CENTRAL COASTAL PROVINCE (011)

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With a section on the Cuyama Basin by M.E. Tennyson

INTRODUCTION

Province 11 includes much of central coastal California from Point Arena southward to the western Transverse Ranges (but does not include the Santa Maria Province, which is being assessed separately). Province 11 is bounded on the east by the San Andreas Fault, on the south by the Big Pine Fault, on the southwest by the Sur-Nacimiento Fault, and on the west by the 3-mi limit offshore. The province is about 390 mi long from northwest to southeast, about 40 mi wide at its widest near Soledad, California, and occupies an area of about 8,000 sq mi.

The main petroleum exploration objectives in Province 11 are in moderately deformed Tertiary sedimentary rocks, which locally exhibit a composite thickness of more than about 48,000 ft. Upper Cretaceous sedimentary rocks as thick as 13,000 ft are present locally but are believed to have poor petroleum potential. Over most of the province, the Tertiary and Upper Cretaceous sedimentary rocks overlie Cretaceous and older granitic and metamorphic rocks of the Salinia terrane. However, parts of the Santa Cruz Mountains are underlain by rocks of the Franciscan assemblage, and a small coastal area near Point Arena, California, appears to be underlain by unnamed and undated spilite that may represent a fragment of Mesozoic oceanic crust.

The earliest drilling operations in Province 11, exclusive of the Cuyama Basin, apparently occurred about 1867 near surface oil seeps in the Half Moon Bay, California area. The biggest oil field in the province, San Ardo (about 530-860 MMBO), was discovered in 1947. Since then, several smaller fields have been found in the Salinas, La Honda, and Bitterwater areas; the largest of these, King City oil field (about 2.1-3.3 MMBO), was discovered in 1959. By the end of 1991, cumulative production from Province 11, exclusive of the Cuyama Basin, was about 425 MMBO of oil and 72 BCFG. More than 99 percent of this petroleum was obtained from reservoirs in Miocene sandstones, and the remainder was produced from Eocene and Oligocene sandstones and Miocene limestone.

Exclusive of the Cuyama Basin, the province includes two confirmed plays, the Salinas (1106) and La Honda (1104) Oil Plays, and four hypothetical plays (listed from north to south): the Point Arena (1101), Point Reyes (1102), Pescadero (1103), and Bitterwater (1105) Oil Plays. The Bitterwater Play (1105) contains only one commercial oil field, and that field is smaller than 1 MMBO. Surface indications of oil and gas (e.g., tar sands, oil and gas seeps) are known from all six plays. However, some areas of Province 11 can be rejected outright as having no petroleum potential; these areas include extensive surface exposures of granitic and metamorphic rocks in the Point Reyes, Ben Lomond Mountain, Montara Mountain, Santa Lucia Range, Gabilan Range, and La Panza Range areas, and surface exposures of Franciscan rocks between the Pilarcitos and San Andreas Faults.

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CONVENTIONAL PLAYS

1101. POINT ARENA OIL PLAY (HYPOTHETICAL)

This hypothetical play is located immediately west of the San Andreas Fault in coastal Mendocino County, about 100 mi northwest of San Francisco. The Point Arena Oil Play includes known and hypothetical accumulations of petroleum in moderately deformed Miocene sedimentary rocks more than 5,250 ft thick. In this area, the Miocene rocks overlie as much as 30,000 ft of Paleogene and Upper Cretaceous clastic marine strata, which in turn presumably rest on spilite of unknown but possible Mesozoic age. The stratigraphy, structure, and geologic history of the area have been described by Weaver (1944), Boyle (1965), Addicott (1967), Wentworth (1968, 1972), Phillips and others (1976), Miller (1981), and Ingle (1987). The Point Arena Oil Play is bounded on the northeast by the San Andreas Fault, on the southeast by outcrops of the Paleocene and Eocene strata of German Rancho (Wentworth, 1968), and on the north and west by the 3-mi limit offshore. The surface area of the play is about 100 sq mi.

Reservoirs: Potential reservoirs include lenticular turbidite channel sandstones (some thicker than 30 ft) in the Miocene Gallaway and Point Arena Formations, and thick-bedded sandstone in the lower Miocene Skooner Gulch Formation. Fractured reservoirs may occur in siliceous fine-grained rocks in the Point Arena and Gallaway Formations; pervasively fractured rocks are common in outcrops of these units. Very speculatively, the upper Oligocene and lower Miocene Iversen Basalt may be overlain in places by small bodies of reservoir-quality limestone analogous to that found in the La Honda field of the Santa Cruz Mountains. Sandstones in units older than Oligocene--including the strata of German Rancho and the Cretaceous strata of Stewarts Point and Anchor Bay (Wentworth, 1968)--are very hard and strongly folded and faulted in outcrop; these sandstones appear to have little reservoir potential onshore, but they may be productive offshore.

Source rocks and hydrocarbons: Oil seeps and bituminous sandstones occur in the Point Arena and Gallaway Formations (Hodgson, 1980), and shows of oil have been reported from several wells. Oil in the bituminous sands is high in sulfur, severely biodegraded, and likely was derived from Miocene source rocks of low thermal maturity, according to unpublished organic geochemical studies (Alan Kornacki, Shell Oil Co., oral commun., 1992). The oil may have been generated locally, or it may have migrated from an unknown oil-generative center offshore. Onshore, unpublished Rock-Eval pyrolysis results suggest that shales and mudstones in the Gallaway and Point Arena Formations are likely source rocks; outcrop samples from these units are organic rich (values of total organic carbon up to 8 percent), oil prone, and thermally mature to immature with respect to the oil window (Karl Mertz, consultant, written commun., 1992).

Little published information is available on the timing of hydrocarbon generation and migration. In the offshore Point Arena Basin, exploratory wells and seismic reflection surveys show that upper Miocene to

Holocene strata are as thick as 9,000 ft. A comparably thick section of upper Miocene and younger rocks may once have covered the onshore Point Arena area, prior to removal by uplift and erosion during the Quaternary. In this hypothesis, deep burial resulting in maturation and migration of the hydrocarbons in the Gallaway and Point Arena Formations may have occurred anytime from the middle Miocene to the end of the Pliocene.

Traps: Anticlines are the major expected trap type. Each of the large surface anticlines along the sea cliff has been penetrated by at least one dry exploratory well, but the potential for small accumulations of oil on these structures cannot yet be dismissed. At least three smaller surface anticlines onshore have never been drilled; additional anticlines almost surely are present offshore between the shoreline and the 3-mi limit. Stratigraphic and tar-seal traps are possible in the Gallaway and Point Arena Formations, which contain many lenticular turbidite channel sandstones encased within thick sequences of shale. Additional undiscovered accumulations may be found in stratigraphic traps where sandstone in the Skooner Gulch Formation laps out onto the Iversen Basalt or pre-Iversen strata; and in fractured reservoirs beneath permeability barriers related to silica phase transitions in fine-grained siliceous rocks in the Gallaway and Point Arena Formations.

Exploration status: No commercial production of petroleum has been obtained from this area. Outcropping interbeds of bituminous sandstone in the Miocene Point Arena Formation contain an estimated 1.3 MMBO (Holmes and others, 1951). At least five wells have been drilled onshore. The deepest, the Sun Oil Co. Joseph Soldani 1-A, reached TD (total depth) of 7,800 ft in Oligocene (?) or possibly Cretaceous rocks in 1963 and reported slight shows of tar, live oil, and gas. The Standard Oil Co. of California Sun- Lepori No. 1 well tested 10 MCF/D from presumed Eocene rocks and reached TD of 6,361 ft in "green metamorphic rocks" that may be correlative with the Mesozoic (?) spilite that crops out at Black Point, south of Gualala, California. The Twin State Oil Co. No. 1 well allegedly swabbed 8 BOPD of 43û API oil from pre-Miocene rocks and reached TD of 7,632 ft in 1932. Both the N.F. Keyt No. 1 well (TD 1,738 ft in 1941) and the Brandenstein Silverberg No. 1 well (TD 780 ft in 1918) found shows of heavy oil in sandstones and fractured fine-grained rocks of the Point Arena Formation.

Resource potential: Within the Point Arena Oil Play, the most prospective area (about 40 sq mi) straddles the coastline between the Hathaway Creek Fault onshore and the 3-mi limit offshore. This area includes all the known tar sands and test wells but remains lightly explored. There is a strong possibility of undrilled anticlines between the shoreline and the 3-mi limit offshore. However, the area is close to the San Andreas Fault, so structures are likely to be small and complexly faulted and petroleum accumulations correspondingly small. Therefore, I have assigned a probability of 0.8 to occurrence of traps of sufficient size. Additional problems are the small size of the most prospective area, the lack of a regional upper Miocene to Pliocene seal (analogous to the Purisima, Etchegoin, and Pancho Rico

Formations in other petroliferous sedimentary basins of central California), and the fact that all the potential source and reservoir units have been exposed to the surface, greatly increasing the likelihood of degradation and loss of hydrocarbons.

The area between the Hathaway Creek and San Andreas Fault is regarded as having little or no potential because the Point Arena Formation is absent, the Skooner Gulch and Gallaway Formations are exposed at the surface, bedding dips are steep to overturned, and surface geologic maps show that the area is riddled by closely spaced, northwest-trending faults related to the nearby San Andreas Fault. The geology and petroleum potential of the offshore area seaward of two unnamed, throughgoing faults near the 3-mi limit (Wagner and Bortugno, 1982; McCulloch, 1987) are unknown.

In the most prospective part of the Point Arena Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be about 30 MMBO by very loose analogy with the so-called Patterson tar sands on the Lockwood High in the Salinas Basin. The Patterson tar sands are a reasonable analog because they occur in a generally similar, complex structural setting adjacent to a major strike-slip fault (the Reliz-Rinconada Fault), the principal reservoirs are Miocene feldspathic sandstones, and oil in both areas was most likely derived from nearby oil-generative centers in the Monterey Formation. The median undiscovered accumulation size in the Point Arena Oil Play is estimated to be about 1.5 MMBO; this is an outright guess and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps and only slightly larger than the minimum size (1 MMBO).

I estimated the median number of undiscovered accumulations by applying a modified form of the Checkerboard method to the most prospective part of the Point Arena Oil Play. I counted about 34 undrilled sections. Using a success ratio of 0.05 (from the Salinas Oil Play), I calculated about two sections with undiscovered accumulations in the Point Arena Oil Play, and accepted two as the probable median number of undiscovered accumulations. The least number of accumulations is estimated at 1. The largest number of accumulations is estimated to be about 10, or somewhat more than one accumulation for every four undrilled sections, by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be as high as 35 or 40, or about one accumulation for every undrilled section, but this seems too optimistic.

1102. POINT REYES OIL PLAY (HYPOTHETICAL)

This hypothetical play is located in the general vicinity of the Point Reyes Peninsula in Marin County, less than 15 mi northwest of San Francisco. The Point Reyes Oil Play comprises hypothetical accumulations of petroleum in gently to moderately deformed Tertiary sedimentary and minor volcanic strata as thick as 14,330 ft, which rest on granitic and metamorphic rocks of the Salinia terrane. The geology of the Point

Reyes area has been mapped and described by Galloway (1977) and Clark and others (1984), while laterally contiguous rocks in the adjacent offshore Bodega Basin are discussed by Hoskins and Griffiths (1971), McCulloch (1987), Webster and Yenne (1987), and Heck and others (1990). The play is bounded on the northeast by the San Andreas Fault and on the northwest, southwest, and southeast by the 3-mi limit offshore. The area of the play is about 225 sq mi. Most of the onshore part of the play is within the Point Reyes National Seashore, whereas the offshore part is part of the Gulf of the Farallones National Marine Sanctuary.

Reservoirs: The best potential reservoirs are Neogene sandstones, most notably the shallow-marine Miocene Laird Sandstone, which locally is as thick as 660 ft. The Laird was evidently a major objective in several wells drilled onshore during the late 1940s and early 1950s. The Laird was encountered at 4,685-4,795 ft in the Standard Oil Co. of California (SOCAL) Tevis No. 1 well but was found to be water wet in its lower part and tight in its upper part (Galloway, 1977). Some of the eight wells drilled in the nearby Federal offshore during the 1960's reported shows of oil from the Laird. Within the upper Miocene Santa Cruz Mudstone and Miocene Monterey Formation are lenticular channel sandstones that appear to be of reservoir quality. Fractured reservoirs may occur in siliceous fine-grained rocks in the Monterey Formation and the Santa Cruz Mudstone; minor shows of oil and gas were found in fractured chert and shale in the SOCAL Robson No. 1 and L.M. Lockhart RCA No. 3-1 wells. Within the area of the play, the Monterey Formation consists largely of intensely folded quartz cherts and porcelanites (White, 1990). Additional fractured reservoirs may be found in the generally tightly cemented sandstones of the Paleocene Point Reyes Conglomerate.

Source rocks and hydrocarbons: Oil is abundant in the Point Reyes area in surface seeps and shows in wells (Galloway, 1977; Hodgson, 1980). This oil may have been derived from organic-rich source beds in the Monterey Formation (locally at least 5,000 ft thick) or the Santa Cruz Mudstone (as much as 6,500 ft thick), but I have no organic geochemical data from these or any other potential source rocks in this play. Much oil may have been generated in the southeastern part of the play, where the Tertiary is more than 8,000 ft thick; additional oil may have been generated in some unidentified offshore area and then migrated updip and onshore.

Also unknown is the timing of petroleum generation and migration. Speculatively, these events may have occurred during the late Miocene and later, when the Monterey Formation was buried beneath at least 8,200 ft of overlying Santa Cruz Mudstone and Purisima Formation. Oil generation probably ceased over most of the area following late Pliocene and Quaternary uplift but may be ongoing in the southeastern part of the play and in the offshore. All of the potential source and reservoir units have been exposed to the surface, greatly increasing the chances for degradation and loss of hydrocarbons.

Traps: The most likely trap types, on the basis of available surface geologic maps and by analogy with the geologically similar Salinas and La Honda Basins, are small anticlines, fault truncations, and stratigraphic traps. The surface geology strongly suggests that buried anticlines of pre-late Miocene age are present in the southeastern part of the play beneath the regional angular unconformities that underlie the Santa Cruz Mudstone and the Purisima Formation. Small stratigraphic traps in the Santa Cruz Mudstone, in which lenticular channel sandstones are encased in siliceous shale, also may occur in the southeastern part of the play. In the Point Reyes lighthouse area, subthrust traps involving reservoirs in the Laird Sandstone and Monterey Formation may occur in the footwall of the offshore, northeast-dipping Point Reyes Thrust Fault; a possible analog for such accumulations is the Oakridge field of the Ventura Basin. A southwest-northeast structural cross-section from Point Reyes to Inverness, California, published by Galloway (1977), implies a stratigraphic trap in which the Laird Sandstone and Monterey Formation are truncated and sealed updip by the angular unconformity at the base of the Purisima Formation. Tar-seal traps, perhaps analogous to the Sargent oil field of Santa Clara County, may occur in the Laird and Monterey along the southwest flank of Inverness Ridge.

Thick, laterally persistent sequences of mudrock in the Santa Cruz Mudstone and lower part of the Purisima Formation are potential seals of regional extent.

Exploration status: No commercial production of petroleum has been established in the area of this play. However, there are abundant signs of petroleum in the form of oil seeps, bituminous sandstones, and shows in wells. Seeps of gas and oil have been reported from between Double Point and Duxbury Point, California, including one that was "big enough to cook fish on when lighted" (Galloway, 1977). Occurrences of bituminous sandstone are abundant in the Santa Cruz Mudstone and less abundant in the Laird Sandstone and Monterey Formation. Some interbeds of bituminous sandstone in the Santa Cruz Mudstone are as thick as 15 ft, but apparently have never been commercially mined. The oil sands and seeps in the area attracted oil well drilling as early as 1865 (Galloway, 1977). At least 14 wells were drilled, ranging in depth from 80 ft to more than 8,400 ft. The last well was abandoned in 1954. A well near Duxbury Point reportedly produced a few barrels of heavy oil for a short time about 1905. Three coreholes drilled a few mi north of Point Reyes by the Standard Oil Company of California found the upper Miocene and Pliocene Purisima Formation resting directly on granite at depths ranging from 950 to 1,620 ft. The deepest well in the area is evidently the Lockhart RCA well, drilled in 1949 about 2 mi east of Bolinas, California, which reached total depth in Luisian shale at 8,409 ft (Galloway, 1977).

Resource potential: The play is very lightly explored. The most prospective area is the southern part of the play, where the Tertiary section thickens to at least 8,400 ft; in this area, buried anticlines and stratigraphic traps in the Monterey and older units may be hidden and perhaps sealed beneath the more gently deformed Santa Cruz Mudstone. However, the area is close to the San Andreas Fault, so structures are likely to be small and complexly faulted and petroleum accumulations correspondingly small. Therefore, I have assigned a probability of 0.8 to occurrence of traps of sufficient size. Most of the northern part of the play is regarded as less prospective because it is apparently underlain by shallow granitic basement.

In the most prospective part of the Point Reyes Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be 30 MMBO, by very rough analogy with the Oakridge field of the Ventura Basin, which currently is estimated to be about 16 MMBO in size (sum of cumulative production to 12/31/92 and estimated reserves, according to California Division of Oil and Gas, 1993). The median undiscovered accumulation size in the Point Reyes Oil Play is estimated to be about 1.5 MMBO and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps, and only slightly larger than the minimum size (1 MMBO).

I estimated the median number of undiscovered accumulations by applying a modified form of the Checkerboard method. I counted about 110 undrilled sections in the most prospective part of the Point Reyes Oil Play. Using a success ratio of 0.05 (from the Salinas Oil Play), I calculated about six sections with undiscovered accumulations in the Point Reyes play, and settled on 5 as the probable median number of undiscovered accumulations. The least number of accumulations is estimated at 1. The largest number of accumulations is estimated to be about 25, or somewhat less than one accumulation (≥ 1 MMBO) for every four undrilled sections by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be as high as 100, or about one accumulation for every undrilled section, but this seems too optimistic.

1103. PESCADERO OIL PLAY (HYPOTHETICAL)

The hypothetical Pescadero Oil Play is located west of the San Gregorio Fault Zone in coastal San Mateo county, about 40 mi south of San Francisco. The area of this play appears to be the onshore, northeastern margin of a major offshore sedimentary basin, the A–o Nuevo Basin (also known as the Outer Santa Cruz Basin). The Pescadero Oil Play is bounded on the northeast and east by the Frijoles segment of the San Gregorio Fault Zone, and on the northwest, south, and west by the 3-mi limit offshore. The surface area of the play is about 175 sq mi. Much of the area of the play is devoted to public parks and wildlife sanctuaries.

The Pescadero Oil Play includes hypothetical accumulations of petroleum in moderately deformed Neogene sedimentary and volcanic rocks. The Neogene strata are more than 1,700 ft thick, range in age from late Oligocene (?) to Pliocene, and have been assigned to the Vaqueros (?), Monterey, and Purisima Formations (Brabb and others, 1977; Clark and Brabb, 1978; Clark, 1981). The Neogene rocks rest in angular unconformity on the Upper Cretaceous Pigeon Point Formation, which is at least 8,500 ft thick and consists of conglomerate, hard sandstone, and mudstone that were deposited in environments ranging from deep-sea fan to shallow-marine shelf. Strata of the Pigeon Point Formation are moderately folded, moderately to complexly faulted, apparently devoid of source rocks and reservoir-quality sandstone, and appear to have little or no potential for hydrocarbon reserves. The base of the Pigeon Point Formation is not exposed, and the nature of older rocks in the area is controversial. The Pigeon Point Formation may be underlain by granitic rocks of the Salinia Terrane (Hoskins and Griffiths, 1971, p. 216; Webster and Yenne, 1987) or by silicic volcanic rocks of Cretaceous or older age and unknown tectonic affinity (Clark and Babb, 1978).

Reservoirs: The most likely potential reservoirs in the Pescadero Oil Play are sandstones in the Vaqueros (?) and Purisima Formations. Little information is available on reservoir quality and thickness in this play. Sandstones in the Vaqueros (?) include deep-sea turbidites as thick as 7 ft near Point A–o Nuevo and shoreline deposits as thick as 66 ft at Pescadero Beach (Taylor, 1988). In the offshore A–o Nuevo Basin, estimates of porosity from logs of sub-Monterey sandstones range from 2 to 23 percent and average about 13 percent (Cathie Dunkel, Minerals Management Service, written commun., 1994). Numerous sidewall samples of friable sandstone (probably from the Purisima and (or) Pigeon Point Formations) were recovered from the Richfield Oil Corporation Steele Core Hole, No. 1 near Point A–o Nuevo, but many were described as having low porosity and permeability. Estimates of upper Miocene and Pliocene sandstone porosity from logs of wells in the offshore A–o Nuevo Basin range from 29 to 46 percent (Cathie Dunkel, written commun., 1994). Fractured reservoirs may occur in siliceous fine-grained rocks of the Monterey Formation; the outcrops at Point A–o Nuevo include opal-CT porcelanite and chert, as well as black, glassy, quartz chert (White, 1990). Estimates of fractured Monterey porosity from logs of wells in the offshore A–o Nuevo basin range from 21 to 38 percent and average about 30 percent (Cathie Dunkel, written commun., 1994). Additional fractured reservoirs also may occur in basalt and limestone of the Vaqueros (?) Formation and hard sandstone and shale of the Pigeon Point Formation.

Source rocks and hydrocarbons: The most likely source rocks are bathyal marine, organic-rich shales and mudstones in the upper Oligocene (?) and lower Miocene Vaqueros (?) Formation and the middle Miocene Monterey Formation. Available organic geochemical data from outcrop samples indicate TOC values as high as 12 percent and the presence of oil-prone kerogens (R.G. Stanley, unpub. data). Values of Rock-Eval T_{max} suggest that mudstones in the Vaqueros (?) and Monterey are thermally immature with respect to the traditional oil generation window (R.G. Stanley, unpub. data); however, many people believe that the Monterey can generate oil at lower than expected levels of organic metamorphism. The distribution of potential source rocks in the subsurface is unknown but may be patchy, with erosional remnants of Miocene shales beneath the regional sub-Purisima unconformity. The Miocene shales are not present everywhere in the play as shown by the fact that the Pliocene Purisima Formation rests unconformably on the Cretaceous Pigeon Point Formation in several outcrops east of the Green Oaks

Fault. Oil in the Pescadero Oil Play may have been generated locally, or it may have migrated from offshore. A potential offshore oil-generative center in the Monterey Formation, located just south of Point A–o Nuevo and partly within the 3-mi limit, has been identified by Cathie Dunkel (written commun., 1994).

The expected hydrocarbon types in this play are oil and associated gas, on the basis of (1) the oil-prone character of the potential source rocks, (2) an outcrop of tar-impregnated sandstone in the Vaqueros (?) Formation east of Point A–o Nuevo (Taylor, 1988), (3) weak shows of oil reported from the Richfield Steele well onshore (noted above), and (4) abundant shows of oil in two wells offshore. In 1967, Shell Oil Company drilled the OCS P-035 No. 1 about 8 mi WSW of Pigeon Point and the OCS P-036 No. 1 about 14 mi W of Pescadero Point. Both wells found abundant shows of free, tarry oil and associated gas in fractured strata of the Monterey Formation. Additionally, the P-035 well found shows of tarry oil in Miocene sandstone beneath the Monterey. No production tests were conducted for either well. Heck and others (1990) suggest that oil from the offshore A–o Nuevo basin is likely to be heavy (about 16-22¡ API) and high in sulfur (about 2-4 weight percent) by analogy with petroliferous basins in southern California. Possible offshore gas seeps, inferred from water-column anomalies on high-resolution seismic profiles, occur in the southern part of the play (Mullins and Nagel, 1982).

Traps: The most likely trap types, by analogy with known hydrocarbon accumulations in nearby parts of coastal central California, include anticlines; fault truncations; stratigraphic traps formed by sandstone pinchouts, diagenetic boundaries, or tar seals; and stratigraphic traps in tilted strata beneath the regional sub-Purisima unconformity. Much of the area is structurally complicated, probably owing to tectonism along the right-lateral San Gregorio-Hosgri Fault Zone, so traps are likely to be small. The onshore surface anticline just east of Point A–o Nuevo has never been drilled, perhaps because the potential reservoir section in the Vaqueros (?) Formation is thin and exposed at the surface. However, it is possible that unbreached structures of similar size occur offshore, west of the Green Oaks Fault.

Potential seals include mudstone and shale in the Vaqueros (?), Monterey, and Purisima Formations. East of Point A–o Nuevo, a mudstone unit in the lower part of the Purisima rests unconformably on the Monterey; this mudstone, if laterally persistent, may provide a regional seal for hydrocarbon accumulations in the Monterey and older units. Stratigraphic columns by Brabb and others (1977, p. 84, 85) suggest that the upper part of the Purisima Formation consists mainly of sandstone, with a paucity of shales that might serve as seals.

Exploration status: No commercial production of petroleum has been established in this play. Only three exploratory wells have been drilled. The earliest, the Smuggler Divide Mining Co. No. 1, spudded near the mouth of Cascade Creek in December 1927, drilled to TD of 900 ft in September 1928 and was abandoned as a dry hole by November 1930. This well penetrated clay from 0 to 30 ft, hard yellow sandstone (probably Purisima Formation) from 30 to 115 ft, and blue and gray shale (perhaps also Purisima) from 115 to 900 ft. According to available well records, "no oil or gas bearing formations were encountered."

The Richfield Oil Corporation Steele Core Hole No. 1 spudded (in Quaternary dune sands?) near Point A–o Nuevo on September 12, 1963, and was abandoned at TD of 2,675 ft on September 24, 1963. Both the location and the stratigraphy of this well are controversial. The location published by the California Division of Oil and Gas (1988) places the well southwest of surface trace of the Green Oaks Fault, but Brabb and others (1977) and Clark (1981) show it northeast of the fault. Clark (1981), citing unpublished biostratigraphic data on foraminifers from R.L. Pierce, concluded that the well penetrated the unconformity between the Purisima and Pigeon Point Formations at about 160 ft. An alternative interpretation, which ignores the biostratigraphic data as unreliable and relies mainly on logs and sample descriptions, is that the well penetrated about 1,800 to 2,000 ft of Neogene rocks--including the Purisima and possibly the Vaqueros (?) Formations--before reaching the top of the Pigeon Point Formation. (Nothing in the available data suggests that the well encountered siliceous rocks resembling nearby outcrops of the Monterey Formation.) Faint petroleum odors, yellow to orange fluorescence, and "splotchy oil stained" sandstone were noted in sidewall samples from about 200 to 345 ft. A test through perforated casing at 210-265 ft recovered "no gas or oil shows," according to available well records. During this test, nitrogen pumped into the hole at 700 psi was observed to "break out" at the surface about 50 ft from the drill rig, suggesting a lack of effective seals in the upper part of the hole. Steep to vertical dips were described from some cores in this well, suggesting complicated structure consistent with proximity to a fault, perhaps the Green Oaks Fault.

The Ebert and Brandt Latta No. 1 well spudded in the Cretaceous Pigeon Point Formation on November 2, 1968, and was abandoned at TD of 3,409 ft on November 26, 1968. Geological data from this well are sparse, but it reportedly bottomed in hard sandstone and shale of the Pigeon Point Formation. Available records state that no shows of oil or gas were encountered and no tests conducted.

Resource potential: The Pescadero Oil Play is almost entirely unexplored. The part of the play with the highest potential for undiscovered accumulations of petroleum is at Point A–o Nuevo and the adjacent State waters, where the Vaqueros (?), Monterey, and Purisima Formations are present in outcrop and subsurface. Within this area, however, there are significant uncertainties associated with trap size and seal integrity. The region underlain by the Pigeon Point Formation in outcrop and shallow subsurface probably has little or no petroleum potential because the Pigeon Point apparently lacks source rocks and reservoir-quality sandstones, and its structure is characterized by numerous small folds and ubiquitous faults. The potential of the small area around Pescadero Beach, California, is uncertain but probably low because possible source rocks have not been found onshore and because the Monterey Formation (the most likely potential source of hydrocarbons) is very thin or missing in the nearby offshore (Cathie Dunkel, written commun., 1994).

In the most prospective part of the Pescadero Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be about 30 MMBO, by very loose analogy with the so-called Patterson tar sands on the Lockwood High in the Salinas Basin. The Patterson tar sands were chosen for comparison because they occur in a generally similar, complex structural setting along a major strike-slip fault (the Reliz-Rinconada Fault); the reservoirs are in about the same stratigraphic position as the Vaqueros (?) Formation of the Pescadero Oil Play; and both areas occur along the flanks of nearby hydrocarbon generative centers in the Monterey Formation. The median undiscovered accumulation size in the Pescadero Oil Play is estimated to be about 1.5 MMBO and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps and only slightly larger than the minimum size (1 MMBO).

I estimated the median number of undiscovered accumulations by applying a modified form of the Checkerboard method to the most prospective part of the Pescadero Oil Play. I counted 45 undrilled sections in the most prospective part of the play. Using a success ratio of 0.05 (from the Salinas Oil Play), I calculated about 2 sections with undiscovered accumulations in the Pescadero Oil Play. I accepted 2 as median number of undiscovered accumulations. The least number of accumulations is estimated at 1. The largest number of accumulations is estimated to be about 10, or somewhat less than one accumulation (≥ 1 MMBO) for every 4 undrilled sections, by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be as high as 50, or about one accumulation for every undrilled section, but this seems too optimistic.

1104. LA HONDA OIL PLAY

The confirmed La Honda Oil Play is located in the La Honda Basin along the central California coast, immediately south of San Francisco. The play includes known and hypothetical accumulations of hydrocarbons in moderately deformed Tertiary sedimentary and volcanic strata with a composite thickness of more than 48,000 ft. In places, these strata rest on granitic and metamorphic rocks of the Salinia terrane. The stratigraphy, structure, and geologic history of the area have been the subject of numerous reports, summarized by Cummings and others (1962), Clark and Rietman (1973), Clark (1981), and Stanley (1985, 1990). The La Honda Oil Play is bounded on the northwest by granitic rocks of Montara Mountain; on the northeast by the San Andreas and Pilarcitos Faults; on the southwest by the Zayante-Vergeles Fault, the pinchout of the Santa Cruz Mudstone, and the edge of the Monterey submarine canyon; and on the west by the Frijoles segment of the San Gregorio-Hosgri Fault Zone, and the 3-mi limit offshore. The surface area of the play is about 565 sq mi.

Reservoirs: Commercial production has been obtained from sandstone reservoirs in the Eocene Butano Sandstone, the Eocene and Oligocene San Lorenzo Formation, the Oligocene and Miocene Vaqueros Formation, and the Miocene and Pliocene Purisima Formation, and from a limestone reservoir--the so-called Burns sand (Stanley, 1985; El-Sabbagh and Ingle, 1990)--associated with volcanic rocks of late Oligocene and early Miocene age. Average reservoir depths are about 1,800 ft. Additional potential reservoirs include shallow marine sandstone and conglomerate in the Miocene Santa Margarita Sandstone; lenticular interbeds of sandstone in the Miocene Santa Cruz Mudstone; fractured siliceous fine-grained rocks in the Miocene Monterey Formation, the Santa Cruz Mudstone, and the Purisima Formation; and fractured and (or) deeply weathered granitic rocks.

Source rocks and hydrocarbons: Oils in the La Honda Basin are generally low in sulfur (less than 1 percent), and vary in gravity from 40-50¡ API in the Half Moon Bay and Oil Creek oil fields, to 15-20û API in the south area of the La Honda oil field. Unpublished geochemical evidence suggests that oils in the La Honda Basin were derived from at least one source of Eocene age, and two sources of Miocene age (Alan Kornacki, Shell Oil Co., oral commun., 1992). Some oils in the La Honda and Half Moon Bay fields are hybrids that consist of mixtures of heavy, biodegraded oils from a Miocene source and lighter oils from an Eocene source. High-gravity oil from the Oil Creek field may have been generated by the Eocene Twobar Shale Member of the San Lorenzo Formation. Heavy oil produced from limestone reservoirs in the south area of the La Honda oil field may have been generated by Miocene rocks. Unpublished Rock-Eval results from outcrop samples suggest that organic-rich, potential source rocks occur in the Twobar Shale, the Oligocene and Miocene Lambert Shale, the Monterey Formation, and the Santa Cruz Mudstone. In addition to commercial production, numerous surface seeps of oil and gas have been reported (Cummings and others, 1962; Hodgson, 1980), and shows of oil and gas have been noted in dozens of exploratory wells. Possible offshore gas seeps, inferred from water-column anomalies on high-resolution seismic profiles, are common near Santa Cruz (Mullins and Nagel, 1982). Gas from a shallow water well in the Santa Cruz Mudstone near Davenport, California is of probable thermogenic origin, on the basis of isotopic analysis (Mullins and Nagel, 1982).

Timing and migration of hydrocarbons: The timing of petroleum generation and migration is unknown. Generation in the Eocene Twobar Shale may have begun as early as the Oligocene and (or) early Miocene, when thick sequences of mudstone, sandstone, and volcanic rocks were deposited in the area, and geothermal gradients may have been unusually high owing to extended, thinned crust and the presence of local volcanic centers. Generation of hydrocarbons from the Lambert Shale, Monterey Formation, and Santa Cruz Mudstone must have occurred later, possibly as a result of burial by the late Miocene and Pliocene Purisima Formation. Oil generation and migration in most of the area probably ceased following late Pliocene and Quaternary deformation and uplift, but it may be ongoing in the deeply buried parts of the Santa Cruz Mudstone in the area west and northwest of Santa Cruz, California.

Traps: A wide variety of trapping styles are present in the La Honda Oil Play. Commercial production has been obtained from anticlines (e.g., La Honda main area, Oil Creek, and Half Moon Bay fields), stratigraphic traps beneath the regional sub-Purisima unconformity (La Honda south area), and from a possible tar-seal trap (Moody Gulch field). Speculatively, subthrust traps might be associated with low-angle faults, of which the Butano Fault may be an example.

Exploration status: Five small oil fields in the La Honda Basin have produced a total of 1.7 MMBO of oil and 300 MMCF of gas, mostly from reservoirs in Eocene turbidite sandstone and Miocene limestone. The oldest field, Moody Gulch, was discovered in 1878. The largest field, the main area of the La Honda oil field, was discovered in 1956; cumulative production from this area by the end of 1991 was about 804 MBO (California Division of Oil and Gas, 1992), and estimates of reserves range from 42 MBO (California Division of Oil and Gas, 1992) to 400 MBO (S.T. Hector, North Valley Oil and Gas Co., written commun., 1993).

More than 100 exploratory wells have been drilled in the area, with numerous reported shows of oil and (or) gas. The deepest well in the area, the Champlin Santa Cruz Lumber, was drilled in 1984 to total depth of 11,052 ft on the Butano Anticline. The Champlin well reportedly found slight shows of gas, but no oil, and bottomed in tight sandstones of possible Paleocene age. Surface and near-surface outcrops of bituminous sandstones with nearly 10 MMBO of severely biodegraded oil (about 4û API) occur in the Miocene Santa Margarita Sandstone northwest of Santa Cruz; these tar sands were quarried for paving material for many years (Page and Holmes, 1945). From 1955 to 1959, Husky Oil Company recovered about 2.7 MBO of 27¡ API oil and 420 MCF gas from these tar sands using downhole gas-fired heaters, but the project was abandoned as unprofitable (Adams and Beatty, 1962; Hallmark, 1980).

Resource potential: The most prospective part of the La Honda Oil Play is the area blanketed by the upper Miocene Santa Cruz Mudstone (as thick as 8,900 ft) and the upper Miocene and Pliocene Purisima Formation (as thick as 7,900 ft). These two units are generally much less deformed than older rocks and include thick sequences of mudstone that are potentially excellent regional seals. The most prospective area extends from Half Moon Bay southward to Santa Cruz, and from the San Gregorio Fault and 3-mi limit eastward to the western edge of outcrops of middle Miocene and older rocks. This area includes existing commercial production in the Half Moon Bay and La Honda oil fields. Probably, most undiscovered accumulations in this area are in anticlinal and stratigraphic traps similar to those already found. Along the coast from Point A–o Nuevo south to Santa Cruz, there may also be stratigraphic and tar-seal traps involving reservoirs in the Santa Margarita Sandstone, as well as lenticular sandstones and fractured shale reservoirs in the Santa Cruz Mudstone. Most, but not all, of the surface anticlines in the area of the play have been penetrated by at least one well. Away from the commercial fields, the drilling density is generally low, allowing plenty of room for more discoveries to be made. There is an intriguing possibility of one or more large accumulations along the southwest slope of Ben Lomond Mountain, where the Santa Cruz Mudstone is unusually thick, at least 8,900 ft. In this area, some geologists have speculated that there may one or more buried and previously unrecognized faults, and (or) a major buttress unconformity.

The area between the San Andreas and Zayante-Vergeles Faults, and extending from near Highway 17 northwestward to Montara Mountain, is regarded as less prospective because of complex structure and the fact that many of the best source and reservoir units are widely exposed at the surface. Nevertheless, this area includes the Moody Gulch and Oil Creek fields, so the potential for more small commercial fields cannot be completely ignored.

In the area between the San Andreas and Zayante-Vergeles Faults, and extending from near Highway 17 southeastward to near San Juan Bautista, California, the prospective Tertiary section is largely covered by the Purisima Formation. No producing fields have been found in this area, but oil shows are reported from several exploratory wells. Drilling density in this area is light; its potential is uncertain, but proximity to the San Andreas Fault suggests that structures will be small and complexly faulted, with correspondingly small accumulations of petroleum.

Within the most prospective part of the La Honda Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be about 30 MMBO, by very loose analogy with the so-called Patterson tar sands on the Lockwood High in the Salinas Basin. The median undiscovered accumulation size is estimated to be about 1.5 MMBO and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps and only slightly larger than the minimum size (1 MMBO).

I estimated the median number of undiscovered accumulations by applying the Checkerboard method to the most prospective part of the play. I counted two producing sections (assuming that the La Honda main area and the Santa Cruz tar sands are accumulations larger than the minimum size of 1 MMBO), 57 drilled sections, and about 235 undrilled sections. I calculated a success ratio of 0.034 and about eight sections with undiscovered accumulations. I rounded the latter upward to a probable median of 10 undiscovered accumulations. The least number of undiscovered accumulations is estimated at 2, which is equal to the number of known accumulations. The largest number of undiscovered accumulations is estimated to be about 50, or about one accumulation (≥ 1 MMBO) for every four undrilled sections, by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be about 200, or one accumulation for every undrilled section, but this seems overly optimistic.

1105. BITTERWATER OIL PLAY (HYPOTHETICAL)

The hypothetical Bitterwater Oil Play is located in the Bitterwater and Peach Tree Valleys, adjacent to the San Andreas Fault and east of the crest of the Gabilan Range, about 120 mi southeast of San Francisco. The play includes known and hypothetical accumulations of petroleum in moderately deformed Miocene sedimentary rocks that are at least 7,500 ft thick (Christensen and Knight, 1964; Forrest and Payne, 1964).

Very little published information is available on the stratigraphy, structure, and petroleum geology of this play. Over most of the area, Miocene rocks overlie granitic and metamorphic rocks of the Salinia terrane; however, fault-bounded slivers of Upper Cretaceous and Eocene rocks are present in the subsurface near the San Andreas Fault (California Division of Oil and Gas, 1985). The petroliferous Miocene section is in most places unconformably overlain and concealed by the upper Miocene and Pliocene Pancho Rico Formation, which in this area is at least 3,300 ft thick and consists of diatomaceous mudstone and subordinate sandstone (Durham, 1974). The play is bounded on the northeast by the San Andreas Fault. The southwestern margin of the play is provisionally placed along the Chalone Creek Fault, then southward along the eastern edges of granite outcrops in Topo Valley and along San Lorenzo Creek, then southeastward generally parallel to the creek and Highway 25 as far as the San Andreas Fault. The area of the play is about 150 sq mi.

Reservoirs: Known and potential reservoirs include Miocene nonmarine sandstones, shallow-marine sandstone in the basal part of the Pancho Rico Formation, fractured Miocene marine shales, and fractured granite.

Source rocks and hydrocarbons: The source of the oil in this play is unknown. Unpublished organic geochemical data obtained from the Texaco California Land and Cattle No. 1 well, about 10 mi southeast of the Bitterwater field, suggest that a shale similar to the lower Miocene Soda Lake Shale of the Cuyama Basin is a possible source rock (K.E. Peters, M.H. Pytte, T.D. Elam, and P. Sundaraman, Chevron U.S.A., unpub. report, 1992). However, the well is located adjacent to the San Andreas Fault, possibly on a fault sliver, so the source rocks found in this well may have very limited lateral extent or even be absent from the rest of play. Middle Miocene shales assigned to the Monterey Formation are believed to be present elsewhere in the Bitterwater Basin, but I have no information on their source potential. The timing of petroleum generation and migration is uncertain, but some migration must have occurred after deposition of sandstone, now tar-saturated, in the upper Miocene and Pliocene Pancho Rico Formation. It is possible that the oil at Bitterwater field was not generated locally but, instead, migrated from some unknown source located northeast of the San Andreas Fault; subsequently, this hypothetical source may have been displaced many tens of mi to the southeast by right-lateral motion along the fault.

Traps: By analogy with the discovered accumulation at Bitterwater, anticlines are the major expected trap type. Buried anticlines, fault traps, and stratigraphic traps involving reservoirs in upper Miocene and older rocks are almost certainly hidden beneath the sub-Pancho Rico unconformity. However, these structures are likely to be small and highly faulted, owing to tectonism associated with movement along the nearby San Andreas Fault. The small structure size, in turn, implies that most accumulations of petroleum also will be small.

Exploration status: One small commercial oil field, Bitterwater, was discovered in 1952. By the end of 1991, this field had produced a total of 296 MBO of 23-27û API oil, with estimated reserves of 25 MBO (California Division of Oil and Gas, 1992). The oil is obtained from reservoirs at depths of 1,100 to 1,400 ft in nonmarine sandstone and conglomerate of the so-called O'Connor sand (of Gribi, 1963a) in the lower part of the upper Miocene Bickmore Canyon arkose (of Gribi, 1963a). Gross pay thickness is 300-450 ft; net pay thickness is 125-135 ft; average porosity is 18-25 percent; and average permeability is 100-200 mD. The trap is a complexly faulted anticline that is truncated on the northeast by the San Andreas Fault Zone (Gribi, 1963a). Away from the Bitterwater field, more than 50 exploratory wells have been drilled in the area, many with shows of oil in sandstones and fractured shales. Just outside the area of the play is an occurrence of bituminous sandstone and conglomerate in the basal part of the Paso Robles Formation; this deposit was quarried before 1900 and used to pave the streets of King City (Durham, 1974, p. 78-79).

Resource potential: The play is lightly to moderately explored; the potential for further discoveries seems good. The most prospective area appears to be the central part of the play, where one commercial field has been found, several wells report good oil shows, and the sedimentary section is at least 7,500 ft thick. However, this area is geographically small and apparently structurally complex; no accumulations larger than 1 MMBO have been found, even though 50 wells have been drilled in the play. Therefore, I have assigned a probability of 0.8 to trap occurrence.

In the most prospective part of the Bitterwater Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be about 30 MMBO, by analogy with the so-called Patterson tar sands on the Lockwood High in the Salinas Basin. The median undiscovered accumulation size is estimated to be about 1.5 MMBO and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps and only slightly larger than the minimum size assessed (1 MMBO).

I estimated the median number of undiscovered accumulations in the most prospective part of the Bitterwater Oil Play using a modified form of the Checkerboard method. I counted about 70 undrilled sections. Using a success ratio of 0.05 (from the Salinas Oil Play), I calculated about four sections with undiscovered accumulations, and accepted 4 as the probable median number of undiscovered accumulations. The least number of undiscovered accumulations is estimated at 1. The largest number of undiscovered accumulations is estimated to be about 15, or somewhat less than one accumulation (≥ 1 MMBO) for every four undrilled sections, by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be as high as 70, or one accumulation for every undrilled section, but this seems overly optimistic.

1106. SALINAS OIL PLAY

This confirmed play is located in the Salinas Valley area about 150 mi southeast of San Francisco. The play includes known and hypothetical accumulations of hydrocarbons (mainly oil and associated gas) in gently to moderately deformed Tertiary rocks more than 19,000 ft thick. In many places, these rocks overlie Mesozoic granitic and metamorphic rocks of the Salinia terrane. Upper Cretaceous strata as thick as 7,000 ft occur locally but are generally regarded as nonprospective. Good summaries of the geology and petroleum potential of the Salinas Valley area include those published by Payne (1963), Durham (1974), Graham (1976, 1978), Marion (1986), and Graham and others (1991). The Salinas Oil Play is generally surrounded by uplifted areas of granitic and metamorphic rocks, including the Gabilan Range and Gabilan Mesa on the northeast, the Santa Lucia Range on the southwest, and the La Panza Range on the south. The area of the play is roughly 1,300 sq mi.

Reservoirs: All commercial production to date has been from reservoirs in shelf and turbidite (?) sandstones of middle and upper Miocene age; these sandstones are usually assigned to the Monterey, Santa Margarita, and Tierra Redonda Formations (Durham, 1974). In the Hames Valley Syncline, subcommercial quantities of light oil reportedly were tested from fractured fine-grained rocks of the Monterey Formation; initial production rates were apparently as much as 360 bbl/day, but the wells rapidly watered out. Shows of oil have also been reported from reservoirs in the Vaqueros Sandstone; however, unpublished industry reports indicate that, in some areas, porosity in the Vaqueros is plugged by laumontite. Additional reservoirs may occur in sandstones of Paleocene and Eocene age in the Arroyo Seco Syncline and in fractured and (or) weathered granitic rocks.

Source rocks: On the basis of oil and source rock geochemistry and geohistory analysis, the main hydrocarbon source horizons are believed to be the Hames and Sandholdt Members of the Monterey Formation (Marion, 1986; Alan Kornacki, Shell Oil Co., oral commun., 1992). The main area of hydrocarbon generation is believed to be a deep syncline in the Hames Valley area, but other oil-generative centers may have been located in the Arroyo Seco Syncline and an unnamed syncline northeast of Paso Robles, California (Marion, 1986). Petroleum generation and migration from the Hames Valley area probably occurred during the late Miocene and Pliocene, prior to extensive deformation and uplift of the region during the late Pliocene and Pleistocene. Most commercial production to date has been heavy oil (generally 10-19û API) with 1-2 percent sulfur, minor amounts of associated gas, and very large volumes of water (California Division of Oil and Gas, 1991).

Traps: The discovered oil accumulations (and probably many undiscovered ones, as well) are in anticlines (e.g., San Ardo, Paris Valley, and King City fields) and in stratigraphic traps formed by permeability barriers, sandstone pinchouts, and (or) tar seals (e.g., Monroe Swell, Lynch Canyon, and McCool Ranch fields, and possibly also the Quinado Canyon field). Speculatively, additional undiscovered accumulations may be found in stratigraphic traps where the Vaqueros Sandstone laps out onto pre-early Miocene highs, subthrust traps along low-angle faults such as the Reliz-Rinconada, and in fractured reservoirs beneath permeability barriers related to silica phase transitions in fine-grained siliceous rocks in the Monterey Formation.

Exploration status: The Salinas Oil Play includes one giant oil field, San Ardo (about 530-860 MMBO); the much smaller King City field (about 2.1-3.3 MMBO); and five fields smaller than 1 MMBO. Average producing reservoir depths are generally 2,500 ft or less. In addition, there are numerous occurrences of bituminous rock, some of which were mined for paving material; stratigraphically, these occur in the Hames Member of the Monterey Formation, the upper Miocene and Pliocene Pancho Rico Formation, and the Pliocene and Pleistocene (?) Paso Robles Formation (Durham, 1974). On the Lockwood High, the so-called Patterson tar sands may contain 49 MMBO of oil in place and 17 MMBO recoverable; proposals to produce this oil using a steam flood were rejected by local governmental authorities (Ross Brunetti, California Division of Oil and Gas, oral commun., 1993). In the Paris Valley area northwest of the San Ardo oil field, bituminous sandstones at the base of the Pancho Rico Formation may contain 100 MMBO of 11û API oil in place (Hallmark, 1980); attempts to recover this oil using steam and *in situ* combustion have been economically unsuccessful (Ross Brunetti, California Division of Oil and Gas, oral commun., 1993). Tar sands of Pliocene (?) age in the area near San Antonio dam (southeast of Bradley) may contain as much as 300 MMBO of oil in place (D.M. Sparks, oral commun., 1994). The deepest well in the Salinas Basin, the Texaco Shell NCT-11, was drilled in the Hames Valley Syncline; it spudded in the Monterey Formation and was still in the Monterey at total depth of 11,994 ft.

Estimates of the size of the San Ardo field range from 530 MMBO of oil and 71,420 MMCF of gas (sum of cumulative production to 12/31/91 and estimated reserves, according to California Division of Oil and Gas, 1992) to 862 MMBO of oil and 108,020 MMCF of gas (NRG Associates, 1993). In the San Ardo field, the gas/oil ratio ranges from 108 to 148 CF/bbl; average gravity is 10-13û API; average porosity is 23-38 percent; average permeability is about 2,000-8,000 mD; average depth of producing reservoirs is about 2,100 ft; and average net pay thickness is about 40-150 ft (California Division of Oil and Gas, 1991; NRG Associates, computer printout of 8/4/93). Oil from the San Ardo field is extremely biodegraded, according to unpublished geochemical studies (Alan Kornacki, Shell Oil Co., oral commun., 1992).

Estimates of the size of the King City field range from 2.1 MMBO of oil and 62 MMCF of gas according to California Division of Oil and Gas, 1992) to 3.3 MMBO oil and 109 MMCF of gas (NRG Associates, 1993).

In the King City field, the gas/oil ratio is about 33 CF/bbl; average gravity is 13-16û API; average porosity is 32 percent; average permeability is about 1,000 mD; average depth of producing reservoirs is about 2,000 ft; and average net pay thickness is about 100 ft.

Resource potential: On the basis of the foregoing, the most prospective part of the Salinas Oil Play appears to be the central part of the Salinas Valley, from the Arroyo Seco southeastward to a NNE.-trending subsurface basement high east of Camp Roberts, California. This area includes all commercial fields discovered to date, as well as the Hames Valley area, where much of the oil presumably was generated. The northeastern side of the play from Soledad to San Ardo, California, along the so-called King City Hinge Line (Gribi, 1963b, p. 21) includes all the discovered fields and is moderately well explored. However, much of the rest of the play--including the Hames Valley--is only lightly explored, with the potential for many more field discoveries. Some geologists believe that one or more very large accumulations (perhaps comparable in size to the San Ardo field) may lie hidden in the sparsely drilled Camp Roberts area, which is updip from the Hames Valley Syncline. Here, a well was drilled during late 1992 by Amoco; at this writing, the results are still confidential, but unconfirmed reports indicate that the well was drilled on one of several anticlinal structures and reached total depth in granite without finding the expected sandstone reservoir.

The petroleum potential of the area east of San Miguel and Paso Robles, California and north of the La Panza Range is uncertain but probably low. Several large structures in the area have been drilled, and some wells have reported oil shows. Unconfirmed industry reports and a Stanford Master's thesis maintain that potential source rocks in the Monterey Formation in this area are thermally immature; however, many geologists believe that the Monterey can generate oil at lower than expected levels of organic metamorphism. According to available well data, the organic-rich potential source rocks in the Monterey disappear as the formation becomes thinner and more sandstone-rich to the southeast and east, toward the La Panza Range and the San Andreas Fault.

The area from Greenfield northwest to Salinas, California is sparsely drilled and considered generally nonprospective because the few wells in this area have penetrated mostly nonmarine rocks with no hydrocarbon shows. However, there is an intriguing possibility of stratigraphic traps associated with the nonmarine/marine transition in the area immediately northwest of Greenfield.

In the most prospective part of the Salinas Oil Play, the largest accumulation expected at a 5 percent chance is estimated to be about 500 MMBO, somewhat less than the size of the largest discovered field (San Ardo, at about 530-860 MMBO), based in part on informal discussions with several petroleum geologists who have first-hand experience in the area. The median undiscovered accumulation size is estimated to be about 2 MMBO and reflects the feeling that most of the undiscovered accumulations in this play are likely to be in small structural and stratigraphic traps and only slightly larger than the minimum size (1 MMBO).

The median number of undiscovered accumulations in the most prospective part of the Salinas Oil Play was estimated by the Checkerboard method. I counted 14 producing sections (from the San Ardo, King City, Paris Valley, Bradley, and Patterson accumulations only), 245 drilled sections, and about 530 undrilled sections. I calculated a success ratio of 0.05, and about 28 sections with undiscovered accumulations. From the latter, I inferred a probable median of 25 conventional accumulations and 5 subeconomic tar-sand accumulations. The least number of accumulations is estimated to include eight conventional accumulations and two subeconomic tar-sand accumulations. The largest number of conventional accumulations is estimated to be about 125, or somewhat less than one accumulation (≥ 1 MMBO) for every four undrilled sections, by analogy with the most densely drilled and productive parts of the Powder River Basin of Wyoming. Alternatively, the largest number could be as high as 500, or about one accumulation for every undrilled section, but this seems overly optimistic.

CUYAMA BASIN

By Marilyn E. Tennyson

The Cuyama Basin is a subprovince at the southeastern end of the Central Coastal Province (011) of the Pacific Region. It is located about 40 mi inland from the coast on the eastern flank of the southeasternmost California Coast Range.

The basin lies between the Temblor Range on the northeast and the Sierra Madre Range of the southern Coast Ranges on the south and southwest. Its northwestern end is continuous with the southeastern end of the Salinas Basin. The San Andreas Fault juxtaposes the basin with the Temblor Ranges, which bound the southwestern side of the San Joaquin Basin. The southwestern margin of the basin is structurally complex; it consisted originally of at least two early Miocene down-to-the-northeast normal or strike-slip faults (Russell and La Panza Faults) that have been partially overridden by a Pliocene to Quaternary southwest-verging thrust system. The southern edge of the basin is a buried down-to-the-north normal fault north of and subparallel to the younger left-lateral and (or) reverse Big Pine Fault.

The Cuyama Basin is about 85 mi long and about 20 mi across at its widest point. It encompasses about 1,400 sq mi.

EXPLORATION HISTORY

Other than a shallow exploratory well drilled in 1922 in an area near the present Russell Ranch field, no significant exploration took place in the Cuyama Basin area until the mid-1940's, mainly because the subsurface geology along the productive trend is not well expressed by surface geology. In 1945-47, several dry holes with significant shows of gas and oil were drilled. The Russell Ranch field was discovered in 1948 by Norris Oil Company and developed mainly by Richfield Oil Company; 142 producing wells were drilled in the first 2 years as compared to 26 during the period 1950-1953 (Barger and Zulberti, 1952). The field has cumulative production plus reserves of about 68 MMBO. The other major field in the basin, the South Cuyama field, was discovered in 1949 by Richfield Oil Company with the aid of seismic prospecting techniques (Zulberti, 1954). It has cumulative production plus reserves of about 225 MMBO. Associated gas was reinjected throughout much of the field's production history but was eventually produced, resulting in a drop in pressure that reduces the likely ultimate production to an additional 5-10 MMBO beyond cumulative production to date (W. D. Lowry, Hallador Production Company, oral commun., 1992). The Morales Canyon field was discovered in 1950. It includes two widely separated pools of about 1 million barrels each, in small thrust slices. The Taylor Canyon field was also discovered in 1950 and abandoned in 1985 after producing 486,000 bbl of oil and 141,000 MCF of gas. The Central Cuyama field was discovered in 1951 and abandoned in 1958 after producing 33,000 BO and 12,000 MCF of gas. A few small pools (all less than 1 MMBO), including small gas accumulations, have been discovered within the main fields since the mid-1950's, but no additional major accumulations have been found despite continued exploration. Three very deep wells (up to 17,000 ft), based on exhaustive interpretation of seismic coverage and regional geology (Davis and others, 1988), were drilled into the subthrust part of the basin in the late 1970's and early 1980's by Arco. There were shows of oil in some of the wells, but no discoveries were made.

Two conventional plays are defined for assessment. The Western Cuyama Basin Play (1107) is a confirmed play with discoveries confined to a single structural trend. Also included in this play, however, is most of the western part of the basin where prospective rocks similar to those along the productive trend are buried beneath a complex of thrust sheets; all these rocks share a common zone of mature source rocks. The subthrust part of the play was originally defined as a separate play but has been combined with the productive trend for assessment. The second play, the hypothetical Cox Graben Play (1109), encompasses a smaller area southeast of the productive trend where additional source rocks are mature and potential reservoir strata may differ somewhat from correlative units in the first play.

1107. WESTERN CUYAMA BASIN PLAY

This confirmed structural oil play comprises lower and middle Miocene normal-fault-influenced or Pliocene to Quaternary thrust-controlled sandstone reservoirs in the western part of a thick, filled Miocene extensional basin in the lower plate of a Pliocene-Quaternary thrust-fault system. It encompasses the known or inferred extent of Miocene or Pliocene sandstones updip westward from mature lower to middle Miocene source rocks in the lower part of the basin-filling section beneath the thrusts.

Reservoirs: The principal reservoir unit is the shallow-marine Painted Rock sandstone member of the lower Miocene Vaqueros Formation (informally named "Dibblee" sandstone). It ranges in thickness between 0 and 6,000 ft; in producing reservoirs it is between 70 and 400 ft thick. Porosity ranges between about 23 percent and over 40 percent; permeability is about 100 to 350 mD in producing reservoirs. Other sandstone reservoir units are (1) the 0-300-ft-thick shallow-marine Quail Canyon sandstone member of the Vaqueros Formation (informally named "Colgrove" or "Soda Lake" sandstone), (2) bathyal sandstones interbedded with the lower to middle Miocene Saltos Shale Member of the Monterey Formation, (3) the shallow-marine/deltaic middle Miocene Branch Canyon Formation, (4) the shallow-marine middle and upper Miocene Santa Margarita Formation, and (5) the shallow-marine to nonmarine Pliocene Morales Formation. Porosity is generally about 20-40 percent in these units, permeability ranges from 100 to 1,330 mD, and thicknesses of producing reservoir units is between 60 and 200 ft. In unsuccessfully explored areas away from the main producing trend, the thickness of the Painted Rock and Branch Canyon sandstones is greater than in the producing fields, but reservoir quality is lower.

Source rocks: The Soda Lake Shale member of Vaqueros Formation and Saltos Shale Member of Monterey Formation are potential source rocks. The thickness of the Soda Lake shale is 0 to 1,200 ft (Hill and others, 1958). It contains 0.5 percent to 6.7 percent TOC (average 2.13 percent), mostly type II-III

(Lillis, 1992). The total thickness of the Saltos Shale is 0-2,250 ft (Hill and others, 1958). It contains up to about 6 percent TOC (average 3.03 percent), mostly type II-III (Lillis, 1992).

Timing and migration of hydrocarbons: Oil production, vitrinite-reflectance data, pyrolysis and biomarker data, and burial-history-calculation estimates of maturity indicate that the Soda Lake Shale member of the Vaqueros Formation is mature within this play: vitrinite reflectance ranges between 0.8 and 1.2 percent (Kornacki, 1988) or 0.5-0.6 5 (Lillis, 1992); pyrolysis results indicate T_{max} ³ 435¡C (Lillis, 1988, 1992). Burial-history calculations suggest that maturation took place in late Miocene-early Pliocene time, roughly 18 Ma to 3 Ma (Lillis, 1992). The Saltos Shale member of the Monterey Formation is mostly immature where sampled but is probably mature in deeply buried parts of the basin below the thrust sheets; Lillis (1992) reported T_{max} values slightly exceeding 435¡C in Saltos subsurface samples below the Morales Thrust at a depth of ~14,470 ft, updip from more deeply buried Saltos to the east. The lower part of the Saltos is mature in the Cox Graben according to both vitrinite and pyrolysis data, and maturation is inferred to have taken place within the last 5 Ma, based on thermal/burial-history modeling (Lillis, 1992).

Traps: Traps for discovered accumulations are formed by very gentle anticlines or updip normal-fault truncations of Quail Canyon and Painted Rock sandstones along the Russell fault, a down-to-the-east normal and (or) strike-slip fault on the western side of the basin. There is evidence for basin-edge normal-fault traps below the thrust sheets in the central part of the basin east of the discovered fields (Davis and others, 1988). The traps formed in early to late Miocene time (Pliocene and younger thrust-related traps are empty with one known exception, the Clayton pool of the Morales Canyon field). Seals consist of the Soda Lake shale, Saltos Shale, shale interbeds in the Branch Canyon sandstone, and thrust-fault surfaces.

Exploration status: All of the major accumulations in the play (South Cuyama field, 220 MMBO; Russell Ranch field, 68 MMBO; Morales Canyon field, 2.5 MMBO) were discovered between 1948 and 1950; several relatively small accumulations (0.5 to 1.6 MMBO) were discovered between 1950 and 1956. No significant discoveries have been made since 1956. Small amounts of gas were discovered in 1975-81 south and east of the main South Cuyama field in the upper Miocene Santa Margarita Formation. Oil is the principal type of hydrocarbon produced. Oil gravity averages about 33¡ API and ranges from 25¡ to about 46¡ API. Minor amounts of associated gas are produced with the oil, and there is one small nonassociated gas accumulation. The depths of the producing accumulations are between about 2,000 and 6,000 ft, with most in the 2,500 – 4,300-ft range. Most of the accumulations along the Russell Fault trend have probably been discovered; additional accumulations below the South Cuyama, Whiterock, Big Spring, Ozena, and Morales Thrusts, if present, will probably be at substantially greater depths, up to 15,000 – 18,000 ft.

Resource potential: The play has been fairly thoroughly explored in the area where substantial thicknesses of overlying thrust plates are absent, so additional potential along the trend of discoveries adjacent to the Russell Fault is limited. The deep basin below the thrusts to the east has been only incipiently explored, and the postulated targets may not actually have been tested, so there is a possibility of significant accumulations there. Accumulations below thrusts west of the discovered fields are possible but less likely because reservoirs there may have been cut off by structural highs along the Russell Fault from source rocks to the east. It seems very possible that a number of small accumulations of possibly 0.5-3 MMBO like those at Morales Canyon and Taylor Canyon, may be trapped in small fault blocks in the structurally complex area in the footwalls of the thrusts.

A hypothetical accumulation along a down-to-the-basin normal fault in the subthrust part of the basin could be quite large. A reservoir 500 ft thick and 3 sq mi could contain 163 MMBO of recoverable oil using values for porosity, formation volume factor, oil saturation, and recovery factor typical of the area. The probability of such a big discovery is considered to be very low but it cannot be ruled out.

1109. COX GRABEN PLAY

This hypothetical conventional oil play is a combination structural-stratigraphic play encompassing the north-northeast-trending Cox Graben or half-graben bounded by normal faults (Cox 46-5 Fault on west, Becker-Heller Fault on east). Oil and associated gas could be trapped in sandstone below the graben-filling section, in sandstone wedges along the margin(s) of the graben, in submarine-fan sandstone within the graben fill, or in shallow-marine or deltaic sandstone overlying the source-rock section within the graben. The play is coincident with marked thickness changes in the Saltos Shale member of the Monterey Formation, from less than 1,000 ft to as much as 5,000 ft in the central part of graben. The play is bounded on the southwest by the Russell Fault. Its northeastern limit is uncertain.

Reservoirs: Potential reservoirs include the shallow marine lower Miocene Painted Rock ("Dibblee") and Quail Canyon ("Colgrove") sandstone members of Vaqueros Formation, sandstone interbedded in the Saltos Shale member of Monterey Formation, and, less likely, the informally named "Johnston sand" at the top of the Saltos Shale and the upper bathyal to neritic middle Miocene Branch Canyon Formation sandstone. Minor amounts of oil have been produced from the Branch Canyon sandstone (abandoned Central Cuyama field; net reservoir thickness 45 ft, porosity 19 percent), Painted Rock (Dibblee pool in abandoned East Area of South Cuyama field; net reservoir thickness 84 ft, porosity 20-23 percent), and Quail Canyon (Cox pool of South Cuyama field; net reservoir thickness 50 ft, porosity 34 percent) in or near the area of the play. The Painted Rock sandstone ranges from 500 to 1,000 ft thick in the area of the graben (Lagoe, 1981); porosity in the Painted Rock elsewhere in the basin is typically 23-40 percent.

Source rocks: The Soda Lake Shale member of the lower Miocene Vaqueros Formation and lower to middle Miocene Saltos Shale Member of the Monterey Formation are potential source rocks. The thickness of the Soda Lake Shale in the area of the play is about 400 ft (Spitz, 1988). It contains 0.7 percent to 1.5 percent TOC, mostly type II (Lillis, 1992). The thickness of the Saltos shale in the area of the graben is 1,000 to 4,500 ft (Lagoe, 1981; Spitz, 1988). It contains 0.9 percent to 4.6 percent TOC, mostly type II (Lillis, 1992).

Timing and migration of hydrocarbons: Geochemical data and burial-history-calculation estimates of maturity indicate that both of these potential source rocks are mature within this play (Lillis, 1992). According to Lillis' (1992) data, the lower part of the Saltos Shale (below ~9,000 ft) and all of the Soda Lake Shale have T_{max} > 435¡C. Burial history calculations suggest that maturation took place in Pliocene to Quaternary time, about 5 Ma to the present (Lillis, 1992).

Traps: Traps are formed by updip normal-fault truncations of Quail Canyon and Painted Rock sandstones at the sides of the graben and possibly by stratigraphic pinchouts in proximal submarine fan deposits in the Saltos Shale or the Johnston and Branch Canyon sandstones. The traps formed in the early to middle Miocene (Relizian-Luisian)--the time of the faulting that accommodated the thick Saltos section and the time of deposition of Saltos, Johnston, and Branch Canyon sands that could be stratigraphic traps. Trap thicknesses in the small discovered accumulations in this play are ~50-100 ft. Potential trap thicknesses are less than 50 ft to as much as 500 ft.

Exploration status: The first discoveries in the play (Cox or Colgrove pool of Southeast Area of South Cuyama field and Central Cuyama field) were made in 1951, and the East Area of the South Cuyama field was discovered in 1975. The Cox pool produced 109,000 BO; the Central Cuyama field produced 33,000 BO; and the East Area of the South Cuyama field produced 42,000 BO before being abandoned. Oil gravities are 34- 46¡ API. Oil is the principal type of hydrocarbon produced, but minor amounts of associated gas are produced with the oil. The depths of the accumulations are 5,840, 7,270, and 7,500 ft.

Resource potential: The play has been moderately well explored, with most obvious targets tested. Exploration has clarified the probable location of normal faults that control the play, and there are undrilled zones right along the faults where undiscovered accumulations trapped against the faults might conceivably lie. The largest such accumulation that could fit into a zone along these faults is probably about 28 MMBO, based on a trap 3 mi long, .33 mi across, and 250 ft thick, with a recovery factor of 15 percent The very small size of the accumulations that have been discovered in this play suggests that the most likely accumulations present are small.

UNCONVENTIONAL PLAYS

There are no unconventional plays described in this province report. However, unconventional plays listed in the surrounding provinces may include parts of this province. Individual unconventional plays are usually discussed under the province in which the play is principally located.

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<tr><td rowspan="2">Santa Margarita Formation</td><td>Buttle Member of Monterey Formation</td><td rowspan="3">Monterey Formation</td></tr>
<tr><td>Hames Member of Monterey Formation</td></tr>
<tr><td>Tierra Redonda Formation</td><td>Sandholdt Member of Monterey Fm.</td></tr>
<tr><td colspan="3">Vaqueros Formation</td></tr>
<tr><td>OLIGOCENE</td><td colspan="3">Berry Formation</td></tr>
<tr><td>EOCENE</td><td rowspan="2" colspan="3">Reliz Canyon Formation</td></tr>
<tr><td>PALEOCENE</td></tr>
<tr><td colspan="2">CRETACEOUS</td><td colspan="3">Unnamed sedimentary rocks</td></tr>
<tr><td colspan="2">PRE–CRETACEOUS</td><td colspan="3">Granitic and metamorphic rocks of Salinia terrane</td></tr>
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