes that the islands lie within the Salinian block.

Palo Colorado-San Gregorio Fault Zone

1. Cypress Point-Point Sur shelf

Two faults trend northwest from the coast, north of the zone of poor reflectivity; the southernmost leaves the coast near Hurricane Point, the northernmost near Kaslar Point (pl. 1). The former comprises three segments. The central and northern segments are delimited where well-defined reflectors southwest of the fault end abruptly against a zone of seismic incoherency (pl. 3, section N-N'); the southernmost segment may bend eastward and join the Serra Hill fault. The Serra Hill fault (Sierra Hill thrust of Trask, 1926), as described by Gilbert (1971, p. 46), is a major thrust fault that emerges from the ocean just north of Hurricane Point and trends southeast. Near Hurricane Point, the fault dips 50°-60° NE. Granodiorite northeast of the fault is thrust over upper Miocene sandstone. Gilbert (1971) estimated that the vertical separation on the fault was probably at least 300 meters.

Seismic profiles across the probable offshore extension also show what appears to be a fault contact between well-bedded sedimentary rocks to the south, and rocks with seismic reflection typical of crystalline and well-indurated rocks to the north. The fault trends northwest down the axis of the western tributary of Carmel Canyon and may have controlled the location of this submarine canyon (pl. 1 and 3, section M-M').

Northeast of the offshore extension of the Serra Hill fault, a well-defined, fairly continuous offshore fault has been identified. The southern part of the fault has been located by seismic reflection and bathymetric profiles. Like the offshore extension of the Serra Hill fault, this fault lies between stratified rocks, some locally disturbed, and seismic reflectors that indicate crystalline or well-indurated rocks (pl. 3, section M-M'). The sea floor is about 2 meters higher east of the fault, forming a west facing scarp that may be related to recent faulting. Dohrenwend (1971) and Ellsworth (1971) obtained high-resolution (7.5 KHz) bathymetric profiles which indicate that this scarp swings eastward and may connect with the Palo Colorado fault on land (pl. 1).

Trask (1926, p. 164-165) has described the Palo Colorado fault onshore as a southeast-trending thrust that parallels the coast for approximately 2 km, and then bends to the east. On the northeast side of the fault, quartz diorite is thrust over sandstones of Cretaceous age. The fault plane probably dips 70° NE., and separation may be as much as a thousand meters (Trask, 1926, p. 165).

The probable seaward extension of the Palo Colorado fault also appears to be upthrown on the northeast side, and Dohrenwend (1971) calculated that Pliocene and Pleistocene sedimentary rocks at least 200 meters thick have been brought into fault contact with the quartz diorite. However, sandy siltstone, rather than quartz diorite, was dredged on the surface and near-surface parts of the upthrown side of the scarp (Dohrenwend, 1971; Ellsworth, 1971). On this upthrown side, seismic records show a reflecting unit typical of crystalline rocks lying north of the fault. Thus, if sediment overlies the quartz diorite east of the fault, it must lie within the bubble pulse (i.e., it must be less than 3 meters thick). Ellsworth and Dohrenwend (1971) have suggested that because the scarp consists of easily eroded siltstone, it was probably produced by recent fault offset, rather than differential erosion.

Offshore of Point Lobos, the Palo Colorado fault is well defined in seismic reflection profiles across a deeply incised eastern tributary of Carmel Canyon (pl. 3, section M-M'). The east wall of the tributary is composed of granitic rock. On the west wall, stratified sediments 120 meters thick overlie a probably granitic basement, suggesting at least 120 meters of separation, with relative upward movement of the east wall. A dredge haul at the base of the west wall of this tributary collected a quartz diorite with cataclastic texture (tectonically deformed quartz diorite with broken and bent phenocrysts), which also suggests that the fault lies in the tributary valley.

2. Monterey Bay

The Palo Colorado-San Gregorio fault zone, which includes the offshore extension of the Serra Hill fault, trends approximately N. 25° W. down Carmel Canyon in outer Monterey Bay. Seismic reflection is of little assistance in following the faults in Carmel and Monterey Canyons because steep bottom topography produces complex seismic reflections (side echos and hyperbolic reflections) that obscure subbottom reflections. However, Martin and Emery (1967, p. 2291, fig. 5) mapped a fault in Carmle Canyon on the basis of dredge hauls and unpublished geophysical data; they recovered well-indurated middle Miocene limestone along the outer west wall in contrast to granodiorite along the east wall. On this basis, and the linear elements in the sea floor topography, as determined by high precision depth recorder, the Palo Colorado-San Gregorio fault is projected along the axis of Carmel Canyon.

Near the junction of Carmel and Monterey Canyons, Martin and Emery (1967, p. 2289) mapped a narrow band of pre-Cretaceous(?) metamorphic rocks lying between two northwest-trending parallel faults that separate it from middle Miocene siliceous siltstones on the west and Cretaceous intrusive rocks on the east. On plate 1 these faults are generalized as a single fault, which is projected to the northwest, following linear topographic elements to the southern edge of Año Nuevo Point-Santa Cruz shelf, where seismic records clearly indicate faulting.

3. Año Nuevo Point-Santa Cruz Shelf

Two northwest-trending parallel faults cut across the Año Nuevo Point-Santa Cruz shelf. As far as can be determined by the spacing of the seismic profile lines, the faults appear to be continuous for more than 26 km and bound a deformed zone in which the rocks dip more steeply than in adjacent areas. The character of the seismic reflection in this zone indicates that in some areas dips may exceed 35° or that the rocks may have been sheared by additional faulting (pl. 4, profiles A-A'-D-D'). Hoskins and Griffiths (1971) indicated faults at about the same locations. They suggested that these faults did not affect rocks above a buried erosional unconformity of late Miocene age. However, both the intermediate-penetration and high-resolution profiles indicate that these faults also cut the overlying younger rocks, and in some places closely approach the modern ocean floor.

Onshore faults that are the probable continuation of these offshore faults also indicate relatively recent displacement. The easternmost fault lies directly on trend with the San Gregorio fault, which juxtaposes the Pliocene Purisima Formation and the upper Miocene Santa Cruz Mudstone (Clark, 1970a). The western fault lies on trend with a fault on Año Nuevo Point along which the Miocene Monterey Shale has been thrust (northeast side up) over Pleistocene marine terrace deposits (Clark, 1970a; J. G. Evans and K. R. Lajoie, written commun., 1971). A shear zone several meters wide on Año Nuevo Point, between the thrust fault and the San Gregorio fault, suggests a fault trending N. 30° W. (K. R. Lajoie, G. E. Weber and J. C. Tinsley, written commun., 1971) that probably continues offshore into the deformed zone, but is not discernible on the high-resolution records. Thus the deformed zone appears to come ashore in what might be called the San Gregorio fault zone.

To the south, the easternmost offshore fault bounding this narrow fault zone either ends or changes its character so that it is unrecognizable by seismic profiling. Hoskins and Griffiths (1971) mapped the end of the fault in about the same location as on plate 1. The westernmost offshore fault that bounds the western side of the zone (pl. 1) is extended across Monterey Canyon along linear bottom topographic features, and is joined with the Carmel Canyon fault. If this interpretation is correct, the San Gregorio fault zone joins the Palo Colorado fault.

Monterey Bay Fault Zone

1. Southern Monterey Bay

South of Monterey Canyon, the Monterey Bay fault zone comprises many en echelon faults identified from both high-resolution and intermediate-penetration seismic-reflection profiles (pls. 1 and 4, intermediate-penetration sections J-J' through L-L'). A third of the faults are at least 1.6 km long, or longer, and have been correlated between two or more track lines on the basis of similar structural characteristics. Two-thirds of the faults, however, were identified on one track line only and have been mapped as parallel to the adjacent more continuous faults.

Onshore and offshore faults in southern Monterey Bay cannot be correlated owing to insufficient data in the onshore coastal region. However, among the generally discontinuous faults in southern Monterey Bay, the three most continuous appear to extend onshore between Sand City and Marina. Two are about 9 km long, and the third is about 3 km. One of the longer faults may be the offshore extension of the Chupines fault, which may enter the ocean north of Monterey near Seaside.

Interpretation of offshore seismic reflection profiles and onland geophysical data indicates that the two longer continuous offshore faults and the onland Chupines fault exhibit the same sense of separation. At depth, all three faults have Tertiary sedimentary rocks downthrown on the northeast against Mesozoic granite on the southwest (pl. 3, section K-K', fix 14.5 and sections K-K' and L-L', between fixes 11 and 12). The high-resolution profiles across the nearshore part of the southernmost continuous fault, where the fault offsets the modern sea floor, show drag folding that indicates the opposite sense of displacement. The drag folding may be the result of recent motion on the fault, which might differ from the predominant displacement, or may indicate that the fault has some strike-slip component.

On land, the Chupines fault trends northwestward from the Sierra de Salinas Mountains and extends beneath an area of alluvial deposits several kilometers wide near the coast. Southeast of the alluvial cover, the fault is well defined in the mountains where the Miocene Monterey Formation is faulted against the lower Pleistocene Aromas Red Sands (Allen, 1946) and younger surficial alluvial deposits (Jennings and Strand, 1958; Bowen, 1969; Calif. Dept. Water Resources, 1970). At depth the Monterey Formation is in fault contact with the granitic basement rocks. H. C. Sieck interpreted gravity data (1964) as indicating that the Chupines fault lies beneath the alluvium at the base of the mountains and suggested that strike-slip movement along the fault may have displaced the Monterey Formation near Canyon del Rey. The fault also has a vertical separation of possibly 300 meters, with the upthrown block on the southwest. If it connects with one of the continuous offshore faults, the Chupines fault is over 26 km long.

Another major onshore fault that may be continuous with offshore faults in southern Monterey Bay is the Tularcitos fault. Plate 1 shows the Tularcitos fault bending northwest, under Carmel Valley (Bowen, 1969), but it may instead continue in a more northerly direction across the Meadow Tract area of the mountains of Monterey Peninsula, then pass under the alluvium at the northern base of the mountains near Seaside, and finally trend out to sea near Laguna del Rey (R. R. Thorup, consulting geologist, Monterey, oral commun., 1972). If it does continue uninterrupted into Monterey Bay and joins the southern continuous offshore fault, the Tularcitos fault is over 42 km long. T. W. Dibblee (oral commun., 1973) suggests that rather than continuing across the Meadow Tract area, the Tularcitos fault, which is a southwest-dipping reverse fault where locally exposed, bends slightly to the west, then dies out northwestward in Carmel Valley. However, he suggests that a branch of the fault may extend as a zone of discontinuous faults northwest across the Meadow Tract area toward Seaside.

In southern Monterey Bay, the northeastern boundary of the Monterey Bay fault zone is gradational and lies along a continuous fault and several en echelon discontinuous faults (pls. 1 and 3, section P-P', fix 10.5). The northeastern boundary may be the offshore extension of a major fault here referred to as the King City fault (B. L. Clark, 1929; R. D. Reed, 1933). Onland projection of the more continuous fault is alined with an inferred hidden trace of the King City fault (also called Gabilan fault) as projected from the base of the Sierra de Salinas to the ocean just south of the town of Marina.

On land the King City fault is a major structural feature, a high-angle reverse fault along which granitic rocks of the Sierra de Salinas were uplifted to form the western border of the Salinas Valley (Reed, 1925, 1933; Clark, 1929; and Sieck, 1964, p. 20). The vertical separation along this fault decreases to the north, toward Monterey Bay, where it may die out. To the southeast, the King City fault was presumed to extend concealed under the southwest margin of the Salinas Valley (Clark, 1929, p. 204; Reed, 1933, p. 43, 44). Schombel (1943, p. 467-470) projects the King City fault only a short distance into the Salinas Valley west of Greenfield and Durham (oral commun., 1972) suggests that the fault extends up the Salinas Valley from Monterey Bay to just west of Greenfield where it apparently dies out. Along the southern margin of the Salinas Valley, beneath the alluvial fans near the mouth of Pine Canyon, gravity data (Fairborn, 1963) suggest about 2500 meters separation, whereas at the west end of the Sierra de Salinas, gravity data (Sieck, 1964) indicate between 900 and 1200 meters separation. If the offshore correlation is correct, the vertical separation has decreased to approximately 240 meters where the fault crosses section P-P' offshore (pls. 1 and 3).

The Reliz fault, first mapped by Schombel (1943, p. 467) across Arroyo Seco Creek, was interpreted to be a branch of the King City fault; however, Durham (1970, pl. 2) terminates the Reliz fault near Olsen Ranch. Gribi (1967, p. 91) and Walrond and others (1967), on the other hand, extend the Reliz fault northwest into the fault previously designated as the King City fault along the base of Sierra de Salinas and call the entire combination the Reliz fault. Dibblee (1972) concurs with this designation, on the basis of the linear position of the steep front of the Sierra de Salinas and its near alinement with the Reliz fault of Schombel (1943) south of Olsen Ranch. Dibblee (1972) also alines the Reliz fault with the Rinconada fault, which he considers to extend for over 110 km to the southeast.

The projection of the King City fault beneath the alluvial cover near the coast along the lower Salinas Valley is inferred from water wells by the California Department of Water Resources (1970). From well data, within 3 km of the coast near the town of Marina, it appears that the King City fault has a probable post-Pleistocene vertical separation of 30 meters, south side up (Calif. Dept. Water Resources, 1970, sheet 5, pl. 2). Movement along the fault has brought the Miocene Monterey Formation, on the southwest, against the upper Pliocene and lower Pleistocene Paso Robles Formation. At Fort Ord, wells penetrate the Paso Robles Formation at an altitude of 30 meters above sea level southwest of the fault. Across the fault, to the northeast, only post-Paso Robles alluvial materials are penetrated; the Paso Robles on this side is downdropped more than 160 meters below sea level, below the depth of the deepest (180 meters) wells (R. S. Ford, written commun., 1972).

The southwestern limit of the Monterey Bay fault zone in southern Monterey Bay is represented by a series of parallel faults trending northwestward from Cypress Point (pl. 1). Three of these faults displace the sea floor by 1 to 5 meters; two show relative uplift on the southwest, the other shows relative uplift on the northeast. The most continuous fault along this boundary may connect with the onland Cypress Point fault that extends southeastward from Cypress Point to Pescadero Point and across Carmel Bay to connect with a fault on a point, "Abalone Point," just north of the mouth of the Carmel River (Bowen, 1969). Bowen (1969) continues this fault from Abalone Point across the mouth of Carmel Valley, beneath terrace and alluvial deposits, and joins it to the Tularcitos fault.

2. Northern Monterey Bay

North of Monterey Canyon, the Monterey Bay fault zone is composed of many faults identified primarily from high-resolution seismic records (pls. 1 and 3, high-resolution sections A-A' through E-E'). A high-powered seismic survey made in Monterey Bay late in 1972 appears to show deeper faults in this area than can be seen in the high-resolution and intermediate-penetration profiles discussed here. Most faults are downthrown on the landward side. A third are 1.6 km long, or longer, and have been correlated between two or more track lines on the basis of similar separation of the same seismic reflectors and from similar associations with other subsurface structural features (i.e., anticlines, synclines, drag folds, etc.). Two-thirds of the faults, however, cannot be correlated between two track lines and have been mapped as oriented parallel with adjacent continuous faults.

The longest fault lies in the center of the zone and extends at least 9.6 km (pls. 1 and 3, sections C-C' and E-E', between fixes 9 and 10). High-resolution records show that it is accompanied by drag folding and offsetting of gently dipping reflectors that can be correlated from line to line. In areas where high-resolution profiles do not give good, correlatable seismic characteristics, the fault has been continued from observations of similar seismic characteristics in intermediate-penetration profiles.

The northeastern limit of the Monterey Bay fault zone in northern Monterey Bay is a gradational boundary represented by a decreasing number of discontinuous faults. The fault zone does not appear to cross the Palo Colorado-San Gregorio fault zone.

Faults probably continue beneath the canyons, but they could not be identified by the seismic-reflection method used in this investigation, for reasons noted earlier. However, linear trends in the topography of the bay floor within the Monterey Bay fault zone parallel and may be controlled by the faulting; the large northwest-southeast meander in Monterey Canyon is parallel to the trend of the faulting, as are the channels of small valleys tributary to the canyons.

A 1972 geophysical survey along the central California continental shelf produced evidence for the "Monterey Canyon fault," which had been previously inferred to lie beneath, and parallel to, the headward axis of Monterey Canyon (Greene, 1970). The sparker used in this survey (160 kj) was more powerful than seismic systems discussed in this report, and thus able to penetrate deeper. In the higher powered sparker profiles the acoustic basement (Cretaceous granites) generally lies at a shallower depth on the south side of the canyon than on the north and suggests a vertical separation of approximately 60 to 150 meters, south side up (fig. 2), with greater apparent offset offshore.

The Monterey Canyon fault is about 10 km long. It follows the axis of the canyon from the meander to the mouth of Elkhorn Slough and may extend onland (pl. 1). If the fault does extend onshore, it may be responsible for the trough in the basement beneath Elkhorn Slough that Starke and Howard (1968) showed.

The coarse definition of the shallower reflectors in the 160-kj seismic profiles makes it difficult to determine the stratigraphically highest strata the fault cuts. However, it appears to extend up to the base of the modern canyon fill. Faulting in the granites, and possibly in overlying strata, has probably influenced the development of Monterey Canyon.

SEA-FLOOR SCARPS AND DISCONTINUITIES NOT DUE TO FAULTING

Several sea floor scarps mapped in the Monterey Bay region resemble faults in some respects but appear to have had other origins. These features are generally restricted to central Monterey Bay, in and around Monterey Canyon near Moss Landing, and along the shelf break at the top of the continental slope. The most pronounced and abundant features are slump scarps that lie along most of the walls in the headward part of Monterey Canyon (dashed single-hachured line on plate 1; plate 3, section 8-8'). Similar scarps occur at a depth of about 125 meters near the edge of the continental shelf. Hummocky topography downslope from some of these scarps indicates that they are related to slumping of unconsolidated sediment.

Other seaward-facing scarps at the edge of the continental shelf appear to be erosional features at the landward edge of young sediments deposited with foreset bedding, on a prograding continental slope (dashed double-hachured line, pl. 1; pl. 3, section E-E', fix 14). Eli Silver (oral commun., 1971) attributes similar features along the northern California coast to wave erosion and accompanying deposition that occurred while sea level was lower, and Dietz (1952, p. 1809) advanced a similar explanation. However, some of the scarps may be associated with downslope creep of continental shelf sediments.

An arcuate subsurface break, covered with about 10 meters of unbroken sediment, lies on the south side of the head of Monterey Canyon (dot-dash line, pl. 1). It roughly parallels the canyon, and in the subsurface the north side has been downdropped an unknown amount. This subsurface break appears to be the head of an incipient slump that has moved toward Monterey Canyon. It may have become stable and covered with late Holocene sediment, or the slump may still be active and the break may be propagating toward the surface.

SEISMICITY AND EVIDENCE FOR RECENT FAULTING

Earthquakes in the Monterey Bay region indicate that the Palo Colorado-San Gregorio and Monterey Bay fault zones are seismically active. Historical accounts of earthquakes in the region date back to 1836. Information prior to the installation of seismographs in 1934 is based on reports of "felt" earthquakes, locations of which cannot be accurately determined. (For a review of the earthquake history of the region from 1836 to 1968, see Griggs, 1973.)

Sites of reliably located earthquakes that occurred from 1926 through November 1972 in the Monterey Bay area are shown on plate 2. Epicenters of earthquakes east of the San Andreas fault are not shown, nor are epicenters east of the Salinas Valley in the south and the Zayante fault in the north. Epicenters of all earthquakes after June 1972 are approximately located (R. L. Wesson, written commun., 1973).

The largest recorded earthquakes in the Monterey Bay region occurred in 1926. Steinbrugge (1968, p. 77) described them as follows:

> "1926 October 22, 4:35 a.m. Center on the continental shelf off Monterey Bay. Intensity VIII at Santa Cruz, where many chimneys were thrown down; VII at Capitola, Monterey, Salinas and Soquel. Felt from Healdsburg to Lompoc [a distance of 250 miles or 450 kilometers] and east to the Sierra, an area of nearly 100,000 square miles [180,000 square kilometers]. Another shock one hour later was similar to the first in almost every respect."

Detection of earthquakes and determination of their location and focal depth (hypocenter) in the Monterey Bay area are difficult because the area lies largely outside the network of seismographic stations. Epicenter locations for earthquakes that occurred before 1969 are

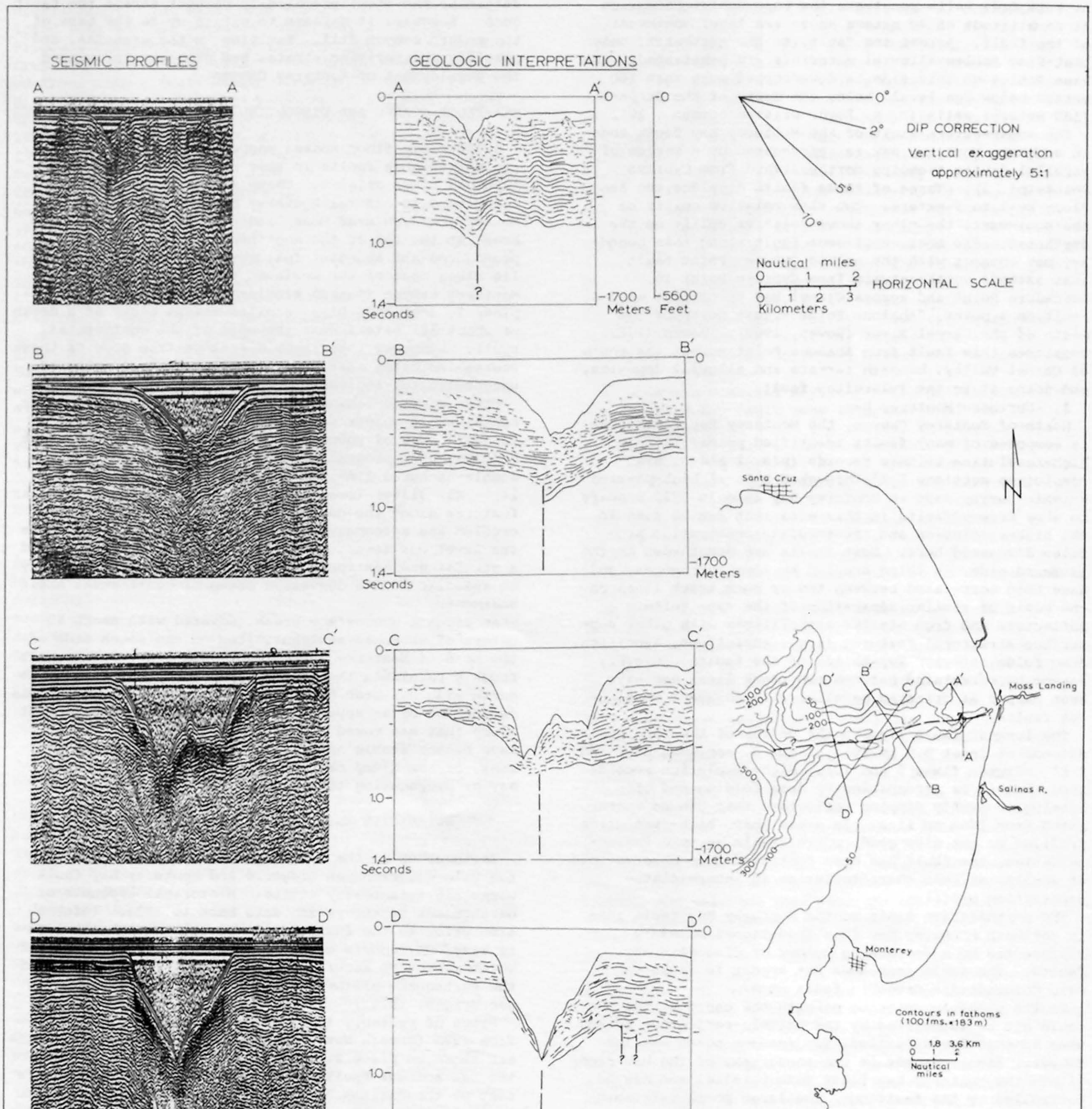

Figure 2.--Deep penetration (160 kj) seismic profiles and geologic interpretations across Monterey Canyon showing location of Monterey Canyon fault.

probably accurate to ±10 km. Epicenters of earthquakes since 1969, the year that additional seismographs were installed, are probably accurate to ±5 km. Focal depths are probably accurate to ±10 km, and most appear to be shallow--within 15 km of the surface.

In the offshore area and the narrow onland fringe of the bay (as defined by lat 36°30'N to 37°00'N and long 121°45'W to 122°30'W) there were 82 earthquakes of magnitude 0.9 to 6.1 from 1926 through November 1972. The number of small earthquakes reported has greatly increased owing to improved methods of detection, as the list of earthquakes in table 1 shows: 2 earthquakes of magnitude 6.1 in 1926, 15 earthquakes of magnitude 4 or greater from 1934 through 1961, 14 earthquakes of magnitude 2.5 or greater from 1962 through 1968, 45 earthquakes of magnitude 0.9 or greater from 1969 through 1971, and 6 earthquakes of magnitude 1.0 or greater from 1971 through November 1972.

Distribution of Epicenters

The distribution of epicenters in space and time indicates where and how often faulting occurs. Using seismic records (fault-plane solutions), the direction of movement can be determined on some faults.

In the Monterey Bay area, many epicenters lie within discrete zones associated with faults, whereas others are more widely dispersed. The greatest concentration lies along the San Andreas fault; the more recent epicenters (solid circles on plate 2) are closer to the fault than those previously located. This apparent difference in distribution may reflect the recent refinement in the determinations of epicenter locations. Epicenters are also concentrated in two groups in central Monterey Bay, where the southwestern edge of the Monterey Bay fault zone abuts the Palo Colorado-San Gregorio fault zone, and in a linear zone that trends to the northwest along the Palo Colorado-San Gregorio fault zone. There is also a small group of epicenters to the south where the Palo Colorado-San Gregorio fault zone comes ashore.

In the southeastern onland area there are three discrete groups of epicenters. One group of 13 (magnitude 1.0-4.5), possibly related to the King City fault, lies at the junction of the Salinas Valley and the northeastern edge of the Santa Lucia Range, a few kilometers southwest of the town of Gonzales. North of the first group is a smaller group of epicenters (magnitude 1.2-2.4) of six earthquakes that occurred in 1972 and may be associated with movement along the King City fault. Seven earthquake epicenters (magnitude 1.0-3.5) are located in the vicinity of Basin Creek and may be related to movement along faults mapped by Durham (1970) between Bruce Ranch and Reliz fault (pl. 2).

In the northwestern onland area the earthquake epicenters are generally scattered, and most appear to be associated with the San Andreas fault. However, some of the earthquakes that have occurred along a narrow (2 km wide) northwest-trending zone west of the San Andreas fault, between San Juan Bautista in the south and Redwood Estates in the north, may be related to movement along the Vergeles, Zayante, and Butano faults. Two earthquakes (magnitude 2.4-2.5) occurred near the base of Sugarloaf Mountain, on the southwestern side of the Gabilan Range, in October and November, 1972. Eleven earthquakes have occurred in Happy Valley, just north of Capitola, 10 (magnitude 4.0-4.5) between 1934 and 1956 and one (magnitude 1.6) in 1969. The 10 events are located to the nearest 1/4 degree of latitude and longitude, thus their exact location is unknown.

1. Monterey Bay fault zone

Eight epicenters are clustered in the Monterey Bay fault zone just north of Monterey Canyon. The earthquakes ranged from 0.9 to 4.7 in magnitude. Three (magnitude 3.0, 3.7, and 4.7) occurred in August 1970. Seismic records have been analyzed to determine the direction of movement of the rocks on either side of the fault during these earthquakes. If the movement is toward a seismograph, the first motion of seismic waves is directed upward (indicating the ground is undergoing compression); if away, it is directed downward (indicating the ground is undergoing dilatation). Knowing the location of the hypocenter and the direction of first motion that reaches several seismographs, it is possible to define two quadrants of compression, and two of dilatation. However, this kind of analysis produces two possible planes along which the fault displacement might have occurred, and these planes lie at right angles to each other.

Analysis of the epicenter cluster in the Monterey Bay fault zone (epicenters 6-8, pl. 2) indicates that the fault planes are nearly vertical and that strike-slip (horizontal) movement has occurred along a fault that trends northeast or northwest (as indicated by the lines that divide each corresponding first-motion diagram into the four quadrants on the insert on plate 2). The reflection profiles show evidence of faults parallel to the northwest trend, but none parallel to the northeast trend, so we interpret the first-motion studies as indicating that right-lateral strike-slip displacement is occurring on northwest-trending faults.

The locations of two large earthquakes of magnitude 6.1 that occurred in 1926, noted earlier, are placed within the Monterey Bay fault zone by Richter (1958). However, these epicenters were probably not located accurately enough for them to be assigned with certainty to a particular fault zone, whether the Monterey Bay zone, the Palo Colorado-San Gregorio zone, or elsewhere.

Most faults in the Monterey Bay fault zone displace late Tertiary and Pleistocene sediments and are thus geologically young. North of Monterey Canyon, faults extend to within 6 meters of the ocean floor; most displace late Pliocene strata, some displace Pleistocene deposits, and a few may displace Holocene deposits. South of Monterey Canyon, most faults close to shore near Monterey also extend to within 6 meters of the ocean floor and cut Pleistocene deposits. Some cut Holocene deposits as well. Farther offshore, in southern Monterey Bay, faults appear to be older because they cut only upper Tertiary strata and are covered with about 100 meters of unfaulted sediment. A few faults cut only Cretaceous granites and lower and middle Tertiary strata.

Scarps on the modern sea floor occur on seven faults in the Monterey Bay fault zone (indicated by a bar and box symbol on pl. 2): three along the southwestern limit of the zone, two on the shelf around the head of Soquel Canyon, one just offshore of the town of Seaside, and one on the southern shelf near the meander in Monterey Canyon. All but two of the scarps face landward, and the rocks appear to be similar on both sides of the scarps. Thus, five are not wave-cut scarps associated with a lower stand of sea level, nor are they likely due to differential erosion.

2. Palo Colorado-San Gregorio fault zone

A cluster of 14 epicenters in the Palo Colorado-San Gregorio fault zone (pl. 2) represents earthquakes that ranged in magnitude from 1.0 to 4.4. Three, in the magnitude 4.1 to 4.4 range, occurred in the spring of 1971. Fault-plane solutions for five earthquakes since 1969 (inset on pl. 2) are interpreted as showing nearly vertical fault planes and right-lateral strike-slip motion. Solutions for four indicate a trend of approximately N. 20° W. parallel to the Palo Colorado-San Gregorio fault zone. The solution for the fifth indicates a trend parallel to the strike of the Monterey Bay fault zone (N. 60° W., ±10°), suggesting a relatively close spatial tie between the two fault zones.

North of this cluster, 14 more epicenters lie in, or close to the fault zone offshore and along its onland equivalent, the San Gregorio fault. The earthquakes ranged from magnitude 1.0 to 2.3, and two occurred in July and September, 1972.

The two faults mapped between Año Nuevo Point and the epicenter cluster appear in the seismic reflection profiles to extend up to within 6 meters or less of the ocean floor (pls. 1 and 4, sections A-A', B-B', and C-C'). These faults cut latest Tertiary strata and probably also Holocene deposits. Much of the easternmost of these two faults coincides with a topographic break in the ocean floor separating flat-lying young sediment on the west from higher standing bedrock on the east. This topographic break might result in part from recent fault displacement.

Southeast of the epicenter cluster, the Palo Colorado-San Gregorio fault zone has been relatively quiet seismically throughout the period of record, but there is no guarantee that it will remain so. Indeed, the segment of the San Andreas fault that generated the 1906 San Francisco earthquake is also quiet, although most agree that it will probably generate another large earthquake.

Table 1.--Earthquakes in the Monterey Bay area (within lat 36°30'N to 37°00'N and long 121°45'W to 122°30'W), October 22, 1926, through November 30, 1972

Origin Time (Greenwich Mean Time)										
Year	Month	Day	Hour	Minute	Second	Latitude (N)	Longitude (W)	Focal Depth (Km)	Magnitude	Reference
1926	OCT	22	12	35	11.0	36°45.0'	122° 0.0'		6.1	Richter, 1958
1926	OCT	22	13	35	27.0	36°45.0'	122° 0.0'		6.1	
1934	APR	23	16	8	0.0	37° 0.0'	122° 0.0'		4.0	California Department of Water Resources (1964)
1935	JUN	18	4	15	0.0	37° 0.0'	122° 0.0'		4.0	
1936	SEP	24	14	12	0.0	37° 0.0'	122° 0.0'		4.0	
1937	OCT	27	15	53	0.0	37° 0.0'	122° 0.0'		4.5	
1937	NOV	12	2	50	0.0	37° 0.0'	122° 0.0'		4.0	
1938	FEB	12	20	0	0.0	37° 0.0'	122° 0.0'		4.5	
1939	JUL	17	9	24	0.0	37° 0.0'	122° 0.0'		4.5	
1940	MAR	2	13	27	0.0	37° 0.0'	122° 0.0'		4.0	
1941	APR	14	16	16	54.0	36°48.0'	121°48.0'		4.0	
1941	MAY	28	6	23	18.0	37° 0.0'	122° 0.0'		4.5	
1946	AUG	5	4	8	44.0	36°51.0'	121°47.0'		4.1	
1947	JUN	22	23	30	0.0	37° 0.0'	121°46.0'		4.7	
1947	NOV	15	22	30	0.0	36°47.0'	122° 7.0'		4.1	
1956	NOV	22	16	43	50.0	37° 0.0'	122° 0.0'		4.2	
1958	NOV	7	21	33	24.0	36°52.0'	121°53.0'		4.3	
1962	AUG	5	10	58	26.3	36°52.7'	122°17.5'		2.7	Bulletin of Seismographic Stations, University of California, Berkeley (1962-1968)
1962	SEP	14	0	49	49.9	36°38.4'	121°46.7'		3.0	
1962	SEP	17	7	16	34.3	36°35.2'	121°52.6'		2.6	
1962	DEC	24	0	16	23.4	36°50.9'	121°47.4'		3.7	
1963	MAR	19	18	30	5.0	36°56.6'	121°45.5'		3.0	
1964	AUG	31	17	10	19.1	36°59.1'	121°47.0'		2.5	
1965	APR	6	10	31	59.1	36°48.0'	121°58.0'		3.3	
1965	APR	6	11	23	10.4	36°49.6'	122° 6.7'		2.5	
1966	APR	3	21	17	58.5	37° 0.0'	121°46.0'		2.6	
1966	MAY	5	15	7	10.5	36°56.0'	122°13.0'		2.5	
1966	JUN	2	13	12	20.4	36°58.0'	122°12.0'		2.9	
1966	OCT	25	20	54	42.5	36°55.8'	121°48.2'		2.9	
1967	FEB	5	7	36	23.3	36°47.5'	122° 7.4'		2.6	
1968	MAR	6	9	14	6.0	36°58.0'	122°10.0'		2.5	
1969	JAN	13	5	12	32.9	36°45.9'	122° 5.6'	5.0	2.0	Lee and others, 1972a
1969	MAY	6	7	8	43.4	36°46.0'	122° 1.4'	12.6	0.9	
1969	JUN	19	6	46	4.3	36°36.2'	121°47.6'	5.0	1.1	
1969	JUL	29	21	48	17.2	36°53.7'	122° 8.9'	11.6	1.9	
1969	OCT	14	15	1	58.6	36°45.2'	122° 2.6'	7.2	1.7	
1969	NOV	6	19	40	26.6	36°51.8'	122° 8.5'	9.7	2.6	
1970	FEB	2	19	23	17.5	36°59.0'	122°14.1'	8.7	2.2	Lee and others, 1972b
1970	FEB	27	23	21	45.6	36°46.0'	121°58.9'	5.0	2.2	
1970	APR	15	21	0	14.1	36°44.9'	121°51.5'	5.0	1.2	
1970	MAY	14	8	26	6.6	36°44.5'	122° 3.7'	10.0	1.0	
1970	AUG	4	4	14	23.4	36°45.0'	122° 3.5'	9.0	4.7	
1970	AUG	4	4	44	7.4	36°45.0'	122° 2.6'	9.2	3.0	
1970	AUG	4	4	48	53.8	36°45.8'	122° 1.8'	13.3	1.6	
1970	AUG	7	7	44	59.6	36°58.4'	122° 6.4'	5.0	1.0	
1970	AUG	7	8	15	17.1	36°59.4'	122° 7.1'	5.0	1.1	
1970	AUG	23	17	53	48.6	36°45.4'	122° 2.8'	9.6	3.7	
1970	SEP	29	10	58	32.4	36°59.3'	121°47.4'	12.6	2.0	
1970	SEP	29	11	1	28.7	36°59.4'	121°47.8'	13.2	1.3	
1970	SEP	29	11	58	33.1	36°59.4'	121°47.5'	9.8	1.3	
1970	SEP	29	23	17	2.7	36°59.2'	121°48.7'	13.7	1.0	
1970	SEP	30	13	41	56.8	36°59.3'	121°47.6'	11.9	1.3	
1970	SEP	30	18	27	3.6	36°59.6'	121°47.4'	11.7	1.3	
1970	OCT	1	0	3	51.7	36°59.3'	121°48.7'	13.9	1.2	
1970	OCT	17	8	28	41.1	36°59.1'	121°48.0'	12.8	1.6	
1970	DEC	4	0	14	46.1	36°49.6'	122° 7.0'	10.0	1.1	
1971	JAN	15	1	3	55.6	36°46.5'	122° 1.8'	10.0	1.3	Lee and others, 1972c
1971	MAR	3	8	41	38.8	36°51.9'	121°56.3'	11.1	1.1	
1971	MAR	8	9	10	18.9	36°48.5'	122° 6.4'	8.5	2.3	
1971	MAR	8	18	31	46.5	36°48.1'	122° 7.2'	8.6	4.1	
1971	MAR	9	15	35	16.3	36°48.4'	122° 7.5'	9.0	4.4	
1971	MAR	9	23	7	0.6	36°48.1'	122° 5.8'	10.0	1.4	
1971	MAR	10	4	31	22.0	36°48.8'	122° 7.2'	9.2	1.9	
1971	MAR	10	9	15	42.8	36°47.9'	122° 7.1'	8.4	2.6	
1971	MAR	11	12	12	17.8	36°48.3'	122° 7.0'	9.3	1.8	
1971	MAR	11	16	33	37.8	36°48.2'	122° 7.2'	9.8	1.6	
1971	MAR	26	1	2	40.1	36°48.4'	122° 6.4'	8.2	2.3	
1971	MAR	26	1	41	18.8	36°48.5'	122° 6.4'	9.3	2.0	
1971	APR	16	12	58	32.2	36°49.2'	122° 6.6'	8.2	4.4	
1971	APR	16	14	11	18.7	36°49.4'	122° 6.7'	10.0	1.8	
1971	APR	16	16	15	50.5	36°49.4'	122° 6.4'	7.2	1.2	
1971	APR	16	16	19	33.3	36°49.1'	122° 6.6'	9.3	1.8	
1971	MAY	21	20	10	30.0	36°59.4'	121°47.4'	13.4	1.7	
1971	MAY	28	8	57	33.2	36°47.8'	122° 6.1'	8.2	1.8	
1971	JUL	13	14	17	31.9	36°41.9'	121°47.8'	12.9	1.2	
1971	SEP	18	8	28	52.9	36°36.1'	121°56.9'	3.0	1.0	
1972	APR	30	12	43	26.0	36°40.3'	122° 0.2'	5.2	2.1	Wesson and others, 1973
1972	JUN	29	15	9	4.8	36°33.4'	121°50.6'	7.5	1.6	
1972	JUL	5	18	54	56.2	36°32.2'	121°56.7'	2.1	1.0	Wesson, written commun., 1973 (preliminary locations)
1972	JUL	8	22	16	47.5	36°59.2'	122°13.2'	10.0	1.5	
1972	AUG	26	2	53	27.1	36°46.0'	121°48.7'	8.9	1.5	
1972	SEP	19	20	19	31.3	36°59.9'	122°13.8'	8.3	1.8	

Two epicenters lie offshore of Kasler Point, and one is on the Palo Colorado fault onshore near Rocky Point, but the probable inaccuracy in epicenter location does not allow a definite tie to movement on a specific fault. There is, however, geologic evidence for relatively recent fault displacement in this area. The previously discussed sea-floor scarp on the Palo Colorado-San Gregorio fault zone that lies just north of Kasler Point can be followed for 5 km and cuts Holocene deposits. Furthermore, recent onshore reconnaissance mapping by Greene along the Point Sur-Cypress Point coast has revealed a highly faulted and sheared zone in the coastal terrace between Rocky Point and Kasler Point, in which many of the faults may extend into deposits of probable Pleistocene age. Some faults appear to have offset an elevated Pleistocene wave-cut platform and may have displaced overlying Holocene alluvial deposits.

Onland north of the Palo Colorado fault three earthquakes (magnitude 1.0-2.3) occurred in 1972; two are alined with a possible extension of the Church Creek fault. One (magnitude 1.4) occurred in August 1972 near the Big Sur fault in the Sur thrust zone.

Faults on the Cypress Point-Point Sur shelf vary in age. Those west and southwest of Hurricane Point, including the offshore projection of the Sur fault, extend to between 50 and 200 meters of the ocean floor and cut late Tertiary strata; they appear to be covered with unfaulted Quaternary sediments. Northwest of Hurricane Point the two faults mapped on the shelf appear from seismic-reflection profiles to generally extend to within 6 meters of the ocean floor, and locally cut Holocene deposits. The probable offshore continuation of the Serra Hill fault seems to become younger toward the north; it extends up to within 10 meters of the ocean floor in the south, cutting only late Tertiary strata, and up to 6 meters in the north, cutting late Pleistocene and possibly Holocene strata.

ESTIMATE OF HOW LARGE AN EARTHQUAKE COULD OCCUR ON THE PALO COLORADO-SAN GREGORIO FAULT

In order to anticipate the seismic forces that the man-made structures in an area might be subject to, it is necessary to estimate how large an earthquake can occur on nearby faults. At present there is no absolute way of determining how large an earthquake may be expected in a given area. One technique that has been used is an analysis of the historic record in which the length of surface breakage on faults is compared with the magnitudes of the associated earthquakes (Tocher, 1958; Iida, 1965; Albee and Smith, 1967; Bonilla, 1967; Bonilla and Buchanan, 1970).

Estimating the possible magnitude of a large earthquake by this empirical relation necessitates making an assumption as to what part of the fault might rupture in a single event. In a study done for the Atomic Energy Commission, Wentworth and others (1972) used a rupture length equal to half the fault length in estimating the magnitude of earthquakes that might occur on several faults in California. They argued that rupture is not likely to occur along the entire length of a fault in a single event. After comparing fault length and fault rupture length for data from southern California (Allen and others, 1965) and also comparing data from Bonilla (1967) and original literature that indicates surface rupture length for 10 historic North American events in which 2 to 75 percent of the fault length ruptured, they suggested that the half length be used but cautioned that it must be considered only approximate at best.

Application of this empirical relation to the Palo Colorado-San Gregorio fault zone also necessitates defining the fault length. The continuously mapped fault zone is about 135 km long, from the south end of the Palo Colorado fault to the northern end of the San Gregorio fault. However, the fault may be as much as 205 km long, for as noted earlier, it may continue to the north and include the Seal Cove fault at Half Moon Bay and its offshore extension, which Cooper (1971) mapped as joining the San Andreas fault zone at Bolinas. For this reason, two different half lengths, 65 and 100 km, were used in calculating the estimates of magnitude listed in table 2. There are several reasons why these estimates do not preclude the possibility that the Palo Colorado-San Gregorio fault can produce an earthquake of even greater magnitude than indicated. First, the magnitudes listed in table 2 are derived from least-squares approximations (that is, some earthquakes have larger and smaller magnitudes for a given rupture length); second, the rupture length might exceed half the mapped length; and, finally, the Palo Colorado fault might extend farther south than shown on the map.

An estimate of how large an earthquake can occur on the Palo Colorado-San Gregorio fault zone can also be made by a comparison with the geometry and seismic history of the nearby Hayward fault. Without a considerably better understanding than is presently available of the structural relations of these two faults to each other and to the San Andreas fault, and the driving forces that produce earthquakes on each fault, there are valid objections to concluding that because an earthquake of a certain magnitude occurred on the Hayward fault it should be expected to occur on the other fault. However, the comparison may be valid for establishing the possibility that an earthquake of similar magnitude can occur on the Palo Colorado-San Gregorio fault.

These faults are similar in gross aspect. Both approach the San Andreas at one end (Hayward at the south, Palo Colorado-San Gregorio at the north). Both are long: the Hayward is 160 km long, including the on-trend strands of the active Rodgers Creek and Healdsburg faults (Brown, 1970) and the Palo Colorado-San Gregorio is 205 km long. Both faults exhibit right-lateral strike-slip displacement. Finally, earthquake hypocenters are at approximately the same depth along both faults.

The Hayward and the Palo Colorado-San Gregorio faults are also both part of the San Andreas fault system, and thus respond to stress-generating forces that produce earthquakes on the San Andreas fault. The Hayward fault, which has been called an "active branch" of the San Andreas fault (Richter, 1958, p. 476), undergoes tectonic creep (Radbruch and others, 1966) and has a long history of seismic activity. An indication that the Palo Colorado-San Gregorio fault also acts in response to stress along the San Andreas fault is suggested by the following. Burford (1971) noted that a sequence of fault creep and small earthquakes on the San Andreas fault near Pinnacles National Monument started at about the time of a magnitude 2.6 earthquake (July 22, 1970) near San Juan Bautista, and ended with a magnitude 4.3 earthquake (August 3, 1970) in Monterey Bay.

Two major earthquakes have occurred on the Hayward fault during historic time, in 1836 and 1868. There are no direct measurements of the magnitudes of these earthquakes, but the damage they caused suggests that they were of large magnitude. Lawson (1908, p. 434) noted that observers regarded the 1868 earthquake as severe as the 1906 earthquake. Steinbrugge (1968, p. 73-74) summarizes these earthquakes as follows:

"1836 June 10, 7:30 a.m. One of the five largest earthquakes centered in the San Francisco Bay region in historic times. Ground breakage along the line of the Hayward fault at the base of the hills east of the bay, extending from Mission San Jose to San Pablo. As strong or stronger than the shock of October 21, 1868, which had its center along the same fault. At least one foreshock; numberous aftershocks for at least a month.

1868 October 21, 7:53 a.m. One of California's great shocks, and second of the two large Bay Area shocks of the 1860's. Surface breakage was observed on the Hayward fault from Warm Springs to San Leandro, a distance of about 20 miles. The maximum horizontal offset was about 3 feet. Intensity X at Hayward, where every building was damaged, and many demolished. Intensity IX at San Francisco, where, as in earlier large shocks, damage was chiefly confined to buildings on filled ground along the bayshore. About 30 persons lost their lives in this shock. This earthquake was felt at places 175 miles from the source."

Slemmons (1967) has assigned magnitudes of 7 ±.5 to these two earthquakes. This is in agreement with magnitudes estiamted in table 2. Insofar as the analogy between the Hayward and the Palo Colorado-San Gregorio fault is valid, it appears that the latter is capable of

Table 2.--Estimates of earthquake magnitude for the Palo Colorado-San Gregorio fault zone

Fault half length (km)	Estimated magnitude					
	1. Tocher (1958)	2. Iida (1965)	3. Albee and Smith (1967)	4. Bonilla (1967)	5. Bonilla and Buchanan (1970)	Average
65	7.2	7.4	7.6	7.6	7.4	7.4
100	7.4	7.6	7.8	7.8	7.9	7.7

Magnitudes were established as follows:

1. M = 0.9 X log surface rupture length (L) in km + 5.6
2. M = 0.76 (log L km) + 6.07
3. Least-squares fit of M vs L for California, Nevada and Baja California earthquakes on Albee and Smith's figure 4.
4. M = 1.51 (log L miles) + 5.14
5. Read from graph of M vs L for worldwide strike-slip earthquakes.

Table 3.--General specifications of seismic systems used in the 1969 and 1970 surveys

High-resolution sparker system	Energy (kj)	Filters Hi cut/Lo cut	Sweep rate (sec)	Fire rate (sec)	Fundamental source frequency (Hz)	Sound source: Depth towed (m)	Sound source: Distance towed behind vessel (m)	Hydrophones: Depth towed (m)	Hydrophones: Separation from source (m)	Remarks
1969 survey	0.6	645/250	0.25	0.75	1000	0.6	3	1.5	30.5 in line	A 6-meter, non-preamplified hydrophone cable with 11 crystal elements spaced 0.3 m apart was used. A single multipoint electrode sound source was used (see fig. 3).
1970 survey	.6-.8	590/100	0.25	0.50	800	0.6	1.2-2.4	1.5	1.5 in line	A 6-meter, non-preamplified hydrophone streamer with 11 crystal elements spaced 0.3 m apart was used. Two electrode sound sources spaced 1.2 m apart and towed abeam were used. Hydrophone streamer was towed between sparker electrodes (see fig. 4).
Intermediate-penetration sparker system										
1969 survey	8-12	125/40	1.0	3.0	85	4.5	Abeam	4.5	55 & 70	A 61-meter active section, preamplified hydrophone cable with 100 crystal elements spaced ~.6 m apart was used. Four 3-electrod EG&G sparker cage soun sources towed in a planar array were used (see fig. 3).
1970 survey	23	125/20	1.5	3.0	80	4.5	7.6	4.5	53.4 & 68.4	A 42.6 m active sectio preamplified hydrophon cable with 100 crystal elements spaced .3 to .6 m apart and a 50-phone, 22.8 m active section preamplified streamer were used. Only 1 streamer was used at a time. A single point sparker electrode called a "ladder," a name coine because of wooden step like braces that separ ate the positive electrode from the ground electrode, was used (see fig. 4).

producing major earthquakes.

SUMMARY AND CONCLUSIONS

1. There are two major fault zones in the offshore Monterey Bay area. The longest, the Palo Colorado-San Gregorio fault zone, is a narrow, northwest-trending zone that joins onland faults--the Palo Colorado fault south of Monterey, and the San Gregorio fault zone to the north at Año Nuevo Point. The other zone, the Monterey Bay fault zone, lies on trend with the Salinas Valley and faults in the Salinas Valley and the Sierra de Salinas. It is a wide belt of faults that crosses the bay floor and Monterey submarine canyon and closely approaches, but does not appear to cross, the Palo Colorado-San Gregorio fault zone.

2. The offshore part of the Palo Colorado-San Gregorio fault zone has been mapped by other investigators, who used marine geophysical surveys and bottom dredge hauls as their source of data. The southern part of the Monterey Bay fault zone has also been previously mapped.

3. New detailed geophysical data (continuous subbottom acoustic profiles) are interpreted as indicating that these fault zones have had a long history. Evidence of fairly recent movement is seen in the displacement of young sediment on the sea floor and the presence of scarps on the modern sea floor on some segments of these faults.

4. Both zones are seismically active, as the earthquakes that have occurred on them indicate.

5. Fault-plane solutions of eight recent earthquakes in these fault zones indicate that the accompanying fault displacement is similar to that on the San Andreas fault. Movement on these nearly vertical faults has been horizontal (strike-slip), with rocks on the seaward side displaced to the north.

6. The proximity of these fault zones to areas of growing population necessitates estimating how large an earthquake might be produced by the Palo Colorado-San Gregorio fault zone, the longer of the two. Judging from empirical relations between fault rupture length and magnitude of associated earthquakes on other faults, an earthquake of at least magnitude 7.2 to 7.9 could occur on the Palo Colorado-San Gregorio fault zone. Similarities between this zone and the Hayward fault support the suggestion that the Palo Colorado-San Gregorio fault zone can produce earthquakes of large magnitude (estimated magnitude 7 ±0.5).

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APPENDIX

Equipment, Procedures, and Methods

Both high-resolution and intermediate-penetration seismic profiles were gathered. The high-resolution system obtained 60 meters of penetration with about 1 meter resolution, and the intermediate-penetration system obtained about 1,500 meters of penetration with approximately 5 meters resolution. General specifications of seismic systems used in the 1969 and 1970 surveys are given in table 3. Towing arrangement of the sound sources and hydrophone streamers are shown in figures 3 and 4.

Navigation

A modified anti-aircraft radar artillery director system mounted in a mobile van was used for precision navigation in the Monterey Bay region during the 1969 survey. The system was placed in position near Moss Landing, on a hill 18 meters high, where it could direct the movement of the survey vessel. An antenna producing high-accuracy, narrow-beam radar signals electronically "locked" onto the survey vessel and tracked it throughout a 38-km radius. Movement of the vessel was monitored and recorded by an X-Y plotting system within the van. By placing a 1:50,000-scale mapped representation of the survey grid lines on the X-Y plotter, the radar operator could direct the survey vessel to make course and speed changes that would keep it tracking along a certain grid line. This system was very successful and gave an accuracy of ±15 meters.

Navigation during the 1970 survey, and along the continental shelves from Point Sur to Cypress Point and from Santa Cruz to San Francisco during the 1969 survey, was not as accurate as during the 1969 Monterey Bay survey. Locations were determined primarily by shipboard radar bearing and range fixes that gave an accuracy of probably ±300 meters. Supplementary polaris-bearing fixes were occasionally taken when visibility permitted.

Seismic profiles were obtained along approximately 1,600 km of track line in Monterey Bay during the 1969 survey. These lines were orientated northwest-southeast and northeast-southwest, forming a rectilinear grid with a 1.8-km (1 mile) line spacing (fig. 4). Approximately 1,000 km of track line was run in a sawtooth pattern along shelves north and south of Monterey Bay during both the 1969 and 1970 surveys.

Interpretation

Criteria used in the interpretation of seismic records are the following: Well-defined faults: (1) distinct displacement of prominent reflectors, (2) a sharp discontinuation of prominent reflectors or reflectors brought into juxtaposition with an area of contrasting seismic characteristic, or (3) a sharp contrast in dip of reflectors along a distinct boundary. Inferred faults: (1) small displacement of prominent reflectors, some upper or shallow reflectors may be bent rather than broken, (2) a zone where prominent reflectors are discontinued and contrasting seismic characteristics occur on either side of an abscure seismically disturbed zone, or (3) apparent changes in dip on either side of a seismically disturbed zone. Questionable faults were mapped where obscure interruptions of seismic reflectors occurred in the subsurface. Such interruptions consist of (1) a shift in phase of reflectors that was not caused by instrumental malfunction, (2) bent or possibly broken reflectors that can be correlated with known faults on other lines, (3) apparent discontinuation of weak reflectors, or (4) any other zone where contrasting seismic characteristics may occur or where such characteristics appear to be similar to and correlatable with known faults mapped along adjacent lines. Some questionable and inferred faults have been mapped where anomalous topographic alinements appear to support the continuation of known faults. Slump scarps were based on both the characteristics discussed above and on geomorphic features such as sharp, nearly vertical or steeply dipping slopes associated with the hummocky, distorted strata of slumps.

Orientation of faults is principally determined from the correlation of a fault from one line to another. Faults are correlated from one track to the next mainly by the identification of similar structural and seismic features in adjacent profiles. These features may consist of similar reflectors displaced in the same direction, with drag or other folding exhibited in a like manner, or they may consist of contrasting seismic characteristics on either side of the fault that is common to both features. Those faults that cannot be correlated from one line to another are oriented parallel to continuous faults that are close together (within 2 km). If there are no adjacent continuous faults by which strike can be inferred, the fault is represented by an open diamond symbol.

Where the fault planes dip more than about 35°, the vertical exaggeration inherent in seismic profile records precludes determining actual dip, even though records clearly indicate that a fault is present. Thus, in profiles shown on plates 3 and 4, all faults that dip 35° or more are drawn as vertical. The amount and direction of movement on a fault are very difficult to ascertain. Only the vertical component (vertical separation) can be obtained from the seismic reflection profiles; the horizontal component (strike-slip separation) is almost impossible to determine.

Subsurface depths were calculated using averaged velocities of 1.5 km/sec in water, 2.0 km/sec for unconsolidated to semiconsolidated materials existing in the top 150 meters of section, and 2.5 km/sec for consolidated sediments below 150 meters and overlying the acoustic basement. No corrections were made for changes in sea level during the survey.

Depth of a fault, or the stratigraphically highest unit that a fault cuts, is calculated by assuming a velocity (velocity estimates given above) through the sediments and multiplying it by half of the two-way seismic traveltime obtained at the shallowest subsurface reflector that the fault cuts in the seismic reflection profile. Generally, the highest point at which a fault can be detected in a seismic reflection profile is at the base of the "bubble pulse"1/, 6 meters beneath the ocean floor in high-resolution records and 60 meters below the floor in intermediate-penetration records (except in areas where the sea floor is displaced above the fault).

1/ A bubble-pulse consists of attenuating reverberations that linger in the water column after the primary pulse has been produced. These reverberations are reflected back from the ocean bottom and appear as psuedo-sea-floor traces on the seismic record and effectively cancel any signals reflected from shallow structures immediately beneath the sea floor.

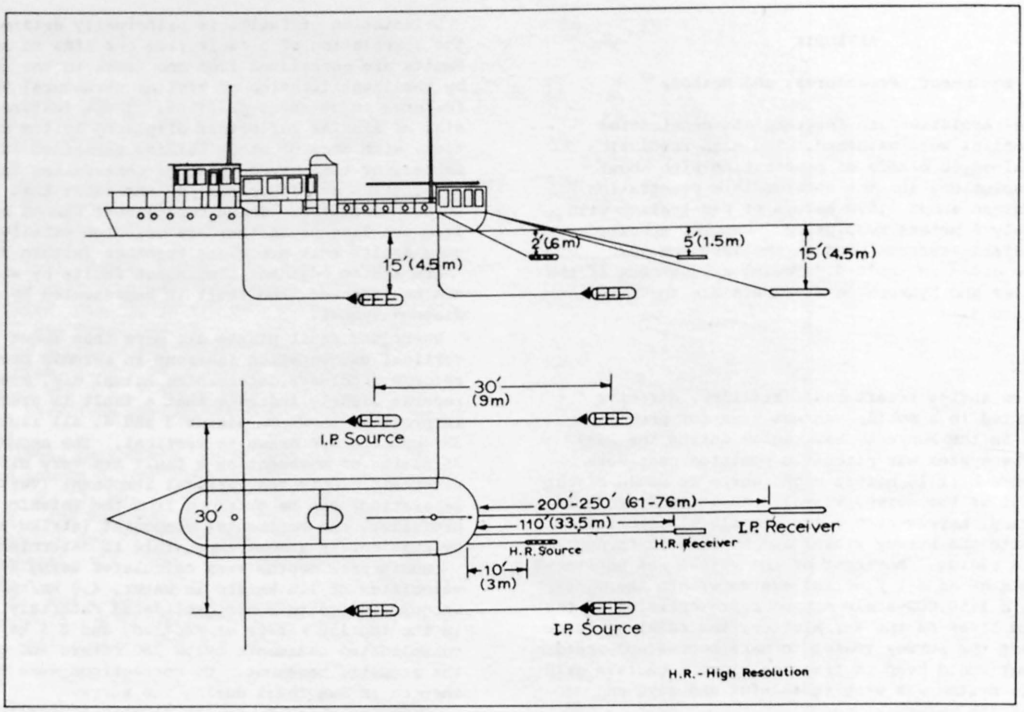

Figure 3.--Towing arrangement of seismic sound sources and hydrophone streamers used in the 1969 survey. Not drawn to scale.

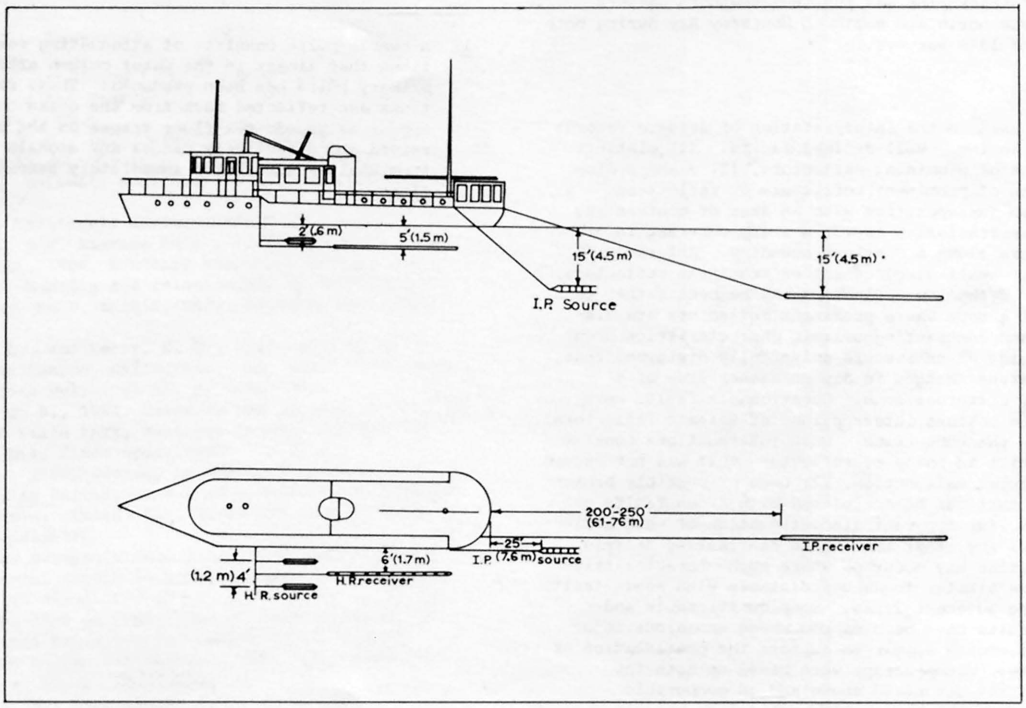

Figure 4.--Towing arrangement of seismic sound sources and hydrophone streamers used in the 1970 survey. Not drawn to scale.