Geology, Petroleum Development, and Seismicity of the Santa Barbara Channel Region, California

A. Geologic Framework of the Santa Barbara Channel Region

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C. Geologic Characteristics of the Dos Cuadras Offshore Oil Field

D. Seismicity and Associated Effects, Santa Barbara Region

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D. Seismicity and Associated Effects, Santa Barbara Region

By R. M. HAMILTON, R. F. YERKES, R. D. BROWN, JR., R. O. BURFORD, *and* J. M. DENOYER

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FOREWORD

Southern California is rich in petroleum and natural gas accumulations both on land and offshore. Over the past century, California has produced more than 8 billion barrels of oil and more than 23 trillion cubic feet of gas. The petroleum industry is one of the major economic factors of the State and involves a capital investment in excess of $7 billion and employs more than 100,000 people. Daily production of petroleum measures in excess of 1 million barrels of oil, which is about 65 percent of the requirements for the region. The situation is one of current shortage of production and projected increase in need. As a natural extension of development of State tidelands, which began in earnest in 1958, a public sale of Federal wildcat leases in 1968 drew a surprisingly large total of $603 million.

During normal development of a prospective petroleum-bearing oil pool on the Rincon structural trend, about 6½ miles southeast of Santa Barbara, a gas blowout occurred on January 28, 1969, during completion of the fifth well being drilled from Platform A on Federal Tract OCS P-0241. Until February 7, when the well was killed by cementing, uncontrolled flow led to local oil pollution on the sea surface. Reservoir damage during this period caused a subsequent moderate and steady oil seepage from the sea floor that has since caused a continual slick on the surface. This seepage, estimated to be at a daily average rate of 30 barrels in the 4-month period March through June 1969, was substantially reduced by early September to less than 10 barrels per day as a result of a drilling and grouting program authorized by the Secretary of the Interior following recommendations of a special Presidential Advisory Panel.

The Santa Barbara incident was the first significant oil-pollution experience resulting from drilling or working 7,860 wells under Federal jurisdiction on the Outer Continental Shelf since 1953. In consequence of this event, by direction of the Secretary of the Interior, Federal operating and leasing regulations have been strengthened, and additional safeguards have been added in all Federally supervised operations.

The purpose of this report is to present specific information that will help provide a better understanding of the geologic framework of the Channel region and of the circumstances relating to the oil seepage in the vicinity of Platform A. The four chapters of this report and accompanying appendixes have been compiled by staff members of the U.S. Geological Survey. Several petroleum companies have permitted use of their proprietary technical data in order to prepare a balanced and complete report. Opportunity to include these data is gratefully acknowledged.

This report incorporates information upon which the recommendations of the Presidential Advisory Panel were based as well as information that subsequently has become available.

W. T. Pecora
Director, U.S. Geological Survey

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GEOLOGIC FRAMEWORK OF THE SANTA BARBARA CHANNEL REGION

By J. G. VEDDER, H. C. WAGNER, and J. E. SCHOELLHAMER

REGIONAL SETTING

The Santa Barbara Channel region forms the westernmost part of the Transverse Range province, which is one of several large geomorphic and structural provinces of southern California (fig. 1). As here defined, the channel region includes the Santa Ynez Mountains to the north and the Channel Islands to the south; Point Conception and San Miguel Island lie near the west margin; the town of Ojai and Hueneme Canyon are situated near the east edge (pl. 1).

The west-trending topographic features of the elongate Transverse Range province transect the dominant regional northwest structural grain of California. The high terrain in the eastern part of the province is composed primarily of crystalline rocks that are older than most of the exposed rocks in the Santa Barbara Channel region. The channel region forms the western part of the province; it is the partly submerged extension of the Ventura basin, a topographic and structural depression that contains more than 50,000 feet of Cretaceous and Tertiary strata. The bordering mountain ranges and islands consist of complexly folded and faulted sedimentary and igneous rocks that are underlain by a basement complex, part of which is equivalent in age and lithology to that exposed in the high ranges to the east.

The characteristic west-trending structural grain of the Transverse Range province is clearly reflected in the channel region by the Santa Ynez Mountains, which rise to heights of more than 4,000 feet to form the picturesque backdrop for Santa Barbara, and by the Channel Islands, which culminate in the 2,450-foot Devils Peak on Santa Cruz Island. The channel itself has a length of nearly 80 miles, a width of about 25 miles, and an area of about 1,750 square miles. The deepest part, about 2,050 feet below sea level, lies about midway between El Capitan Beach on the mainland and Carrington Point, the northernmost promontory on Santa Rosa Island. The configuration of this sea-floor topographic basin is illustrated by the bathymetric contours on plate 1.

STRATIGRAPHIC SUMMARY [1]

Strata in the western Ventura basin and Santa Ynez Mountains range in age from Early Cretaceous to Holocene and unconformably overlie, or are faulted against, basement rocks that are pre-Cretaceous(?) in age (pl. 1). The basement rocks consist of three distinct assemblages, one of which occurs in fault slivers along the Santa Ynez fault and the other two as belts of outcrops on the south half of Santa Cruz Island. In the Santa Ynez Range, the so-called basement rock consists of discontinuous pods and lenses of sheared graywacke, shale, and chert that commonly are assigned to the Franciscan Formation. These severely deformed strata are intruded by greenstone and serpentine. On Santa Cruz Island, metamorphic rocks, in part schistose, are intruded by hornblende diorite and may be related to similar rocks that form the basement complex in the eastern Santa Monica Mountains. The location of the subsurface boundary between Franciscan-type basement rocks of the Santa Ynez Range and the crystalline rocks that underlie the Channel Islands is not known.

[1] The stratigraphic nomenclature used in this report is from many sources and may not entirely conform to Geological Survey usage.

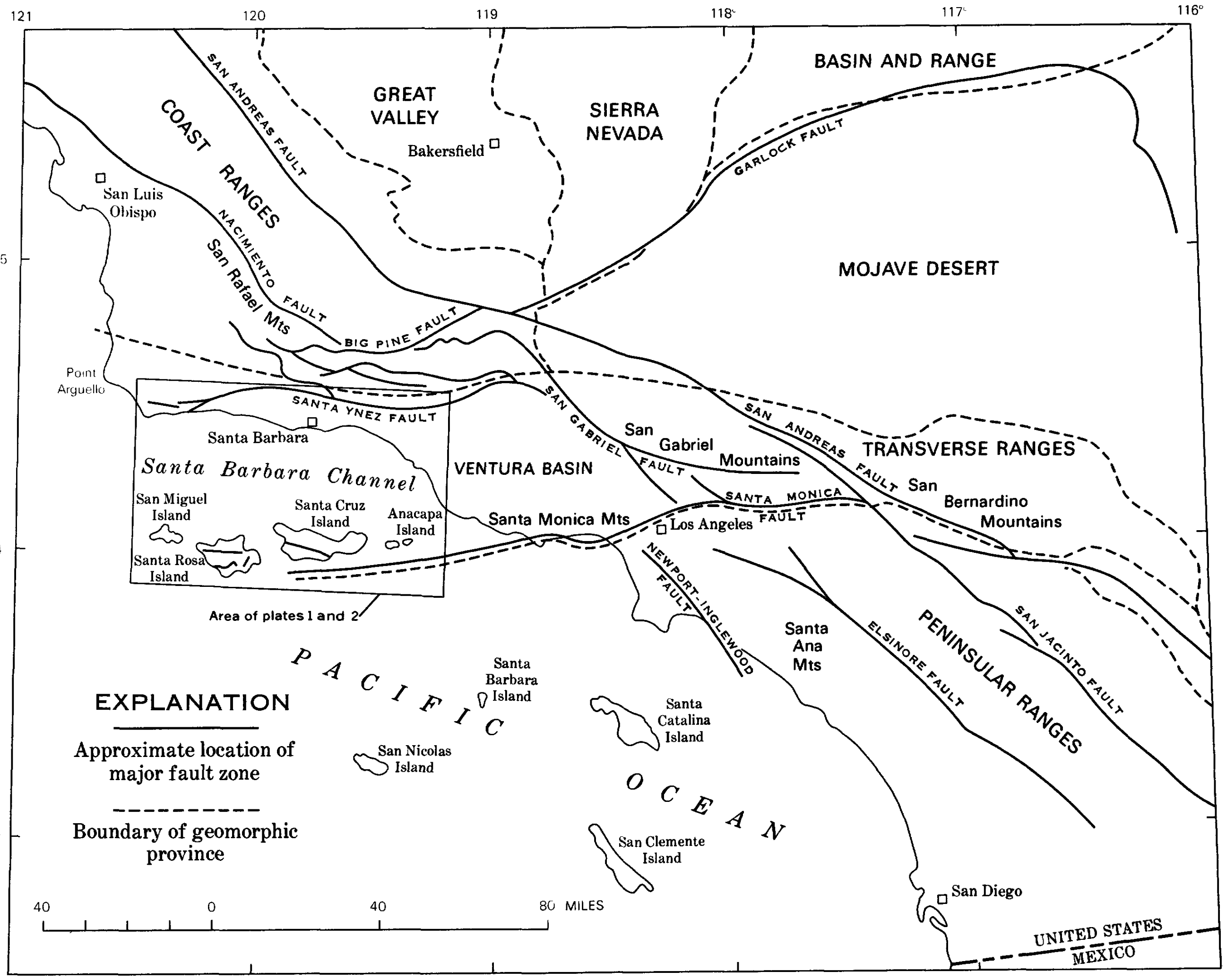


FIGURE 1.—Index map showing major geomorphic provinces of southern California. Modified from Yerkes and others (1965).

CRETACEOUS MARINE ROCKS

An enormous thickness of Lower and Upper Cretaceous marine sedimentary rocks lies in the San Rafael Mountains to the north of the Santa Ynez Mountains, and it is possible that similar thick successions may also be widely distributed deep in the subsurface beneath much of the Santa Barbara Channel region. South of the Santa Ynez fault (pl. 1), Lower Cretaceous strata crop out in the western Santa Ynez Mountains, and fragmentary sections of Upper Cretaceous strata are scattered along the fault throughout its length. Middle Cretaceous rocks have not been found in the channel region. Much of the western part of San Miguel Island is formed by Upper Cretaceous sedimentary rocks, and equivalent strata have been penetrated by wells on Santa Cruz Island and farther east on the mainland. An exploratory well near the middle of the channel between More's Landing on the mainland and Diablo Point on Santa Cruz Island is reported to have bottomed in Cretaceous rocks. In general, the Upper Cretaceous sequences are composed of interlayered sandstone, silty claystone, and small amounts of pebble and cobble conglomerate that contain fossil faunas that range from the Campanian Stage to the Lower Maestrichtian Stage (Popenoe and others, 1960). On San Miguel Island the Upper Cretaceous succession is about 10,000 feet thick (Kennett, in Redwine and others, 1952); north of the Santa Ynez fault the combined Lower and Upper Cretaceous formations are more than 20,000 feet thick. Jalama is the formation name commonly applied to the Upper Cretaceous rocks and Espada to the Lower Cretaceous rocks (Dibblee, 1950).

PALEOCENE AND EOCENE MARINE ROCKS

Paleocene rocks are very limited in extent within the Santa Barbara Channel region. They are known from a narrow belt of sea-cliff exposures on San Miguel Island, where they consist of about 1,600 feet of interlayered sandstone, claystone, and conglomerate (Kennett, in Redwine and others, 1952), and from a single small area in the southwestern part of Santa Cruz Island (Bremner, 1932 [as Martinez Formation]). At San Miguel Island the base is faulted against Upper Cretaceous rocks and on Santa Cruz Island it is not exposed.

Many of the resistant strata that form the crest and south face of the Santa Ynez Mountains are marine sandstone beds of Eocene age. Similar Eocene rocks are exposed on San Miguel and Santa Rosa Islands and south of the Santa Cruz Island fault. They have been penetrated at depth beneath the central part of the channel and in the subsurface section in many of the oil fields along the north and east margins. Several relatively persistent formational units have been differentiated in the Santa Ynez Mountains. These units consist primarily of clayey siltstone or sandstone and small amounts of conglomerate; locally, a distinctive algal limestone, which is unconformable on Cretaceous rocks, occurs at the base. North of Santa Barbara these formations have a composite maximum thickness of nearly 15,000 feet. The entire succession ranges in age from early to late Eocene and includes fossil faunas that are assigned to Mallory's (1959) Bulitian, Penutian, Ulatisian, and Narizian Stages. Commonly used formation names (Dibblee, 1966) in ascending order are Sierra Blanca Limestone, Juncal Formation (or Anita Shale), Matilija Sandstone, Cozy Dell Shale, and Coldwater Sandstone (or Sacate Formation).

OLIGOCENE MARINE AND NONMARINE ROCKS

Variegated strata, including red beds, that disconformably overlie the Eocene succession from the vicinity of Goleta eastward are composed chiefly of nonmarine conglomerate, sandstone, and claystone. These nonmarine strata are as much as 5,000 feet thick in the Carpinteria district, but westward they thin, tongue into, and are underlain by marine sandstone and siltstone beds that have an aggregate thickness of about 3,500 feet. The western limit of the red-bed section is in the vicinity of Gaviota Pass. Nonmarine beds also crop out on Santa Rosa Island and are present in the subsurface sections in deeper parts of onshore and offshore oil fields. East of the area of plate 1, the nonmarine section thickens to as much as 8,000 feet and incorporates both older and younger rocks, so that both late Eocene and early Miocene strata are included at the base and top. The marine beds, which extend westward at least to the vicinity of Point Conception, contain mollusks and foraminifers that are assigned to the Refugian Stage (Schenck and Kleinpell, 1936). Nonmarine beds east of the channel region have yielded vertebrate remains that range in age from Uintan to Arikareean (Wood, H. E., 2d, and others, 1941). The names "Gaviota Formation" and "Alegria Sandstone" are commonly used for the marine units, and "Sespe Formation" is used for the nonmarine sequence (Dibblee, 1950, 1966).

MIOCENE MARINE ROCKS

The diverse Miocene stratigraphic succession can be divided conveniently into lower, middle, and upper parts, which, in turn, can be subdivided into relatively persistent map units along the coastal side of the Santa Ynez Mountains and on parts of the Channel Islands. Similar units are recognized in the subsurface sections in onshore and offshore oil fields.

Lower Part

Thick-bedded shallow marine sandstone lenses, in part conglomeratic, form the bulk of the basal formation of the Miocene succession along the south flank of the Santa Ynez Mountains from the vicinity of Point Conception to Santa Barbara. This unit is disconformable on the underlying red-bed section, and it forms a persistent narrow belt of outcrop. At places in the western Santa Ynez Mountains these coarse-grained strata are as much as 600 feet thick, but elsewhere, they average about 300 feet in thickness. A few hundred feet of stratigraphically equivalent beds crop out on the southern part of Santa Rosa Island. Fossil mollusks from both the island and the mainland suggest an early Miocene age, and the unit is assigned to the Vaqueros Formation (Vaqueros Sandstone; Dibblee, 1950, 1966).

Conformably overlying the basal sandstone unit is a sequence of concretionary claystone, mudstone, and siltstone beds that have a total thickness of as much as 1,800 feet along the coast west of Santa Barbara and 2,500 feet in the Ventura area. Somewhat similar strata crop out on San Miguel and Santa Rosa Islands, but generally they are coarser grained and are more than 2,000 feet thick. Zones of bentonitic clay occur in the upper and lower parts of the section along the mainland coast. Foraminifers diagnostic of Kleinpell's (1938) Zemorrian and Saucesian Stages are present in this fine-grained unit which is called the Rincon Shale (Dibblee, 1950, 1966).

Middle Part

Sedimentary breccia beds and associated sandstone and siltstone interbeds that are genetically unrelated to any of the adjacent mainland Miocene rocks attain a thickness of about 2,000 feet on the southern part of Santa Cruz Island. These distinctive strata include lenses of glaucophane schist breccia that are similar to the San Onofre Breccia of the northern Peninsular Range province. A unit having similar lithology and stratigraphic position is interbedded in the volcanic sequence on Anacapa Island.

The bulk of the middle part of the Miocene succession along the mainland coast is a remarkably uniform siliceous shale that includes diatomaceous and phosphatic beds as well as chert and limestone. Rhyolitic tuff and bentonite are present at the base westward from the vicinity of Gaviota Canyon. Exposures of this formation extend along much of the shoreline in the sea cliffs between Point Conception and Santa Barbara and between Carpinteria and Rincon Point. At most places this formation gradationally overlies the Rincon Shale and is as much as 2,300 feet thick just west of Santa Barbara; its foraminiferal assemblages span most of the Relizian, Luisian, and Mohnian Stages (Kleinpell, 1938). Laminated units of the same age and lithology are present on San Miguel Island and north of the main faults on Santa Rosa and Santa Cruz Islands. Assignment of these stratigraphic sequences to the Monterey Shale is widely accepted.

Upper Part

Along parts of the mainland coast an indistinctly bedded unit composed predominantly of diatomaceous mudstone, claystone, and siltstone gradationally or disconformably overlies the hard laminated shales of the middle part of the Miocene succession. At some places these beds contain dolomitic concretions and lenses. The sand content of the unit increases eastward. This fine-grained formation varies in thickness, but is more than 2,000 feet thick east of Carpinteria; in the vicinity of Santa Barbara it has been eroded completely. Diagnostic fossils are sparse, but microfaunal assemblages are assigned to the upper Mohnian and Delmontian Stages of Kleinpell (1938). On the mainland the names "Santa Margarita Shale" and "Sisquoc Formation" are used interchangeably for this formation. Lenticular sandy siltstone and tuffaceous sandstone beds more than 3,000 feet thick are associated with volcanic agglomerates north of the Santa Rosa Island fault. The island beds disconformably overlie the Monterey Shale and are assigned to the "Santa Margarita Formation" by Kennett (in Redwine and others, 1952).

MIOCENE VOLCANIC ROCKS

Extrusive and intrusive sequences of basaltic, andesitic, and rhyolitic composition form a significant part of the rock sequence on the Channel Islands, in the western Santa Monica Mountains, and in the westernmost Santa Ynez Mountains (chiefly outside the map). On Santa Cruz and Santa Rosa Islands, the Monterey Shale separates the volcanic sequence into lower and upper units. In the western Santa Monica Mountains east of the Channel Islands, these volcanic rocks are more than 15,000 feet thick; on Santa Cruz Island the lower volcanic unit alone aggregates more than 6,000 feet in thickness. The name "Conejo Volcanics" has been applied to the basaltic and andesitic rocks in the middle part of the Miocene succession on the mainland southeast of the Montalvo oil field and in the western Santa Monica Mountains. On the islands the name "Conejo" has been used informally for the lower volcanic unit, and andesitic and rhyolitic rocks higher in the Miocene section have been assigned to the "Santa Margarita Formation" (Kennett, in Redwine and others, 1952). Both units of volcanic rocks seem to thin rapidly northward; they are not present in the coastal section near Santa Barbara. The rhyolitic extrusives at the west end of the Santa Ynez Mountains are as much as 1,200 feet thick and are named "Tranquillon Volcanics" (Dibblee, 1950).

LOWER AND UPPER PLIOCENE MARINE ROCKS

Outcrops of interbedded siltstone, sandstone, and thin lenticular conglomerate form the lower part of the Pliocene succession and conformably overlie the marine Miocene rocks in the coastal area near Rincon Point and just offshore. Within the onshore part of the map area, exposures are restricted to the Rincon Beach-Ventura area and to the sea cliff near Goleta, where only the upper part crops out. Pliocene strata are not present in the Santa Ynez Mountains or on the Channel Islands; if they ever were deposited on those margins of the Pliocene basin, they have been eroded completely. However, great thicknesses of Pliocene rocks are present along the basin axis onshore and presumably are widespread beneath the channel floor. In the vicinity of Ventura, the upper part of the Pliocene stratigraphic sequence is composed of interlayered and intertongued mudstone, siltstone, sandstone, and conglomerate. Eastward, these strata become increasingly coarse and lenticular. A thin bed of vitric tuff occurs in the uppermost part; the source probably was far distant, for there is no other evidence for a center of Pliocene volcanism in or near the Santa Barbara Channel region.

A few miles northeast of Ventura, the Pliocene sequence has an aggregate thickness of more than 12,000 feet, thus forming one of the thickest marine Pliocene successions in the world. This remarkable section thins westward beneath the channel; it is not represented on the Channel Islands. Fossil foraminifers and mollusks indicate that most of Pliocene time is represented in this extraordinarily complete section.

Throughout much of the Ventura district the lower part of the Pliocene section contains a deep-water foraminiferal facies and is designated "Repetto Formation." In the basin the name "Pico Formation" has two connotations; in the eastern part it is applied to most of the marine Pliocene sequence, but in the western part (area of pl. 1) it is commonly restricted to the upper portion. The names "Repetto" and "Pico" are here used in the latter sense to correspond with common usage.

Thin belts of marine conglomeratic sandstone beds that have been assigned a Pliocene age (Dibblee, 1966) also are exposed along Santa Ynez Valley north of the Santa Ynez Mountains.

LOWER AND UPPER PLEISTOCENE DEPOSITS

Limited exposures of marine sandstone, siltstone, and small amounts of conglomerate unconformably overlie Pliocene and older strata in the Santa Barbara area. However, at places between Santa Barbara and Rincon Point these isolated remnants of poorly consolidated marine deposits grade upward and laterally into nonmarine clayey sandstone and conglomerate beds that are lenticular and indistinctly stratified. Near Ventura these deposits appear to be gradational with upper Pliocene strata.

In the vicinity of Santa Barbara both the marine and nonmarine lower Pleistocene deposits vary greatly in thickness. They total more than 3,000 feet near Carpinteria, and east of the Ventura River they thicken to 6,000 feet and contain lenticular marine and nonmarine beds in the upper part. Fossil mollusks indicate that the bulk of the marine section near Santa Barbara is early Pleistocene in age, but the lowermost part may be late Pliocene. Mammal remains, including diagnostic horse teeth of Blancan age (Wood, H. E., 2d, and others, 1941), occur in nonmarine equivalents near Ventura. In the vicinity of Santa Barbara the name "Santa Barbara Formation" has been applied to the marine beds and "Casitas Formation" to the nonmarine beds (fig. 2, col. 2). Near and east of Ventura the informal names "marine Saugus," "San Pedro," and "Las Posas" have been used for strata that correlate in part with those farther west (fig. 2, col. 3).

Poorly consolidated nonmarine gravels that contain a large amount of siliceous shale fragments border the Santa Ynez River Valley (pl. 1). The lower part of these deformed alluvial deposits may be as old as late Pliocene, but the bulk of the unit is inferred to be Pleistocene in age. The name "Paso Robles Formation" is commonly applied to these beds.

Upper Pleistocene marine deposits occur mainly as a discontinuous thin veneer on elevated wave-cut platforms that are as high as 700 feet above sea level along the south side of Rincon Mountain (Putnam, 1942). Similar platforms are evident at 1,200 feet above sea level, but have no identifiable marine cover. At most places the marine remnants are covered by slope-wash detritus or stream deposits. Both the marine and nonmarine sediments truncate older Pleistocene formations and are composed primarily of poorly consolidated silt, sand, and gravel. Mollusks from the marine layers generally are assigned a late Pleistocene age, as are vertebrate assemblages and floras from the nonmarine terrace cover. Fossil floras and dwarf elephant remains from nonmarine terrace deposits on the islands corroborate these age interpretations. Except for the tar-saturated and diversely fossiliferous deposits southeast of Carpinteria, informally designated "Carpinteria Formation," these deposits are unnamed in the Santa Barbara coastal area. Informal names also have been applied to terrace deposits and wave-cut platforms near Ventura (Putnam, 1942) and on Santa Rosa Island (Orr, 1960).

HOLOCENE DEPOSITS

Alluvial deposits composed of clay, silt, sand, and gravel fill most of the coastal valleys and flood plains. Beach sand and gravel cover segments of both the mainland and island coasts; eolian sand, both active and inactive, blankets the windward parts of the larger islands and the coastal area near Point Conception. Alluvial deposits in Goleta Valley are as much as 225 feet thick and extend below present sea level off major drainage systems (Upson, 1949; Thomas and others, 1954). Sand, silt, and mud mask much of the shelf along the mainland coast, except in very nearshore areas and on crestal parts of some offshore anticlines where older rocks are present. Generally, these unconsolidated sediments are progressively finer grained seaward, except for an unusual concentration of highly organic clayey silt between Santa Barbara and Pitas Point. It may be significant that bottom sediments near natural oil and gas seeps are stiff and dark colored. This condition is especially evident west of Pitas Point where a notably dense population of *Listriolobus*, an echiuroid worm, thrives in the silt-covered tract, in contrast to its sporadic distribution elsewhere on the shelf (Stevenson and others, 1959). An isolated patch of coarse-grained sand within the tract has also been noted and interpreted as a possible relict beach ridge formed at a lower stand of sea level. Holocene sediments are sparse on the nearshore parts of the island shelves, and large areas of bare rock are common, particularly in the passages and on the windward shelf west of San Miguel Island.

GENERALIZED STRUCTURE OF THE SANTA BARBARA CHANNEL REGION

The Santa Barbara Channel is a tectonic depression that forms the westward extension of the Ventura basin and a submerged part of the Transverse Range

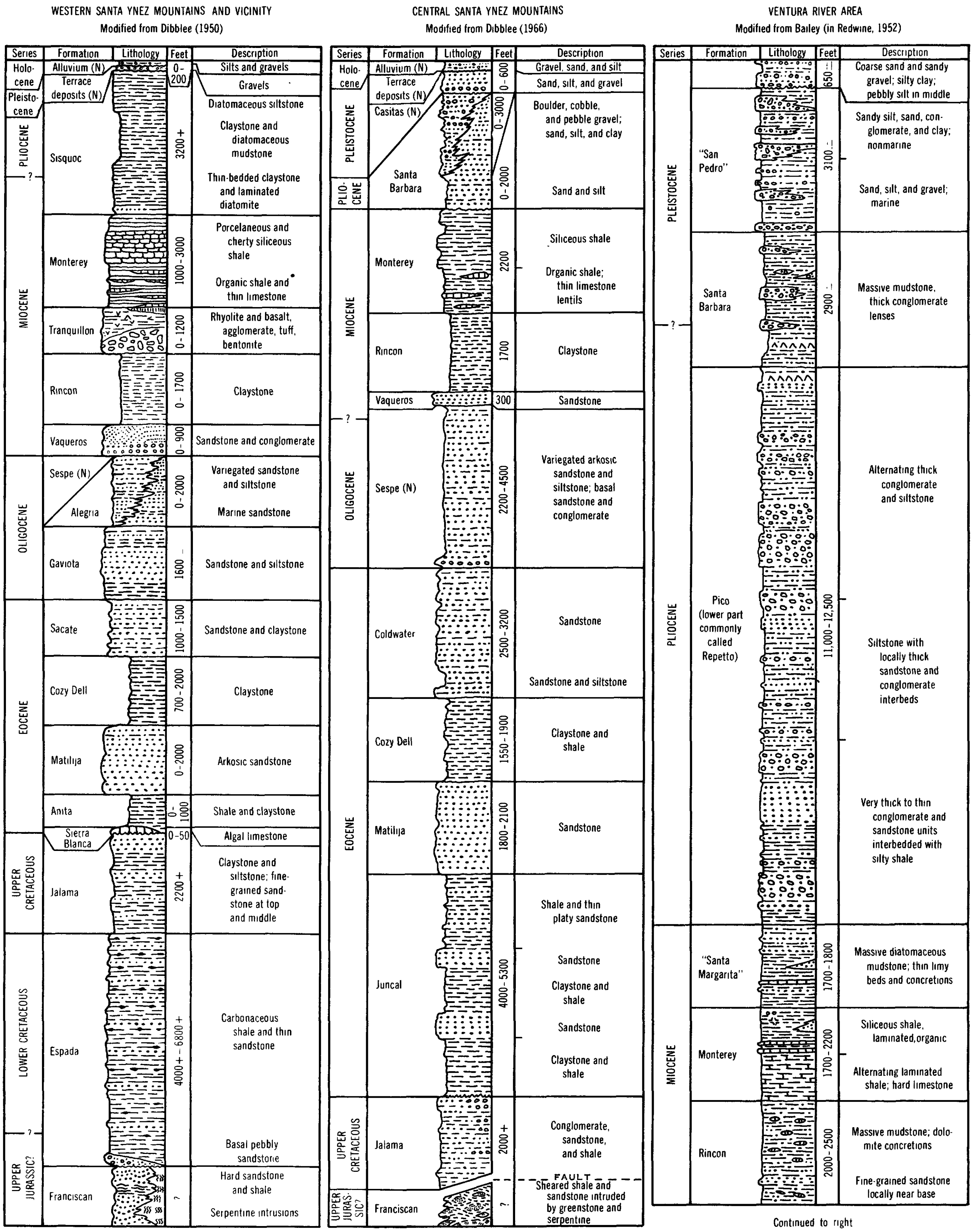
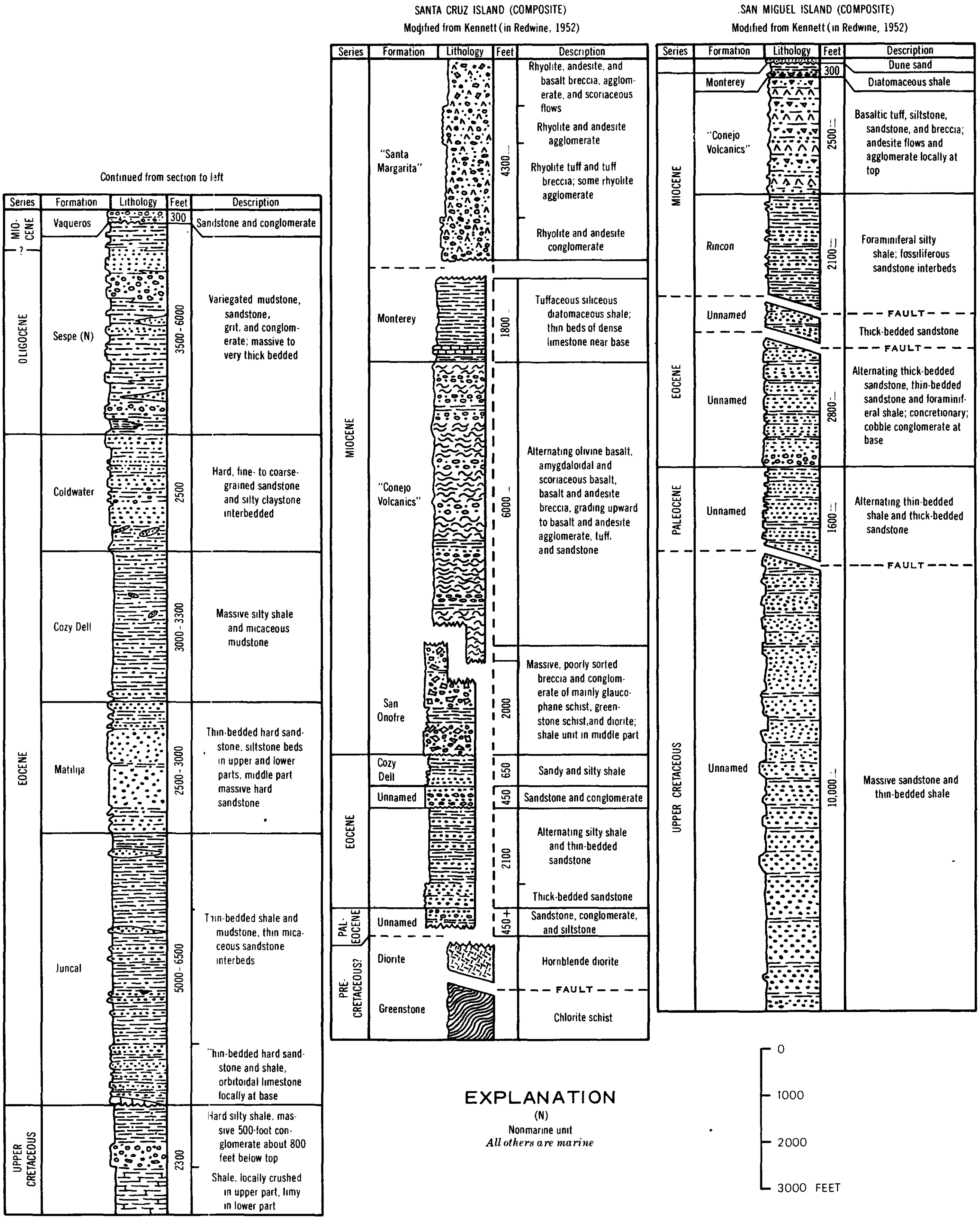


FIGURE 2.—Selected stratigraphic sections



of the Santa Barbara Channel region.

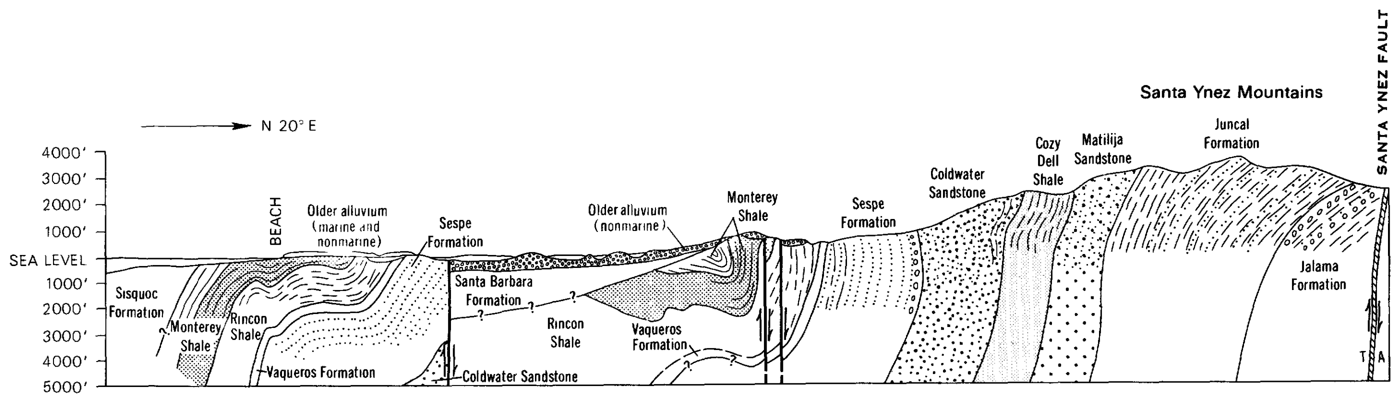


FIGURE 3.—Onshore structure section, Santa Barbara to Santa Ynez fault. T on fault indicates movement toward observer; A, movement away from observer.

province of southern California (fig. 1). The Santa Barbara Channel is bounded on the north by the homoclinal Santa Ynez Mountains and the Santa Ynez fault zone; on the south it is bounded by the Channel Islands, which, in turn, may be bounded on the south by the westward extension of the Santa Monica fault zone. The western limit is not definitely known, but a shallowing of the ocean and a northwestward bend of the structures in the area south of Point Conception may indicate a change of structural pattern.

Although basement rocks have not been reached by the deepest wells drilled within the area, presumably they form the floor of the entire basin area. A total structural relief on the order of 60,000 feet exists between the deep central part of the basin and its elevated north and south margins. Imposed on this regional structural basin and its north and south margins are numerous normal and reverse faults and steep-limbed folds indicative of intense deformation. On shore these features can be observed and studied directly; but in the areas covered by the ocean, only such indirect methods as geophysical techniques, shallow coring, and deep stratigraphic drilling are available to decipher the geology. Land areas surrounding the channel have been studied in considerable detail; and, although some offshore areas such as the Montalvo and Rincon trends are fairly well known, little is known about others because information does not exist or is unavailable. Many such offshore areas undoubtedly have structures that are as complicated as those on the adjoining mainland. Known major structural features are shown on plate 1.

The dominant structural feature north of the Santa Barbara area is the Santa Ynez fault. It extends from east of the map area to the vicinity of Point Conception where its northern branch seems to die out and where its southern branch extends seaward in a southwesterly direction. In general, the fault dips steeply to the south, and the south side apparently has been raised 5,000–10,000 feet relative to the north side. The net slip on the fault has not been determined because of complex stratigraphic and structural relations, but some geologists suggest that it is a major active fault zone along which there has been left-lateral oblique slip (Page and others, 1951; Dibblee, 1966).

The structure of the Santa Ynez Mountains between the Santa Ynez fault and the channel is, in general, a steeply south-dipping homocline (fig. 3), which incorporates Cretaceous to Miocene rocks west of Santa Barbara and includes strata as young as Pleistocene east of Santa Barbara. In the area north of Carpinteria, an overturned syncline and a faulted anticline disrupt the homoclinal nature of the structure (Lian, 1954), and a faulted syncline complicates the pattern at Santa Barbara. On the north side of the mountains northwest of Santa Barbara, a reversal in dip forms an anticline against the Santa Ynez fault.

Along the mainland coast of the channel the younger and less competent late Cenozoic rocks are cut by many faults that generally trend parallel to the range front. The strata have been folded into complex anticlines and synclines that vary in size from a few inches to prominent folds, such as the Ventura anticline which is nearly 17 miles long and about 4 miles wide. Other, less prominent anticlines are present in the areas of Summerland, Montecito, the Mesa of Santa Barbara, Goleta, Capitan, and Elwood. Numerous small folds are evident along the sea cliffs and on wave-cut platforms when the tide is low.

The Channel Islands form the southern margin of the Santa Barbara basin. Faults with a west or northwest trend are the dominating structural features, and the fault-bounded anticlines and synclines on Santa Rosa and Santa Cruz Islands have similar trends. Santa Rosa and Santa Cruz are each cut by a large median fault that divides the island into dissimilar geologic parts; both faults are believed to

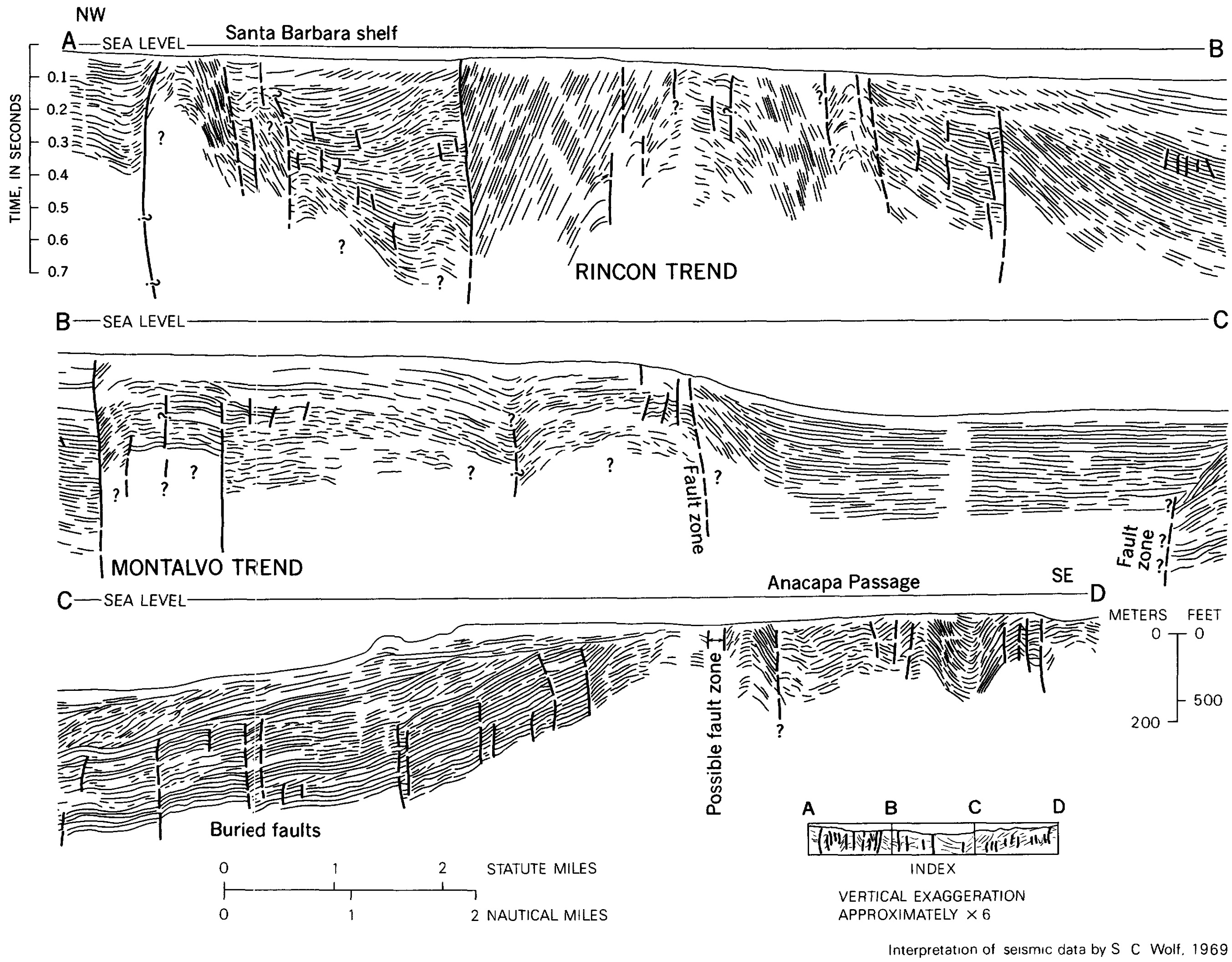


FIGURE 4.—Interpretive acoustic subbottom profile, Santa Barbara to Anacapa Passage.

have a component of left-lateral displacement. In general, the Channel Islands form a complexly folded and faulted anticlinal uplift that is a seaward structural extension of the Santa Monica Mountains (fig. 1).

The west-trending Santa Monica fault zone, which bounds the Santa Monica Mountains on the south and which may extend westward beneath the sea south of Santa Cruz Island, is a north-dipping reverse fault that juxtaposes completely dissimilar basement and younger rocks. Only north-over-south reverse fault movement can be demonstrated from outcrop relations in the Santa Monica Mountains, but left-lateral displacement may have occurred before late Miocene time.

The eastern part of the channel floor is divided into subparallel segments by large west-trending faults (pl. 1). Each segment includes numerous small faults and folds that generally are alined with the regional structural grain. The western part of the channel is not known well enough to project or correlate individual structural features.

A zone of faults closely follows the 200-meter bathymetric contour along the south margin of the deep trough of the channel. Most of the faults within this zone have steep north dips, but some are nearly vertical or dip steeply to the south. The type and amount of displacement is not known. Another zone of faults extends along the 200-meter contour along the north side of the central trough; individual faults in this zone dip to the south. In combination with the bottom topography, these two zones suggest that an elongate, grabenlike feature forms the deeper part of the channel (fig. 4).

The east-central part of the shelf includes the offshore extension of the Montalvo trend, which is bordered on the north by north-dipping normal faults. The northern of these faults appears to die out to the

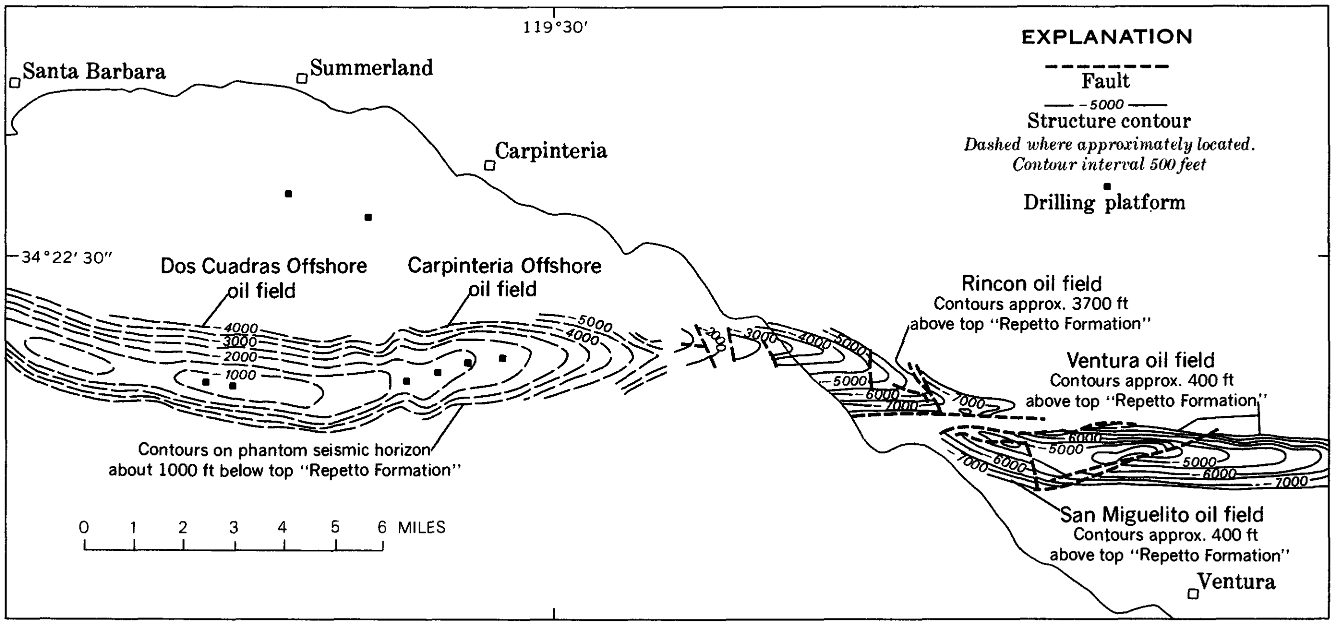


FIGURE 5.—Schematic structure contour map of the Rincon trend.

west as it approaches the deeper part of the channel. West of the longitude of Santa Barbara, the Montalvo trend and related structures adjacent to it on the north and south seem to merge westward.

The offshore part of the Rincon trend lies within the nearshore shelf area where its eastern end is bounded on the south by a fault that extends west from the vicinity of Pitas Point. Similarly, the north boundary of this part of the trend is the offshore extension of the Red Mountain fault. Several faults parallel the Rincon trend and displace the axial part upward; others trend northeasterly and may offset the axis toward the southwest. The northernmost structural unit in the eastern part of the channel lies north of the western extension of the Red Mountain fault. The fault-bounded anticline that forms the Summerland Offshore field is located in this structural block.

Geologic information on the shelf area between Coal Oil Point and Point Conception is sparse, but the configuration of the offshore oil fields in the area suggests that the structures follow the regional westerly trend. The exact location of the offshore extension of the south branch of the Santa Ynez fault is not known; presumably, it continues southwest for a considerable distance.

It should be emphasized that the exact nature of fault movement in the offshore region is not definitely known, for lateral components of offset that are difficult to detect may have developed on many of the faults that are shown as normal faults on plate 1.

The Rincon anticlinal trend is one of the most prominent in the Santa Barbara Channel (fig. 5; pl. 2). It extends westward from the Rincon oil field through the Carpinteria Offshore and Dos Cuadras Offshore fields into the Federal Ecological Preserve, where it may merge with the structures of the Coal Oil Point Offshore and South Elwood Offshore fields. West of the South Elwood field, a similar structure may merge with the structure of the Molino Offshore field or that of a recently discovered unnamed field to the south. Thus, there seem to be two parallel trends west of the South Elwood Offshore field. One lies within the 3-mile boundary and includes several fields; another parallel trend is roughly 3 miles to the south and includes the new oil field.

Another prominent anticlinal trend in the channel lies just south of the Montalvo trend and may extend west and northwest for more than 20 miles. This structure is recorded on subbottom acoustical profiles and is plainly discernible from the configuration of the bathymetric contours.

Seismic information indicates that the young sediments in the central deep of the Santa Barbara Channel are not greatly faulted, but they may be locally deformed by small discontinuous folds beneath the deepest part. In contrast, the region between the Channel Islands and the 200-meter bathymetric contour appears to be extensively faulted, resembling the structure of the islands (fig. 4).

GEOLOGIC HISTORY

The geologic record of the Santa Barbara Channel region is traceable for more than 100 million years and indicates recurrent tectonic activity followed by periods of relative quiescence. Because of the short duration of the historic record, however, it is difficult to determine which part of this cycle is now operative.

The Franciscan assemblage in the Santa Ynez and San Rafael Mountains may have originated on and beneath the deep sea floor far west of the present shoreline. During Early Cretaceous time the marine strata (Espada Formation) that now occupy parts of the same area may have been deposited on ancestral outer continental shelves and slopes. Great lateral dislocations, perhaps resulting from underthrusting at the continental margin, or from great strike-slip faulting, may have brought these contrasting rocks into their present juxtaposition during middle Cretaceous or later time. The middle Cretaceous record is obscure, for strata of this age are missing throughout the region. Much of the pre-Late Cretaceous geologic history is thus conjectural.

Throughout most of Late Cretaceous time, regional subsidence of an older erosional surface permitted the sea to transgress the area, and a thick succession of argillaceous sediments, sands, and gravels was deposited. This deposition was followed by uplift and erosion over much of the area during latest Cretaceous and earliest Tertiary time, but deposition continued locally as indicated by isolated remnants of Paleocene strata that are preserved only in the southern part of the area. Regional subsidence early in Eocene time permitted the sea to reenter the area, and simultaneous uplift of the margins and accelerating depressions of the sea floor resulted in the deposition of thick accumulations of argillaceous and arenaceous sediments on what may have been the outer shelf and slope. Near the close of Eocene time, the sea once again shallowed, resulting in widespread deposition of sands typical of an episode of regression.

Major tectonic activity occurred during Oligocene time. Uplift north of the present site of the Santa Ynez Mountains caused the sea to withdraw westward and southward with concurrent deposition of shallow-water marine sediments that, in turn, were buried by a thick sequence of terrestrial gravel, sand, and clay. During early Miocene time a new episode of subsidence, widespread transgression, and sediment deposition began. As the sea advanced northward across a broad sinking land surface, the shallow-water marine sands were successively covered and overlapped by argillaceous sediments as the area continued to subside and the water deepened. Deposition of calcareous, phosphatic, and siliceous sediments in widespread seas containing abundant micro-organisms continued during much of middle and late Miocene time. During this time thick sea-floor extrusions and explosive emanations of volcanic material interrupted normal sedimentation along the south, east, and northwest margins of the region, and coarse blueschist detritus derived from an unknown source was distributed locally along the south edge.

Restriction of the basin began during early Pliocene time as the margins to the north and south were elevated above sea level. At the same time axial parts of the basin subsided so rapidly that some sediments were deposited in water as deep as 4,000 feet. Structural deformation continued throughout the region during the latter part of the epoch and intensified at places, resulting in localized deposits of extremely varied nature and origin. The same general pattern of restriction of the basin and sedimentation continued uninterrupted into early Pleistocene time. About midway through the Pleistocene epoch, major tectonism began to produce most of the structural and geomorphic features that are evident in the Santa Barbara Channel region today. Prominent anticlines, such as the Rincon trend, started to form, and many faults originated throughout the area. During the same time several thousand feet of Pliocene and early Pleistocene strata were eroded from the crest of the growing anticline that now forms the Dos Cuadras Offshore oil field (pl. 2). Following this episode of intense deformation, local differential movements coupled with warping and minor faulting continued into the Holocene epoch. Sea-level changes and the development of marine terraces both above and below present sea level also modified the landscape.

Petroleum Development in the Region of the Santa Barbara Channel

By R. F. YERKES, H. C. WAGNER, *and* K. A. YENNE

GEOLOGY, PETROLEUM DEVELOPMENT, AND SEISMICITY OF THE SANTA BARBARA CHANNEL REGION, CALIFORNIA

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PETROLEUM DEVELOPMENT IN THE SANTA BARBARA CHANNEL REGION

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PRODUCTION

Petroleum has been associated with human culture in the region of the Santa Barbara Channel for many hundreds of years. Active natural seeps of tar, oil, and gas are present in and along the margins of the channel, and in prehistoric times asphalt from them was used in tool- and weapon-making. At the present time, there are about 20 producing oil and gas fields in the immediate channel area, and products from these dominate the local economy. A recent survey estimates that of the $310 million income annually developed in Santa Barbara County alone, about one-third (32 percent) comes from oil and gas production (Bickmore, 1967). Lesser percentages are from agriculture (21 percent), manufacturing (20 percent), tourism (13 percent), and others (14 percent).

California is the dominant crude oil producer in the U.S. Bureau of Mines District V, which also includes Arizona, Nevada, Oregon, and Washington. In 1968 District V had a total supply of 1,877,800 bpd (barrels per day) of crude oil, of which California oil fields produced about 65 percent, or 1,216,500 bpd, and of which 661,300 bpd were imported, chiefly from foreign sources (Conservation Committee of California Oil Producers, 1969).

California's 1968 crude oil production of 375 million barrels was valued at nearly $1 billion; of this total, the fields of the Santa Barbara Channel region produced 22.9 million barrels (table 1) or 6.1 percent. For comparison, oil fields of the Los Angeles basin produced 160.9 million barrels, or 43 percent of California's total. At the end of 1968 the Santa Barbara Channel region had produced 1.1 billion barrels of crude oil or about 7.5 percent of California's cumulative production, compared with the Los Angeles basin's 5.87 billion barrels or 40 percent.

The development of the petroleum resources of the area can be traced from early descriptions of natural seeps, on which the first wells were located, through extensions to offshore and onshore fields, to discovery of fields by sophisticated geologic and geophysical methods in areas covered by hundreds of feet of water.

NATURAL SEEPS NEAR SANTA BARBARA

Many active natural seeps of asphalt or tar, and oil and gas, occur onshore along the inland margins of the channel as well as offshore in the tidal zone and on the deeper sea floor (pl. 2).

ONSHORE ASPHALT DEPOSITS

Although many of the onshore asphalt deposits have been obliterated, the existence of an extensive literature makes it possible to describe some of the more important ones. The largest ones were at Carpinteria and at More's Landing; numerous others occur along the sea cliffs between Point Conception and Punta Gorda near the Rincon oil field (pl. 2).

The asphalt deposit at Carpinteria was located near the sea cliff, about half a mile southeast of town. The archeologic record reveals that aborigines used asphalt for holding points on weapons (Abbott, 1879); and Spanish explorers, dating back to at least 1775, observed that Indians near the present site of Carpinteria used tar from those deposits to calk their boats and to seal their water pitchers (Heizer, 1943). As early as 1857 the Carpinteria deposit supplied material from which illuminating oil was distilled; the quarry pits were as deep as 25 feet and covered several acres (Eldridge, 1901). The asphalt impregnates the basal 12-15 feet of flat-lying older alluvium where it rests on steeply dipping Monterey Shale that forms the sea cliff. Eldridge also reported several active tar seeps, and one of these, a "tar volcano," is illustrated by Arnold (1907, pl. III*B*).

The asphalt deposit near More's Landing consists of asphalt-impregnated sandstone at the base of the Pliocene strata, which unconformably overlie steeply dipping Monterey Shale. The asphalt accumulated to a thickness of about 20 feet near the trough of a gentle syncline in the Pliocene sandstone where the asphalt issues from large seeps at the unconformable contact. This deposit was once mined as a source of roofing and paving material (Whitney, 1865). A similar deposit near the coast at Elwood (the La Patera mine of Eldridge, 1901) consisted of veins so thick, extensive and pure that they were mined to depths of about 100 feet. Eldridge also notes that a point on the coast half a mile east of the mine was heavily coated by petroleum washed ashore from offshore seeps.

Veinlike deposits of asphalt in the Monterey Shale were also mined at Punta Gorda, 2½ miles southeast of Rincon Point. Nearby, on the seaward slope of Rincon Mountain, a 4-foot-thick bed of bituminous sandstone of Pliocene age rests unconformably on shale (Eldridge, 1901). Other asphalt or tar sands are known, especially near the inland edge of the terrace near and west of Gaviota and near Point Conception.

ONSHORE OIL AND GAS SEEPS

Petroliferous seeps are also very common along the northern coast of the channel; they occur along the sea cliffs southeast of Carpinteria and at the base of nonmarine gravels at and near Summerland. Other seeps are widely distributed along the sea cliffs westward to Point Conception, especially at the Mesa near Santa Barbara and westward to Goleta and Elwood. The approximate positions of these and other seeps are shown on plate 2.

Most of the onshore seeps have been desiccated to asphaltic tar or heavy asphalt-base oil. The seeps are believed to be indigenous to the Monterey Shale, as most of them issue from or near exposures of fractured shale that affords routes for migration from depth (Dibblee, 1966).

OFFSHORE OIL SEEPS AND ASPHALT DEPOSITS

Written records, dating from as early as 1792, describe effects of offshore seeps in the Santa Barbara Channel. Oil and tar "slicks" have long been a trademark of the channel. In 1792, Captain Cook's navigator, Vancouver, recorded on passing through the Channel (Imray, 1868):

> The surface of the sea, which was perfectly smooth and tranquil, was covered with a thick, slimy substance, which when separated or disturbed by a little agitation, became very luminous, whilst the light breeze, which came principally from the shore, brought with it a strong smell of tar, or some such resinous substance. The next morning the sea had the appearance of dissolved tar floating on its surface, which covered the sea in all directions within the limits of our view....

In 1889, another trained observer, A. B. Alexander, of the U.S. Commission of Fish and Fisheries, also reported extensive "slicks" caused by petroleum bubbling up through the water about 4 miles south of Santa Barbara Light (Alexander, 1892). During this same year J. W. Fewkes, returning from a biological collecting trip to Santa Cruz Island, reported as follows:

> ... sailed through a most extraordinary region of the channel in which there is a submarine petroleum well. The surface for a considerable distance is covered with oil, which oozes up from sources below the water, and its odor is very marked.

(Fewkes, 1889). Evidence of submarine seeps recorded by the U.S. Coast and Geodetic Survey during channel crossings prior to 1900 is also reported in several annual reports, such as for 1855 and 1859.

Sea-floor deposits of tar in the Point Conception, Goleta, and Carpinteria areas have been studied by Vernon and Slater (1963), who photographed tar mounds 1½ miles offshore and east of Point Conception, in 90 feet of water. There, a sheet of tar covers an area of at least one-fourth of a square mile and has a 10- to 12-foot scarp at its seaward edge. Elsewhere, near Point Conception, tar mounds are as much as 100 feet in diameter and 8 feet in height. They appear to be distributed along east-trending anticlines in Monterey Shale. At Coal Oil Point and off Carpinteria, the mounds are only a few inches high, and some are elongated along fractures in the Monterey. Prolific gas and oil seeps also issue from the sea floor about a mile off Coal Oil Point.

Tar mounds are formed where tar is slowly extruded from sea-floor vents forming mounds like shield "volcanos." In some places, pencillike strands or "whips" of tar, through which the more fluid tar flows, were observed issuing from the centers of the mounds. If seepage through the whips is slow enough, they become more dense than sea water and sink to form part of the mound; if seepage is faster, the whip is torn away by agitation of the water and it floats to the surface to become part of the drifting tar so common to beaches of the area.

Drill cores from a group of mounds show that the tar fills all fractures and interstices in the host rock to a depth of 10 feet; below 10 feet the fractures are free of tar at this locality. Oil and gas also issue from some of the mounds, but more commonly from fractures or sand nearby. It is inferred, on the basis of sea-level changes, that the mounds formed during the last 9,000 years (Vernon and Slater, 1963).

OIL AND GAS FIELDS

The first oil well in the Ventura basin, and probably the first commercially successful well drilled in California, was completed in 1866 by the California Petroleum Company about 8 miles east of Ojai. Oil had previously been produced here from shafts and tunnels. Within the map area (pl. 2), the first field well was completed near Summerland in 1894.

Offshore oil exploitation in the Santa Barbara Channel region began in 1896 with the extension seaward of the Summerland oil field. Since then more than 1,100 holes have been drilled offshore, and about 250 of these have been completed as producers. In 1921 the State of California introduced regulations governing offshore development, and many exploration permits and leases were granted. The development resulted in the discovery of the offshore parts of the Rincon field in 1927 and the Capitan and Elwood fields in 1929 (Frame, 1960). The first production in California from an offshore platform was in 1958 from platform Hazel in the Summerland Offshore oil field.

Shortly after World War II several major oil companies began extensive geological and geophysical exploration of the offshore area by means of piston and jet coring of surficial deposits, as well as shallow and deep test drilling programs and seismic surveying. A peak in the exploration program was reached in 1956-59; new methods and improved equipment made it feasible to drill to depths of 7,500 feet and to operate in water as much as 400 feet deep. In 1958, new and accelerated development of the tideland part of the Rincon field followed the completion of Rincon Island 2,800 feet offshore, near which the first ocean-floor completions were made in 1961 in about 55 feet of water. Later the same year, the first important new offshore discovery in the channel was made about 2 miles off the coast in the Summerland Offshore oil field.

In July 1958, five tideland parcels were awarded by the State in one area between Goleta Point and Point Conception, and new discoveries in that area began early the following year—Gaviota Offshore gas field in 1958, Cuarta Offshore in April 1959, Conception Offshore in November 1959, and Naples Offshore gas field in September 1960.

Following discovery of the Coal Oil Point Offshore field in 1961 and the Alegria, Caliente, and Molino Offshore fields in 1962, no new discoveries were made in the tidelands until the South Elwood and Carpinteria Offshore fields were discovered in 1966; the latter discovery led to the first sale of Federal leases in the Santa Barbara Channel—a drainage sale of lease OCS P-0166. Since 1966, offshore developments have been on Federal leases, chiefly on the westward extension of the Rincon trend, OCS leases P-0166, P-0240, and P-0241 (Carpinteria Offshore field and the Dos Cuadras Offshore field).

The channel region contains 24 producing oil and gas fields. The reservoir rocks are varied but consist chiefly of sandstone and interbedded siltstone and sandstone: the age of the reservoir rocks ranges from Eocene to Pleistocene, but strata of Pliocene age have yielded the greatest amount of oil. Most of the oil and gas accumulated in faulted anticlines that were formed chiefly during the Pleistocene deformation. Production statistics and basic geologic data for the fields are presented in table 1. The fields are divided into five groups on geologic-geographic grounds: the Rincon trend area, the Ojai area, the Goleta area, the Point Conception area, and the Montalvo area.

RINCON TREND AREA

The Rincon trend area includes the Ventura, San Miguelito, Rincon, Carpinteria Offshore, and the Dos Cuadras Offshore oil fields. All these fields are on the intensely folded and faulted Rincon anticlinal trend (pls. 1, 2). The general eastward plunge of this structural feature is indicated by the fact that at the Dos Cuadras field, at the west, the top of the "Repetto Formation" is exposed at the sea floor; in the eastern part of Carpinteria Offshore, it is at a depth of about 2,000 feet; and at the point where the Rincon field crosses the shoreline, it is at a depth of about 6,700 feet. The flanks of this trend are cut by intersecting en echelon reverse faults, and the result is repetition of the stratigraphic section and formation of a thick producing sequence, which at Ventura is about 7,500 feet in thickness.

Ventura oil field

Gas and oil were first found at Ventura in 1885 in a 200- to 300-foot-deep water well near the axis of the field, just east of the Ventura River. The Ventura anticline was mapped in 1898 and recommended for exploration, but exploration was not attempted until 1903, when nine commercial gas wells were drilled to depths of 400-800 feet in the Ventura River bed. However, the gas wells were difficult to drill in the river bed with the cable-tool rigs, the water could not be controlled, and the wells were abandoned. For many years the Ventura oil field had the reputation of being one of the most difficult in California in which to complete deep wells (Hertel, 1929).

Exploratory drilling for oil was begun in 1914, but the first well was suspended after 2 years of work, because formation water could not be controlled. The second discovery well was begun in May 1916; in September the well blew out at 2,253 feet. The blowout destroyed the rotary rig and formed a crater around the well from which gas, oil, and water were sprayed, confirming the presence of petroleum under high pressure. Subsequent efforts to develop oil production from this level, known as the upper "light oil" zone, were relatively unsuccessful. Water shutoff was difficult to attain, the zone was flooded, and the excessive gas pressures caused several more severe blowouts. One well, after being shut in, broke out at the surface 400 to 500 feet from the well, where a geyser of water, oil, and gas shot 8 or 10 feet into the air until the well bore was reopened (Hertel, 1929). Finally, in April 1919, hard-won experience and improved methods resulted in successful completion of a commercial well at about 3,500 feet in what is called the upper "heavy oil" zone. After this success, additional and better wells were completed in successively deeper zones: 3,700 feet in 1921; 3,855 feet in 1922; and also in 1922, a well for 1,900 bpd from 5,050 feet. In 1925, a real "gusher" was completed for more than 4,600 bpd from 5,150 feet. By 1928, more than 100 wells, some flowing at rates of 5,700 bpd, had been completed at depths to 7,100 feet. At the same time, the field was being expanded areally; it is now about 7 miles along the east-west axis and about 1 mile wide.

In addition to the difficulties of controlling formation water, the Ventura field is almost unique in California for its abnormal reservoir pressures below depths of about minus 6,000 feet. Although these conditions had long required the use of heavy-mineral drilling muds, considerably higher pressures were encountered in the early 1940's in the "D-7" zone at depths below about minus 9,000 feet. Initial reservoir pressures in the "D-7" zone near the crest of the anticline range from about 85 percent of inferred lithostatic pressure at minus 6,000 feet to about 92 percent of that at minus 9,000 feet (Watts, 1948). These pressures produce very high gradients in the well bore and well-head pressures as great as 5,300 psi (pounds per square inch). In addition to drilling hazards resulting from these high fluid pressures, wells commonly failed by collapse and shearing of pipe (Watts, 1948).

San Miguelito oil field

San Miguelito field adjoins the Rincon field on the northwest. It was discovered by surface geologic mapping. The discovery well flowed 600 bpd from 6,750 feet on completion in November 1931. Later development extended the productive section to depths of about 11,000 feet, for a total of about 3,940 feet in vertical dimension, and by 1961 the section had been tested to a depth of 14,155 feet in the Miocene. However, production comes only from Pliocene strata. As at the adjoining Ventura oil field, reservoir pressures exceed "normal" hydrostatic pressure at depths 5,500 feet below sea level and greater (fig. 11). Reservoir pressures exceeding 10,000 psi in the interval 11,300-15,600 feet below sea level were reported by McClellan and Haines (1951). Reservoir pressure of 10,000 psi would be about 90 percent of inferred lithostatic pressure at a depth of 11,000 feet below sea level.

The field lies in an east-trending asymmetrical closed anticlinal structure. It is separated from the Rincon field to the northwest by a south-dipping reverse fault: its eastern boundary is an arbitrary line near the west edge of R. 23 W. The reverse fault marks the upper boundary of a very thick zone of crushed beds; it apparently formed in the south limb of a tightly compressed, overturned anticline.

Rincon oil field

Although the Rincon area was explored after the success at Ventura in the 1920's, it was not until December 1927 that sustained commercial production was obtained from the present limits of the field by a well drilled onshore and extended seaward. The second well of the field was completed in 1931 at 7,825 feet after having been plugged back from 10,030 feet. Although contemporary accounts of drilling history do not mention abnormal reservoir pressures, all the early completions were flowing wells.

As in the Ventura field, production is from Pliocene strata; the structure, also similar to that of Ventura, is an elongate anticline with limbs sheared by reverse faults. The producing section is about 6,000 feet in vertical dimension.

The State tideland part of the Rincon field was developed very slowly by wells drilled from piers until completion in 1958 of the manmade Rincon Island about 2,800 feet from shore in 45 feet of water. The first well was completed in October of that year, and 46 wells had been completed by August 1960. All the wells were directionally drilled, and hole angles were as great as 68° from vertical. The deepest drilled depth was 7,725 feet, but all production comes from Pliocene strata above about 3,000 feet subsea (Frame, 1960). In March 1961, California's first ocean-bottom completion was made at Rincon. The well was drilled from an anchored barge in 55 feet of water to a depth of 2,290 feet; the well was completed flowing 64 bpd clean 28°-gravity oil and 18 Mcf (thousand cubic feet) gas through a 3,000-foot ocean-floor pipeline to shore (Frame, 1960).

Carpinteria Offshore oil field

The Carpinteria Offshore field extends about 4 miles from State tideland tract PRC 3150 westward into Federal OCS P-0166 and P-0240. The inferred producing area is about half in State tidelands and half in Federal OCS tracts. Production was obtained in February 1966 by a well drilled from platform "Hope," the second platform west of the Rincon Island; the well had an initial production of more than 250 bpd flowing. Since then, 89 wells have been drilled from four platforms, and 88 of them produced in 1968 (see table 1). The peak production year was 1967, when the average was 9,894 bpd.

Dos Cuadras Offshore oil field

The Dos Cuadras Offshore field, in Federal OCS P-0241, is a western development on the Rincon trend. An early test from 2,000 to 2,700 feet flowed at the rate of 1,800 bpd of 27.8°-gravity oil; a test from 725 to 1,205 feet flowed at 346 bpd of 23.4°-gravity oil. All production is from the "Repetto Formation" of early Pliocene age. The first platform, "A," was set in September 1968, and the first well drilled from the platform, No. A-20, bottomed at 3,673 feet and was completed between 2,137 and 3,427 feet, flowing at 1,080 bpd (data from Californa Oil World, 1969).

Federal OCS P-0240 adjoins P-0241 on the east. The second well drilled on P-0240 was tested in July 1968; it flowed at an average rate of 1,042 bpd of 34.2°-gravity oil from 3,437 to 3,535 feet.

OJAI AREA

The Ojai area includes the Tip Top, Lion Mountain, Weldon Canyon, Oakview, and Canada Larga oil fields.

The first successful oil well in California was completed in 1866 about 20 miles east-northeast of Rincon Point in the east part of what is now the Ojai oil field area; oil had previously been recovered from tunnels in the same area. Several small fields were later discovered in the same area, including Lion Mountain, Tip Top, Weldon Canyon, and Oakview. These fields are located in the northeast part of the present map and are included as part of the Ojai group (pl. 2, table 1).

Tip Top oil field

The Tip Top field, located about 5 miles south-southwest of Ojai, was discovered in 1918. The discovery well had an initial production of 15 bpd from a depth of about 430 feet in fractured Miocene shale that is exposed at the surface. Only small production was obtained from a total of eight wells. The peak production year was 1935, when the daily average was 18 barrels of oil. The area did not produce in 1968.

Lion Mountain oil field

The Lion Mountain field, located about 1 mile south of Ojai, was discovered in 1893 by a well that produced about 20 bpd from a depth of about 1,200 feet in the Sespe Formation. Production was discovered in Eocene strata in 1949 by a well that produced about 26 bpd from a depth of about 3,500 feet. Peak production of about 55 bpd was attained in 1950. The structure of the field is a faulted asymmetrical anticline, bounded on the north by a south-dipping, east-northeast-trending reverse fault.

Weldon Canyon oil field

The Weldon Canyon field adjoins the Tip Top field on the south. The discovery well was completed in 1951 with an initial production of 133 bpd from about 3,050 feet in Pliocene strata. The peak production year was 1954, when the daily average was 118 barrels. In 1968 the area produced 22,000 barrels from two wells. The structure is a pinchout on the steep south flank of an anticline.

Oakview oil field (abandoned)

The Oakview field is located about 6 miles southwest of Ojai. The discovery well was completed in April 1955 and pumped 15 bpd of 35°-gravity oil from about 1,545 feet in the Vaqueros Formation. Only one well was completed; the field was abandoned in September 1955 after producing 726 barrels of oil.

Production came from the crestal part of a broad east-plunging anticline, which has been drilled to 4,709 feet, or about 3,100 feet into the Sespe Formation.

Canada Larga oil field

The Canada Larga field is located about 5 miles south of Ojai. The discovery well was completed in August 1955 for 128 bpd of 26°-gravity oil, 48 percent cut. Recompletion the following month resulted in production of 75 bpd of clean oil. By 1960, only three wells had been completed. Production comes from a depth of about 2,500 feet in the "Repetto Formation." The structure consists of a stratigraphic trap on the south flank of a faulted anticline, which at Canada Larga has been drilled to 5,770 feet, or about 970 feet into upper Miocene strata below the "Repetto."

GOLETA AREA

The Goleta area includes the following fields· Summerland (abandoned), Summerland Offshore, Mesa, Goleta (abandoned), La Goleta gas (abandoned), Coal Oil Point Offshore, Elwood, South Elwood Offshore, Las Varas (abandoned), and Glen Annie gas (abandoned).

Summerland oil field (abandoned)

Oil production in the channel area dates from about 1894, when the Summerland oil field was discovered from oil seeps. Early development of the field was along the inland margin of the marine terrace; beginning in 1896, development was extended seaward and then out over the ocean by means of wells drilled from wooden piers as much as 700 feet offshore. More than 400 wells were drilled from the piers to depths of 100-600 feet. This field brought in the first known offshore production in the United States. Peak production of the field was attained in 1899, when the daily average was 571 barrels of oil, chiefly from shallow Pliocene strata. Later exploration led to the development of small pools in the Vaqueros(?) Formation of early Miocene age, and a second, lower production peak was attained in 1929. The field has been virtually abandoned for many years.

Summerland Offshore oil field

In 1957, during the peak of offshore exploration, several test holes were drilled from a barge in State tideland tract 1824, offshore from the old Summerland field. As a result, a permanent drilling platform ("Hazel") was constructed in 100 feet of water. The first well to be drilled from Hazel was completed in November 1958; it was reported to have flowed at a rate of 865 bpd. The well was drilled to a total depth of 7,531 feet (Frame, 1960). By the end of 1960, a total of 16 wells had been drilled, of which 14 were producers. A second platform ("Hilda") was constructed about 2 miles west of Hazel in August 1960. By the end of 1968, 46 wells had been drilled, of which 31 were producing; the average drilled depth is 7,937 feet. Production is from unnamed sands in the Vaqueros Formation. The peak production year was 1964, when the daily average was 10,362 barrels. Details of the structure are not available.

Mesa oil field

The Mesa field was discovered in 1929, a small production of oil being obtained from the Vaqueros Formation at about 2,200 feet. One well was drilled to 10,047 feet in the Sespe Formation, but no oil was found. Initial production of some wells was 200 bpd, but by 1950 oil had given way to water; at the end of 1968 there were only three active wells, which produced chiefly water. The structure is a gently arched dome transected on the northeast by a northwest-trending, south-dipping reverse fault, about half a mile inland from the coast (California Division of Oil and Gas, 1961).

Goleta oil field (abandoned)

Surface mapping led to identification of an anticline in Tecolote Canyon, and in 1926 a well was drilled to test the Eocene strata. The test was unsuccessful, but two oil zones were found in the Sespe Formation at depths of 613 and 1,527 feet. A second well was completed in 1927 for 450 bpd, and a third well was completed for 1,040 bpd. Only eight of 27 wells drilled were completed, and these were soon depleted as edge water encroached; the field was abandoned 13 months after its discovery.

La Goleta gas field (abandoned)

Gas seeps had been known for many years along the east edge of Goleta Slough. The La Goleta gas field was discovered in the same area in 1929 by a well that blew out at 4,533 feet and later was completed, flowing 58 M^2cf (million cubic feet) gas per day from the Vaqueros Formation. One well was drilled through the Sespe Formation to bottom in Eocene at 6,912 feet; although several oil shows were reported from the Sespe, none yielded commercial production. The six wells that were completed from the Vaqueros included one well that produced at the rate of 145 M^2cf per day. At one time this field contained some of the largest gas-producing wells in California. The field was credited with a cumulative production of 15,363 M^2cf on December 31, 1968. It is now used for gas storage.

The structure of the field is a small asymmetric anticlinal dome, bounded on the north by a south-dipping reverse fault that trends parallel to the coast about 2,000 feet inland (Swayze, 1943). The structure is offset in plan about 800 feet by a northeast-trending normal fault (California Division of Oil and Gas, 1961).

Coal Oil Point Offshore oil field

The Coal Oil Point Offshore field is located in State tideland tract PRC 308. The field was discovered in 1948 by a nearshore well that had an initial production of 89 bpd from the Vaqueros Formation. Peak annual production of 1,279 barrels was attained in 1948. Two wells were drilled to an average depth of 10,047 feet, but only one was completed. This area of the field is now abandoned.

In 1961, additional production was obtained about 2 miles offshore in Sespe-equivalent strata from a well drilled from a barge to a depth of about 5,598 feet. Peak production averaging 637 bpd was attained in 1966.

Elwood oil field

The discovery well at Elwood was completed in 1928. The well flowed 1,775 bpd of 38°-gravity clean oil from 3,208 feet in the Vaqueros Formation. The field was extended westward offshore by wells drilled from piers and was also extended eastward onshore. By the end of 1930 there were six producing tideland wells. Peak production was attained in 1930 when 33 wells averaged 40,069 bpd, accounting for 6 percent of California's production for that year. In 1931, 22 more tideland wells were completed, and beginning in 1944, slant drilling from shore extended the field a mile or more westward. The reserves of the field were thus increased, but the production peak of 1930 was not surpassed. Although several wells produce from the Sespe Formation at depths between 3,700 and 5,700 feet, the bulk of the production comes from the Vaqueros Formation at shallower depths.

The field includes two elongate east-trending en echelon anticlines, the western of which is entirely offshore. Closure of the eastern anticline is provided by a south-dipping reverse fault that trends subparallel to the coast (California Division of Oil and Gas, 1961).

South Elwood Offshore oil field

The South Elwood Offshore field is located in State tideland tract PRC 3120 and 3242, about 2¼ miles offshore from the Elwood field. The discovery well was drilled in November 1966 to a depth of 6,287 feet. Production is from sands in the Vaqueros and Sespe Formations. The average drilled depth of 11 wells completed from platform "Holly" is 6,290 feet. The peak production year was 1967, when the average was 4,167 bpd.

Las Varas oil field (abandoned)

The Las Varas field was discovered in 1958; all producing zones were in the Sespe Formation at depths of about 2,400-3,000 feet. The deepest test was to 3,404 feet in Eocene beds. Only two of seven wells drilled were completed. The peak production year was 1958, and the field was abandoned in 1960. The structure consists of a small northeast-trending anticline that is bounded on the south by an east-trending south-dipping reverse fault (California Division of Oil and Gas, 1961).

Glen Annie gas field (abandoned)

The Glen Annie field was discovered in 1959; the initial production of the discovery well was 855 Mcf per day. Production was from an 80-foot sand in the Vaqueros Formation at an average depth of 3,350 feet. Only two wells were drilled and one completed; the field was abandoned in 1961 after producing 491,000 Mcf of gas.

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POINT CONCEPTION AREA

The Point Conception area includes the following fields: Naples Offshore, Capitan, Refugio Cove (abandoned), Molino Offshore, Gaviota Offshore, Caliente Offshore, Alegria, Alegria Offshore, Cuarta Offshore, Conception Offshore, Point Conception Offshore, and two unnamed offshore oil fields in Federal OCS P-0188-90 and P-0197.

Naples Offshore gas field

The Naples Offshore gas field is located in State tideland tract PRC 2205. It was discovered by a well drilled from onshore to a depth of 8,871 feet and completed in September 1960. The initial production was estimated at 70,000 Mcf per day. The production apparently comes from Vaqueros-equivalent sands. The cumulative production on December 31, 1968, was 20,815 M^2cf; no wells produced in 1968 (Conservation Committee of California Oil Producers, 1969).

Capitan oil field

The Capitan oil field was discovered in 1929, after discovery of the Elwood oil field. The discovery well was completed for 180 bpd from 1,446 feet in the Vaqueros Formation. Several wells produce from the Sespe Formation at depths as great as 3,400 feet, but the Vaqueros is the most important producer. The deepest test by 1960 was 10,216 feet in Eocene.

Commercial production was not obtained from the tideland part of the field until 1932. In that year the discovery well blew out during plugging operations after being deepened to 2,821 feet in the Sespe Formation. Only seven tideland wells were drilled, all from wooden piers; tideland production was suspended in 1958.

The field is developed in a broad, gently arched, north-trending dome that is transected on the north by a folded west-northwest-trending, north-dipping normal fault (California Division of Oil and Gas, 1961).

Refugio Cove gas field (abandoned)

The Refugio Cove field consists of two separate accumulations, one on either side of Refugio Canyon. The initial discovery in 1946 was east of the canyon. The discovery well produced 5,000 Mcf gas per day from a depth of 2,500 feet in the Vaqueros Formation. Minor production was discovered in 1958 west of the canyon. This production came from about 3,550 feet in the Sespe Formation. The deepest test, 6,148 feet, bottomed in the Eocene. Of the 18 wells drilled, only three were completed. The fields were abandoned in 1961 after producing 990,000 Mcf of gas and 3,000 barrels of oil.

Molino Offshore gas field

The Molino Offshore field, the largest natural gas field in southern California, was discovered in December 1962. It is located in State tideland tracts 2920 and 2933 and reportedly produces from the Vaqueros Formation. Production for 1968 was 28.5 M^2cf gas from nine wells; the cumulative production on December 31, 1968, was 139 M^2cf.

Gaviota Offshore gas field

Located in State tideland tract PRC 2199, the Gaviota Offshore gas field was discovered in 1958, but the first well was not completed until August 1960. The first three wells were drilled from a barge, but the first three to be completed were slant-drilled from shore. In 1960, the three completed wells produced 1,113 M^2cf of gas; the cumulative production on December 31, 1968, was 57,093 M^2cf from three producing wells. Production is apparently from Vaqueros-equivalent sands.

Caliente Offshore gas field

The Caliente Offshore gas field was discovered in October 1962. Production, reported from the Vaqueros Formation, was 3,804 M^2cf from two wells in 1968; the cumulative production on December 31, 1968, was 19,625 M^2cf.

Alegria oil field

The Alegria onshore field was discovered in 1959; its minor oil and gas production comes from about 4,350 feet in the Rincon Formation. Only eight wells were drilled, none of which were producing in 1968.

Alegria Offshore area

The Alegria Offshore field was discovered in February 1962. Production in this one-well field is from a depth of 4,033 feet in Sespe-equivalent sands. The peak production year was 1964, when the average was 748 bpd. Production for 1968 was 23,000 barrels of oil and 439 M^2cf gas.

Cuarta Offshore oil field

Located in State tideland tracts PRC 2206 and 2793, the discovery well of the Cuarta Offshore oil field had an estimated initial production of 1,393 bpd of 35°-gravity oil and a large amount of gas; total depth was 6,751 feet. The well was suspended in April 1959 pending completion of facilities. A platform ("Helen") was constructed in PRC 2206 about 2,200 feet southeast of the discovery well in 94 feet of water, and production started in January 1961. On December 31, 1968, eight wells had been drilled; their average depth was 6,910 feet, and six wells were producers. Production is from Vaqueros and Sespe equivalents. The peak production year was 1962, when the daily average was 518 barrels of oil. Production for 1968 was 20,000 barrels of oil and 815,588 Mcf gas.

Conception Offshore oil field

The Conception Offshore field was discovered in November 1959. It is located in State tideland tracts PRC 2207 and 2725 between 3 and 7 miles east of Point Conception. The discovery well was drilled from a barge to a depth of 6,854 feet, and the well was suspended. A platform ("Harry") was later erected over the site, and the well was recompleted. By the end of 1960, a total of 11 wells had been drilled, and by the end of 1968, 45 wells had been drilled, of which 32 were producers. Production is from Sespe Formation, and the average drilled depth is 6,845 feet. The peak production year was 1964, when the average production was 13,539 bpd. A new pool discovery in February 1969, made at about 4,050 feet in the Alegria Formation, produced 384 bpd of 35°-gravity oil.

Point Conception Offshore oil field

The Point Conception Offshore field, located about 1 mile southeast of the point on State tideland tract 2879, was discovered in 1965. The discovery well had an initial production estimated at 214 bpd from Eocene-, Sespe-, and Vaqueros-equivalent sands. In the first year of production, 1968, about 5,000 barrels of oil and 2 Mcf gas were produced from three wells. By February 1969, the three wells had a combined production of 406 bpd of oil.

OCS P-0197 unnamed offshore oil field

An unnamed offshore oil field is located 4 miles south of Point Conception in OCS P-0197. The discovery of commercial oil in "substantial quantities" was announced in September 1968. Two holes have been drilled in more than 600 feet of water, but no completions have been made (California Oil World, 1969, v. 62, no. 4).

OCS P-0188 and P-0190 unnamed offshore oil field

On July 9, 1969, the discovery of a new offshore oil field in Federal OCS P-0188 and P-0190 was announced. Of the four wells now drilled, three have been tested at rates ranging from 900 to 6,000 bpd for each well. The oil was 17° to more than 40° gravity and came from five separate producing horizons which were found between the depths of 6,945 feet and more than 12,000 feet. The first well in OCS P-0190 was drilled in a record 1,300 feet of water (Rintoul, 1969).

MONTALVO AREA

This area includes two fields—the West Montalvo oil field and an unnamed offshore oil field in Federal OCS P-0202.

West Montalvo oil field

This field includes three areas that were discovered separately: the McGrath in 1947, the Colonia in 1951, and the tideland in 1953.

The discovery well of the McGrath area was completed for 154 bpd from a depth of about 9,000 feet in the "Repetto" Formation; Pico gas sands above this oil zone produce the only dry gas in Ventura County. A structural-stratigraphic trap is developed in an arch; the axial area includes a buried east-northeast-trending branch of the Oakridge fault—a reverse fault dipping steeply to the south (California Division of Oil and Gas, 1961).

The discovery well of the Colonia area was completed in 1951 for 191 bpd of 13°- to 27°-gravity oil. Production comes from about 11,500 feet in a series of discontinuous sand bodies in a complexly faulted north-dipping homocline in the Sespe Formation.

The discovery well of the tideland area was completed for 390 bpd of clean oil from a depth of 12,318-12,529 feet (Frame, 1960) in the Sespe Formation. By the end of 1960, 13 wells had been slant-drilled from onshore. One of these, the deepest offshore well known at the time, bottomed at a drilled depth of 14,850 feet, a vertical depth of 13,622 feet, and a horizontal distance of 5,632 feet from the surface location.

OCS P-0202 unnamed offshore oil field

An unnamed field is located 3½ miles off Point Hueneme in Federal OCS P-0202. The field was discovered in July(?) 1969 by a well drilled to a total depth of 8,452 feet. It flowed 15.8°-gravity oil at a rate of about 1,000 bpd from a depth of about 5,000 feet (Californa Oil World, 1969, v. 62, no. 7 [13]).

SUMMARY

Oil, tar, and gas have been features of the natural environment of the Santa Barbara Channel region for thousands of years; petroleum has been the chief mineral resource of the region for decades.

In 1968, the oil fields of the channel area produced 22.9 million barrels of oil, about 6 percent of California's production. Cumulative oil production at the end of 1968 for these fields was about 1.1 billion barrels, or about 7½ percent of California's cumulative production. Dry gas production for the offshore gas fields in 1968 was about 12 percent of the State production, and their cumulative production was about 5 percent of the State total.

The first commercial oil well in California was completed in 1866 just east of the channel region; it was located on the basis of oil seeps. Since that time, the channel region has participated directly in the successful development of every phase of southern California's oil industry, from prospecting on land because of the presence of oil seeps, to prospecting offshore by geophysical methods.

The oil fields along the Rincon anticlinal trend, including the offshore Carpinteria field, have completely dominated the production statistics of all the other channel-region fields combined:

Field	Production (1,000 bbl) 1968	Cumulative on 1-1-69
Rincon, San Miguelito, Ventura	11,814	884,853
Carpinteria Offshore	5,564	9,884
Subtotal	17,378	894,737
All others	5,516	203,576
Total	22,894	1,098,313

Note that the 1968 production from Carpinteria Offshore alone exceeds that from all the other non-Rincon trend fields combined. The large production of the Rincon trend fields is attributable to thick, oil-saturated sections and relatively high porosities and permeabilities.

TABLE 1.—*Production and geologic data on oil*

[Except as noted, data are from Conservation

FIELD, area, and pool	Date of discovery	Average depth to shallowest production [1] (feet)	Average API gravity (degrees)	Number of wells, December 1968: Producing	Number of wells, December 1968: Total [2]
ALEGRIA-------------------	July 1959	4,300±	22	------	8
ALEGRIA OFFSHORE-----------	Feb. 1962	4,000±	38	1	1
CALIENTE OFFSHORE (gas)----	Oct. 1962	------	---------	2	3
CANADA LARGA---------------	Aug. 1955	2,558	26	3	4
CAPITAN--------------------	---------	------	---------	45	75
Vaqueros-----------------	Oct. 1929	1,300	22	33	41
Sespe--------------------	Jan. 1931 Feb. 1945	2,000	40	12	33
Coldwater----------------	Aug. 1945	2,850	39	------	1
CARPINTERIA OFFSHORE-------	Feb. 1966	2,600±	26	88	89
COAL OIL POINT OFFSHORE----	---------	------	---------	3	3
Nearshore area-----------	Aug. 1948	------	---------	Abandoned	
Offshore area------------	Aug. 1961	------	30	3	3
CONCEPTION OFFSHORE--------	Mar. 1961	------	40	32	45
CUARTA OFFSHORE------------	Jan. 1961	------	34	6	8
DOS CUADRAS OFFSHORE[3]------	Mar. 1968	2,137	---------	------	----
ELWOOD---------------------	---------	------	---------	22	56
Vaqueros-----------------	July 1928	3,400	35	21	48
Sespe--------------------	Oct. 1931	3,700	37	1	8
GAVIOTA OFFSHORE (Gas)-----	July 1960	------	---------	3	----
GLEN ANNIE (Gas)-----------	Nov. 1958	3,350	---------	Abandoned 1961	
GOLETA---------------------	Feb. 1927	400	42	Abandoned 1928	
LA GOLETA (Gas storage)----	July 1932	3,800	---------	------	15
LAS VARAS------------------	Mar. 1958	2,400	38	Abandoned 1960	
MESA-----------------------	May 1929	2,200	17	1	5
MOLINO OFFSHORE (Gas)------	Dec. 1962	------	---------	9	10
NAPLES OFFSHORE (Gas)------	Sept. 1960	------	---------	Abandoned 1966	
LION MOUNTAIN--------------	--------	------	---------	2	10
Sespe--------------------	May 1935	1,200	21	------	8
Eocene-------------------	June 1949	3,550	29	2	2
OAKVIEW--------------------	Apr. 1955	1,545	30	Abandoned 1955	
TIP TOP--------------------	1918	430	24	------	8
WELDON CANYON--------------	June 1951	3,050	29	2	2
POINT CONCEPTION OFFSHORE--	Mar. 1965	------	31	3	3
REFUGIO COVE---------------	1946	2,900	63	Abandoned 1961	
RINCON---------------------	---------	------	---------	327	421
Main area----------------	Dec. 1927	2,400	30	218	291
Oak Grove area-----------	Dec. 1937	6,800	31	34	47
Padre Canyon area--------	Oct. 1953	4,150	26	75	83
SAN MIGUELITO--------------	Nov. 1931	7,000	31	82	118
SOUTH ELWOOD OFFSHORE------	Nov. 1966	6,200±	31	11	11
SUMMERLAND-----------------	1894	140	19	------	8
SUMMERLAND OFFSHORE--------	Nov. 1958	------	34	31	46
VENTURA--------------------	June 1917	3,000	30	986	1,295
WEST MONTALVO--------------	---------	------	---------	57	86
McGrath------------------	Apr. 1947	9,000	29	9	18
Colonia------------------	Feb. 1951	11,500	16	47	67
Fleischer----------------	Aug. 1957	------	15	1	1
Laubacher----------------	July 1955	------	28	Abandoned	
Totals------------------	---------	------	---------	------	----

and gas fields of the Santa Barbara Channel region

Committee of California Oil Producers (1969)]

Oil production (thousands of barrels)		Net withdrawal formation gas (millions of cu ft)		Water production (thousands of barrels)	
1968	Cumulative to 1-1-69	1968	Cumulative to 1-1-69	1968	Cumulative to 1-1-69
-------	7	--------	13	1	34
23	80	439	2,206	1	16
-------	------	3,805	19,625	-----	------
3	78	--------	77	-----	48
102	18,993	109	14,819	4,138	------
74	12,067	34	3,958	3,526	------
28	6,549	75	10,476	612	13,629
-------	377	--------	385	------	1,289
5,564	9,884	3,893	6,951	1,938	3,156
116	986	227	2,494	107	------
-------	1	--------	18	------	------
116	985	227	2,476	107	433
642	19,226	483	12,426	4,944	16,669
20	581	0.816	11,178	933	4,580
-------	------	--------	---------	------	------
265	102,792	418	84,996	2,963	------
260	99,131	406	29,967	2,888	------
5	3,520	12	54,973	75	------
-------	------	6,816	57,093	------	------
-------	------	--------	490,983	------	------
-------	141	--------	56	------	------
-------	------	--------	15,363	------	------
-------	1	--------	---------	------	------
3	3,733	--------	8	------	20
-------	------	28.5	139,007	------	------
-------	------	--------	20,815	------	------
12	363	1	207	6	------
6	181	--------	130	5	------
6	182	1	77	1	------
-------	1	--------	---------	------	------
-------	106	--------	67	------	------
22	512	19	302	3	22
5	5	2	2	------	------
-------	3	--------	*0.990	------	------
2,568	99,493	4,527	152,978	4,453	------
1,612	65,212	2,323	83,134	3,287	------
259	13,568	630	37,729	258	3,856
697	20,713	1,574	32,115	908	12,342
831	53,262	972	155,054	628	10,463
1,929	3,449	2,812	4,444	299	364
-------	3,210	-------	*1,704	------	------
1,285	20,783	8,537	64,602	1,021	6,743
8,415	732,098	18,566	1,914,819	8,567	------
1,089	29,107	561.578	*10,312	1,105	14,203
102	3,257	[4]23	7,613	33	520
980	25,598	0.578	*10,291	1,072	13,681
7	161	--------	9	------	2
-------	91	--------	39	------	------
22,894	1,098,894	80,685	2,927,386	------	------

TABLE 1.—*Production and geologic data on oil and gas*

FIELD, area, and pool	Peak Production Year	Peak Production Bpd	Geologic data: Producing formation and age
ALEGRIA	1964	748	Rincon, early Miocene
ALEGRIA OFFSHORE	1964		Sespe equivalent, Oligocene
CALIENTE OFFSHORE (Gas)	----	-----	Vaqueros, early Miocene
CANADA LARGA	1956	55	"Repetto," early Pliocene
CAPITAN	----	-----	----------------------------
Vaqueros	1943	3,105	Vaqueros, early Miocene
Sespe	1935	1,261	Sespe, Oligocene
	1946	1,728	
Coldwater	1947	160	Coldwater, Eocene
CARPINTERIA OFFSHORE	1967	9,894	"Repetto," early Pliocene
COAL OIL POINT OFFSHORE	----	-----	----------------------------
Nearshore area	1948	2	Vaqueros, early Miocene
			Sespe, Oligocene
Offshore area	1966	637	Sespe equivalent
CONCEPTION OFFSHORE	1964	13,539	Vaqueros, early Miocene
			Sespe equivalent
CUARTA OFFSHORE	1962	518	Vaqueros, early Miocene
			Sespe equivalent
DOS CUADRAS OFFSHORE[3]	----	-----	"Repetto," early Pliocene
ELWOOD	----	-----	----------------------------
Vaqueros	1930	40,069	Vaqueros, early Miocene
Sespe	1936	2,698	Sespe, Oligocene
GAVIOTA OFFSHORE (Gas)	----	------	Vaqueros, early Miocene
GLEN ANNIE (Gas)	----	-----	Vaqueros, early Miocene
GOLETA	----	-----	Sespe, Oligocene
LA GOLETA (Gas storage)	----	-----	Vaqueros, early Miocene
LAS VARAS	1958	2	Sespe, Oligocene
MESA	1935	3,027	Vaqueros, early Miocene
MOLINO OFFSHORE (Gas)	----	-----	Vaqueros equivalent
NAPLES OFFSHORE (Gas)	----	-----	Vaqueros, early Miocene
LION MOUNTAIN	----	-----	----------------------------
Sespe	1938	45	Sespe, Oligocene
Eocene	1950	55	Eocene
OAKVIEW	1955	2	Vaqueros, early Miocene
TIP TOP	1935	18	Mid-late Miocene
WELDON CANYON	1954	118	Pico, late Pliocene
POINT CONCEPTION OFFSHORE	----	-----	Vaqueros, early Miocene
			Sespe, Oligocene
REFUGIO COVE	1959	4	Sespe, Oligocene
RINCON	----	-----	----------------------------
Main area	1961	6,735	Pico and "Repetto," late and early Pliocene.
Oak Grove area	1950	3,515	Pico, late Pliocene
Padre Canyon area	1954	2,918	Pico, late Pliocene
SAN MIGUELITO	1951	6,758	Pico, late Pliocene
SOUTH ELWOOD OFFSHORE	1967	4,164	Vaqueros, early Miocene
			Sespe, Oligocene
SUMMERLAND	1899	571	Pliocene, Miocene
SUMMERLAND OFFSHORE	1964	10,362	Vaqueros, early Miocene

See footnotes at end of tables.

fields of the Santa Barbara Channel region—Continued

Geologic data--Continued		Remarks [1] [3]
Nature of trap [1]	Method of discovery [3]	Offshore tract No. and completion data
---- ----------------	----------------------------	
--------------------	----------------------------	
--------------------	----------------------------	State 2199.
Stratigraphic trap--	----------------------------	
--------------------	----------------------------	
Faulted anticlinal nose.	Geologic mapping------------	Seven tideland wells drilled from piers.
Faulted anticline on Rincon trend.	Geophysical and geological--	State 3150; Federal OCS 166. Wells completed from platforms "Hope," "Heidi," "Hogan," and "Houchin."
--------------------	----------------------------	
--------------------	----------------------------	
--------------------	----------------------------	
--------------------	----------------------------	State 308; wells completed on ocean floor.
--------------------	----------------------------	State 2207 and 2725; wells completed from platforms "Harry" and "Herman."
--------------------	----------------------------	State 2206; wells completed from platform "Helen."
Faulted anticline on Rincon trend.	Geophysical and geological-	Federal OCS 402, platforms "A" and "B".
{Faulted anticline---	Geologic mapping-----------	Gas injected for pressure maintenance.
--------------------	----------------------------	
--------------------	----------------------------	State 2199; completed wells drilled from shore.
Stratigraphic trap in fold.	----------------------------	
Asymmetrical anticline.	Geologic mapping-----------	Produced for only 18 months.
Anticlinal dome-----	Geologic mapping-----------	Gas storage since 1941.
Faulted anticline---	Geologic mapping-----------	
Faulted dome--------	Geologic mapping-----------	Inactive.
--------------------	----------------------------	State 2920 and 2933.
--------------------	----------------------------	State 2205; wells drilled and completed from onshore.
Faulted asymmetric anticline.	----------------------------	
Faulted anticline---	----------------------------	
--------------------	----------------------------	
Pinchout------------	----------------------------	
--------------------	----------------------------	State 2879; wells completed on ocean floor.
Stratigraphic trap.	----------------------------	
--------------------	----------------------------	
Faulted anticline on Rincon trend.	Geologic mapping-----------	State 1466; wells completed from manmade Rincon Island; first ocean-bottom well completed in tideland (1961).
Faulted anticline on Rincon trend.	Geologic mapping-----------	Excessively high reservoir pressures at 11,300 ft subsea.
--------------------	----------------------------	State 3120 and 3242; wells completed from platform "Holly."
Faulted anticline---	Drilling on oil seeps------	More than 400 shallow wells drilled in tideland from piers beginning 1896.
Anticline-----------	----------------------------	State 1824; wells completed from platforms "Hazel" and "Hilda."

TABLE 1.—*Production and geologic data on oil and gas*

FIELD, area, and pool	Peak Production		Geologic data
	Year	Bpd	Producing formation and age
VENTURA	1930	45,323	Pico and "Repetto," late and early Pliocene.
WEST MONTALVO	----	------	-----------------------------
McGrath	1952	815	"Repetto," early Pliocene
Colonia	1962	7,501	Sespe, Oligocene
Fleischer	1958	106	Sespe, Oligocene
Laubacher	1956	107	Sespe, Oligocene
Totals	----	-----	-----------------------------

[1]Data from California Division of Oil and Gas (1961).
[2]Total includes storage, idle, and active service wells.
[3]Data from various sources.
[4]Injected gas deducted.
*Chiefly dry gas.

fields of the Santa Barbara Channel region—Continued

Geologic data--Continued		Remarks[1] [2]
Nature of trap[1]	Method of discovery[3]	Offshore tract No. and completion area
Faulted anticline on Rincon trend.	Geologic mapping and gas seeps.	Excessively high reservoir pressures below 6,000 ft subsea.
-------------------	------------------------------	
Stratigraphic trap in faulted arch.	------------------------------	Includes a tideland lease, developed by wells drilled from shore.
---------------------	------------------------------	

Geologic Characteristics of the Dos Cuadras Offshore Oil Field

By T. H. McCULLOH

GEOLOGY, PETROLEUM DEVELOPMENT, AND SEISMICITY OF THE SANTA BARBARA CHANNEL REGION, CALIFORNIA

GEOLOGICAL SURVEY PROFESSIONAL PAPER 679-C

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GEOLOGIC CHARACTERISTICS OF THE DOS CUADRAS OFFSHORE OIL FIELD

By T. H. McCulloh

INTRODUCTION

The Dos Cuadras Offshore oil field is a large multizone anticlinal accumulation of oil of intermediate gravity in a sandstone and siltstone sequence of early Pliocene age ("Repetto Formation"). The accumulation occurs in an elongate, doubly plunging, faulted culmination of the Rincon anticlinal trend beneath OCS leases P-0241 and P-0240, about 5½ miles south of Santa Barbara. Figure 5 shows the generalized structure along that part of the Rincon trend from the eastern part of the Ventura oil field to the area south of Santa Barbara. An area of roughly 1,000 acres is estimated to be potentially productive from multiple sandstone reservoirs at subsea depths of 4,000 feet and less, but revisions to the estimate will probably be required as more detailed geologic information becomes available from drilling.

When compared with any other known anticlinal oil field of "giant" dimensions[1] and comparable area in the Santa Barbara Channel region, in the eastern Ventura basin, or in California, the Dos Cuadras petroleum accumulation is unique in one special way. The shallowest commercial reservoirs of the other small-area "giant" anticlinal fields are covered and confined by a thousand to many thousands of feet of relatively impermeable strata incapable of yielding commercial amounts of fluid hydrocarbons to a well bore. By contrast, at the structurally highest point beneath OCS P-0241, the top of the shallowest major reservoir of the Dos Cuadras field is overlain by a section of less than 300 feet of interbedded siltstone, claystone, and minor sandstone. Even these uppermost 300 feet of strata are porous and permeable enough to contain mobile hydrocarbons that locally are producible.

Development of the Dos Cuadras field began late in 1968 when the first of 54 wells planned for drilling and completion from Platform A on OCS lease P-0241 was spudded. The normal development of the field was stopped when the fifth well on Platform A (A-21) blew out on January 28, 1969, prior to logging.

ACKNOWLEDGMENTS

The engineering, exploration, and exploitation data on which this report is based were made available to the author between February 14 and August 20, 1969. Data regarding OCS P-0241 were provided chiefly by the Union Oil Co., and came either directly to the author from company representatives, from the files of the U.S. Geological Survey, and through documents provided to the Presidential Advisory Panel. Data regarding leases to the east of OCS P-0241 came from several operators. The very valuable assistance of R. L. Brennan, K. S. Fox, and G. W. Lester of Union Oil Co., and of K. A. Yenne, R. J. Lantz, and V. C. Kennedy of the Geological Survey is gratefully acknowledged. Many other persons and organizations contributed in numerous important ways; among them H. C. Wagner, J. E. Schoellhamer, and R. E. von Huene deserve special thanks, together with the staffs of the Los Angeles and New Orleans offices of the U.S. Geological Survey Conservation Division.

[1] An oil field is termed "giant" if it contains producible reserves of 100 million barrels or more.

STRUCTURE

The writer's present knowledge of the structure of the Dos Cuadras field is based upon his examination of data from 17 of 27 wells coupled with interpretations of reflection seismic surveys and supplemented by sea-floor geologic mapping and extrapolation based on better known parts of the structurally lower part of the Rincon trend east of OCS lease P-0241 and P-0240.

Of primary importance in the structural interpretations are the data derived from logging and sampling of holes drilled to explore for, or to produce oil and gas. In August 1969, data were available from one deep well, one well of intermediate depth, and six shallow exploratory wells; from 15 development or evaluation wells of shallow to very shallow vertical depths (including the unlogged blown-out well A-21 and its very shallow redrill); from an abandoned shallow hole begun as a relief well to the A-21 (well OCS P-0241 No. 4); and from three extremely shallow abandoned cement grouting holes. On January 28, 1969, the date of the blowout, only the exploratory wells and five of the development wells had been drilled. However, the data acquired from subsequent drilling has served only to refine local details of the earlier geological interpretations.

Correlations from well to well by electric logs permit determination of local structural elevations of many distinctive subsurface stratigraphic horizons. Similarly, stratigraphic repetition (or deletion) by faulting in a well can be detected by electric log interpretation once the local normal stratigraphic section has been determined. Dip-meter data provide reliable indications of local bedding-plane attitudes of the strata penetrated by a well. Micropaleontological analyses of samples of drill cuttings and of conventional cores permit faunal zonation and faunal correlations of the rocks penetrated relative to rocks encountered in other wells and outcrops in the Santa Barbara Channel region. Each of these well-established techniques has been used in arriving at the present interpretation of the structure of the Dos Cuadras part of the Rincon anticlinal trend, particularly in the axial region, and especially within the area of present and potential oil production.

Also of primary importance in the structural interpretations are reflection seismic data. Somewhat curiously, seismic data quality is poor along and over the structurally highest parts of the Rincon trend, particularly the productive area of the Dos Cuadras field. In that important region, strong parabolic reflections from point or line reflectors at or just below the sea floor are so numerous and predominant as to partly or wholly obscure seismic signals that might be generated by velocity contrasts associated with flat or gently dipping strata below. Therefore, the near-surface seismic data are virtually useless for crestal structural interpretations. On the other hand, seismic data quality along the outer flanks of the Dos Cuadras part of the Rincon trend is excellent, and, after correction for change of velocity with depth, permits fairly accurate general delineation of the anticlinal flanks.

Geologic mapping on shore led to early recognition of the conspicuously large and very productive Ventura Avenue anticline, the complexly faulted, doubly plunging eastern culmination of the Rincon trend. Similarly, discovery of the Rincon field in 1927 and of the San Miguelito field in 1931 resulted from drilling of prospects selected on the basis of surface geologic mapping of the deeply eroded, though geologically young, strata astride the Rincon anticlinal axis.

Geologic mapping of selected parts of the Santa Barbara Channel floor was conducted by various companies, including the Union Oil Co. of California, for years prior to leasing of Federal offshore lands for oil and gas exploration. Lithologic and paleontologic analyses of spot samples of sea-floor outcrops and some diver observations of stratal attitudes were used to compile geologic maps of variable quality. The offshore Rincon trend was one such area mapped, and it was recognized that the area now known as the Dos Cuadras field is one of the structurally highest culminations along the trend. Although sea-floor geologic information is a helpful supplement to the well data and the reflection seismic data now available for OCS lease P-0241 and P-0240, it provides only sufficient detail for supporting or confirmatory use in present structural interpretations.

The current interpretation of the shallow structure of the major part of the Dos Cuadras field is shown on plate 3 by structure contours drawn principally on the basis of electric log correlations that are supplemented locally by dip-meter measurements and extrapolated down the flanks using reflection seismic interpretations. The stratigraphic horizon used to contour the structure is the top of the sandstone unit that forms the shallowest major commercial oil zone in the Dos Cuadras field. This horizon, the C electric log marker (fig. 6), lies within a conformable sequence of clastic marine strata of early Pliocene age and about 900 feet stratigraphically below the faunally determined boundary between rocks of the upper Pliocene "Pico Formation" and the lower Pliocene sequence called "Repetto Formation" (pl. 3). At the C horizon, the anticline is elongate, faulted, and doubly plunging, with nearly symmetrical flanks

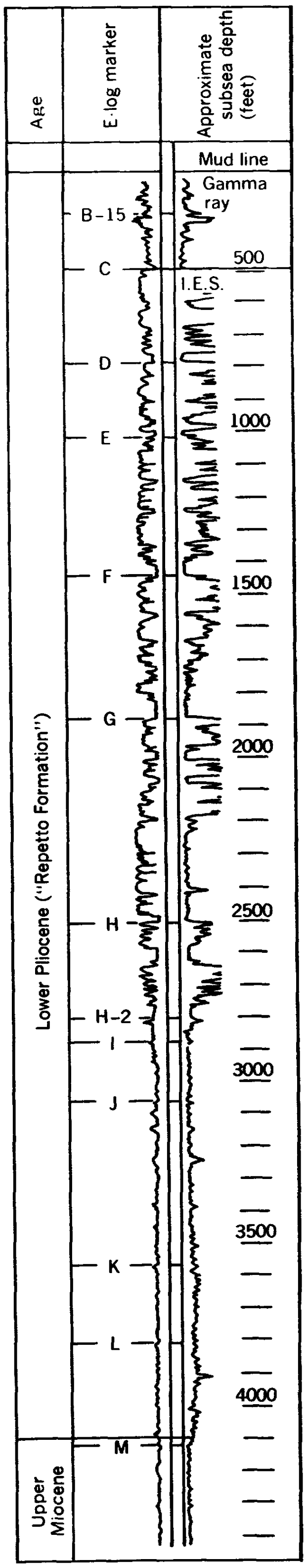

FIGURE 6.—Composite type log of the Dos Cuadras oil field.

that dip as much as 33° north and south from the nearly east-trending fold axis.

Just north of the area contoured on plate 3, the C horizon is presumably broken by a south-dipping thrust fault of area-wide extent that has been penetrated in the majority of wells drilled in the Dos Cuadras field and down the plunge to the east. This thrust fault divides the rocks into an upper and lower fault block (pl. 3). Just south of the area contoured, the south dip of the C horizon increases progressively. This dip indicates a strongly asymmetrical, locally overturned, and probably faulted south limb.

Too few wells have been drilled through the thrust fault to clearly define structural detail in the lower fault block. Enough is known to state confidently that the major structure in the lower fault block is anticlinal (pl. 3). The fold axis immediately below the fault is displaced about 500 feet from the axis above the fault at the C horizon. Moreover, dipmeter data in the directionally drilled deep redrill of the OCS P-0241 No. 1 indicate that the axial surface of the anticline dips north at greater depth. Other structural complications in the lower fault block will almost certainly emerge as more information is acquired from drilling. These are suggested by the mismatching oil-water contacts below the F and above the H horizons between wells of Platform A and the No. 2 exploratory hole shown on the longitudinal structure section (pl. 3).

Two important faults that break the C horizon in the block above the thrust are well defined and displace the contours on the structure contour map (pl. 3). Toward the west end of the field is an east-northeast-trending oblique slip fault that dips steeply northwest and has reverse displacements over most of its length. This fault presumably cuts the thrust fault, but may be a genetically related tear fault. Like many other faults along the Rincon trend, this fault is a permeability barrier to unimpeded movement of fluid hydrocarbons, as shown by the different distributions of oil and water in the permeable strata of the two structural blocks that it separates (pl. 3). A south-dipping normal fault located about 500 feet south of the anticlinal axis extends parallel to the axis at the C horizon for much of the length of the field. This fault has a throw ranging from 30 to 60 feet in the western part and 120 feet at the southeastern end. A difference of 160 feet in the level of the oil-water contacts in the C sand reservoirs on opposite sides of this fault indicates that it also is a barrier to movement of oil. It is not known with certainty if the east- to southeast-trending normal fault stops at the deeper thrust fault, cuts it, or is cut by it. Also uncertain is the relationship between the

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normal fault and the east-northeast-trending tear fault.

Near the eastern limits of the Dos Cuadras field, understanding of the structure of the east-plunging Rincon trend beneath OCS P-0240 is very incomplete. Not only are fewer data available here, but also less time and attention have been directed by the writer to interpretation of the structural data. The sea-floor geology and the data from exploratory wells indicate that the general structure is a steeply plunging anticlinal fold (pl. 3). The generalized seismic interpretation is consistent with this view. The irregular distribution of hydrocarbons suggests the presence of permeability barriers produced by faults across the fold axis; similar conditions exist farther east along the Rincon trend in the productive strata beneath OCS P-0166.

The deformation responsible for the structure along the Rincon trend cannot be precisely dated at the Dos Cuadras field; the strongly folded and extensively faulted conformable sequence ranges in age from late Miocene through late Pliocene and is unconformably overlain by a nearly flat lying and slightly faulted thin veneer of stiff fossiliferous silt and sand. The fossil shells have yielded radiocarbon dates ranging from 8,750±300 to 13,920±350 years.

Onshore, on the south limb of the Ventura Avenue anticline, early Pleistocene strata dip steeply and are conformable with folded Pliocene beds. This dip indicates a mid-Pleistocene date for the greatest part of the deformation. Evidence of continuing deformation and uplift along structural elements that are associated with the Ventura Avenue anticline is described by Putnam (1942).

LITHOLOGY AND STRATIGRAPHY

Sandstone, siltstone, claystone, and shale are the predominant rock types (in order of decreasing abundance) comprising the lower Pliocene and uppermost Miocene strata penetrated by drilling in the Dos Cuadras field. A limited number of rubber-sleeve and conventional cores and some sidewall cores permit direct observation of some of the rocks and lithologic description by conventional petrographic means. However, for most of the section, less direct methods of determining lithology have been used. Logs of spontaneous potential and electrical resistivity (IES logs), gamma radiation, and gamma-gamma radiation ("formation density") were recorded in most of the wells drilled. These logs have been interpreted in the light of core samples recovered from these wells and with knowledge and experience gained in equivalent or similar rocks elsewhere. The results have been used for continuous, accurate, and fairly detailed lithologic determinations in nearly all the wells drilled.

The stratal sequence beneath Platform A on OCS P-0241 is best discussed by reference to the type log, figure 6. Three parts of the logs of two wells (Nos. 1 and 5), drilled 500-700 feet east of Platform A, have been joined to form one idealized log showing standard borehole electrical (or induction-gamma ray) properties of the complete 4,200-foot-thick stratigraphic column penetrated between 200 feet and about 4,850 feet below sea level. This composite log is uncomplicated by the repetitions or deletions of some strata in actual logs of most of the wells. The type log shows three major lithologic divisions in the section. The uppermost 287 feet (from the top down to the C horizon) displays electrical properties like those of a section in which siltstone and claystone or shale predominate and sandstone lenses and beds are subordinate. Beneath this cap of fine-grained and thinly bedded strata is a 2,250-foot section (between the C and the H-2 horizons) in which the predominant lithology is sandstone interbedded with subordinate siltstone, mudstone, or shale. Below the base of the predominantly sandstone section (below the H-2 horizon and about 3,400 feet drilled depth in the No. 1 hole), the section is composed almost entirely of siltstone, claystone, and shale, interrupted by a few scattered thin beds of sandstone. The rocks of these three major subdivisions are considered in some detail below.

At the time of the drilling of well A-21 the uppermost 200 feet of strata beneath Platform A had been cored only in small part and had been subjected to borehole geophysical logging in only one well on OCS P-0241. Knowledge of these strata was restricted to the following: log measurements in stratigraphically equivalent beds in wells about half a mile east, southeast, and north of Platform A; percussion core samples taken at 5- to 15-foot intervals in three shallow (greatest depth, 150 feet) holes drilled at and near the Platform A site for engineering investigations prior to platform construction; and information gleaned from responses to problems encountered during construction of the platform supports and during drilling of the shallowest parts of the first four exploitation wells. Taken together, these diverse and fragmentary sources indicate the following characteristics for the strata between the sea floor and the C horizon at the location of the platform. Siltstone and claystone predominate in the section and are interbedded with subordinate lenses and thin (as much as a few feet) beds of fine-grained sandstone, in part calcareous and weakly cemented. Oil saturation was reported by Dames and Moore, Inc. (under contract to the operator) in samples of some of the sandstones (the shallowest noted at a depth of 30 feet below the mudline), and volatile hydrocarbon odors were detected in some of the fine-grained rocks. These beds are exceptionally tough or resistant (under penetrative compression) when compared with younger strata at other platform sites along the Rincon trend. This conclusion was reached mainly from empirical relationships between the number of standard blows required to drive a rock-coring device a certain increment of depth in foundation-site investigation holes. It was further corroborated by data on the depths of penetration into the ocean floor at different locations along the trend of the jack-up legs of the floating drilling vessel used in preliminary exploration, and by data obtained in driving the pilings for the foundation of the platform. Oil and gas were found in these rocks at the time the pilings were being driven, and gas was bubbling from the ocean while the platform was being emplaced.

In each of the four development wells drilled to total depth from Platform A prior to the blowout, lost circulation of drilling fluid caused difficulties while penetrating the rocks below the shoe of the drive pipe and above the point selected for cementing the first conductor casing string. This point was between 50 and 100 feet (drilled) above the C horizon and was from 155 to 242 feet vertically below the sea floor. This repeated loss of circulation indicated qualitatively that some part or parts of the capping strata above the shallowest major reservoir of the Dos Cuadras field were permeable to drilling fluid and cement (or had a very low hydraulic fracturing threshold) prior to the blowout, in spite of being mainly fine-grained argillaceous rock exceptionally resistant to driving penetration.

Subsequent to the blowout, and particularly since May 1969, much detailed information about the rocks above the C horizon was acquired. Part of the interval was logged in the relief well (OCS P-0241 No. 4). Evaluation holes on Platform A (well A-24) and Platform B (well B-18) were extensively cored and logged through the interval. This information was supplemented by the drilling or coring, logging, and cementing operations conducted in three of the six shallow grout holes about 600 feet east of Platform A. Eighty-nine percent was recovered of the 246 feet of rubber-sleeve cores attempted in well A-24 between 23 and 269 feet below the sea floor (the latter depth is 18 feet above the C horizon). Of the recovered core, predominantly fine-grained light-colored slightly calcareous silty oil sand constitutes nearly 7 percent; whereas claystone, some of it also oil-bearing in pores and cracks, constitutes 88 percent. Some calcareous claystone and some of the more indurated sandstone are brittle and hard enough to fracture, but most of the core is so porous and soft that it can be crumbled or mashed in the fingers. Lithologies in the A-24 cores correlate well with lithologic interpretations of the induction-gamma ray log of that hole, thus providing corroboration of the earlier lithologic interpretations based on the fragmentary data available at the time of the blowout.

Beginning a few feet above the C horizon, there is a rapid downward transition from the sequence of capping rocks, in which claystones without hydrocarbon saturation predominate, into a sequence of predominantly permeable sandy rocks in which most of the pore space is saturated by oil containing some dissolved gas. Such strata predominate from the C horizon to the base of the sandstone unit about 40 feet above the H-2 marker (fig. 6). Beneath Platform A nearly all the beds that are permeable enough to permit entry of hydrocarbons under moderate pressure differentials are saturated with petroleum. Enough logging and conventional and sidewall coring had been done before the blowout to permit a fairly satisfactory understanding of the lithology of this part of the section. Sandstone beds range in grain size from very fine grained and silty to coarse grained and pebbly. Almost all are quartz rich and fairly well sorted. Most are composed of grains that are well rounded to subrounded. Beds are well defined and range in thickness from laminations to massive beds several feet thick. Most of the sandstone is firm but friable and uncemented. Cemented beds are calcareous and tend to occur close to contacts of oil and water, except for some thin hard gray "shells" that separate uncemented rich oil sand from siltstone or mudstone layers of relatively low permeability. Interbedded fine-grained argillaceous and silty strata are subordinate, thin, and numerous but sporadic. More than 60 percent of the interval is estimated to be sandstone (as judged by the S.P. curve), and fewer than 20 discrete siltstone or "shale" interbeds of major significance (thickness greater than 10 feet) occur. The two thickest are above the G marker (55 feet) and at the F marker (45 feet).

From 40 feet above the H-2 marker to below the M marker (the approximate base of the "Repetto Formation") the strata beneath Platform A are almost entirely siltstone and shale. Thin interbeds of permeable fine-grained sandstone as much as 15 feet thick are oil saturated in appropriate structural positions but are so few and so widely separated that they are of minor commercial importance.

Assignment of the strata portrayed on the type log for OCS P-0241 to the lower Pliocene and uppermost Miocene series is based upon paleontological analyses of microfossils, primarily Foraminifera, from drill cuttings and cores. These analyses have been conducted entirely by the paleontological staffs of the Union Oil Co. of California and its partners, and their determinations and conclusions are accepted. The interpretations are in close agreement with determinations based on electric-log correlations with wells to the east in which faunal interpretations by other workers are available.

Within the Dos Cuadras field, stratigraphic variations are minor but significant. Most of the thicker lithologic units may be readily traced by electric-log correlations throughout the field and for considerable distances along the trend and to the north and south. In general, the "Repetto Formation" thins from east to west, and the relative abundance of sandstone decreases as individual sandstone units thin and grade into siltstone and shale. These relationships are depicted on the longitudinal section (pl. 3). The extent to which such stratigraphic changes affect the distribution of hydrocarbons in the Dos Cuadras field is difficult to evaluate now, but it is likely that some of the reservoirs will be far more productive in the eastern than in the western end of the field because some of the sandstone units there are thicker, more permeable, and probably coarser.

PETROPHYSICAL CHARACTERISTICS

The ease and rapidity with which a fluid, including hydrocarbon fluids such as oil (or gas), moves through a sequence of granular rocks depends upon the percentage of the total rock volume that is intergranular pore space (porosity) and upon the number and absolute size of the pore openings and the capillary connections between them. Other factors, such as the number of fluid phases in the pores, the viscosity of the mobile phase or phases, and the driving pressure differentials are influential, but total porosity and average capillary size (or, conversely, grain size) fundamentally control the permeability. In general, fine-grained rocks, especially those composed chiefly of platy grains such as clay crystals or mica flakes, have smaller pores and pore connections than coarser grained rocks composed of more nearly equidimensional grains. In addition, moderately to well compacted fine-grained rocks tend to be less porous than interbedded coarser grained rocks. Thus, most sandstone is both more porous and more permeable than interbedded shale, claystone, mudstone, or siltstone.

Knowledge of the distribution of porosity and permeability in the rocks of the Dos Cuadras field stems from laboratory measurements of core samples and from interpretation of well logs, particularly gamma-gamma (density) logs. A plot of porosity in percentage versus depth for all samples of punch cores, rubber-sleeve cores, and conventional cores that were available from the vicinity of Platform A immediately following the blowout of well A-21 is shown in figure 7. Measurements of 238 samples are plotted, 199 of them from sandstone beds below the C marker, the remaining 39 being mostly from claystone beds above the B-15 marker and within 150 feet of the sea floor. Nearly all the plotted porosities exceed 15 percent, and most of them exceed 20 percent. All but two of the samples within 1,500 feet of the sea floor exceed 25 percent porosity, and the samples within 150 feet of the sea floor cluster around median values that range from 34 to nearly 40 percent. Interpretations of gamma-gamma (Schlumberger FDC) logs from the No. 1 exploratory hole and the A-20 well are in substantial agreement with core analyses in the parts of

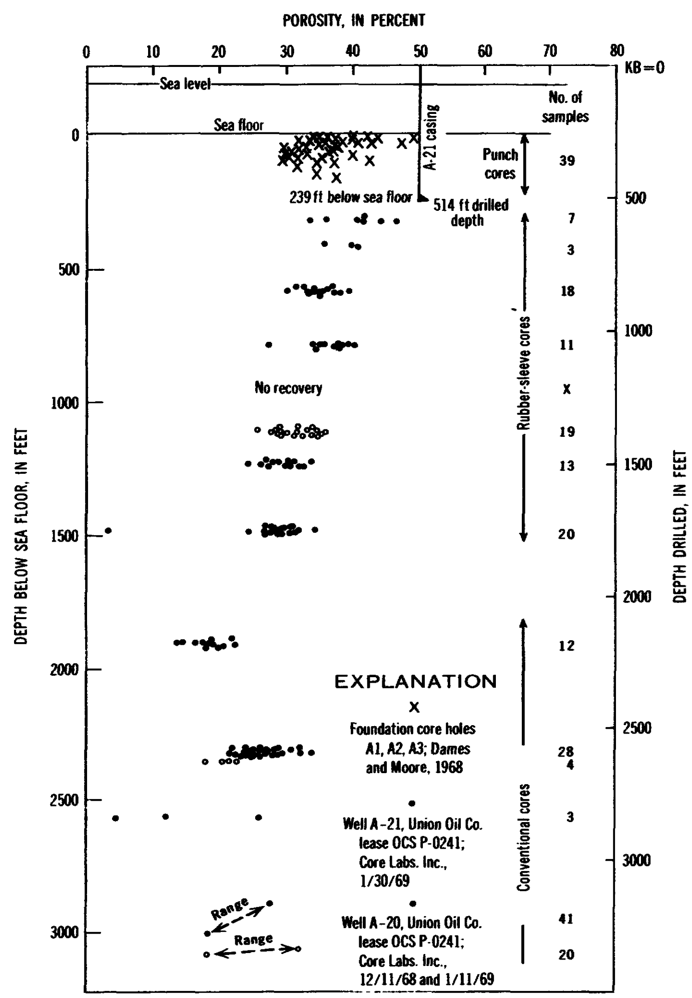


FIGURE 7.—Porosity versus depth for analyzed core samples, Dos Cuadras oil field.

the wells where hole caliper data indicate a hole that is not seriously washed out. From the core data and the logs available prior to or at the time of the blowout it can be concluded that extremely high porosities characterize both the sandstone beds and the fine-grained rocks within 1,500 feet of the sea floor beneath the vicinity of Platform A. However, neither cores (and core measurements) nor gamma-gamma logs provide any measure of widely spaced fracture porosity if present. Cores and gamma-gamma logs yield measurements that are *least* representative of the *most* porous materials.

Extensive coring and logging since the blowout have provided (mainly in June 1969) a large additional amount of data of high quality to corroborate the conclusions reached on earlier scanty evidence. For example, the average porosity measured by Core Labs, Inc., from 20 samples of sandstone and claystone selected from nearly continuous rubber-sleeve cores between 40 and 284 feet below the sea floor in well A-24 is 38.7 percent. This value is slightly *higher than*, but in general agreement with, the results (fig. 7) obtained in 1968 by Dames and Moore on punch cores taken for engineering site investigations. This slightly higher value may reflect the relatively greater abundance of measurements on sandstone samples and particularly on interbedded oil sands.

The relationship between porosity and permeability of sandstone from the shallower part of the section in the vicinity of Platform A was also established from core samples available at the time of the blowout. Figure 8 is a plot of porosity versus permeability for 39 samples of sandstone selected from rubber-sleeve cores from well A-21 between about 300 and 800 feet below the sea floor. Permeabilities of these soft highly porous sandstone samples range from approximately 50 millidarcys to nearly 5 darcys, and there seems to be a slight tendency for permeability to increase as the porosity increases. Additional measurements from newly available samples from well A-24 between 40 and 284 feet below the sea floor average 773 millidarcys at an average porosity of 38.7 percent and include some claystone and some very fine grained silty sandstone, together with oil sands. The lowest permeability measured is 4.1 millidarcys at 33.2 percent porosity and the highest is more than 8 darcys at 43.4 percent porosity. These additional measurements indicate that the capping rocks above the C marker at Platform A are not unlike the silty oil sands at greater depths in their range of porosities and permeabilities. Lower and higher permeabilities occur in the cap samples. In addition, the average permeability of capping rock probably is much lower because of the greater abundance there of fine-grained claystone. However, if widely spaced fractures are present, core samples provide no means of measuring overall rock permeability. The fact that the capping layer at the Dos Cuadras field confines and preserves large reserves of mobile hydrocarbons in the shallowest major reservoirs, in spite of the very high porosities and low to extremely high permeabilities measured on core samples, attests to the relatively low effective permeabilities of the capping strata as a whole. If an important fracture system had existed in the capping layer prior to the blowout, more complete dissipation of the mobile hydrocarbons in the shallower reservoirs should have resulted. Nonetheless, it is known that natural seepage was occurring on this tract prior to drilling.

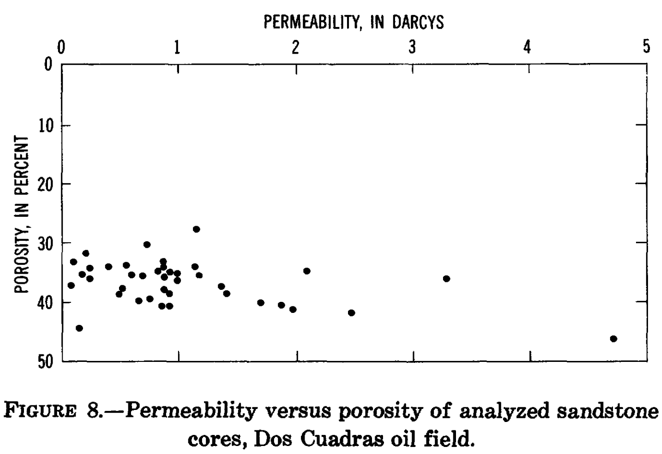


FIGURE 8.—Permeability versus porosity of analyzed sandstone cores, Dos Cuadras oil field.

The previously mentioned problems of loss of circulation of drilling fluid while drilling in rocks of the capping layer prior to the blowout attest to high permeabilities of the capping beds or their low resistance to hydraulic fracturing. However, quantitative evaluation of these matters is not possible without detailed records of mud pressures and thorough understanding of the possibly damaging effects on the surficial rocks of driving the platform foundation pilings and (or) the drive casings of the wells (both pilings and casing were cemented after driving).

Another qualitative measure of the high permeability of the capping formation was obtained after the blowout when cement was emplaced by gravitative flow into six shallow grouting holes drilled into the sea floor about 600 to 900 feet east of Platform A and into two others west of the platform. It was in these areas that large parts of the uncontrolled sea-floor seepage of oil occurred. Each of the holes was cased from the sea floor to about 150 feet and then drilled to a total depth of about 250 feet below the mud line. In successive gravity grouting operations, a total of 24,855 sacks of cement were emplaced through the uncased parts of these holes. Much of this massive volume may have gone into open fractures, fissures, or partings. An attempt to identify grossly megascopic fractures in the first of these shallow holes (OCS P-0241 No. 5) by use of a novel Borehole Televiewer yielded completely negative results and there is no other direct evidence of fracture channels. How much may have entered the more permeable beds within the mid-part of the section (the sandstone units close to the B-15 marker) is unknown.

This section should be concluded with a summary comparison of petrophysical characteristics of the capping rocks at Platform A and at Platform B about 2,600 feet to the west. The C marker in well A-24 (directly beneath Platform A) is at a subsea elevation of minus 475 feet. The same stratigraphic horizon in well B-18 (directly beneath Platform B) is at a subsea elevation of minus 556 feet, some 81 feet lower. Rocks cored above the C marker at Platform B (both those cored for engineering site investigations prior to the blowout of A and those cored for control and information following the blowout at A) contain no fluid hydrocarbons identifiable by sight, smell, or fluorescence. Hydrocarbon traces were detected in a few samples during laboratory core analysis. The average porosity and permeability of the 17 samples of rubber-sleeve cores from the B-18 well selected for analysis by Core Labs, Inc., are 35.4 percent and 882 millidarcys (in a range from 16 to 2,900) versus the 38.7 percent and 773-millidarcy averages measured from the samples from well A-24. No surface seepage oil has been detected in the vicinity of Platform B.

FLUID PROPERTIES

Petroleum and natural gas are complex fluid hydrocarbons of widely ranging composition and physical properties. They are uncommon, mobile, and highly fugacious constituents of certain especially favored parts of the discontinuous veneer of sedimentary rocks that rests on essentially non-oil-bearing rocks in the deeper parts of the earth's crust. Petroleum has a tendency to escape from underground natural reservoirs and seep to the surface. It is well known that seepages served as guides to early prospectors and still form the basis for some petroleum exploration. This escaping tendency is also used in the controlled production of crude oil and accounts in large part for the expulsion of oil from reservoir rocks through flowing wells. Unfortunately the tendency also accounts for the *uncontrolled* flow of oil from "gushers," "wild wells," and blowouts and has necessitated the use of numerous precautionary procedures and special mechanical devices.

The motive force behind the tendency for oil and gas to escape from the pore spaces of rocks and move to the surface is the force of gravity. Crude oil is generally lighter than the water that saturates the pores of most underground rocks, and it tends to be buoyant and to float to the highest possible level. Natural gas dissolved in the oil increases its buoyancy and decreases its viscosity, thus increasing its mobility. A solution of crude oil and "gases" is a relatively compressible fluid. It has a strong tendency to expand and to become less dense and more buoyant as the pressure confining it in an underground reservoir rock is reduced. Additionally, as a natural solution of "gases" in crude oil is decompressed, it boils at its saturation pressure. As the solution is decompressed below this saturation pressure, gaseous hydrocarbons of extremely low density (compared with pore water) may be released in large volumes. The explosive violence of many well blowouts is attributable to uncontrolled expansion of solution gas resulting from sudden accidental lowering of the pressure in a well bore.

In order to understand the manner in which fluid hydrocarbons tend to flow (or not flow) through porous and permeable rocks, it is necessary to know the fluid compositions (density and dissolved gas content), compressibilities, saturation pressures, natural fluid pressures, and pressure gradients. To understand the possible damaging effects on rocks by the uncontrolled flow of large volumes of fluids from regions of higher pressure to shallow regions of lower pressure, it is necessary to know the natural lithostatic pressure gradients and the hydraulic fracturing gradients of the rocks. These topics are considered below.

Data available regarding oil gravities and producing gas-oil ratios in the "Repetto Formation" of the Dos Cuadras field at the time well A-21 blew out include the following: (1) fluids recovered during one drill-stem test and one clean-up production test of perforated intervals in the deeper zone exploitation well A-25, (2) the gravity of oil produced during a clean-up test in the shallow- to intermediate-depth exploitation well A-41, and (3) complete analytical data, including saturation pressures and oil and gas compositions, for recombined separator samples obtained during two tests at an intermediate depth and a shallow depth in exploratory hole No. 2. Gravities of oil extractable from conventional cores recovered during drilling of well A-21 were potentially available. These compositional data are shown in figure 9. They indicate that the densities of the mobile fluid hydrocarbons decrease systematically and markedly with increasing depth from API gravity values of about 21° above minus 1,000 feet to 33° and possibly greater in the range from minus 3,000 to minus 4,000 feet. Also plotted in figure 9 are equivalent data measured

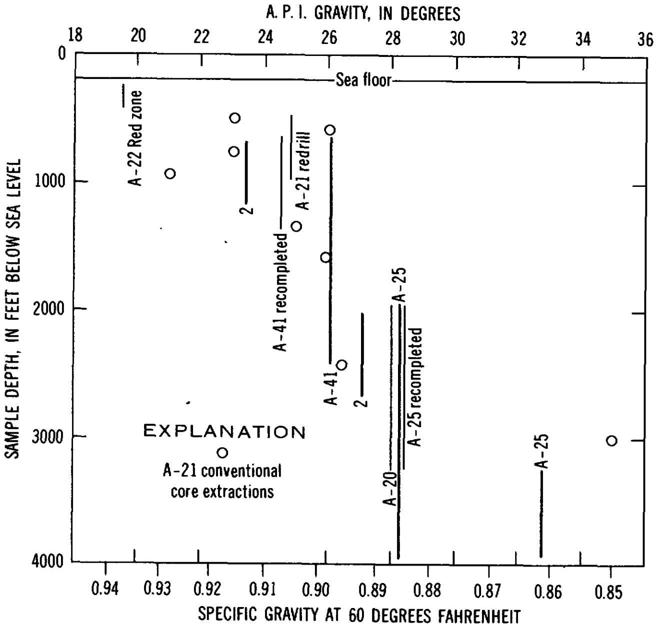


Figure 9.—Oil gravity versus depth, Dos Cuadras oil field.

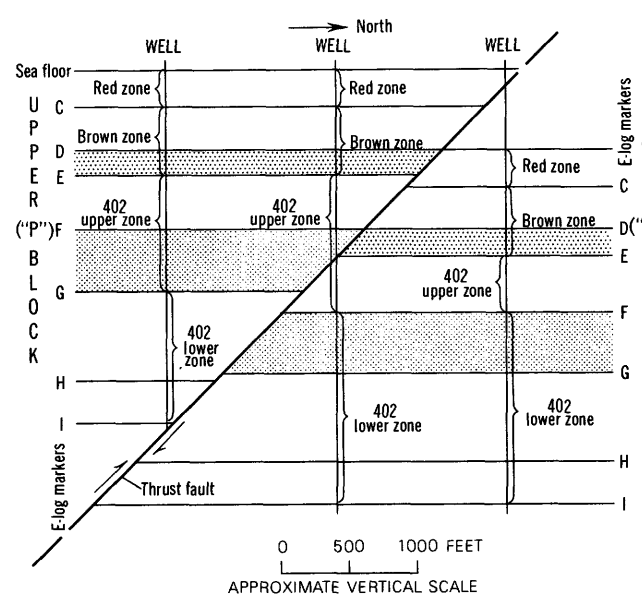
on samples of fluid obtained from selected exploitation wells that had achieved settled rates of production following the blowout. These latter data are consistent with the pre-blowout data and indicate that the tendency for the oil to be more dense in reservoirs nearer the surface extends upward into the so-called "Red zone" (fig. 10), the name applied to the thin producible sands within the capping layer close to the B-15 marker.

Analogies between the crude-oil gravities of the Dos Cuadras field and those of other fields in California lead to the conclusion that the denser crudes in the shallower reservoirs at Dos Cuadras contain limited quantities of potentially gaseous constituents in solution and probably are undersaturated. By the same reasoning, the less dense crudes from the deeper reservoirs in the "Repetto Formation" might be expected to contain appreciable quantities of dissolved low-molecular-weight fractions and to be saturated or nearly saturated with gas. This expectation is supported by the limited data available at the time of completion of well A-20, and by the somewhat more extensive data made available to the Presidential Advisory Panel in May 1969 by the operator (lessee).

Analyses of the recombined separator samples from tests of exploratory hole No. 2 give the following data: (1) Lower zone sample (minus 2,677 to minus 2,028 feet) at average reservoir pressure and temperature of 1,095 psig (pounds per square inch gage) and 105° F at minus 2,350 feet had a field-tested gravity of 27.1° and a producing GOR (gas-oil ratio) of 165 cubic feet per barrel. Laboratory determinations indicate a saturation pressure of 983 psig, a reservoir fluid GOR of 183 and FVF (formation volume factor) of 1,090 (barrels of fluid in the reservoir per barrel of stock tank oil), and a gas specific gravity of 0.820 (relative to air). (2) Upper zone sample (minus 698 to minus 1,178 feet) at an average reservoir pressure and temperature of 470 psig and 85°F at minus 938 feet had a field-tested gravity of 23.4° and producing GOR of 50 cubic feet per barrel. Laboratory analyses show a saturation pressure of 351 psig, a reservoir GOR of 52, and a FVF of 1.031.

During a flowing drill-stem test on January 9-10, 1969, well A-25 produced from the interval minus 3,962 to minus 3,300 feet (interval below the base of the predominantly sandstone section above the I marker) 32.8° oil at a producing GOR of 595 cubic feet per barrel. From mud weights required to control the well during drilling of this interval, a formation fluid pressure of 2,140 psi is indicated for the base of the tested interval. Assuming a temperature of 138.6°F (by extrapolation), and a gas gravity of 0.85, calculations using the table of Standing (1947) indicate that the formation fluid is saturated with respect to gas with a reservoir GOR of 510 and FVF of 1.252.

In summary, it is evident from the data existing at the end of January 1969 that the Dos Cuadras field is a many-zoned composite oil accumulation in which



Note: F-G markers are included in 402 upper zone above thrust fault and in 402 lower zone below thrust fault

Figure 10.—Schematic relations between producing "zones," stratigraphic subdivisions, and structural divisions in the Dos Cuadras oil field.

the mobile (producible) hydrocarbons decrease in density (increase in API gravity) with increasing depths, from 21° or less at depths less than minus 1,000 feet to 33° or more at depths greater than minus 3,500 feet. Also evident is the fact that the reservoir fluids range from strongly undersaturated (with respect to gas) at shallow depths to saturated and at bubble-point pressures for the deepest interval tested (minus 3,962 to 3,300 feet).

California oil fields generally are characterized by so-called "normal" fluid pressures, that is, fluid pressures equal to the hydrostatic pressure exerted by a column of nearly fresh water extending from the subsurface point of measurement to the surface (or to the natural ground- water level in the aquifer). In contrast to this are the fluid pressures in the deeper zones of the onshore fields along the Rincon trend, particularly the Ventura field, where fluid pressures range upward from "hydrostatic" to values approaching the "lithostatic" pressure, or pressure due to the weight of a column of rock extending from the subsurface point of measurement to the surface vertically above that point. The "lithostatic" pressure gradient is commonly assumed to be 1 psi per foot of depth, and most calculated gradients depart very little from this assumption. Figure 11 summarizes the published pressure data from onshore Rincon trend fields (Watts, 1948; Glenn, 1950; Duggan, 1964) and from the Dos Cuadras field. Pressures in onshore wells between

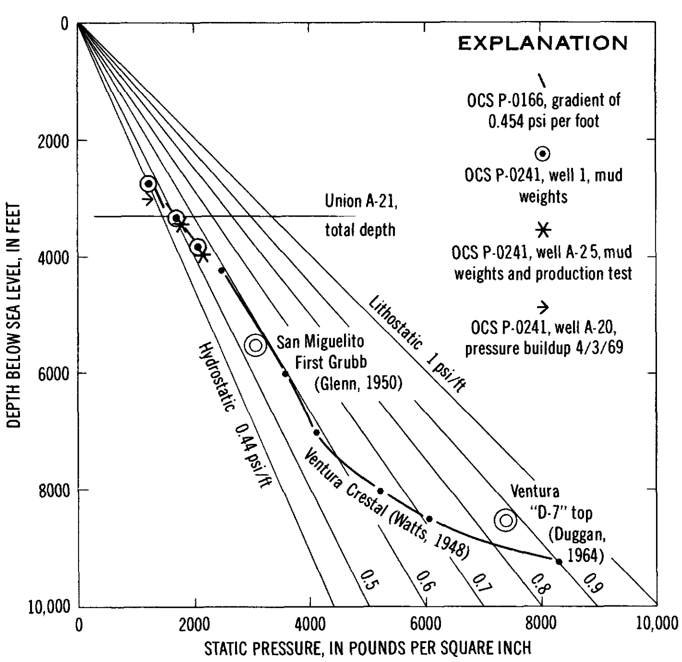


FIGURE 11.—Fluid pressures and fluid-pressure gradients versus depth for the Rincon trend including the Dos Cuadras oil field.

depths of minus 4,000 and about minus 9,000 feet range above "normal" along gradients of 0.6–0.9 psi per foot of depth. These well-known abnormalities raise questions concerning fluid pressure gradients at the Dos Cuadras field, since it is located along the same structural trend.

Data regarding fluid pressures in reservoirs of the Dos Cuadras field come from measurements made during drill-stem tests, production tests, and pressure-buildup tests, and from determinations based on the weights of drilling fluids required to maintain pressure control in drilling wells. Prior to the leasing of OCS P-0241, a gradient of 0.454 psi per foot was well established on lease OCS P-0166 in the "Repetto Formation" reservoirs (fig. 11) from many determinations. Before Platform A was constructed, exploratory hole No. 1 had demonstrated that 71 and 72 pounds per cubic foot drilling mud (0.493 psi per foot and 0.500 psi per foot gradients, respectively) could be safely used in drilling near the Platform A site to depths of minus 3,356 feet (1,680 psi). At greater depths "kicking" of the mud column necessitated higher mud weights (at minus 3,821 feet, 80-pound mud was required, indicating a fluid pressure of 2,120 psi on a gradient of 0.555 psi per foot). Trial production tests in exploratory well No. 2 about 1 mile west of the Platform A site yielded pressure measurements consistent with a pressure gradient of 0.44 psi per foot down to minus 2,677 feet. Before the blowout of well A-21, exploitation well A-25 was drilled to a total vertical depth of 4,051 (minus 3,963 feet); gas "kicking" occurred at minus 3,448 feet (after drilling below 9⅝-inch casing cemented at minus 3,318 feet) requiring 73 pounds per cubic foot mud (0.505 psi per foot gradient). At total drilled depth of 4,051 feet the hole began to "unload" 77-pound mud, but use of 78-pound mud led to loss of circulation, indicating a fluid pressure of 2,146 psi on a gradient of about 0.538 psi per foot. These data are shown in figure 11, and have been corroborated by more detailed information gathered since the blowout. Evidently, the "Repetto" reservoir rocks of the Dos Cuadras field, down to the base of the dominantly sandy section, contain fluids that are at or only slightly above "normal" hydrostatic pressures on a gradient of 0.44 psi per foot. Below the base of the dominantly sandy section, and especially below the I marker at about minus 3,440 feet, the minor thin sandstone beds are charged with fluids at notably greater pressures. These same sandstones are also the sources of the gas-saturated oils of lower density (higher API gravity).

Taken together, the compositions and pressures of the fluids in the reservoir rocks of the Dos Cuadras field tell much about the nature of the reservoirs and of the accumulation. The gradual decrease in oil density and increase in solution gas content with increasing sample depth would be unstable and impossible or unlikely in one or several thick reservoirs, each containing oil columns having vertical dimensions totaling several thousands of feet (Sage and Lacey, 1939; Roof, 1959). In addition, the adherence of the fluid pressures to near the gradient of low-salinity water throughout most of this thick oil-bearing section is also indicative of many reservoirs in the Dos Cuadras field. Lastly, multiple oil-water contacts have been recorded by electrical logging of the wells drilled (pl. 3). Each of these reservoirs has a fairly short vertical oil column, and they are stacked one upon another in a sequence that is continuous (or nearly so) in the structurally highest locations, but separated in flank locations by water-saturated sands. The fluids in such a large composite accumulation must have been in a delicate, metastable equilibrium, and any drastic uncontrolled disturbance of this balance could result in far-reaching consequences. The blowout of well A-21 triggered such a disturbance.

In modern, soundly engineered deep drilling, "Well planning . . . includes accurate prediction of formation pressures and fracture gradients in the formations to be drilled" (Records, 1968, p. 66). This statement is equally applicable to shallow drilling in areas such as the offshore Rincon trend where thick permeable sections charged in some places with oil containing solution gas may be present at shallow depths. Fluid pressures in the rocks along the Rincon trend have been examined; the question of lithostatic pressures and hydraulic fracturing pressure gradients in relation to casing practice must also be considered.

The range of densities of fluid-saturated sedimentary rocks is such that the static pressure exerted at the base of a rock column departs very little from a gradient of 1 psi per foot of depth. To verify this assumption, the porosity data summarized in figure 7 were used, together with those data considered reliable from the gamma-gamma (formation density) log of the A-20 well, to construct a profile of rock density versus depth for the Dos Cuadras field. This profile was used to calculate a local "lithostatic pressure" gradient for comparison with the theoretical gradient. Because sea water instead of rock makes up the topmost 188 feet of the column, calculated lithostatic pressures from the sea floor down to about minus 750 feet are notably lower than pressures based on an assumed gradient of 1 psi per foot. However, at depths greater than minus 750 feet the local lithostatic pressure ranges from values equal to the theoretical gradient to values substantially in excess of it at depths of more than minus 2,000 feet. Such close agreement is general and expectable.

The significance of lithostatic pressure gradient in the Dos Cuadras field may be best explained by imagining the effect of connecting a pump to the pore fluids at depth in a sequence of strata. At the outset the indigenous fluid pressure in the rock pores may be roughly one-half the lithostatic pressure at that depth due to the weight of the overlying rock column. By pumping fluid at high rates into the pores at that depth, the fluid pressure will be raised locally and theoretically could be raised to pressure equal to the lithostatic pressure. If this were accomplished, the weight of the overlying rock column would be lifted by the hydraulic action of the pumped fluid; the rocks surrounding the confined high-pressure pore fluid would be deformed, either by plastic yielding or by brittle fracturing or both, depending upon the nature of the material (Whalen, 1968).

This process is known as hydraulic fracturing and is a well-established technique used in many oil-producing regions for increasing well productivity. High-pressure fluids are pumped *down* cased wells and into the rock pore spaces through open intervals or perforations in casing until fractures form and open up around the well bore. Hydraulic fracturing (or, in soft rocks, its equivalent, plastic parting or rupturing) occurs whenever the pore fluid pressure exceeds the lithostatic pressure. In most regions rock fracturing occurs if pore fluid pressure exceeds a threshold value somewhat lower than the lithostatic pressure, giving rise to the concept and term "hydraulic fracturing gradient." These gradients range between 1 psi per foot and perhaps 0.6 psi per foot. In most California oil fields hydraulic fracturing has proved ineffective as a means for increasing well productivity, so that local data are sparse; from these sparse data it appears that "hydraulic fracturing gradients" in California fields range from 0.7 psi per foot to the lithostatic gradient. In the deeper Pliocene zones of the Ventura field "hydraulic fracturing" pressures must nearly equal the lithostatic pressures, because *natural* fluid pressures have gradients up to 0.9 psi per foot (fig. 11).

Knowledge about hydraulic fracturing has been gained by experiments in artificial well stimulation. The principals involved are generally applicable and help to understand damage that may be done inadvertently to rocks during oil field operations. The consequences of the blowout of well A-21 are clarified in the light of such considerations.

The fluid pressures and the fluid and lithostatic pressure gradients encountered in the Dos Cuadras field are shown in figure 12, together with a vertical

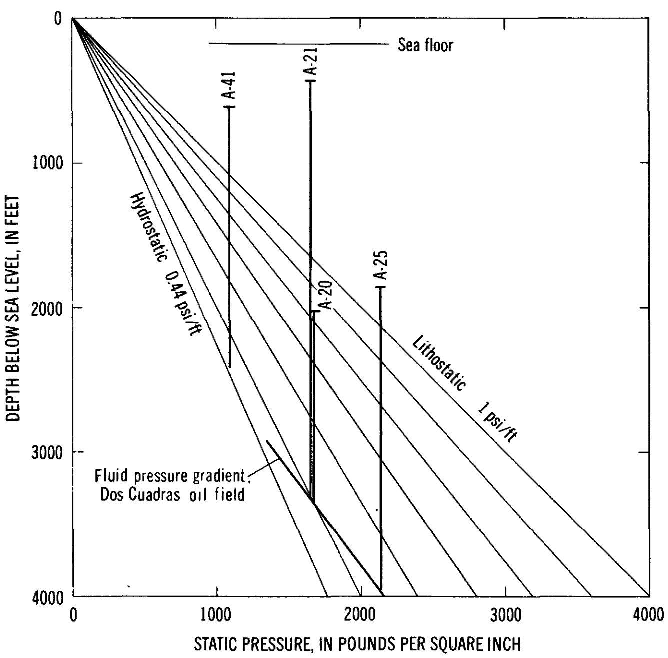


FIGURE 12.—Fluid pressures, fluid-pressure gradients, and uncased and perforated intervals of the Dos Cuadras oil-field wells that were shut in or drilling on January 28, 1969.

line indicating the vertical depth interval in well A-21, which was not protected by casing at the time control of the drilling fluid was lost and the well blew out. A single string of conductor casing was cemented at a drilled depth of 514 feet (238 feet vertically below the sea floor) in fine-grained rocks of the capping layer (fig. 6) between the B-15 and C markers. The bottom of the hole was at a total vertical subsea depth of minus 3,313 feet, presumably characterized by fluid pressures only slightly above "normal" on a pressure gradient of 0.5 psi per foot, and presumably stratigraphically above the base of the predominantly sandstone section. When the hole began to "unload" through the drill string, the drilling mud was followed by what the drilling crew described as a "heavy condensate mist," rather than black oil, thus indicating that the source of the hydrocarbons was either gas-saturated oil or a gas cap (no other evidence of any gas cap is known) and that the fluid column in the well bore had a very low density. For 13 minutes the well blew blinding gaseous mist in large volumes with a deafening roar. After an attempt to stab with the kelley failed, the crew dropped the drill string and closed the blowout preventer, thereby abruptly confining the low-density condensate fluid to the largely uncased well bore (see Appendix A). Within minutes myriads of small gas bubbles unaccompanied by oil rose to the water surface in a large area adjacent to Platform A. No other signs of impending trouble were visible. From 1½ to 2 hours after shutting the rams, the crew observed a large and turbulent boiling of the water about 800 feet east of the platform (fig. 13), the first emergence to the surface of large volumes of seeping gas accompanied by abundant black oil. As this initial boil intensified and expanded, another similar boil began at the northeast corner of the platform and partly beneath it. Within 24 hours oil and gas were seeping vigorously from numerous ocean-floor sources along an east-west zone extending from a point about 250 feet west of the platform to a point about 1,050 feet east of the platform. In time, the area of seepage expanded and changed in character.

Figure 12 offers an explanation for the sequence of events just described, especially when compared with figures 7 and 8 relating rock porosity and permeability to the shallow depth to which the bore of well A-21 was protected by casing. As control of the drilling mud was lost during pulling of the drill pipe from the hole, low-density hydrocarbon fluid entered the well bore, presumably at or near the bottom, at a pressure probably not exceeding about 1,660 psi (0.5 psi/ft×3,313 ft depth). When the rams of the blowout preventer were shut and the column of low-density fluid was prevented from escaping freely from the wellhead, the fluid pressure built up in the well bore below the cemented shoe of the casing. The pressure, potentially capable of reaching a theoretical limiting value somewhere between 1,150 and 1,660 psi, built up until the pore fluid pressure in the strata below the casing shoe was exceeded (normal pore fluid pressure at the casing shoe—minus 514 feet—is estimated to be 226 psi—514 ft×0.44 psi/ft). At that time, higher pressure gas and oil began flowing into the shallow permeable beds from the deeper sands. When the pressure of the newly energized pore fluids in the shallow sands below the C marker had built up to equal the "hydraulic fracturing" pressure of the cover (estimated to be less than 360 psi at the depth of the casing shoe and certainly not greater than the lithostatic pressure of 514 psi for that depth), capping rock rupturing occurred and the "boiling" seeps began.

The first outbreak occurred east of Platform A at what is probably the structurally highest point (the B-15 marker is at minus 313 feet easterly from the A-21 surface location as compared with minus 332 feet in well A-24). The localization of the other major "boil" at the northeast corner of the platform may have resulted from slightly greater penetrations close to that corner of two of the foundation pilings.

Prior to the blowout three production wells (A-20, A-25, A-41) had been drilled without incident, cased, completed, tested, and shut in pending completion of pipeline facilities. The perforated vertical intervals of each of these wells is indicated in figure 12 by a vertical line for comparison with the uncased interval of the well that blew out. Each of these wells was "killed" with heavy-weight mud following the blowout; however, a casing pressure of 1,000 psi was measured at the head of A-20 some days later. This pressure can be interpreted as indicating that the responsible hydrocarbon fluid in the "killed" well had a density of between 0.75 and 0.65 grams per cubic centimeter, indicative of a hole full of oil rather than of gas. Inasmuch as wells A-20 and A-21 both bottom at close to the same subsea vertical depth (minus 3,334 feet and minus 3,313 feet respectively) in structurally similar locations and presumably with nearly the same stratigraphic penetrations, the heavy gaseous mist emitted at the time of the blowout remains puzzling in view of this shut-in casing pressure of well A-20. The most obvious explanation, that well A-21 penetrated a small high-pressure gas reservoir in which pressure dropped rapidly and equalized with other reservoirs by flow to the borehole, is the simplest of several alternative hypotheses consistent with all available facts.

RESERVOIRS AND RESERVOIR CHARACTERISTICS

A natural petroleum reservoir is easily defined in many oil fields where pressure communication throughout a unit is indicated by a single oil-water contact and a hydrocarbon fluid of fixed or consistently depth-variable composition. The problem of defining a single natural reservoir and of determining the total number of such reservoirs is much more difficult in a large, composite, multizone accumulation such as Dos Cuadras field. There an obviously large number of separate oil-water levels and fluid compositions (inconsistently depth-variable) indicate the presence of many reservoirs that could not have been in unimpeded pressure communication prior to drilling of the first exploitation well.

An attempt has been made on plate 3 to portray as accurately as the well data permit the many stratigraphic and structurally controlled subdivisions of the oil-bearing strata of Dos Cuadras field. From the transverse section it is evident that the thicker and more continuous interbeds of siltstone and shale subdivide the Pliocene section in the vicinity of Platform A into not less than six natural stratal reservoir units. Moreover, the section-repeating thrust fault and the high-angle normal fault in the upper block (both of which appear to have constituted barriers to free fluid communication) further divide the section in such a manner that no fewer than eight or nine separate reservoirs may occur in the fault blocks above the thrust and no fewer than four or five below the thrust. Each of these was hypothetically capable of being separately produced, before they were placed in partial communication through pre-blowout exploitation-well completions and the blowout.

To combine so many natural units into "zones" during production in such a manner as to exploit the entire accumulation efficiently and economically requires knowledge not only of the productive characteristics of the major reservoirs and the values of their fluid contents but also of the many and complex economic variables affecting such a large and costly exploitation effort.

Figure 10 shows schematically the zonal subdivisions proposed (and thus far followed) for development of the Dos Cuadras field by the Union Oil Co. of Californa as operator for itself and its partners. The diagram is self-explanatory except for two matters. First, the so-called "Red zone" was introduced after the blowout when it was first recognized that some of the strata in the capping interval above the C marker are producible. Production from this "zone" is probably not commercial because of low well productivity, low-gravity oil, high water cuts, and limited zonal area and thickness. Most likely it will be produced only so long as required to aid in abatement of the surface seepage. Secondly, well A-20 (shown on both structure sections) was completed in the "402 lower zone" and has been producing continuously since March 29, 1969. This well is perforated selectively from just below the F marker in the subthrust (or Q) block down to the base of the dominantly sandstone section between the H and I markers. Since May 25, 1969, it has been flowing commingled 28° oil through a choke at a rate in excess of 2,200 barrels net oil per day and a gas-oil ratio of about 440 cubic feet per barrel from these three major productive intervals (possibly as many as five separate reservoirs). No gage of short-term open-flow potential has been obtained, but crude calculations suggest a figure possibly in excess of 10,000 barrels per day. In contrast, a shallower well (A-41) producing continuously since early March 1969 has yielded much less from selectively perforated intervals between a point midway between the C and D markers down to the F marker in the upper ("P") block. This "Brown zone" to upper "402 upper zone" completion has had a sustained production (pumping) of about 950 barrels net oil per day of about 24.5° oil with a gas-oil ratio averaging about 220 cubic feet per barrel. Well A-21 was scheduled for a completion similar to that of A-20, but when it blew out, communication was opened, at least temporarily, from the highly productive "402 lower zone" sands to all the lower-pressure sands up to the C marker. The documented high rate of controlled production of well A-20 though a choke of less than 1 inch diameter leads one to speculate about the possible rate of flow of well A-21 through a partly blocked bore hole of unknown diameter against only moderate back pressure through the ruptured capping rocks to the sea floor.

All reservoirs in the Dos Cuadras field are sandstone with porosities ranging from nearly 40 percent at the top of the "Brown zone" in the upper (P) block to 25 to 30 percent for sands in the "402 lower zone." Average reservoir permeability ranges between nearly 1 darcy at the top of the "Brown zone" to a low of 50 millidarcys for the interval between the G and H markers in the upper (P) block. Oil gravity ranges between 18.5° API in the "Red zone" to 35° in some of the thin sands below the I marker. Reservoir gas-oil ratios range from negligible in the shallower sands to 185 cubic feet per barrel for the "402 lower zone." The crude oil in the shallower sands is strongly undersaturated, but that in the lower sands of the "402 lower zone" appears to be saturated. Interstitial water content appears to be low to moderate throughout, but data are insufficient to permit setting figures on these quantities. Solution gas analyses are so few that conclusions may have to be revised, but available data show compositions that are normal for such crude oils except for a surprisingly high CO_2 content, suggestive of an unusually oxidized (and perhaps stagnant) accumulation.

Production from the field has been so limited that reservoir performance cannot be evaluated. From analogies between the reservoirs of Dos Cuadras field and those of some other shallow California fields, it might be expected that the reservoir drive mechanism is a combination of solution gas expansion, accompanied and followed by gravity drainage, with natural water drive being of minor importance. Present development plans call for injection of water to help maintain reservoir pressure after sufficient production data are available for sound planning.

On July 28, 1969, 14 wells were producing 10,000 barrels of oil per day from the lower Pliocene zones (one "Red zone," 10 "Brown zone," one lower "Brown zone" to upper "402 upper zone," and two "402 lower zone" wells). A total of 635,000 barrels have been withdrawn since controlled production for pressure drawdown was authorized following the blowout. The amount of seepage estimated by the U.S. Geological Survey for the period March 22 to August 31, 1969, is given in Appendix B.

SEEPAGE AND SUBSURFACE FLUID COMMUNICATION

Although natural seepages of oil and gas have long been a matter of record at several places (both offshore and onshore) along the Rincon trend, no documented observation identified the Dos Cuadras sector as a seepage source until work was undertaken on OCS P-0241 following the lease sale.

In a letter dated February 29, 1968, 11 months prior to the blowout of well A-21, Mr. F. J. Simmons, District Drilling Superintendent for Union Oil Co. of California, notified Mr. D. W. Solanas, Regional Oil and Gas Supervisor for the Conservation Division of the Geological Survey, of observations made on February 23, and confirmed on February 28, 1968, "a fairly large oil slick with some gas bubbles" at a location within OCS P-0241 approximately 2,300 feet west and 3,500 feet south of the northeast corner of the lease. Mr. Simmons further stated, "From all indications and records available to us, this is apparently a natural seep." This opinion is consistent with the tendency toward intermittent activity of some known seeps along the trend. The stated location is almost exactly on a line connecting Platforms A and B (along the C horizon axis of the Dos Cuadras culmination) and about 960 feet westerly along that line from the center of Platform A.

Somewhat later in 1968, after tentative selections had been made for sites for three projected drilling platforms on OCS P-0241, eight shallow coreholes were drilled to obtain on-site information to aid in planning foundations for these large structures. Three coreholes were drilled in the vicinity of what was to become the site of Platform A, three more at Platform B site, and two at the site of proposed Platform C, about 2,600 feet westerly from B. Technicians of Dames and Moore, Inc., who planned and supervised these operations under contract to the operator, observed live oil shows while drilling and coring all three holes at site A, and subsequently reported these findings along with descriptions of oil-saturated core samples and measurements of bulk densities indicative of very high porosities for these oily shallow beds. No fluid hydrocarbons were reported from any of the cores from the coreholes at the B or C sites.

Even though there are no earlier documented observations of natural seepage from the Dos Cuadras field, there is abundant suggestive evidence that the accumulation may have been seeping over a long period of time. Apart from the very general and widespread evidence that most large or highly productive petroleum accumulations seep at least some low-molecular-weight hydrocarbon fractions (McCulloh, 1969) are the facts that the shallower reservoirs of the field are strongly undersaturated with respect to gas and contain high- to intermediate-density crude oils. Both of these characteristics suggest long-continued loss of the potentially gaseous and more mobile liquid fractions from these reservoirs. Consistent with these facts is the gradational decrease in oil density and increase in dissolved gas content from the shallow to the deep reservoirs (fig. 9). Finally, the exceptionally high CO_2 content of the analyzed solution gas samples is suggestive of an unusually oxidized stagnant accumulation, another interpretation consistent with long-continued seepage.

Whatever the duration and rate of natural seepage from the shallow reservoirs of the Dos Cuadras field may have been, the blowout of well A-21 on January 28, 1969, drastically changed that rate and triggered other changes more difficult to evaluate. The sequence of events that occurred at the time of the blowout and during the hours following already has been described. To complete that history it is necessary to add that the blown-out well continued to feed high-pressure fluid to the low-pressure near-surface rocks and thence through many openings of varied dimensions to the sea floor until emergency measures to kill the well and to cement the borehole succeeded on February 8, 1969. Even after cementing, however, there was evidence that suggested continuing movement of fluid from deeper to shallower reservoirs through channels outside the well bore that were opened during the lengthy period of unimpeded flow. The well was reentered, the cement was drilled out of the surface casing, and extensive additional cement grouting was done before sidetracking the original hole and redrilling the well (A-21 RD) for completion and production from the upper part of the "Brown zone." Net oil pumped from this well since early March 1969 has declined from an early high of about 860 barrels per day of 25° crude to a current (August 1969) rate of about 600 barrels per day.

On February 25, while remedial work was being done in well A-41 to help abate the decreased but continuing seepage, a high though intermittent rate of oil flow resumed. It was thought by many at that time that well A-41 was permitting deep-zone oil to enter into the formation at about 900 feet below the ocean floor and subsequently through some type of fissure onto the channel floor. Further remedial work on well A-41, plus the recementing of well A-21, corrected this condition, and there have been no more such incidents. The cause of this second episode of uncontrolled flow is not known, but it is one bit of evidence of the ease with which fluids from some of the major reservoirs at depth are able to find egress to the surface.

The natural seepage reported in February 1968, before Platform A was emplaced, was located about 960 feet westerly from what is now the platform center. The first conspicuous boil of oil and gas following the blowout issued with great energy from a source or group of sources located 800-900 feet easterly from the center of the platform along the anticlinal crest of C horizon. A third boil erupted near the northeast corner leg of the platform and around the point at which the driven slant conductor pipe of well A-41 enters the ocean floor, and smaller boils occurred within a few hundreds of feet west of the platform. Much gas issued with the oil during the days immediately after the blowout, posing continuous danger of fire and forcing repeated suspensions of work and evacuation of personnel from the platform. Although the shallow reservoirs of the field were known to be (and still are) strongly undersaturated with respect to gas, large volumes of gas had evidently found a path or paths into and through these shallow reservoirs over an extensive area.

After the well had been controlled and the energetic flow abated, much gas accompanied by some oil continued to seep from many sources and the area of seepage gradually expanded. Figure 13 is a map showing the limits of the maximum area within which seepage is known or inferred to have occurred. This map has been compiled from aerial photographs; from personal observations made from the air, from surface boat, and from a submersible on the ocean floor; and from submersible diver observations of other U.S. Geological Survey personnel, from visual sighting observations of U.S. Geological Survey personnel on the platform, and from side-scanning sonar data supplied by the operator. At its greatest extent in late February 1969, the zone or belt of seepage, as much as 500 feet wide, extended for about 3,900 feet from a point 1,300 feet westerly of the center of Platform A to a point on OCS P-0240 approximately 2,600 feet easterly of the platform. The total area of seepage was about 50 acres. Gas and some oil were observed rising to the sea surface at the easterly point in late March 1969, from a small fresh-appearing sea-floor crater observed by U.S. Geological Survey personnel from a submersible.

The area of seepage east of Platform A was personally observed in late April 1969 on a calm day. The otherwise smooth water surface was ruffled over a broad area by myriads of small breaking bubbles of gas accompanied by rising globules of light oil that quickly spread as they surfaced to form iridescent films streaked with brown. On the sea floor the oil issued as streamers from pinpoint and larger openings in siltstone outcrops and soft sediment alike. Pits and elongate craters on the sea floor ranged from a few feet to many feet in length and up to several feet in depth. In this vicinity the sea floor was littered with angular rock debris, some of it identifiable as Pleistocene in age from included fossil shell fragments, presumably ejected forcefully from the sea-floor depressions at the time of the blowout eruptions. Whether some of the largest crater- and fissure-like depressions existed prior to the blowout cannot be proved or disproved. However, the abundance of angular soft porous rock fragments, some of them a foot or more across, and their restricted distribution close to and generally north of the sea floor depressions where the most energetic gas and oil flows erupted indicate a genetic relationship. No sea-floor deposit of tar or tar residues indicative of ancient seeps has been seen or reported in this area. However, inactive craters were identified about 200 feet southeast of the active seeps by a sonar survey (fig. 13) under charter to the operator.

Estimates of the varying rate of seepage during or following the blowout range widely and are difficult to evaluate. On-site estimates that 300-500 barrels of oil per day were leaking through the sea floor during the early period of uncontrolled flow of the blown-out well were widely quoted in the press. On the other hand, Allen (1969a) has stated that "During the first ten days of the leak many thousands of barrels of oil were released daily onto surface waters. . . ." Allen's estimates were based primarily on his attempt to interpret discharge from evaluation of areal limits of the slick reported by the U.S. Coast Guard. As noted earlier, the known production rate of well A-20, together with the similarities between it and the blown-out well, is permissive of an independent guess by the author that the rate of uncontrolled flow might have been any place in the range between 500 and 5,000 barrels per day.

J. M. DeNoyer of the Geological Survey has made a special study of data regarding the oil slick and has supplied the following comments (written commun., Sept. 4, 1969).

> Allen's first estimates were based on aerial reconnaissance mapping of the extent of the oil slick during the first few days of leakage. Difficulties in accurately determining the distribution of oil-covered water and open water and thickness of oil slick are recognized by Allen (1969b). Between March 1 and March 22, 1969, the Geological Survey conducted a number of high- and low-altitude detailed aerial photographic missions to determine the extent of oil distribution and dynamic characteristics of oil movement. The method used for mapping the distribution of oil within the slick was to take photographs at frequent intervals and mosaic the sun glint pattern that shows the presence of oil in great detail. Maps prepared from these photographs indicate that an overestimate of the volume of oil is obtained from the extent of the slick. The degree of overestimation ranges between a factor of four and 10, depending on wind and current conditions and the rate of leaking. Reducing Allen's estimates of about 5,000 bpd by a factor of four would give an estimate of 1,250 bpd and a reduction by a factor of 10 would suggest 500 bpd. The latter figure is in agreement with visual estimates made by Union Oil Company and independently by engineers and inspectors of the Geological Survey's Conservation Division but they may be too conservative. A leak rate of slightly over 1,000 bpd during the most severe periods of the spill is consistent with Allen's mapping of the maximum extent when the degree of oil coverage is taken into consideration.

Emergency measures for collecting the oil seeping from the ocean floor were put into effect soon after the blowout but were largely ineffective until late in

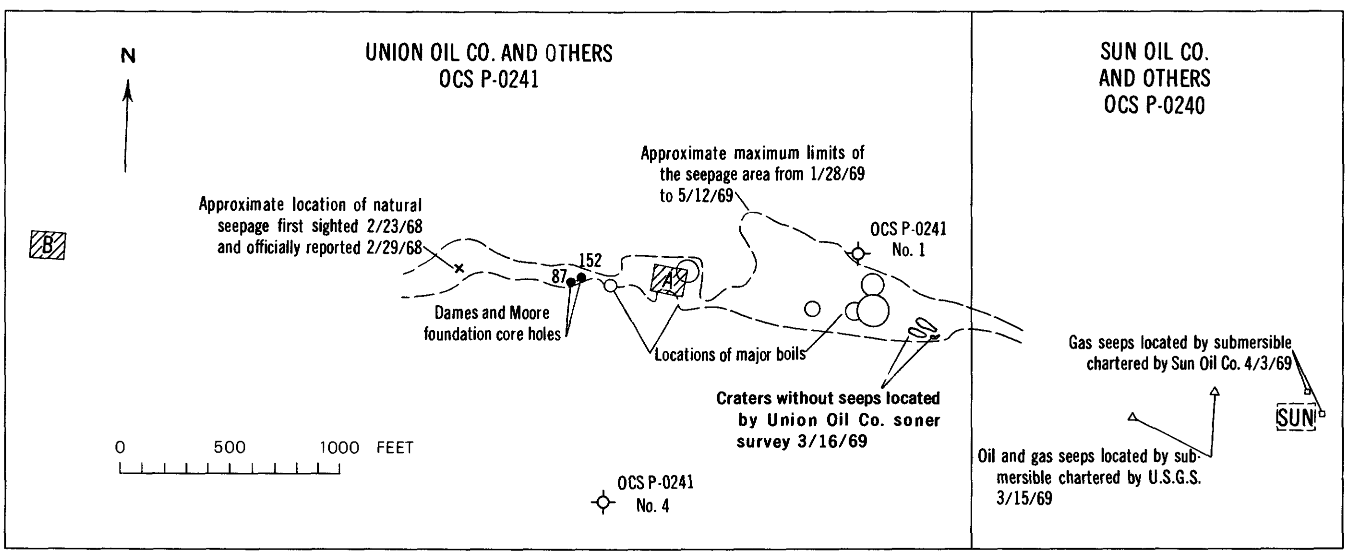


FIGURE 13.—Dos Cuadras oil-field oil and gas seepage area.

March. The Geological Survey Conservation Division visual estimates of total seepage (collected and escaping) were ranging about 24 barrels net oil per day between March 14 and 27.

From late March 1969 to the end of July, methods of collection improved, and methods of measuring seepage rates also improved. A well-verified nearly constant average daily rate of 30 barrels net oil characterize the period from March 22 through July 13, in contrast to Allen's estimate of 200 barrels per day, which he has since revised to a lower figure (oral commun., September 1969). This rate was abruptly reduced from 30 to 20 and then to 15 barrels daily between July 13 and July 31, and it has been still further reduced since then. (See Appendix B.) These reductions have been a result either of shallow cement grouting of the capping rocks in the vicinity of Platform A or of controlled fluid withdrawals from the shallowest reservoirs or both, as consequences of the recommendations of the Presidential Advisory Panel Meeting of May 12-13, 1969. During this same period, the percentage of seepage oil trapped and collected by various means has risen from an estimated 10 percent during the final week of March to more than 50 percent for the last 2 weeks of July. As of early September 1969, the daily seepage rate was reduced to less than 10 barrels.

The composition of the seeping oil is important in trying to determine its source. Colorless gas, low-density greenish-brown crude oil of low viscosity, and high-density brownish-black oil are the seeping materials. These three constituents have been emitted separately or together, and all three seem to have seeped at one time or another from all known major seepage sources. Of the seepage oil collected from sources beneath and close to Platform A, most ranges in API gravity between 18° and 20°, although some measurements range as high as 24°. These high densities (low gravities) suggest a source in the shallowest sands of the "Red zone" (figs. 9, 10), but the lower densities (higher gravities) are more consistent with possible sources in the "Brown zone." Oils from about 900 feet east of Platform A, collected on several dates, range in API gravity between 19° and 28°, and lumps of even heavier black tarry oil have floated to the surface. Analyses of trace metals, molecular structure, acidity, and minor element composition have been made of these surface samples, samples from Platform A seeps, and samples of oils produced from some of the wells. Comparisons of these analyses, like the range of oil gravities, suggest that the seepage oils may come from sources ranging in depth from the shallowest reservoirs of the "Red zone" to at least as deep as the upper part of the "402 lower zone."

SUBSIDENCE POTENTIAL

The possibility must be considered that withdrawal of fluids from the reservoirs of the Dos Cuadras oil field may be accompanied and followed by shallow subsurface readjustments and localized subsidence of the sea floor. The exceptionally shallow depth of much of the reservoir volume, the very high porosities and permeabilities of the reservoir rocks, the imperfect caprock seal above the shallowest major reservoir, and the intentional reduction of reservoir pressures, particularly in the shallowest reservoirs, all suggest that fluid withdrawals may be accompanied by reduction of pore pressure and gradual compaction of the petroliferous rocks. If compaction occurs, readjustments of the demonstrably weak capping stratum would follow, and highly localized differential subsidence of the crestal region of the anticline would occur. It is possible that subsidence would be accompanied by localized peripheral tensional fracturing of the capping layers. It is very difficult to judge whether or not such fracturing, if it did take place, would permit further sea-floor seepage of oil and gas.

Peripheral water injection may be feasible and prove effective in maintaining reservoir pressures in the producing intervals below the F electric-log marker. Water injection into reservoirs above the F horizon in the upper fault block must be pursued with great care and forethought to avoid upsetting the delicate pressure balance. The risks unavoidably entailed in shallow injection may prove to be so undesirable that the risks of differential deformation of the capping layer and the sea floor will be regarded as preferable.

The numerous complexly interrelated variables that determine whether or not subsidence occurs when pore fluids are withdrawn from a reservoir are understood so poorly that accurate prediction beforehand of the amount of subsidence is difficult, if not impossible. Some perspective may be gained for a view of the possibility that Dos Cuadras offshore field may undergo subsidence during exploitation by comparing it with other fields in the same region in regard to those geologic and reservoir parameters that enter into the mechanisms of compaction. The Wilmington, Calif., oil field is well known as a place where oil-field operations have led to extreme surface subsidence (Gilluly and Grant, 1949). Located in the same region, and an offshore field in part, the Wilmington field is the one most closely resembling Dos Cuadras for which the pertinent data are published.

Similarities between the Dos Cuadras and Wilmington fields are numerous and close, and the differences, small (table 2). Nevertheless, opinions of those with

TABLE 2.—*Comparison of certain geologic and engineering characteristics of the Dos Cuadras oil field with the Wilmington, Calif., oil field*

	Wilmington, Calif. (extracted from Gilluly and Grant, 1949)	*Dos Cuadras (compiled by T. H. McCulloh)*
Depth of top of shallowest zone, in feet.	About 2,200 ("Tar")	About 483 (subsea) About 296 (below mudline) ("Brown")
Mean depth of principal zones contributing to subsidence, in feet.	About 2,500 ("Tar" and "Ranger")	1,800 (All zones)
Age of reservoir rock	Early Pliocene ("Repetto Formation")	Early Pliocene ("Repetto Formation")
Average porosity, percent	30	28
Oil gravity range API	12°-25°	21°-33°
Maximum total net oil sand, in feet.	340	299
Fluid pressures	Near normal hydrostatic	Near normal hydrostatic
Well productivity, in barrels of oil per day.	Max 2,700 Min 50	Max 2,200+ Min 50(?)
Maximum flank dip angle.	20°(?)	33°
Maximum width of field (productive limits), in miles.	About 3	About 1
Productive area, in acres	[1]7,800	1,000
Maximum surface subsidence, in feet.	29 (to 1966)	(?)

[1] Halbouty (1968).

whom the author has had opportunity to discuss the matter range from the extreme that no subsidence would occur at Dos Cuadras in any case to the opposite extreme (one held by the author) that some subsidence will occur no matter what preventive measures are employed. The consensus of expert opinion since the May 12-13, 1969, meeting of the Presidential Advisory Panel appears to be that subsidence would accompany production of hydrocarbons, but that maintainance of "optimum" pressures through water injection will limit and control the amount of subsidence.

Seismicity and Associated Effects Santa Barbara Region

By R. M. HAMILTON, R. F. YERKES, R. D. BROWN, JR., R. O. BURFORD, *and* J. M. DeNOYER

GEOLOGY, PETROLEUM DEVELOPMENT, AND SEISMICITY OF THE SANTA BARBARA CHANNEL REGION, CALIFORNIA

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By R. M. HAMILTON, R. F. YERKES, R. D. BROWN, JR., R. O. BURFORD, and J. M. DENOYER

SEISMICITY

The Santa Barbara Channel region is located within the circum-Pacific seismic and volcanic belt and has been tectonically active throughout much of Cenozoic time. This tectonism seems to have been accelerated during the latter part of this era, maximum activity having occurred in Quaternary time. One way of depicting the seismic setting of the Santa Barbara Channel region in relation to the rest of southern California is to show the distribution of recent large earthquakes (fig. 14). Since 1912, more than 20 earthquakes of magnitude 6.0 or larger have occurred in southern California. The San Jacinto fault zone, which trends southeast from San Bernardino and is part of the San Andreas fault system, was the site of eight of these shocks; four others occurred near Bakersfield during the Kern County earthquake sequence of 1952; and two were located in the Santa Barbara Channel. The 1927 earthquake of magnitude 7.5, west of Point Arguello, should perhaps be grouped with the other two events in the channel region because all three may have occurred on faults in the Transverse Range province.

RECENT (INSTRUMENTAL) EVIDENCE

In California, the installation of instruments for recording earthquakes began in the 1920's. Since 1934, southern California earthquake locations have been reported by the Seismological Laboratory of the California Institute of Technology in its quarterly bulletin. Records of earthquakes for the period 1934 through 1967 within about 85 km (53 miles) of Santa Barbara were recently selected from the Seismological Laboratory data by A. G. Sylvester of the University of California, Santa Barbara, and were kindly made available for use in this report.

Epicenters of the 1934-67 earthquakes in and near the channel are plotted in figure 15, which shows most of the events greater than magnitude 3 and a few smaller ones. Each symbol represents at least one earthquake; the dots represent shocks of magnitude 4 or larger. The epicenters prior to June 1961 are given to the nearest minute (about 2 km), whereas more recent ones are given to 0.01 minute; the precision of the earlier data introduces several short, artificial lineations in the epicenter pattern.

The largest shock (magnitude 6.0) during the period occurred on June 30, 1941, approximately 15 km (9 miles) southeast of Santa Barbara. The symbol for this earthquake also represents 72 aftershocks. Although epicenters are scattered throughout the Santa Barbara Channel region, they tend to be more heavily concentrated in its eastern part. In contrast, the western part of the channel has been relatively quiet seismically since 1934. No conspicuous trends are evident in the epicenter pattern.

The reliability of an earthquake location depends on the number of seismograph stations recording the event and on the geometry of the station distribution; maximum precision is obtained where stations are numerous and uniformly distributed around the earthquake source. The difficulty in locating an earthquake with a poorly distributed station net is analogous to determining position by triangulation where either the base line is much shorter than the distance to the point, or the point is near the trend of the base line.

Most of the locations in figure 15 were plotted using readings from seismograph stations that cover

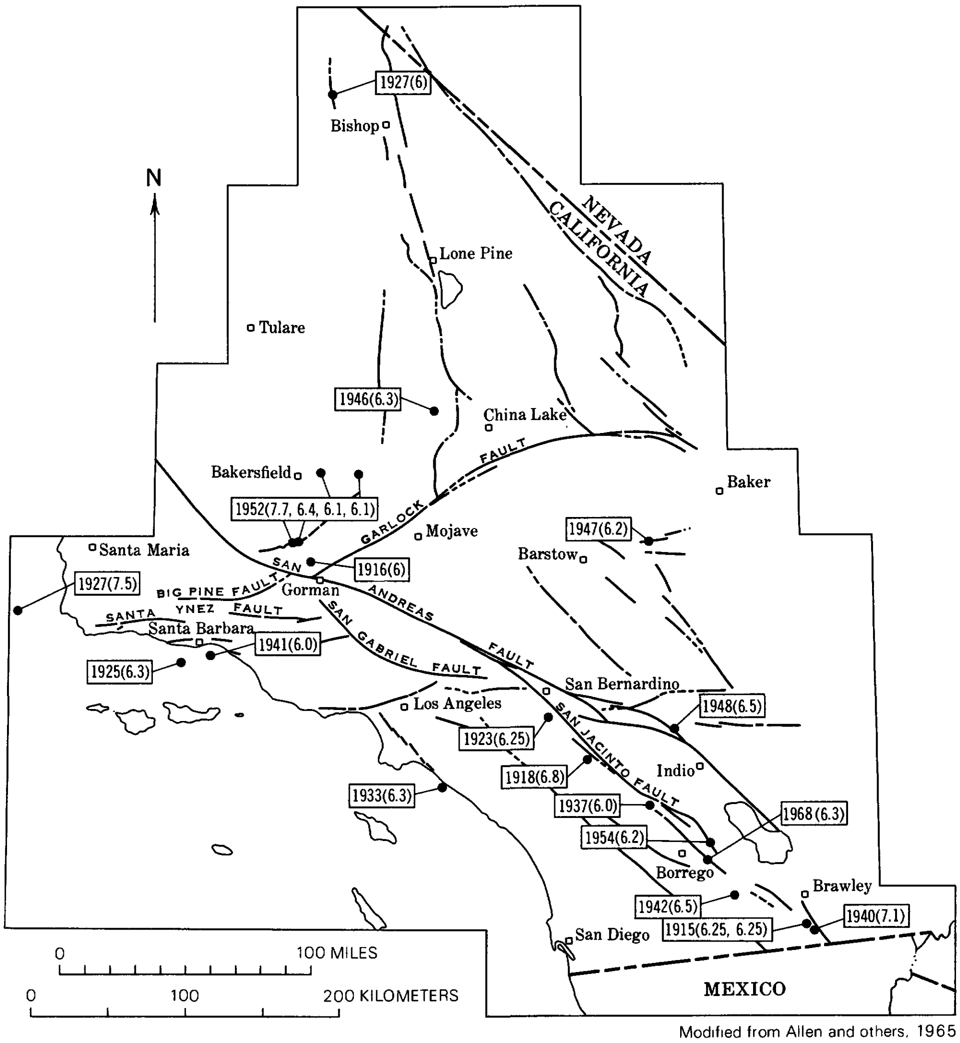

FIGURE 14.—Earthquakes of magnitude 6 and greater in southern California since 1912. Modified from Allen and others (1965).

an azimuthal range of about 135° around the channel. From 1957 to 1968, a seismograph was operated on San Nicolas Island, about 72 miles south of Santa Barbara, but its data were of limited value for locating earthquakes in the channel region. Because of the inadequacy of the network and because of the lack of knowledge of crustal structure in the channel region, individual epicenters cannot be located within 5 or 10 km (3 or 6 miles), and errors at some places exceed 25 km (16 miles). Consequently, the epicenter locations are inadequate to identify or delineate specific active faults in the region.

The principal seismic activity in the Santa Barbara Channel region after 1967 was the earthquake sequence in June, July, and August of 1968. Nineteen of these earthquakes were felt in the Santa Barbara-Goleta Valley area (A. G. Sylvester, written commun.). The largest shock (magnitude 5.2) occurred on July 4 (Pacific time) and in Goleta caused minor damage to merchandise, windows, light fixtures, and acoustic tile; cost of the damage amounted to $12,000. Minor damage also occurred at Carpinteria, but no structural damage is known to have resulted from this earthquake.

Epicentral locations for 63 earthquakes (magnitude $\geq$2.8) in this sequence are shown in figure 16. The epicenters cluster in the channel approximately midway between Santa Cruz Island and the mainland. When the sequence began, only two seismograph stations were operating in the channel area; one at Santa Barbara and the other at Santa Ynez Peak. This coverage was improved on July 7, 1968, by the installation of portable stations on Santa Cruz and Santa Rosa Islands and at several other mainland sites. These stations recorded through July 31, 1968, and substantially increased the precision of locating the epicenters for that period. Overall distribution of the epicenters for earthquakes during the period of operation of the island stations is not significantly different from the distribution of the earlier ones, but 10 of the 22 shocks recorded in this period were grouped in the northeastern part of the area.

The earthquake sequence was centered about 16 miles southeast of Santa Barbara and 10 miles southwest of the Carpinteria Offshore oil field. Pertinent information concerning the relationship between the earthquakes and the drilling operations was also provided by A. G. Sylvester:

According to company officials, production was in no way affected by the earthquakes. A temporary oil well drilling platform, WODECO VI, drilled two exploratory holes in the main fault-bounded anticline and was in the process of drilling a third when the swarm commenced. The drilling was not interrupted, the hole was dry, and it was capped. At least two more dry holes were drilled on the anticline and were capped after the swarm. Platform A, which blew out on 28 January 1969 and resulted in a massive oil spill... was not constructed until 14 September 1968, and drilling did not commence until November 1968.

HISTORIC RECORD

The seismic history prior to the installation of seismographs is given, though in a more qualitative and nonuniform manner, by numerous written descriptions of earthquake effects. Reliable accounts of California earthquakes date from about 1800. The earliest reports are found in notes of Spanish explorers and early settlers, and in the records of the Franciscan Missions. Earthquakes that affected the Santa Barbara Channel region prior to 1953 are listed in table 3.

Four of these earthquakes were especially destructive. The earliest, in 1812, destroyed Missions Santa Barbara and Purisima Concepcion (about 10 miles northeast of Point Arguello) and caused a tsunami along the north coast of the channel. Reported estimates of the high-water mark of this tsunami were as much as 50 feet near Gavita. A recent detailed study[1] of historic records, however, concludes that such accounts are unsubstantiated and cannot be accepted at face value. Several asphalt (crude oil) springs reportedly began to flow at places inland from the coast, and a burning oil spring near Rincon Point was enlarged. In the area of Santa Barbara the destruction had a Rossi-Forel intensity of IX to X. The reported damage and other effects resemble those accompanying other California earthquakes of magnitude 7.

An earthquake on June 29, 1925, caused widespread damage in coastal communities from Pismo Beach on the northwest, through Santa Barbara, to Ventura on the east. Twenty people were killed. Almost the entire business section of Santa Barbara was destroyed or rendered unsafe. The damage was estimated at $6 million and this figure does not include damage to residences. Mission Santa Barbara again was heavily damaged with partial destruction of two bell towers,

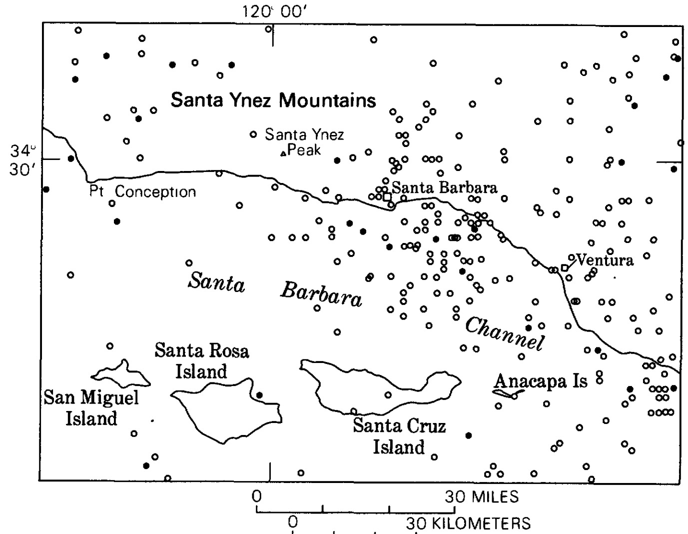

FIGURE 15.—Epicenters of earthquakes in the Santa Barbara Channel region from 1934-67. ○, magnitude less than 4; ●, magnitude greater than or equal to 4.

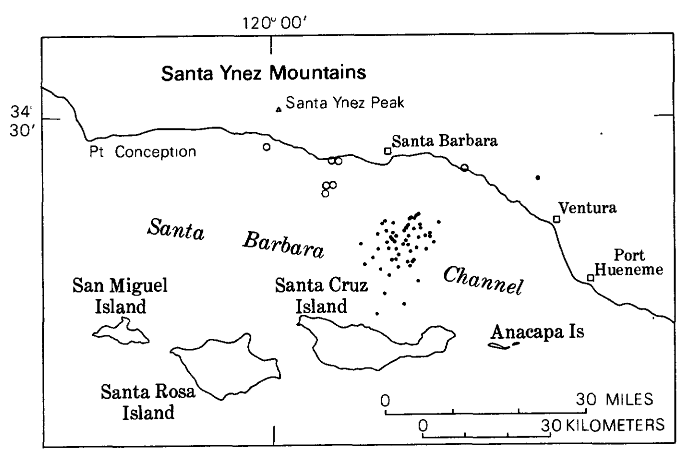

FIGURE 16.—Earthquake sequence in 1968 in the Santa Barbara Channel (Sylvester and others, unpub. data). ●, epicenters of earthquakes that occurred during the period June-August 1968; ○, epicenters of earthquakes that occurred during the period July 1967 to June 1968.

[1] "Examination of Tsunamis Potential at San Onofre Nuclear Generating Station," unpublished report submitted to Southern California Edison Co. by Marine Advisers, Inc., in 1965.

collapse of the front facade, and failure of some older interior adobe walls. Nunn (1925) reports that crude oil was extruded through beach sand at several points along the Santa Barbara coast about 3 hours before the main earthquake and at approximately the same time as a series of slight foreshocks began. An oil spout also was observed at the shoreline near the west end of the present Summerland oil field one night after an earthquake in 1883 (Goodyear, 1888). The epicenter of this magnitude 6.3 earthquake was probably less than 10 miles southwest of Santa Barbara.

The third major earthquake occurred on November 11, 1927, northwest of the channel off Point Arguello (Byerly, 1930). This shock, with a magnitude of 7.5, ranks as the second largest California earthquake since the San Francisco earthquake of 1906. Effects were most pronounced at Surf and Honda, just north of Point Arguello, where people were thrown from their beds, the concrete highway was cracked, a railroad bridge was damaged, and several hundred thousand cubic feet of sand were shaken down from a beach cliff. Buildings were damaged along the coast from Cambria, about 80 miles northwest of Point Arguello, to Gaviota, 28 miles to the east. A seismic sea wave was generated by the main event, and seismic disturbances from the main shock and some of its stronger aftershocks were felt in ships at sea. The seismic sea wave, or tsunami, was observed at Surf and Pismo Beach, 10 and 40 miles, respectively, north of Point Arguello. The wave was at least 6 feet high and resembled a large storm wave. At Port San Luis (Avila) near Pismo Beach, a 5-foot wave was followed by 1 hour of water agitation. Tide gage records at San Francisco and San Diego confirm this tsunami.

The last of the four important earthquakes occurred on June 30, 1941. Its magnitude was 5.9-6.0, and its epicenter was located in the channel about 5 miles south of the coastline between Santa Barbara and Carpinteria. Several communities along the Santa Barbara coast were damaged.

The historic records of the channel region document numerous periods characterized by sequences of frequent or nearly continuous low-magnitude seismic activity without exceptionally large shocks (table 3). Such sequences are called "earthquake swarms" and are commonly associated with volcanic activity; however, there is no evidence of a volcanic origin for the earthquake sequences in the Santa Barbara Channel region.

A more distant earthquake, but one that strongly shook the northern part of the Santa Barbara Channel (Wood, 1955) occurred January 9, 1857. Its epicenter was on the San Andreas fault near Fort Tejon, about 50 miles northeast of Santa Barbara. The surface faulting that accompanied this earthquake was not mapped at the time, but contemporary accounts and recent geologic studies (Wallace, 1968; Vedder and Wallace, 1968) demonstrate substantial right-lateral displacement on a fault break at least 150 miles long. The effects of this earthquake are comparable to those of more recent earthquakes of about 8.0 magnitude. Early descriptions indicate that all the houses in Santa Barbara were damaged (Wood, 1955) and that shaking in the Santa Clara River Valley east of Ventura was severe. Differential subsidence occurred in the river bed, and long cracks formed from which water was ejected to heights of 6 feet.

GEOLOGIC RECORD

An indication of long-term seismic activity is provided by data on the amount, rate, and nature of crustal deformation at the earth's surface. Accurate dating of the deformation of such features as young rock units, terraces, drainages, or other geologic markers yields a useful and reliable extension of historic and instrumental records.

The Santa Barbara Channel region is a part of the Transverse Range province, in which west-trending structures and topographic features contrast with the predominantly northwest structural and topographic trends found elsewhere in California, especially those of the adjoining Coast Range, Sierra Nevada, and Peninsular Range provinces (fig. 1). Many of the latest fault movements in the Santa Barbara Channel region seem to involve vertical slip, although many of the larger fault zones, such as the Santa Ynez, Big Pine, and Santa Monica, may have had major left-lateral components of movement in the geologic past.

The Santa Ynez fault zone, which trends westward for about 82 miles along the northern margin of the Transverse Ranges (fig. 1), exhibits some physiographic evidence that suggests recent movements, and it has been considered an active tectonic feature by some geologists (Page and others, 1951). The magnitude 7.5 earthquake off Point Arguello in 1927 may have occurred on the westward extension of the Santa Ynez fault zone.

The Big Pine fault, a major left-lateral fault with oblique slip near its western end, may have had measurable movement during historic time. The southern California earthquakes of November 1852 (table 3) were accompanied by about 30 miles of surface faulting in Lockwood Valley (Townley and Allen, 1939) about 40 miles northeast of Santa Barbara. The exact trend and location of the surface faulting is unknown, but geologic evidence and contemporary reports indicate that it may have been along the Big Pine fault. Independent evidence of very young movement along the fault includes scarplets that cut Quaternary terrace deposits and apparent left-lateral offset of stream channels (Vedder and Brown, 1968).

The Malibu Coast fault, a segment of the Santa Monica fault zone southeast of the Santa Barbara Channel, is not known to have had recent movement. However, faulting and local warping associated with the fault have deformed upper Pleistocene marine-terrace platforms and their deposits at seven known localities along a 20-mile segment of the fault bordering the south side of the Santa Monica Mountains (Yerkes and Wentworth, 1965).

That recent topographic surfaces and very young rock units have been deformed in the eastern part of the channel region has long been recognized. In the Ventura anticline, lower Pleistocene strata form the upper part of a sedimentary sequence that is more than 40,000 feet thick. These lower Pleistocene beds dip 35°-60° on the south flank of the anticline, and, because they conformably overlie older rocks, they provide clear evidence that the structure has been formed since early Pleistocene time. At Loon Point, 6 miles east of Santa Barbara, upper Pleistocene alluvial fan deposits are tilted and cut by a northeast-trending thrust fault that offsets the base of the oldest fan by at least 400 feet (Lian, 1954). This faulting may have continued into Holocene time. Faulted terrace deposits are well exposed about 2 miles southeast of Carpinteria, where highway cuts reveal a southwest-dipping (40°) reverse fault that juxtaposes upper Pleistocene marine terrace deposits and highly deformed Tertiary sandstone and siltstone. This fault may also cut the present topographic surface; presumably it has moved during Holocene time.

Several west-trending faults have been mapped in the northeast part of the channel (fig. 17), and sub-

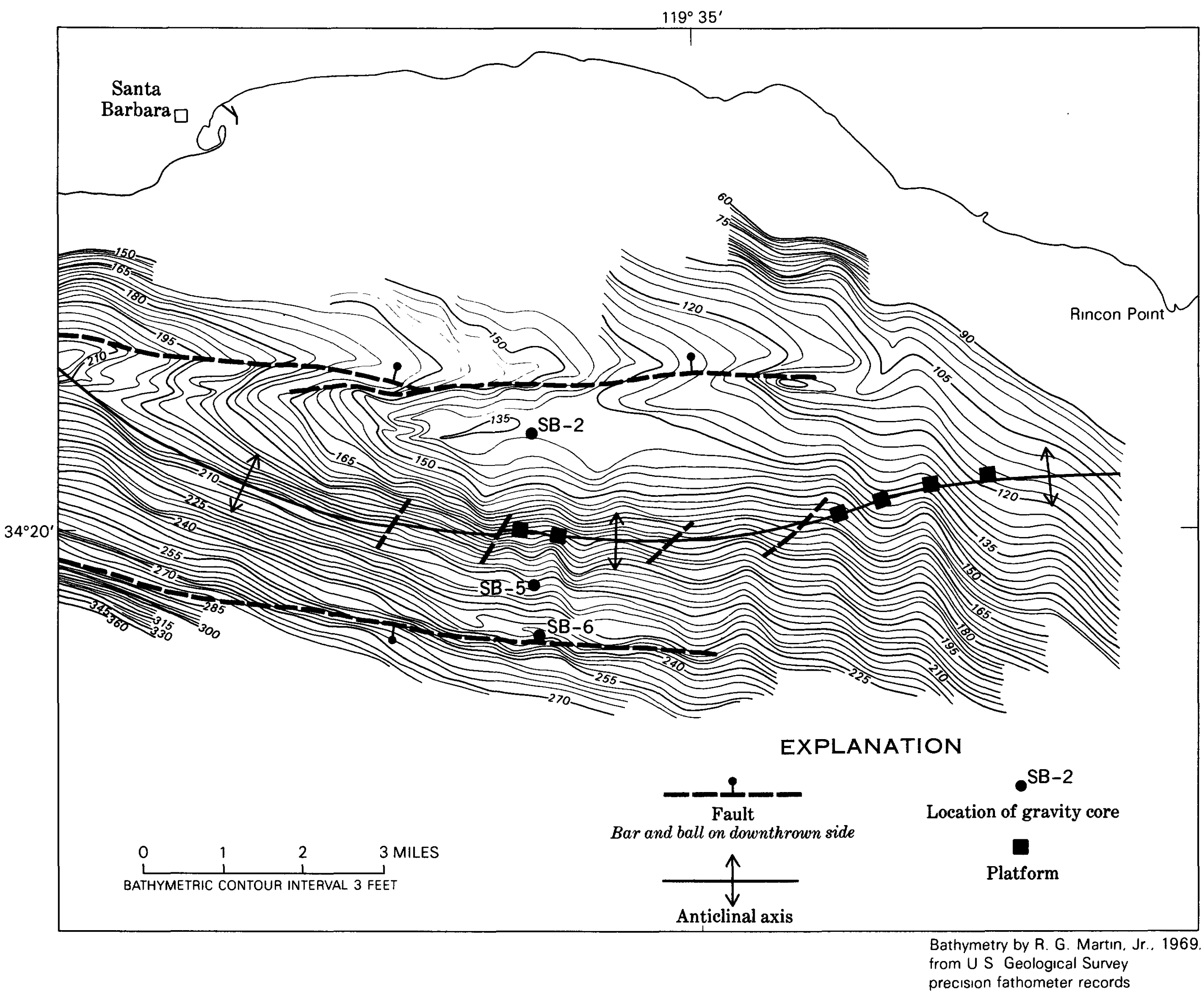

FIGURE 17.—Bathymetric contours and structural features of the central part of the Rincon trend.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*

[Question mark entries are used for original queried entries, or where present author entered an interpretation based on incomplete data. Remarks enclosed in parentheses are interpretations drawn from incomplete accounts. The primary source for the information presented is the catalog of Townley and Allen (1939); data after 1928 have been compiled from various sources and are limited to the larger events]

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
1800----	11-22	13:30	VIII	---------	Southern California-----	VIII	Heavy damage at San Diego, San Juan Capistrano, and Santa Barbara.
1812----	May	---------	I—III(?)	---------	-----do-----------------	------------------	Unconfirmed southern California "swarm" activity, lasting 4.5(?) months.
	10-8 to 11-18.	---------	I—III(?)	---------	San Juan Capistrano-----	------------------	Shocks for 40 days. (Probably a swarm on coast or offshore faults near Mission San Juan Capistrano.)
	12-8	Morning	IX	---------	-----do-----------------	------------------	Mission San Juan Capistrano destroyed, with loss of 30-45 lives; 28 buried in rubble from collapse of massive stone church walls. Possible seaquake damaged Spanish ship at anchor 38 miles from Santa Barbara.
	12-21	10:30	X	---------	Santa Barbara and Purisima Concepcion Missions.	IX—X	Santa Barbara and Purisima Concepcion Missions destroyed (adobe construction). Santa Ynez Mission heavily damaged. Tsunami broke along Santa Barbara coast; wave height unknown, but runup possibly as high as 30—50 feet at some points between Santa Barbara and Gaviota according to unconfirmed reports. Several "asphaltum springs" formed in the mountains.
1815----	1-18 to 1-30.	----------	I—III(?)	---------	Santa Barbara-----------	-----------------	Several small shocks felt (probably swarm of microearthquakes).
	7-8 to 7-9.	----------	I—III(?)	----------	-----do-----------------	------------------	Six felt shocks, (probably swarm of microearthquakes).

1852----	11-27 to 11-30.	---------	IX–X	---------	Northern Ventura County-	------------------	(Probably either on San Andreas or Big Pine fault 40-50 miles northeast of Santa Barbara.)
1853----	1-29	---------	---------	---------	Santa Barbara-----------	------------------	(Probably a local slight shock.)
	3-1	---------	V(?)	---------	San Luis Obispo---------	V(?)	Felt in Santa Barbara.
1854----	4-20 to 5-31.	---------	VI	---------	Santa Barbara-----------	VI	(Probable earthquake swarm.) Sea waves generated during the largest shock of series on May 31, at 4:50 a.m., and many people were alarmed. The large shocks seem to have terminated the series.
1855----	6-25	14:00	V	---------	-----do-----------------	------------------	Also felt strongly in Santa Maria.
	7-10	20:15	IX	---------	Los Angeles-------------	V	Tsunamis broke on coast at Port San Juan (Avila), which indicates possible movement of offshore fault.
1857----	1-8	---------	VII(?)–VIII.	---------	Santa Barbara-----------	------------------	Several slight shocks and one severe shock. Many other southern California shocks.
	1-9	---------	IX–X	---------	Fort Tejon--------------	VIII(?)	Roof of mission at San Buenaventura (Ventura) fell in. All houses in Santa Barbara were damaged, according to unconfirmed reports. Several new springs formed near Santa Barbara. One of California's greatest earthquakes, centered 50 miles east-northeast of Santa Barbara on San Andreas fault.
	3-14	15:00	V	---------	Santa Barbara------------	------------------	Severe shock felt in Santa Barbara and Montecito.
1860----	4-16	19:30	---------	---------	Fort Tejon--------------	III(?)	Felt in Santa Barbara.
1862----	-------	---------	VIII(?)	---------	Goleta------------------	VII(?)	Livestock frightened; trees swayed; people stood with difficulty.
1872----	3-26	02:30	X	---------	Owens Valley------------	V(?)	Probably the greatest earthquake in California's recorded history. Shock was felt over nearly all of California and Nevada and over parts of Utah

See footnote at end of table.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*—Continued

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
							and Arizona, possibly also over the northern part of Mexico. Many widely distributed after-shocks within Inyo County also felt throughout large areas.
1875	12-21	---------	---------	---------	Santa Barbara-----------	------------------	(Probably a local slight shock.)
1877	6-23	23:50	---------	---------	-----do-----------------	V—VI	Three shocks. Also felt in Bakersfield.
1878	1-8	---------	---------	---------	-----do-----------------	III(?)	(Probably a local slight shock.)
1880	4-12	08:30	V	---------	Ventura County----------	IV(?)	Probably a severe shock in vicinity of San Buenaventura (Ventura and lands to north-east.)
	11-12	22:30	---------	---------	Santa Barbara-----------	III(?)	(Probably a local, slight shock.)
1881	8-30	19:00	III	---------	-----do-----------------	III	Two slight shocks.
1883	9-5	04:30	VI	---------	Ventura-----------------	V(?)	Strong shock felt from Santa Barbara to Los Angeles.
	9-13	14:30	IV	---------	Santa Barbara-----------	------------------	Sharp quake lasting 5 seconds.
1884	8-2 to 4	---------	III	---------	-----do-----------------	III(?)	A few very slight shocks felt.
1885	4-7	02:00	III	---------	-----do-----------------	III(?)	Also felt at Ventura and possibly at Bakersfield.
	6-14	03:14	V	---------	Ventura-----------------	IV(?)	A moderate earthquake also felt at Los Angeles.
	7-9	01:20 to 08:15.	V	---------	Santa Barbara-----------	V	A limited swarm of five moderate earthquakes. Felt shocks were of long duration, awakened most sleepers.
1890	(?)	---------	VI(?)	---------	-----do-----------------	V(?)	"Quite a heavy shock."
1893	4-4	11:40	VIII	---------	Pico Canyon-------------	V(?)	An intense local shock centered near Newhall, 35 miles north of Los Angeles. Strongly felt at Ventura, San Bernardino, and Mojave. Felt only lightly at Los Angeles and Santa Ana.

	5-18	16:35	VII(?)	---------	Ventura-----------------	VI(?)	Widely felt shock, most severe southeast of Ventura. Felt from San Diego to Lompoc and inland to San Bernardino. No damage reports. Possible submarine origin off Ventura coast.
	6-1	04:00	VII	---------	Santa Barbara-----------	------------------	Considerably heavier than event on May 18, 1893. Also felt in Ventura and Ojai. Followed by light aftershocks.
1894	7-29	21:12	VII	---------	Southern California-----	V(?)	Widely felt earthquake, most severe at Mojave and Los Angeles.
1895	7-26	16:10	III(?)	---------	Santa Barbara-----------	------------------	Local slight shock.
	12-23	21:30	III(?)	---------	-----do-----------------	------------------	Do.
1897	6-24 to 7-19.	---------	III(?)	---------	Santa Barbara and vicinity.	------------------	A few light shocks and two strong shocks.
1898	5-29 to 6-3.	---------	V	---------	Santa Ynez Valley-------	III(?)	One light and one heavy shock felt in Santa Barbara and vicinity. Heavy shaking on June 3 felt throughout Santa Ynez Valley. Heaviest shock for some years at Santa Barbara.
1902	2-7 to 2-9.	---------	VI(?)	---------	Santa Barbara-----------	------------------	One light shock Feb. 7, 1902, followed by moderate shock on February 9 causing general alarm, but no reported damage.
	7-21	---------	III(?)	---------	Pine Crest--------------	------------------	(Probably slight local shock near Pine Crest, Santa Barbara County.)
	7-27	22:57	VIII	---------	Los Alamos--------------	III(?)	Severe local shock probably centered near Los Alamos, 35 miles west-northwest of Santa Barbara. Considerable local damage at Lompoc and Los Alamos. No damage reported at Santa Barbara.
	7-27 to 8-14.	---------	VIII—IX.	---------	Los Alamos, Santa Barbara, Lompoc, Santa Maria, and San Luis Obispo.	VII(?)	Unusual widespread swarm of felt shocks attaining local intensities as high as R. F. IX. Several events felt at Santa Barbara, but no reports of damage there. Heaviest intensities and most frequent

See footnote at end of table.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*—Continued

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
							reports concentrated at Los Alamos, 45 miles west-northwest of Santa Barbara. Shocks probably originated on various western extensions and branches of the Santa Ynez fault zone. Heavy shocks near Los Alamos on July 31, preceded by 5 days of frequent minor shocks; drove nearly the entire population away.
	9-10	21:30	V	---------	Los Alamos	III(?)	Severe shock preceded by days of light shocks.
	10-21	---------	IV(?)	---------	-----do-----------------	II(?)	Three shocks; the first quite severe. No damage reports. Felt in Lompoc.
	12-12	---------	VIII	---------	-----do-----------------	III(?)	All of north Santa Barbara County shaken by severe quakes. Light damage at Los Alamos and Santa Maria. Felt at Lompoc, San Luis Obispo, and Santa Barbara.
1904	10-14	---------	III(?)	---------	Ventura-----------------	-----------------	(Probably slight local shock.)
	10-15	---------	IV(?)	---------	Los Angeles-------------	III(?)	Light shock probably centered near Los Angeles. Felt at Santa Barbara and Sierra Madre.
	10-20	---------	III(?)	---------	Ventura-----------------	-----------------	(Probably slight local shock at Snedden Ranch near Ventura.)
1905	3-18	20:40	VI	---------	Bakersfield-------------	II(?)	Shocks were heaviest at McKittrick and Sunset oil fields. Flow of oil wells was increased. Shock felt at Nordhoff (Ojai), in Ventura County 25 miles east of Santa Barbara.
1907	7-3	01:10	III(?)	---------	Ojai--------------------	II(?)	Slight local shock near Ojai felt at Santa Barbara.
	August	---------	III(?)	---------	Pine Crest--------------	II(?)	"Slight earthquake felt on same day and hour as at Santa Barbara City."

	9-19	17:45	VII	---------	San Bernardino----------	III(?)	Large shock probably centered near San Bernardino, but felt throughout most of southern California. Light shaking at Montecito, near Santa Barbara.
	12-27	01:15	III(?)	---------	Santa Barbara-----------	------------------	A light local shock also felt at Ventura and Ojai.
1909	1-23	06:68	III(?)	---------	-----do-----------------	------------------	A light local shock also felt at Pine Crest.
	7-2	23:30	III(?)	---------	-----do-----------------	------------------	A sharp local shock also felt at Montecito.
	7-2 to 7-31.	---------	IV	---------	-----do-----------------	II-III(?)	Several slight to moderate shocks felt in Santa Barbara area. One heavy shock July 16, also felt at Los Angeles.
1910	5-15	07:47	VII	---------	Riverside County--------	II(?)	Widely felt earthquake in southern California. (Probably slight at Ventura and Santa Barbara.)
	November	---------	III(?)	---------	Santa Barbara-----------	------------------	Two slight quakes.
1911	3-28	20:25	VI	---------	San Miguel Island-------	III(?)	Moderate quake centered near San Miguel Island, Santa Barbara County. Felt slightly at Santa Barbara.
	5-10	05:00	IV(?)	---------	Oxnard------------------	II(?)	Three light shocks centered near Oxnard, Ventura County. Felt slightly at Los Angeles and at Ojai.
1918	12-14	02:00	IV	---------	San Miguel Island-------	II(?)	(Probably slight local event.)
1919	1-25	14:29	V	---------	Tejon Pass--------------	II	Sharp quake near Tejon Pass, felt at Ojai, Ventura, Bakersfield, and Maricopa with intensity of III—IV. Weak but perceptible at Santa Barbara and Los Angeles.
	2-16	07:57	VII	---------	San Andreas fault south of Maricopa.	II(?)	Strong shock felt over wide area. Intensity was IV at San Luis Obispo and Los Angeles. Los Olivos and Ojai reported intensities III and V, respectively.
	8-26	04:12	V+(?)	---------	Santa Barbara County----	V(?)	Generally felt at Santa Barbara and from San Luis Obispo to Ojai. No damage reported.

See footnote at end of table.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*—Continued

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
1920	6-18	02:08	VIII(?)	---------	Los Angeles region------	III(?)	Sharp quake, felt also on Santa Catalina Island. (Reports seem to indicate an origin on submarine fault in the San Pedro Channel.)
	6-20	18:48	IX	---------	Inglewood, Los Angeles County.	II(?)	High intensity of VIII—IX near the source in small area of the western part of Inglewood. Barely felt at Ventura.
1924	12-30	---------	IV(?)	---------	Santa Barbara-----------	------------------	Two "sharp, heavy blows."
1925	1-28	09:30	IV	---------	Ojai--------------------	II(?)	Two slight shocks.
	2-7 to 4-15.	---------	II—VII	---------	Imperial Valley swarm---	------------------	
	6-29	06:42	IX	6.3	Santa Barbara-----------	------------------	Strong, destructive local earthquake practically destroyed the business section of Santa Barbara. Felt from Watsonville on the northwest to Santa Ana on the southeast and inland to Mojave.
	6-29 to 10-9.	---------	---------	---------	Santa Barbara and Ventura Counties.	------------------	Forty-two earthquake reports from Santa Barbara area. Most of these were aftershocks associated with the event of June 29, 1925. About 32 reports from Santa Barbara alone yield a count of 10 strong aftershocks. Only the aftershocks of some special significance will be listed separately.
	7-3	08:38	VII(?)	---------	Santa Barbara-----------	VII(?)	Also felt at Pasadena, III; Ojai, III; and Ventura IV(?).
	7-3	10:21	VII(?)	---------	-----do-----------------	------------------	Sharp and heavy. Instrumental records indicate this was strongest Santa Barbara aftershock.
	7-5	04:00 to 23:00.	II—III(?)	---------	-----do-----------------	------------------	Eleven-shock swarm of felt tremors. A thermograph instrument recorded almost continuous vibrations between 7 and 10 a.m.

	7-6 to 7-9.	---------	---------	---------	-----do-----------------	------------------	Continued activity during after-shock sequence.
	7-30	---------	IV(?)	---------	Santa Barbara, Ventura, and vicinity.	------------------	Several felt earthquakes.
	8-12	---------	V	---------	Ojai--------------------	III(?)	Abrupt bumping also felt at Ventura (III(?)).
	8-13	---------	III(?)	---------	Santa Barbara-----------	------------------	(Several light shocks.)
	10-30	---------	III(?)	---------	-----do-----------------	------------------	"Little jolt," followed by sharp shock. Second event felt at Ventura also.
1926	1-12	02:15	IV	---------	Ojai--------------------	III(?)	Abrupt bumping, awakened many sleepers. Felt at Santa Barbara.
	2-18	10:18	VI+	---------	Origin at sea southwest of Ventura.	VI(?)	Windows broken at Santa Barbara school, water pipe broken in roundhouse. Felt along the coast from San Luis Obispo on the northwest to south of Santa Ana, a distance of 200 miles. No mention of tsunami.
	5-3	05:53	VI(?)	---------	Origin at sea southwest of Point Hueneme, Ventura County.	III(?)	Felt at San Luis Obispo, 100 miles to northwest. Ventura intensity VI(?). Slight tremor at Santa Barbara. No mention of tsunami.
	5-14	---------	IV+(?)	---------	Ojai--------------------	III(?)	Also felt as slight shock at Santa Barbara.
	6-24	07:30	V	---------	Santa Barbara-----------	------------------	Two shocks, like sharp blows, felt by all; pendulum clocks stopped.
	6-27	17:30	IV	---------	Ventura-----------------	------------------	Two shocks, abrupt; bumping; felt by many.
	6-29	15:21	VIII(?)	---------	Santa Barbara-----------	VIII(?)	Shock from possible offshore fault exactly one year following destructive 1925 earthquake. Child killed by falling chimney. Glass broken, cracks in walls enlarged; surf agitated violently (probably due to seaquake, possibly due to small tsunami).
							Felt from Los Angeles to Buellton, 30 miles west-northwest from Santa Barbara, where shock was felt by all; plaster was cracked.

See footnote at end of table.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*—Continued

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
	7-3	15:00	II	---------	-----do-----------------	------------------	Four slight shocks within 20-minute period. Felt by very few.
	7-6	09:45	V	---------	-----do-----------------	------------------	Three shocks felt by many. Buildings swayed.
	8-6	09:42	IV	---------	Santa Barbara region----	------------------	Sharp quake at Santa Barbara, also felt at Ojai and Ventura.
	8-8	20:12	V+(?)	---------	Santa Barbara-----------	------------------	Shook dishes from shelves and caused noticeable swinging of chandeliers.
	9-28	09:49	V(?)	---------	Ventura-----------------	IV(?)	Located at sea southwest of Ventura. Felt at Santa Barbara and Ojai also.
	11-4 to 11-11.	---------	V–VI	---------	Santa Ana, Yorba Linda, Los Angeles.	------------------	Swarm of felt shocks, no instrumental record for many of these.
	11-24	---------	---------	---------	Imperial Valley---------	------------------	(Possible beginning of Imperial Valley swarm, Nov. 24, 1926, to Feb. 23, 1927.)
	12-19(?) to 12-20(?)	---------	III+	---------	Ventura-----------------	II(?)	Two slight shocks 1 hour and 40 minutes apart.
1927	1-1	00:17	VIII	---------	Imperial Valley---------	------------------	Strong beginning of a long series of shocks (including part of swarm suggested above for Nov. 24, 1926, to Feb. 23, 1927).
	5-15(?)	03:20	V+	---------	Ventura-----------------	III(?)	Pronounced shock which cracked windows in Ventura. Probably originated on offshore fault south of Point Hueneme.
	7-15	17:55	V+	---------	Imperial Valley---------	------------------	Series of shocks (in brief swarm).
	8-4	04:24	VI+	---------	Santa Monica Bay--------	IV(?)	Origin located offshore. Felt from Ventura to Anaheim on coast and to San Bernardino.

	8-26	04:40	V+(?)	---------	Santa Barbara-----------	------------------	Two sharp shocks, causing much alarm. Also felt at Ventura.
	11-4	03:00 to 03:30	V(?)	---------	Point Arguello, Lompoc--	II(?)	Four shocks preceding strong event at 05:51.
	11-4	05:51	IX-X(?)	7.5	At sea west of Point Arguello.	VI-VII	Largest earthquake in California following 1906 San Francisco event, until July 21, 1952 (7.7). Much stronger shock than 1925 Santa Barbara event. Seaquakes generated during some larger aftershocks. Small tsunami broke along coast at Surf and Port San Luis. Tsunami also recorded on tide gages at San Diego and Santa Barbara. Felt from Morgan Hill on the northwest to Whittier on the southeast. Many after-shocks, including some de-structive tremors, occurred through Dec. 31, 1927, and later.
	11-18	19:32	VI-VII	---------	Santa Maria-------------	IV(?)	
1930	8-5	03:25	VIII	---------	Santa Barbara-----------	------------------	
1933	3-10	17:54	IX+	6.3	Long Beach--------------	III(?)	An event of moderate magnitude similar to Santa Barbara 1925 quake, but $40 million in damages and 115 lives lost because of proximity to heavily populated area with many poorly constructed buildings and poor foundation conditions.
1941	6-30	23:51	VII-IX	5.9	Santa Barbara-----------	VIII	Most damaging earthquake since 1925, with origin in Santa Barbara Channel area. Total damage about $100,000. Many structures affected had been damaged in 1925 and had not been adequately repaired.
1945	4-1	15:43	IV	5.4	Santa Rosa Island-------	III(?)	Felt along the coastal area from Santa Maria, south through Santa Barbara and Ventura to Simi.

See footnote at end of table.

TABLE 3.—*Partial list of earthquakes felt in the vicinity of Santa Barbara Channel, 1800 to 1952*—Continued

Year	Month and day	Local time	Maximum R.F. intensity[1]	Magnitude	General location of maximum intensity area and (or) epicentral area	R.F. intensity[1] Santa Barbara area	Remarks
1949----	8-27	06:52	VI	4.9	Near Point Conception---	III(?)	Strong effects at Arlight and Lompoc.
1952----	7-21	03:52	X	7.7	Kern County-------------	VIII(?)	Largest earthquake in the continental United States since 1906. Strongly felt along southern California coast, including Santa Barbara area. Centered about 60 miles northeast of Santa Barbara. Caused damage to buildings in Santa Barbara with losses estimated at $400,000.

[1]The most commonly used form of the Rossi-Forel (R.F.) scale reads as follows (Richter, 1958):

I. Microseismic shock.—Recorded by a single seismograph or by seismographs of the same model, but not by several seismographs of different kinds; the shock felt by an experienced observer.

II. Extremely feeble shock.—Recorded by several seismographs of different kinds; felt by a small number of persons at rest.

III. Very feeble shock.—Felt by several persons at rest; strong enough for the direction or duration to be appreciable.

IV. Feeble shock.—Felt by persons in motion; disturbance of movable objects, doors, windows, cracking of ceilings.

V. Shock of moderate intensity.—Felt generally by everyone; disturbance of furniture and beds, ringing of some bells.

VI. Fairly strong shock.—General awakening of those asleep, general ringing of bells, oscillation of chandeliers, stopping of clocks, visible agitation of trees and shrubs, some startled persons leaving their dwellings.

VII. Strong shock.—Overthrow of movable objects, fall of plaster, ringing of church bells, general panic but no damage to buildings.

VIII. Very strong shock.—Fall of chimneys, cracks in the walls of buildings.

IX. Extremely strong shock.—Partial or total destruction of some buildings.

X. Shock of extreme intensity.—Great disaster, ruins, disturbance of the strata, fissures in the ground, rockfalls from mountains.

bottom profiles show that they extend at least several hundred feet beneath the sea floor. Some of the profiles, and especially the two that bound the offshore extension of the Rincon anticline, form scarps in very young bottom sediments (fig. 17). These bordering scarps are evident on precision depth records; one lies about 1½ miles south of Platform A, the other about 2 miles north.

Three short gravity cores collected in unconsolidated sediments across the axis of the anticline in the vicinity of Union Platform A (fig. 17) penetrated a shell-rich zone. The shells occurred from 0-4.7 inches in core SB-2, 5.3-6.6 inches in SB-5, and 9.8-16.0 inches in SB-6. Meyer Rubin of the U.S. Geological Survey dated these shells by using the radiocarbon method. The following ages were obtained: SB-2, 8,750 ± 300 years (W-2297); SB-5, 13,140 ± 350 years (W-2298); SB-6, 13,920 ± 350 years (W-2299). The locality of core SB-6 is just north of the south boundary fault of the Rincon trend. Because this fault has produced a scarp in the bottom sediments, it probably has moved since the shells were deposited. Core SB-2 is 3,300 feet south of the north boundary fault of the Rincon trend. Again, the presence of a scarp indicates that faulting may have occurred less than 8,750 ± 300 years ago. The facts that the scarps are preserved in relatively soft bottom sediments, and that movement presumably occurred after the shell layer was buried at core SB-6, suggest that the last movement on these faults may have been more recent than the radiocarbon dates.

The fault scarps indicate Holocene tectonic activity, some of which may have been accompanied by felt historic earthquakes in the Santa Barbara Channel. At least two earthquakes of magnitude 6.0 or larger have occurred in the channel; both were large enough to have resulted in surface faulting.

FUTURE EARTHQUAKES

Although the Santa Barbara Channel region is not known to have been the site of a great (magnitude > 8.0) earthquake, the historic record shows that it has experienced several severe shocks. In addition, the geologic record shows that a high level of tectonic activity has continued at least through late Tertiary and Quaternary time.

The history of destructive earthquakes provides an indication of what might happen in the future, but due to the small number of such events the record does not provide a statistically reliable basis for prediction. In many areas, however, the number of large earthquakes that occur in a region is simply related to the number of small earthquakes. More specifically, the numbers of shocks of different magnitudes are related by the equation

$$\log_{10} N = a - bM$$

where M is the Richter magnitude, N is the number of events greater than magnitude M, and a and b are constants that vary with the seismic region being considered (Richter, 1958).

Allen and others (1965) found that for the southern California region (Bishop to Ensenada) the smaller earthquakes provide a fairly good estimate of the rate of occurrence of the larger events. They calculated that on the average a magnitude 6.1 earthquake should occur each year in this entire region, and a magnitude 8.0 earthquake should occur once in 52 years. Such a great earthquake anywhere in southern California probably would have destructive effects in the Santa Barbara Channel region. Its aftershocks, many of which also would be destructive, might be expected to occur over an area the size of southern California.

The record of small shocks could also be used to estimate the frequency of occurrence of large earthquakes in the Santa Barbara Channel region. However, Allen and others (1965) found that for other areas of southern California such an analysis was unreliable and in some places misleading. The best indicator of future activity in the channel region, then, is the historic record.

Since 1900, two earthquakes of magnitude 6 have occurred in the area (in 1925 and 1941). No magnitude 7.5 earthquakes are definitely known, although the 1812 event could have been of that size. The magnitude 7.5 earthquake that occurred in 1927 was located outside the channel area, but it could have relieved stored seismic energy in the region, because it may have been associated with an extension of the Santa Ynez fault. The magnitude 7.7 Kern County earthquake of 1952 along the White Wolf fault, which is also alined transverse to the general structural trend of California, may have had a similar effect.

ASSOCIATED EFFECTS

GROUND MOTION AND FAILURE

The intensity of ground shaking during an earthquake depends largely on local geologic factors; chief of these are the thickness and physical properties of the materials composing the uppermost few hundred meters beneath the site. In general, the greatest amplitudes and longest durations of ground motion have been observed on thick, water-saturated, unconsolidated materials.

Although field experimental data that bear on ground amplification are sparse, research has been been done on seismic waves generated by underground nuclear explosions in Nevada and recorded in the San Francisco Bay region (Borcherdt, 1969). Ground-motion amplitudes recorded on soils and sediments near the margins of the bay were compared with those recorded on nearby bedrock outcrops. Maximum amplifications (in the horizontal component of ground motion) were observed on thick sections of "younger Bay mud" near the margins of the bay. At such sites, the peak ground-motion velocities were as much as 10 times larger than on nearby bedrock sites; and corresponding peak values in the ratio of the Fourier spectra (which reflect the duration and amplitude of shaking) were as much as 30 times larger than those observed on bedrock. This means that the amount of power or energy that is dissipated at a given frequency can be as much as 30 times greater on unconsolidated sediments than on bedrock.

It is probable that soft sediments in the Santa Barbara Channel region would also suffer such amplified shaking. The resulting failure could take one or more of several forms, such as liquefying, cracking, lurching, slumping and sliding, and generating of turbidity currents, with associated effects on bottom installations in the channel. Failures of this nature on the sea floor would be most likely to occur on the steeper offshore slopes. Maximum persistent sea-floor gradients within the channel are 12½°-15° along a short segment of the shelf break about 4 miles southwest of Coal Oil Point. About 12 miles south of Ventura, the steepest gradients on this same feature are as much as 7°. Similar slopes occur about 3 miles north of Santa Cruz Island. For comparison, the steeper persistent slopes on the south flank of the Santa Ynez Mountains are about 25° and shorter slopes are as much as 38° (fig. 3).

TSUNAMIS

The two largest tsunamis known to have been generated on the western coast of the United States formed in the Santa Barbara Channel region. The earthquake of 1812 near Santa Barbara caused waves that reportedly flooded the lower part of the town, and the 1927 shock off Point Arguello caused waves at least 6 feet high. The channel region is not known to have experienced high waves from externally generated tsunamis.

Sudden vertical movement of the sea floor is the most effective means of generating a tsunami, but alternate methods include horizontal movement on a sea floor of high relief and submarine landsliding. Energy radiation by tsunamis is greatest in the direction perpendicular to the axis of sea-floor deformation. Because faults in the channel generally are subparallel to the shoreline, the largest wave amplitudes from a locally generated tsunami probably would be directed toward the Santa Barbara coast or the north sides of the islands. In view of the possibility that tsunamis could be produced in the channel region, their effects on oil installations in Alaska after the 1964 earthquake will be reviewed.

SEISMIC EFFECTS ON OIL-FIELD INSTALLATIONS

Some of the effects that might accompany earthquakes in the channel region have been demonstrated by several moderate earthquakes in the Los Angeles area, the Kern County earthquake of 1952, and the Alaska earthquake of 1964.

In October 1941, a moderate earthquake (magnitude 4.9) affected the southwest part of the Los Angeles basin. The epicenter (as located instrumentally) was about 3 miles southeast of the Dominguez oil field on the Newport-Inglewood zone of faults and folds. On the same date, 15 flowing wells in the western part of the Dominguez field were damaged by subsurface movement on and near a previously recognized south-dipping reverse fault that trends west, subparallel to the Dominguez anticline. Bravinder (1942) concluded (1) that the faulting was due to relief of preexisting stresses near the crest of the anticline, and (2) that the relieved stresses were chiefly tectonic in origin.

In November of the same year (1941) a second earthquake, with a magnitude of 5.4, occurred with an instrumental epicenter about 4 miles south of that of the October earthquake. No subsurface damage was reported, although the Long Beach oil field is less than 2 miles from the epicenter; however, surface installations in the Torrance-Gardena area northwest of the epicenter were damaged. Two storage tanks on unconsolidated alluvium were "destroyed" and two more were badly buckled, a 6-inch oil pipeline (broken in one place during the October earthquake) was ruptured in four additional places, and an 8-inch natural-gas pipeline was broken. Ground cracks formed near the broken oil line (Wood and Heck, 1941).

Two and a half years later, on June 18, 1944, two moderate earthquakes (magnitude 4.4 and 4.5) occurred, with instrumental epicenters between that of the October 1941 shock and the Dominguez oil field. Later the same day, 16 oil wells in the Rosecrans field, 4¼ miles northwest of the epicenters and 2½ miles northwest of the Dominguez field, were found to be damaged by subsurface movement on a south-dipping reverse fault that trends west at a small angle from the axis of the Rosecrans structure (Martner, 1948). The faulting of October 1941 and June 1944 is attributed by Richter (1958) to direct seismic shaking or readjustment of the local strain pattern.

Three oil wells in the Inglewood field, also located along the Newport-Inglewood zone, were damaged during two small earthquakes (magnitudes 3.4 and 3.0) in February and March, 1963 (Hudson and Scott, 1965). The damage occurred at depth along previously recognized faults, but the instrumentally located epicenters were about 6 and 17 miles away. Hudson and Scott (1965) imply that the subsurface displacements at Inglewood were triggered by the earthquakes.

Oil pipelines, storage tanks, and subsurface installations were slightly affected by the Kern County earthquake of July 21, 1952. The magnitude of the shock was 7.7; damage occurred chiefly on unconsolidated alluvium, although pipelines were severed elsewhere by landslide movements and by repeated flexing. Other damage included settling of the ground around wells, which affected the pumping equipment, and collapsing of casing or kinking of tubing in shallow wells. The shock also caused collapse of the supports of two large spherical butane tanks at a gas-cycling plant and rupture of connecting pipelines and release of their contents, which led to an explosion and a costly fire (Johnston, 1955; Steinbrugge and Moran, 1954).

Oil-storage tanks sustained great damage as a result of the 1964 Alaska earthquake, chiefly from seismic shaking; in a few places, tanks were also affected by earthquake-associated subsidence or by landsliding, and some were affected by seismic sea waves. Storage tanks were damaged in Anchorage, Kodiak, Nikiski, Seward, Whittier, and Valdez. At Seward, ground motion caused almost immediate rupture of the storage tanks on the waterfront, and spills and widespread fire resulted; a submarine landslide in the alluvial deposits then carried a large part of the waterfront, including many of the tanks, into Resurrection Bay. The landsliding was followed by seismic sea waves, which inundated the entire waterfront area and severely damaged the remaining fuel tanks. Damage to the tanks was chiefly by seismic vibration, which caused rupture or buckling; some were totally destroyed by fire or waves.

Reports indicate that well equipment was not damaged in the Swanson River oil field and Kenai gas field. A 12-inch gas pipeline extended 93 miles from the Kenai field to Anchorage; an 8-mile, 2-pipe segment embedded in bottom silt of the Turnagain Arm of Cook Inlet was not seriously damaged, and only one small break occurred in the entire line. Extensive rupturing of the gas-distribution system in Anchorage resulted chiefly from landslides (Eckel, 1967).

The Kodiak-Valdez region was a natural laboratory for full-scale testing of a number of standard-design oil-storage tanks, some of which were fully loaded and others of which were partly loaded. Rinne (1967), who investigated the damage to tanks in Seward, Nikiski, and Anchorage, classified the effects as follows: (1) buckling of the shell (tank wall) near its base, (2) buckling of conical roofs and top covers, (3) damage to floating roofs and accessories, and (4) damage to connecting piping. The buckling response of the tank shells near the base received the most study and is attributed to lateral forces that probably acquired substantial amplification during several minutes vibration. Rinne (1967) found that standard-design tanks in the 20- to 70-foot diameter range were considerably less resistant to buckling than other sizes; tanks of about 30 feet diameter were found to be most susceptible. All the damaged tanks were founded on unconsolidated alluvial deposits. Fisher and Merkle (1965) suggest that the buckling may have been due to vertical displacement of the concrete base. The displacement accelerated the liquid and increased the fluid pressure acting on the lower part of the tank.

Seismic sea waves caused much of the damage after the Alaska earthquake, especially at Valdez and Seward. High-water marks of about 30 feet above "normal tide level" were recorded at several places, including Cordova, Kodiak, Seward, and Whittier. In addition, a mark of 170 feet was recorded at Valdez (Grantz and others, 1964, fig. 7). The effects of the waves were devastating in most of these areas, but many of the tanks vulnerable to them had already failed.

OIL-FIELD OPERATIONS

The removal of large volumes of fluid from Cenozoic clastic strata, such as those that contain California oil reservoirs, has led to complex readjustments within and above the reservoirs. Such readjustments commonly result in differential subsidence of the ground surface over and around the reservoir, and, in some places, in earthquakes and fault displacements. Although these effects may be prevented or minimized by maintaining original reservoir fluid pressures through fluid injection during extraction of the petroleum, fluid injection itself has recently been recognized as the probable cause of earthquakes in two places.

More than 40 examples of differential subsidence, horizonal displacement, or surface faulting have been associated with the operation of 28 California and Texas oil fields (Yerkes and Castle, 1969). Maximum recorded movements are: more than 29 feet of differential subsidence and 11 feet of horizontal displacement in the Wilmington oil field and 2.4 feet of fault displacement in the Buena Vista oil field, California.

Differential subsidence is the most common and widespread of the effects, but it is easily detected only in shoreline areas where it may result in local flooding. Where level surveys have determined the size and shape of the subsidence bowl, the subsided areas are centered over and extend well beyond the producing area. Subsidence was first reported in 1926 over the Goose Creek oil field near Houston, on the Texas Gulf Coast (Pratt and Johnson, 1926). The most spectacular and costly example of differential subsidence in the United States is that of the Wilmington oil field, where an elliptical area of more than 29 square miles has been affected. Large subsidence bowls also have been delineated over California oil fields at Huntington Beach, Long Beach, and Inglewood.

Centripetally directed horizontal displacement of the ground surface accompanies differential subsidence, but can be precisely documented only by triangulation surveys, and hence has been determined in only three United States oil fields: Buena Vista, Inglwood, and Wilmington, all in California. Surface installations such as foundations, piers, and piles are most seriously affected by such displacements.

Surface faulting, in addition to being the most conspicuous and easily documented effect, may also occur suddenly, and it is therefore potentially more damaging to oil wells and surface structures. Subsidence-associated surface faulting is most commonly high angle and normal, peripheral to the subsidence bowl, and downthrown on the oil field side; it commonly trends subparallel to the isobase contours. Examples of this type have developed over the Goose Creek and Mykawa fields in Texas and over the Inglewood and Kern Front fields in California. The surface fault at Kern Front developed over a preexisting subsurface fault; the surface break extends for 3 miles and is the longest known example of this type. Displacement has been virtually continuous for at least 20 years and totaled more than 1 foot in 1968.

A thrust fault has formed in response to intense horizontal compression induced by measured subsidence in a unique example at the Buena Vista oil field in California. The fault sheared about 20 wells at depths no greater than 794 feet below the surface and no further than 1,800 feet from the fault trace, but the fault has not been detected in numerous other wells it should intersect if it were a tectonic feature. Cumulative displacement during 38 years of nearly continuous movement totals more than 2.4 feet.

Subsurface effects associated with oil-field operations also have been observed at the Wilmington oil field. In the central part of the field, sharply defined, nearly horizontal shear movements occurred at average depths of 1,550 and 1,770 feet in December 1947 and November 1949 (Frame, 1952). The movements were recorded at Pasadena, 28 miles away, as seismograms that were characterized by unusually large developments of long-period motion, suggestive of a shallow focus and lack of sharpness at the beginning of the motion (Hudson and Scott, 1965). Oil wells intersected by the slippage surfaces were damaged during each event; the maximum horizontal displacement in each event was about 9 inches (Frame, 1952), but the sense of displacement was not recorded. The November 1949 event was a major economic disaster, involving 302 wells, chiefly in the central part of the subsidence bowl; damages exceeded $9 million. Similar, less costly events also occurred in August 1951 and January 1955.

Fluid injection seems to have caused earthquakes in at least two places. The injection of water into a 12,000-foot deep well at the Rocky Mountain Arsenal northeast of Denver, Colo., is generally considered to have initiated the earthquake sequence that began there in 1962 (Healy and others, 1968). Three of these earthquakes had magnitudes greater than 5 and resulted in minor damage. The probable cause of the earthquakes was weakening of rock through increased pore pressure, which allowed natural rock stresses to be released. Another situation that possibly is similar to that in Denver was subsequently recognized in the oil field near Rangely, Colo. (Healy and others, 1968). The earthquakes there occurred in areas of high-pressure gradients generated by injection of water for purposes of secondary recovery.

SUMMARY

The Santa Barbara Channel region is seismically active: since 1900 it has experienced two earthquakes of magnitude 6, and in 1812 it was the site of a shock that may have attained magnitude 7. Several earthquakes greater than magnitude 7 are known to have occurred in nearby regions of California. Tsunamis have been generated in the channel region; however, none was associated with the magnitude 6 earthquakes of 1925 and 1941, which were located under the channel. Earthquakes of magnitude 6 and larger can be expected to occur in the future in the vicinity of the channel, and it would be consistent with past behavior if several such events occurred in the next century. At present it is not known which of the several channel faults are seismically active, because the quality of the existing seismograph network does not allow accurate epicenter location. The possibility must be recognized that natural earthquakes or tectonic deformation could occur in the channel region and mistakenly be associated with oil-field operations. In the past, onshore southern California oil wells have been damaged by subsurface faulting during natural distant earthquakes, as well as by locally induced subsurface and near-surface faulting. No surface spills have resulted from any of these events. Surface installations, chiefly storage tanks and pipelines, have been damaged by the effects of seismic shaking during both moderate- and large-magnitude earthquakes.

A large earthquake (magnitude 7 or greater) in the Santa Barbara Channel region would cause intense shaking with associated ground deformation and failure, particularly in artificially-filled areas, alluviated valleys, and unstable hillside slopes. The resulting damage to manmade structures would no doubt be great, especially during the wet season when water saturated ground would slide more easily. Oil installations would probably also suffer damage, but not out of proportion with other damage. Effects from such damage can be reduced by certain reasonable precautions, many of which are standard practice. The hazards to oil installations, in order of what is considered to be decreasing importance, are tabulated below.

Hazard	*Remarks*
Rupture of storage tanks resulting in leakage and fires.	This hazard can be minimized by: (1) Selecting firm ground for necessary storage areas, (2) designing storage tanks to withstand earthquake forces, (3) using only the minimum number of tanks necessary, (4) constructing well-engineered containment dikes for adequate volumes, and (5) providing fire equipment adequate to cope with numerous, simultaneous fires.
Fracture of ground resulting in oil migration from depth to the surface and into the ocean.	This hazard exists irrespective of the oil operations and would normally be considered " an act of God;" however, the possibility exists that an earthquake could reopen cracks or reactivate leaks that originated from oil field exploitation. Equipment for collecting oil both from the ocean surface and from the leak at the sea floor, techniques for plugging leaks, and oil-slick dispersants can reduce effects from this hazard.
Damage to oil wells, such as sheared casings, resulting in oil leakage into the ocean.	Many wells have been sheared by movement in California without causing serious leaks. In many places the effect of the movement is to pinch off the well casing, which would actually inhibit leakage. The possibility of leakage caused by fault movements in the Santa Barbara Channel region, however, cannot be ignored. If high subsurface pressures were released to the surrounding rocks in shallow reservoirs and fractures formed to the sea floor, a leak could result. Procedures for coping with an event such as this are similar to those described for the preceding hazard.
Rupture of pipelines carrying oil from the platforms to shore resulting in oil leakage into the ocean.	This type of accident would release only a limited volume of oil. A break in the deeper parts of the pipeline would release less oil than a break near shore, but would probably be more difficult to repair. Present regulations require cutoff valves in the pipelines to prevent further oil pumping if a leak occurs. The volume of oil carried in an existing 6-mile-long pipeline owned by Phillips Oil Co. is 515 barrels per mile; a Union Oil Co. pipeline 10½ miles long contains 731 barrels per mile.
Partial or complete destruction of a drilling platform by an earthquake or tsunami.	The major loss in platform destruction would be a financial loss to the producer with minor danger to the environment unless wells are at critical stages of drilling or development. Completed wells have chokes and automatic cutoff valves at the sea floor. Their control does not depend on the integrity of the platform. Uncompleted wells present special problems and must be dealt with as special problems. It is noteworthy that platforms have been destroyed by gulf coast hurricanes and have not resulted in significant oil spills.

Operators have provided the information that platforms on offshore Federal leases have been designed by engineering consultants in conformance with regional construction code standards. For example, the platforms on Dos Cuadras field have a freeboard that exceeds the height of any predicted storm wave or tsunami at that location and are designed for a seismic load factor of 0.15 g (maximum ground acceleration).

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APPENDIX A

History of Well No. A-21, Lease OCS P-0241, as Compiled by M. V. Adams, Petroleum Engineer, U.S. Geological Survey, June 1969

The notice to drill this well was approved by the U.S.G.S District Engineer on January 9, 1969. The coordinates of the rotary table were $X=984{,}848$ and $Y=804{,}198$ with the proposed bottom hole coordinates of $X=984{,}715$ and $Y=803{,}750$ at a measured total depth of 3,455′ KB(3,179′ BOF), or 3,400′ KB(3,124′ BOF) true vertical depth.

There is 20″, 104.13 lb conductor driven to 291′ KB(15′ BOF). The well was spudded with drilling mud at 4:00 p.m. on January 14, 1969, using the Peter Bawden vertical rig. A 12¼″ directional hole was drilled to 520′ KB(244′ BOF) with full returns. The hole was opened to 17½″ and a string of 13⅜″, 61 lb, J-55, surface casing was run to 514′ KB(238′ BOF). The casing was cemented with 300 sacks of class "G" cement with 25 lb of Gilsonite per sack added followed by 100 sacks of class "G" neat cement. Cement returns to the surface were obtained.

While standing cemented a 13⅝″, 3,000 psi working pressure, Shaffer unitized well head was installed. Blowout prevention equipment consisting of a 12″ series 900 double Shaffer gate with blind and 4½″ pipe rams and a 12″ series 900 GK Hydril was installed and tested prior to drilling out the 13⅜″ shoe.

Between January 17 and January 28, a 12¼″ directional hole was drilled to a total depth of 3,479′ KB(3,203′ BOF) measured depth. A directional survey (apparently the last taken) at 3,222′ KB(2,946′ BOF) showed a true vertical depth of 3,143.67′ KB(2,867.67′ BOF), a deviation of 2°30′ and a direction of N. 19° W. The coordinates of the hole at this point were 417.72′ south and 134.59′ west of the surface location.

On the morning of January 28, the drilling crew started out of the hole to run logs. It was reported that the first five stands of drill pipe pulled tight but the next three pulled free. However, while breaking out the eighth stand (at 10:45 a.m.) the well started blowing through the drill pipe. An attempt was made to stab the inside blowout preventer but the well was blowing too hard to do it. They then set out to pick up the kelly to stab it into the drill pipe but in picking it up the rotary hose caught on a bull plug in the standpipe and broke it off. With the standpipe open it was considered too great a fire hazard to pursue stabbing the kelly. Accordingly, they picked up the drill pipe with the elevators until a tool joint was above the pipe rams, closed the rams to hold the pipe while they unlatched the elevators, then opened the rams and dropped the drill pipe down the hole. They then closed the blind rams (at 11:00 a.m.) to shut the well in.

Shortly after closing the well in the surface pressure was 400 psi and boils of gas began to appear on the surface of the water. An attempt was made to kill the well by pumping 90-lb mud down the casing through the kill line and bleeding off the gas through the choke line. This operation was not successful so stripping drill pipe into the hole, under pressure, through a pair of GK Hydril blowout preventers was commenced.

By late January 29 adequate drill pipe had been stripped into the hole and was successfully screwed into the fish. It was attempted to circulate through the drill pipe but the bit was plugged and even at 5,000 psi circulation could not be established. An attempt was then made to pull the drill pipe but although it did move some 7′, it would not pull free.

Several attempts were made to back off the drill pipe deep enough to kill the well with mud but in each instance the pipe backed off above the top of the original fish. During this operation the pressure on the casing was on the order of 180 psi which would drop to 40 to 80 psi by flowing through the casing. Also, sea water was pumped into the casing at rates as high as 15 barrels per minute which would drop the pressure to 60 psi but it would quickly build back up to 180 psi.

When the drill pipe was originally snubbed into the hole to screw into the fish it was, of course, necessary to blank off the inside of the drill pipe at the bottom of the first joint. This was done with a Gray inside blowout preventer. Then, since the drill pipe could not be backed off deep enough to kill the well it was decided to mill out the Gray float. The milling was done using a 2⅛″ mill run on 2⅜″ tubing driven by a power swivel. Milling began at 4:30 a.m. on February 3, at a depth of 731′ KB(455′ BOF).

The milling was completed later in the day and a Schlumberger 1$\frac{9}{16}$″ scallop gun was successfully run to a depth of 2,942′ KB(2,666′ BOF). Since there was heavy weight drill pipe up to 2,913′ KB(2,637′ BOF), it was decided to perforate in the lighter pipe above this point. Accordingly, the pipe was perforated with 97 holes, 0.34″ in diameter, in the interval from 2,860′-2,883′ KB(2,584′-2,607′ BOF). Before perforating, the drill pipe was pressured to 500 psi which bled to zero after perforating, indicating that the perforating job had succeeded.

While rigging up to kill the well, sea water was pumped down the drill pipe at a rate of 23 barrels per minute and a pressure of 2,100 psi with no indication that it was killing the well. On February 5, 100 cubic feet of water with green dye was pumped into the drill pipe and displaced with 685 barrels of water at a rate of 14 barrels per minute and a pressure of 1,000 psi. An additional 100 cubic feet of dye water was pumped down the casing and displaced with 565 barrels of water at a rate of 14 barrels per minute and a pressure of 1,050 psi. None of this dye appeared on the surface of the ocean. The dye water was followed with 250 barrels of 100-lb mud pumped at a rate of 8 barrels per minute and a pressure of 275 psi. After pumping the mud the casing pressure was 180 psi. Pumping sea water down the drill pipe was continued during the night of February 5, and part of the day of February 6, while assembling and hooking up additional HOWCO pumping units on the platform and waiting on a mud barge with an additional supply of mud. While pumping down the drill pipe the annulus was blown down from 190 psi to zero in 10 minutes but when it was closed in, it built back up to 190 psi in 2 hours.

After checking out and testing the HOWCO pumping units 1,000 barrels of sea water was pumped down the drill pipe at a rate of 27 barrels per minute and a pressure of 2,500 psi. The water was followed with 210 barrels of 116-lb mud pumped at a rate of 27 barrels per minute and a pressure of 2,650 psi. At this point a line blew off the fracing head and it was necessary to shut down the HOWCO pumps to repair it. After effecting repairs the mud in the drill pipe was displaced with 230 cubic feet of sea water and the well was shut in. During the entire operation the casing pressure on the well had remained at 190 psi. However, after pumping the mud the bubble at the east end of the platform was noticeably smaller but after 10 minutes it had returned to its original size.

In the meantime a massive effort had been made on the part of essentially all of the operating and service companies in the area to assemble mud, equipment and cement for a maximum effort to kill the well. This effort commenced at 11:05 a.m. on February 7, by pumping sea water with dye, calcium chloride water and mud down the drill pipe while repairing leaks in lines and organizing the pumping operation. Steady pumping down the drill pipe began at 4:00 p.m. and by 5:00 p.m. all nine HOWCO units were in operation pumping mud down the drill pipe at a rate of 30 barrels per minute and a pressure of 3,750 psi. At this time the rig pumps started pumping mud down the annulus. By 5:30 p.m. the bubble began to decrease and the well was eventually killed with 13,000 barrels of 90-lb to 110-lb mud.

APPENDIX B

Seepage at Lease OCS P-0241 estimated by the U.S. Geological Survey for the period March 22 to August 31, 1969

Time period		Days elapsed	Barrels recovered[1] [2]		Barrels lost (estimated)[2]		Seepage (estimated)[2]	
From	To		Total	Daily rate	Total	Daily rate	Total	Daily rate
Mar. 22[3]	Apr. 2	12	36	3.0	324	27	360	30
Apr. 3	May 2	30	220	7.3	681	22.7	901	30
May 3	May 22	20	354	17.7	246	12.3	600	30
May 23[4]	June 14	23	599	25.6	101	4.4	691	30
June 15[5]	June 18	4	37	9.2	83	20.8	120	30
June 19	June 26	8	182	22.8	57	7.2	239	30
June 27[5]	June 28	2	12	6	48	24	60	30
June 29	July 1	3	51	17	39	13	90	30
July 2[5]	---	1	1	1	29	29	30	30
July 3	July 13	11	253	23	77	7	330	30
July 14[5]	July 15	2	4	2	36	18	40	20
July 16[6]	July 31	16	128	8	112	7	240	15
Aug. 1[6] [7]	Aug. 31	31	86	2.8	224	7.2	310	10
Totals------		163	1,954	---	2,057	---	4,011	---

[1]Measured oil recovery (net barrels) from hoods, funnels, and tents, plus oil recovered on surface by skimming boats. Oil slicks, monitored by photographs and daily observations.

[2]One barrel equals 42 gallons.

[3]First installation of collecting devices.

[4]Large tents added east of Platform A.

[5]Hose line damaged.

[6]Remedial shallow drilling and grouting program in progress.

[7]Large tent, 800 feet east of Platform A, damaged.

APPENDIX C

Drilling Programs Authorized for Lease OCS P-0241 Following Recommendations of the Presidential Advisory Panel Transmitted June 2, 1969

Programs authorized June 9, 1969

Well	Rig	Drilling distance, in feet	Producing zones	Perfs. (RT)	Casing depth—vertical penetration, in feet, for indicated casing diameter, in inches					
					20 (drive)	16 (cement)	13 3/8 (cement conductor)	10 3/4 (cement)	9 5/8 (cement)	7 (cement)
A-3---	Vertical	1,260 plug back 1,159	Brown--	608—1,140	19	104	276	801	---	---
A-22--	Vertical	475	Red----	344—471	16	107	---	196	---	---
A-24--	Vertical	1,092	Brown--	578—1,082	101	---	255	797	---	---
A-44--	Slant	1,971 plug back 1,705	Brown--	713—1,677	10	101	261	832	---	---
B-13--	Vertical	1,284	Brown--	738-1,279	15	92	310	886	---	---
B-18--	Vertical	1,150 core hole	Brown test and shut-in	648—53 772—97 1,089—94	15	98	299	---	867	---
B-30--	Vertical	1,275	Brown--	670—1,264	14	101	315	861	---	---
B-40--	Slant	1,610	Brown--	813—1,601	90	---	332	900	---	---
B-47--	Slant	1,588 plug back 1,400	Brown--	826—1,395	10	108	284	811	---	---

Programs authorized August 1, 1969

Well	Rig	Drilling distance, in feet	Producing zones	Perfs. (RT)	Casing depth—vertical pentration, in feet, for indicated casing diameter, in inches				
					20 (drive)	16 (cement)	13 3/8 (cement conductor)	10 3/4 (cement)	7 (cement)
Upper zones									
A—37--	Slant------	2,300	Yellow Purple	1,385—2,210	10±	101	234	857 E	1,744
A—43--	Slant------	2,500	Yellow Purple Yellow	1,350—2,385	10	100	235	855 E	1,975
B—41--	Slant------	2,475	Yellow Purple Yellow	1,470—2,400	10±	98	345	879 E	1,831
B—43--	Slant------	2,750	Yellow Purple Yellow	1,565—2,662	12	100	237	827 E	1,912
Lower zones									
A—30--	Vertical---	3,500	Purple Orange Green	2,180—3,438	10±	100	255	1,052 E—2	3,107
A—36--	Vertical---	4,250	Purple Orange Green	2,810—4,160	11	100	255	1,015 E—1	3,445
B—29--	Vertical---	3,900	Purple Orange Green	2,060—3,818	10±	100	360	1,134 E—1	3,330
B—2---	Vertical---	4,150	Orange Green	2,960—4,090	10±	101	306	1,151 E—1	3,231

APPENDIX D

Status of wells drilled from Platform A on Lease OCS P-0241, May 10, 1969, showing selective pressure drawdown zones authorized

Well	Rig	Drilling distance, in feet	Producing zones	Perforations (drilled depth, in feet)	Production (bbl oil per day)
A-20----	Vertical-------	3,673 plug back 3,442	Purple Orange Green	2,131-3,427	2,110
A-21----	Vertical-------	1,081 (redrill)	Brown	591-1,070	564
A-25----	Vertical-------	4,550 plug back 3,900	Orange Purple Orange Green	2,433-3,876	1,056
A-38----	Slant----------	3,030 plug back 1,086	Brown	685-1,010	Shut-in
A-41----	Slant----------	3,010 plug back 1975	Brown Yellow	946-1,916	982

APPENDIX E

Blowouts from outer Continental Shelf drilling and workovers since enactment of OCS Lands Act of 1953

Wells drilled for oil and gas on OCS-1953 to Aug. 1, 1969 (excludes 254 wells drilled prior to 1953 and 102 salt and sulfur wells):

Drilling wells	133
Wells completed for production or service (7324 zone completions: 5607, oil; 1717, gas)	4428
Dry or abandoned holes	3299
Total wells drilled	7860

No.	Area and block, lease and well No., and operator	Type blowout, depth, and out-of-control period	How controlled	Volume oil spill	Extent of damage
		Gulf coast region			
1	Vermilion Block 26 OCS 029, well A-1 Union Oil of California	Gas; 11,435'; 6-8-56 to 11-7-56.	Drilled relief well.	---------	Lost platform, rig, and two wells by crater.
2	Eugene Island Block 175 OCS 0438, well A-6 Sinclair Oil & Gas Co.	Gas; 11,290'; 10-19-57 (11 hours).	Bridged	---------	Caught fire but continued with same rig.
3	South Pass Block 27 OCS 0353, well 25 Shell Oil Company	Gas; 1,869'; 6-14-58 (2 hours).	Bridged	---------	Caught fire but little damage.
4	West Delta Block 45 OCS 0138, well E-7 CATC	Oil; (swabbing); 10-15-58 to 11-21-58.	By last of three relief wells.	(None reported.)	Explosion, then fire. Two other wells also. Lost platform. Seven casualties.
5	S. Timbalier Block 134 OCS 0461, well D-1 Gulf Oil Corporation	Gas; 4,880'; 7-27-59 (4 hours).	Bridged	---------	Caught fire but little damage.
6	Vermilion Block 115 OCS 0770, well 1 Phillips Petroleum Co.	Gas; 13,001'; 11-18-60 (4 hours).	Bridged	---------	None reported.
7	Grand Isle Block 9 OCS 035-S, well 1-34-B Freeport Sulphur Co.	Gas; (shallow); 3-18-62 (36 hours).	Ceased	---------	Fire. Lost platform and rig.
8	West Delta Block 28 OCS 0384, well 3 Chevron Oil Company	Gas; 10,871'; 1-15-64 (12 hours).	Mud	---------	No damage.
9	West Delta Block 117 OCS-G-1101, well A-5 Gulf Oil Corporation	Gas and oil; (completed); 1-20-64 to 1-27-64.	Bridged	(None reported.)	Caught fire. Platform damaged extensively.
10	Eugene Island Block 273 OCS-G-0987, well 4 Pan American Petroleum Corp.	Gas; 684'; 6-30-64 (2 days)	Ceased	---------	Explosion, fire. Drilling vessel sank. Casualties 22.
11	Eugene Island Block 158 OCS-G-1220, well B-3 Shell Oil Company	Gas; 15,867'; 3-15-65 (5 days).	Bridged	---------	(None reported.)
12	S. Marsh Island Block 48 OCS 0786, well B-4 Gulf Oil Corporation	Gas; (shallow); 9-16-65 (Several days).	Ceased	---------	(None reported.)
13	S. Timbalier Block 21 OCS 0263, well 70 Gulf Oil Corporation	Gas; 11,716'; 9-25-65 to 10-8-65.	Ceased	---------	Removed rig before well cratered.
14	Ship Shoal Block 208 OCS G-1294 Union Oil of California	Oil; (workover); 2-5-66 (15 min.).	Installed valve.	(None reported.)	(None reported.)
15	Eugene Island Block 275 OCS G-0988, well A-9 Texaco Inc.	Oil and gas; 10,561'; 2-13-66 (2 days).	Ceased	(None reported.)	Little damage.
16	S. Timbalier Block 67 OCS 020, well C-12 Humble Oil & Refining Co.	Gas; 1,477'; 4-17-67 (8 hours).	Bridged	----------	One corner platform settled.

	Area and block, lease and well No., and operator	Type blowout, depth, and out-of-control period	How controlled	Volume oil spill	Extent of damage
		Gulf coast region--Continued			
17---	S. Timbalier Block OCS 0463, well J-15 Gulf Oil Corporation	Oil; (workover); 2-21-68 (1 hour).	Closed valve.	(None reported.)	Caught fire, rig destroyed.
18---	South Pass Block 62 OCS G-1294 Shell Oil Company	Gas; 8,426; 4-68.	Cemented drill pipe.	--------- ---------	(None reported.)
19---	Grand Isle Block 43 OCS 0175 Continental Oil Co.	Gas; 14,184'; 9-68 (several days).	Bridged---	---------	(None reported.)
20---	S. Timbalier Block 67 OCS 020, well C-16 Humble Oil & Refining Co.	Gas; 910'; 9-28-68 (9 hours).	Bridged---	---------	Caught fire. Later removed rig, platform settled.
21---	S. Marsh Island Block 38 OCS 0784 Pan American Petroleum Corp.	Gas; 387'; 10-30-68 (1 day).	Bridged---	---------	(None reported.)
22---	Vermilion Block 119 OCS 0487, well D-11 Continental Oil Co.	Gas; 9,544'; 11-24-68 (12 hours).	Bridged---	---------	(None reported.)
23---	Vermilion Block 46 OCS 0709, well A-3 Mobil Oil Corporation	Gas; 8,168' 3-14-69 to 5-16-69.	Mud-------	---------	No. damage.
24---	Ship Shoal Block 72 OCS 060, well 3 Mobil Oil Corporation	Oil; 9,034', 3-16-69 to 3-19-69.	Capped----	900 bbl per day; 2,500 bbl total.	No damage.
		Pacific region			
1----	Santa Barbara Channel OCS P-0241, well A-21 Union Oil Co. of California	Oil and gas; 3,479'; 1-28-69 to 2-7-69.	Cemented--	300-500 bbl per day	(None reported on platform.)

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