

# NORTHERN COASTAL PROVINCE (007)

by Richard G. Stanley

## INTRODUCTION

Province 7 includes much of northwestern coastal California, from near Crescent City in Del Norte County to near Paicines in San Benito County. The province is bounded on the north by the Oregon border; on the west by the San Andreas Fault and the 3-mi limit offshore; and on the east by the Coast Range Thrust (as far south as Lake Berryessa), the Hayward Fault (as far south as the southern boundary of Alameda County), and the Tesla and Ortigalita faults. The province is about 410 mi long from northwest to southeast, about 70 mi wide at its widest near Fort Bragg, and occupies an area of about 14,300 sq mi.

The main petroleum objectives in Province 7 are in gently to moderately deformed Neogene (Miocene and Pliocene) sedimentary rocks in the Eel River and Sargent-Hollister areas. The Neogene strata overlie moderately to intensely deformed rocks of the Jurassic to Tertiary Franciscan Complex. Over most of the province, the Franciscan is generally regarded as economic basement; however, the Franciscan is somewhat prospective for hydrocarbons in some areas, mainly in Humboldt and San Benito Counties.

Province 7 includes two confirmed plays, the Eel River Gas Play (0701) and the Sargent/Hollister Oil and Gas Play (0703); and one hypothetical play, the Franciscan Oil Play (0702). Surface indications of petroleum (e.g., seeps of oil and gas, and outcropping tar sands) are known from all three plays.

The earliest drilling operations in Province 7 occurred about 1865 near surface seeps in the Petrolia area, in western Humboldt County. Since then, dozens of wells have been drilled near Petrolia; many have found abundant shows of oil in fractured Franciscan(?) rocks, but no sustained commercial production has been established. Oil has been produced since 1906 from Neogene sandstones in the Sargent field (about 1-2 MMBO in size). A few miles southeast of the Sargent field, commercial production of non-associated gas from Neogene sandstones was discovered in 1951 in the Flint Hills area of the Hollister field (about 8-12 BCFG in size). In the Eel River Basin, non-associated gas has been produced since 1937 from Pliocene sandstone reservoirs in the Tompkins Hill field (about 112-140 BCFG in size). By the end of 1991, cumulative production from

all of Province 7 was 922 MBO oil and 110 BCFG; nearly all of the oil came from the Sargent field, while more than 90 percent of the gas came from Tompkins Hill.

The numbers of undiscovered accumulations in several plays in Provinces 7 and 11 were estimated by a type of spatial analysis herein named the "Checkerboard method." In this method, the prospective area is divided into sections of 1 sq mi. The sections are then arranged into three categories: (1) producing sections (those with commercial petroleum production from accumulations larger than 1 MMBO oil or 6 BCFG gas ); (2) drilled sections (with at least one exploratory well, but no production); and (3) undrilled sections (with no wells or production). A "success ratio" is calculated by dividing the number of producing sections by the sum of the producing and drilled sections. The success ratio is then multiplied times the number of undrilled sections to give a rough estimate of the number of sections with undiscovered hydrocarbon accumulations. This number may be the same as the number of undiscovered accumulations, if one assumes that most undiscovered accumulations are likely to be small and to occupy surface areas of 1 sq mi or less. Generally, estimates are expressed in round numbers, to emphasize the fact that they are highly uncertain. A more complete discussion of the Checkerboard method, including an analysis of the underlying assumptions and potential problems, is provided in another report (Stanley, in preparation).

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## CONVENTIONAL PLAYS

### 0701. EEL RIVER GAS PLAY

The confirmed Eel River Gas Play is located in coastal Humboldt County about 220 mi north of San Francisco, and includes the onshore Eel River (Humboldt) Basin and adjacent State waters. The area is roughly triangular in outline and is bounded on the northeast by the surface trace of the Freshwater Fault; on the south by the Russ Fault and the southern edge of outcrops of the Wildcat Group; and on the west by the 3-mi offshore limit. The surface area of the play is about 550 sq mi.

This play includes discovered and undiscovered accumulations of non-associated gas, mainly in Neogene marine sandstone reservoirs in anticlinal and stratigraphic traps. The Neogene strata are more than 11,000 ft thick, and rest unconformably on the Franciscan Complex, which in the Eel River Basin area is divided into two belts: the Central Franciscan Belt, which consists of argillite-matrix tectonic melange containing blocks of graywacke, greenstone, serpentinite, and other lithologies, and ranges in age from Early Jurassic to Tertiary; and the Coastal Franciscan Belt, which is an accretionary complex of predominantly Tertiary age (Jayko and Blake, 1987). The Coastal Franciscan Belt in this area is further subdivided into four terranes: (1) the Coastal terrane, typically a broken formation of Upper Cretaceous to Eocene sandstone and argillite, generally metamorphosed to zeolite grade (Jayko and Blake, 1987); (2) the King Range terrane, which includes upper Cretaceous basalt, limestone, and graywacke, plus Paleocene to middle Miocene basalt, chert, graywacke, and argillite, all strongly deformed and metamorphosed to zeolite and prehnite-pumpellyite facies (Jayko and Blake, 1987); (3) the Yager terrane, which consists of as much as 5,000 ft of sandstone and argillite that represent trench-slope and slope-basin deposits of Paleocene(?), Eocene, and Oligocene(?) age (Underwood, 1983); and (4) the False Cape terrane of Aalto and others (1994), composed of Oligocene(?) and Miocene turbidite sandstone, argillite, chert, limestone, diatomite, and tuff.

Regional isoclinal folding, faulting, uplift, and erosion of the Franciscan rocks during Oligocene(?) time was followed by rapid subsidence of the Eel River Basin and deposition of deep-water deposits during the early Miocene. The oldest strata in the Eel River Basin, the lower and middle Miocene Bear River beds, consist of sandstone and somewhat siliceous mudstone that were deposited at lower and middle bathyal depths (Ingle, 1987). The overlying sandstone, siltstone, and mudstone of the upper Miocene to Pleistocene Wildcat Group were deposited at progressively shallower depths upsection

(Piper and others, 1976). At Centerville Beach, inferred depositional environments include basin plain (Pullen Formation), submarine fan and basin slope (Eel River and Rio Dell Formations), and shelf to nonmarine (uppermost Rio Dell, Scotia Bluffs, and Carlotta Formations). The Rio Dell, Scotia Bluffs, and Carlotta Formations generally coarsen upward and eastward, reflecting progressive filling of the basin by sediment derived from river systems flowing from the east. Progressive shoaling of the basin may have been accompanied by syndepositional tectonic uplift that began during the late Pliocene (McCroory, 1989).

The most recent episode of regional compression and uplift began during the Pleistocene about 1.0 to 0.5 Ma. Structurally, the present day onshore Eel River Basin is a broad, west-plunging syncline, with upturned and deeply eroded strata on the south limb, and a fold and thrust belt along the northeast side of the basin that includes the Little Salmon Fault (Clarke, 1992). Several faults in the area, including the Little Salmon, are regarded as active on the basis of historical earthquakes and deformation of the youngest terrace deposits. The anticlines at Tompkins Hill and Table Bluff, along with several other broad anticlines in the basin, may be fault-bend folds that formed above ramps on a hypothetical thrust fault at an unknown depth beneath the Eel River Basin (J.K. Crouch, consultant, Santa Barbara, Calif., written commun., 1993).

**Reservoirs:** All commercial production to date has been from sandstone reservoirs in the Pliocene Rio Dell Formation. Sandstones with reservoir potential and shows of gas also have been reported from wells in the Bear River beds, the Pullen Formation, and the Eel River Formation. Minor shows of paraffinic, high-gravity oil (about 38° API) have been reported from sandstones in the Bear River beds and the Pullen. Some geologists have mapped linear sand bodies, interpreted as deep-sea fan channels, oriented generally WNW. to NNW., within the Bear River beds and the Pullen, Eel River, and Rio Dell Formations. Unpublished data (J.K. Crouch, written commun., 1993) indicate that sands in the Bear River beds are generally 20-120 ft thick, but locally may be as thick as 2,000 ft; sands in the Pullen Formation are 15-20 ft thick, with porosities of 12-30 percent and permeabilities more than 300 mD; sands in the Eel River Formation are as thick as 600 ft, with porosities of 15-30 percent and permeabilities of 4-21 mD; and sands in the Rio Dell Formation, which produces commercial quantities of gas at the Tompkins Hill field, may locally be as thick as 1,000 ft. Horan and Hopps (1987) caution that sandstone reservoirs in the onshore Eel River Basin tend to be laterally discontinuous and generally fine to very fine grained; therefore, sand body

geometry and reservoir quality are probably the most critical elements to consider in evaluating prospect potential in the onshore Eel River Basin.

Sandstones within the Coastal and Yager terranes of the Coastal Franciscan Belt are generally well-cemented and discontinuous; their reservoir potential is generally regarded as low, but they may have some potential as fractured reservoirs (Hopps and Horan, 1983; Horan and Hopps, 1987). Very speculatively, additional reservoirs may be found in fractured, siliceous, fine-grained rocks within the Bear River beds and the Pullen Formation.

**Source rocks, timing and migration:** Accumulations of non-associated gas have been discovered at one commercial field (Tompkins Hill) and two non-commercial fields (Table Bluff and Grizzly Bluff). In addition, shows of gas and minor shows of oil have been encountered in numerous wildcat wells. Surface seeps of gas and oil in and near the Eel River Basin are reported by Ogle (1953) and Hodgson (1980). On the basis of historical production, shows, and seeps, the main hydrocarbon resource in the Eel River Gas Play is non-associated gas, with a small possibility of oil. However, the source rocks for these hydrocarbons are uncertain and controversial. Potential sources include fine-grained strata in the Franciscan Complex (including the Coastal and Yager terranes), the Bear River beds, and the lower part of the Wildcat Group (McLean, 1988).

Unpublished isotopic evidence indicates that gas produced from the Tompkins Hill field is thermogenic in origin. The gas may have been derived from the Coastal and Yager terranes of the Coastal Franciscan Belt, which show values of vitrinite reflectance ranging from 0.40 to 1.5 percent  $R_o$ , and averaging about 0.70 percent  $R_o$  (Underwood, 1987). Shales in the Coastal and Yager terranes reportedly exhibit values of TOC (total organic carbon) ranging from 0.22 to 1.81 percent, averaging slightly more than 0.5 percent (Underwood, 1987). Rock-Eval pyrolysis results show that kerogens in the Coastal and Yager terranes are generally type III, gas-prone kerogens (Underwood, 1987).

Another possibility is that the gas was generated in locally mature rocks of the Bear River beds and (or) the lower part of the Wildcat Group. Unpublished Lopatin (thermal maturation) calculations suggest that Miocene and younger strata are thermally immature onshore, but they may be mature offshore (J.K. Crouch, written commun., 1993). Thus, gas may have been derived from Miocene rocks in one or more offshore generative centers (which remain to be identified); the gas migrated updip and laterally a few miles or tens of miles and became trapped in accumulations onshore. An

alternative scenario is that gas was generated from Miocene or younger strata near buried thermal anomalies (e.g., igneous intrusions or hydrothermal zones); however, no such hot spots have been recognized, either onshore or offshore.

Major compressional deformation and creation of known structural traps in the area, including the anticline at Tompkins Hill, began during the middle Pleistocene, about 1.0 to 0.5 Ma (Carver, 1987, 1992). Therefore, gas generation and migration must be younger than 1.0 Ma and may be happening today.

**Traps:** All discovered accumulations are on anticlines; the principal trapping mechanism clearly is structural, but there also appears to be some stratigraphic trapping in lateral pinchouts of turbidite channel sands on the flanks of the anticlines. Large undiscovered stratigraphic traps may occur along the margins of major sandstone-filled channels, especially where these channels traverse anticlines (Horan and Hopps, 1987). Numerous undiscovered structural traps may occur along the Little Salmon Fault, including subthrust anticlines and homoclines, as well as hanging-wall anticlines.

Known and potential seals include mudstones, which are interbedded with reservoir sandstones, in the Bear River beds and the Wildcat Group.

**Exploration status:** Three gas fields have been discovered in the Eel River Gas Play, but only one, Tompkins Hill, is commercial. The Tompkins Hill field was discovered in 1937 and is still producing. Estimates of field size range from about 112 BCFG (sum of cumulative production to 12/31/91 and estimated reserves, according to California Division of Oil and Gas, 1992) to 120 BCFG (Parker, 1987), to 139 BCFG (NRG Associates, 1993). Cumulative production of condensate to 12/31/91 was less than 500 bbl. The field is on a doubly-plunging, east-west-trending surface anticline in the footwall of the northeast-dipping Little Salmon Fault; the anticline has about 1,200 ft of closure. Gas is produced from depths of 2,100 to 5,800 ft (average about 4,500 ft) from sandstones in the Pliocene and Pleistocene Rio Dell Formation. The sandstones are generally very fine to fine grained, friable to slightly compact, and exhibit porosities of 22-28 percent and permeabilities ranging from less than 1 mD to 12 mD. Most production comes from the so-called Anderson sands, which occur stratigraphically in the middle of the Rio Dell Formation and are believed to represent deep-sea fan channel and lobe deposits. Productive sands range from 1 to 150 ft thick; net pay (including several productive sands in the same interval) ranges from 100 to 300 ft thick. Additional production is obtained from shallower zones, apparently from sandstones

that are generally 10-20 ft thick and were deposited in shelf and nearshore settings. The main trapping mechanism is anticlinal, but there may be some stratigraphic trapping in lateral pinchouts of turbidite channel sands.

Table Bluff field was discovered in 1960 and began production in 1962, when it was thought that the field would eventually produce about 8.5 BCFG (R.A. Reid, California Division of Oil and Gas, oral commun., 1994). However, the field was abandoned in 1968 after producing only 109 MMCF of gas (California Division of Oil and Gas, 1992). The Table Bluff field is located on a northwest-trending, eastward-plunging surface anticline with as much as 2,000 ft of closure. Like the Tompkins Hill structure, the Table Bluff anticline is in the footwall of a northeast-dipping fault. Gas was produced from lenticular sandstones in the Rio Dell Formation at depths of 2,100 to 4,775 ft. The productive sandstones exhibit porosities of 22-27 percent; the sandstones are generally 1-10 ft thick, and net pay is 15-300 ft thick. All production was from the eastern nose of the anticline, from lenticular sandstones that are believed to represent deep-sea fan channel and lobe deposits. As at Tompkins Hill, the main trapping mechanism is anticlinal, but the patchy distribution of producing wells on the top of the Table Bluff structure suggests that the locations of gas accumulations are strongly controlled by the quality or lenticularity of the reservoir sands.

The Grizzly Bluff field was discovered in 1964. Several wells were drilled, but no pipeline was built and no commercial production established. The size of the field is uncertain; unconfirmed oil industry rumors suggest about 2-3 BCFG. Grizzly Bluff field is located on a WNW.-trending surface anticline with about 350-450 ft of closure. The anticline is in the hanging wall of a steeply north-dipping reverse fault. Potential production was reported from thick turbidite sandstones at depths of 4,550-5,296 ft in the lower part of the Rio Dell Formation and upper part of the Eel River Formation. The sands reportedly are up to 10 ft thick, and are believed to be fine grained and thin bedded on the basis of log response; they may be along the margin of a deep-sea fan channel system that is thickest west of Grizzly Bluff. The primary trapping mechanism at the Grizzly Bluff field is believed to be anticlinal.

**Resource potential:** The Eel River Gas Play is only lightly explored. More than 100 wells have been drilled, but more than half of these were near the Tompkins Hill field, and drilling density in most of the rest of the play is quite low (Hopps and Horan, 1983; Horan and Hopps, 1987). Most exploration to date has focused on structural traps, but there is also potential for large stratigraphic traps involving lenticular sandstones in the

Bear River beds and the Wildcat Group (Crouch and Bachman, 1987). Such traps may be found along the margins of major deep-sea fan channels and on the flanks of anticlines. Combination traps may be found where north-south-trending, linear sand bodies traverse east-west-trending anticlines (Horan and Hopps, 1987). Structurally concealed and subthrust anticlines, the largest of which may be the size of Tompkins Hill, may be found in the footwall beneath the Little Salmon Fault. Additional footwall traps may be found where homoclinally dipping reservoirs are truncated and sealed updip by thrust faults. Undrilled anticlinal structures, including possible fault-bend folds, are present in the hanging walls of the Little Salmon and other thrust faults. Additional undrilled structural closures may be concealed by alluvium in the central part of the basin. Finally, the offshore extension of the Table Bluff anticline has not been drilled, but it is certainly a very obvious and attractive prospect.

The largest accumulation expected at a 5 percent chance in this play is estimated to be about 300 BCFG, or about twice the size of the largest discovered field (Tompkins Hill)--an outright guess. The median undiscovered accumulation size is estimated to be about 12 BCFG and reflects my opinion that most of the undiscovered accumulations are likely to be in small structural and stratigraphic traps that are only slightly larger than the minimum size assessed (6 BCFG).

I estimated the median number of undiscovered accumulations by applying the Checkerboard method to the "most prospective" part of the play, which is bounded on the west by the 3-mi limit offshore; on the northeast by a line parallel to the Little Salmon Fault and about 2.5 mi northeast of the fault (to account for subthrust accumulations); and on the south by the southern limit of the Rio Dell Formation (from the 3-mi limit eastward to near Rio Dell) and the edge of outcrops of the Wildcat Group (from near Rio Dell to the east side of the play). I counted 4 producing sections (from the Tompkins Hill and Table Bluff fields), about 40 drilled sections, and about 280 undrilled sections. I calculated a success ratio of 0.09, and about 25 sections with undiscovered accumulations. I inferred a probable median of 20 undiscovered accumulations, based on the presumption that at least two of the undiscovered accumulations will be large enough to occupy two or more sections. The least number of accumulations is estimated at 10, an outright guess. The largest number of accumulations is estimated to be about 70, or about 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

300, or about one accumulation for every undrilled section, but this struck me as wildly optimistic.

#### **0702. FRANCISCAN OIL AND GAS PLAY (HYPOTHETICAL)**

The hypothetical Franciscan Oil Play is located in Humboldt and Mendocino Counties in northern California, in a northwest-trending belt about 12–30 mi wide, stretching from near Ukiah, California (about 100 mi north of San Francisco), to Arcata Bay. The principal exploration targets in this play are known and hypothetical accumulations of oil and gas in poorly understood fractured sandstone and shale reservoirs in the Coastal and Central Belts of the Franciscan Complex. However, the play also includes hypothetical accumulations of hydrocarbons that may occur in isolated patches of Neogene sedimentary rocks that rest unconformably on the Franciscan in certain areas south of the Eel River Basin, most notably near Garberville, Willits, and Ukiah, California (e.g., McLaughlin and Nilsen, 1982; Nilsen and Clarke, 1989). Very little information, published or unpublished, is available on the petroleum geology of this play. The boundaries of the Franciscan Oil Play are poorly defined and arbitrary and are drawn to include the many occurrences of hydrocarbons that have been reported from areas near Petrolia, Honeydew, Garberville, Willits, and Ukiah, California. The area of the play is about 2,300 sq mi.

**Reservoirs:** Undiscovered accumulations of oil and gas in the Franciscan Complex are likely to be in fractured reservoirs, mainly hard sandstones and argillites. Some of these reservoirs may be similar to the fractured hydrothermal reservoirs in graywacke of the Franciscan Complex at the Geysers geothermal field near Clear Lake. At the Geysers, productive fractures occur in clusters that are separated by large intervals of unproductive rock; porosity is generally less than 10 percent and permeability less than 1 mD (Stockton and others, 1986).

Additional reservoirs may be found in sandstones in small patches of Neogene sedimentary rocks that, in most places, depositionally overlie the Franciscan but locally are thrust beneath it (McLaughlin and others, 1994, p. 30). The reservoir properties of the Neogene sandstones are uncertain, but may be comparable to lithologically similar rocks in the Eel River Gas Play (0701)

**Source rocks, timing and migration:** Signs of oil and gas are locally abundant in this play. Minor oil production was obtained from the Petrolia oil field, now abandoned (California Division of Oil and Gas, 1982). Shows of oil and gas have been reported

from exploratory wells drilled near Petrolia, Honeydew, Briceland, Willits, and Ukiah, California (Weber, 1888a, p. 185; MacGinitie, 1943; California Division of Oil and Gas, unpublished data). Oil seeps are abundant in the Petrolia and Honeydew areas, commonly in association with shear zones (Hodgson, 1980). South of Centerville Beach, California, light oil resembling kerosene is oozing from outcrops of fractured argillite of possible Oligocene and (or) early Miocene age in the False Cape terrane (R.J. McLaughlin, U. S. Geological Survey, Menlo Park, Calif., oral commun., 1993). Oil springs occur in the hills east of Potter Valley (Mendocino County), according to Weber (1888b, p. 202). Oil shows have been reported from water wells near Willits, California (Wayne Kremzer, rancher, oral commun., 1993).

The source rocks for these hydrocarbons are unknown and may vary from place to place. According to unpublished organic geochemical studies, oil from the Petrolia field is light (46° API), low in sulfur (0.08 weight percent), and of marine origin, on the basis of biomarkers. This oil, and by implication the oil in nearby seeps and wells, is believed to have been generated by a source rock of Miocene age (Alan Kornacki, Shell Oil Co., oral commun., 1992). Specific Miocene source rocks have not been identified in the Petrolia area, but may include: (1) argillites and diatomites of the False Cape terrane, which may be present in the subsurface at Petrolia; and (2) strata correlative with the Bear River beds and (or) Wildcat Group, in fault-bounded slices that may be structurally interleaved with rocks of the Coastal, Yager, and False Cape terranes (R.J. McLaughlin, oral commun., 1994).

Organic geochemical studies indicate that the argillaceous melange matrix of the Coastal and Central Belts of the Franciscan Complex is a potential source of petroleum. In both the Coastal and Central Belts, values of TOC (total organic carbon) are generally in the range of 1-2 percent, and kerogens are generally gas prone (Underwood, 1987; Larue, 1986, 1991). Thermal maturity investigations using vitrinite reflectance and Rock-Eval  $T_{max}$  show that large tracts of the Coastal and Central Belts are within the oil and wet-gas generative zones (Underwood, 1987; Larue, 1986, 1991). It therefore appears that the Franciscan Complex is a plausible source of gas in the Eel River Basin and nearby areas in northern California, but the ability of the Franciscan to generate oil is uncertain.

**Traps:** Little is known about the nature of traps in fractured reservoirs in the Franciscan. Potential traps may occur wherever a fractured mass of rock is overlain or bounded updip by unfractured rock, a fault, a tar seal, or an angular unconformity. In

the Geysers area, fractured geothermal reservoir rocks are typically sealed by overlying, relatively flat zones of serpentinite or argillaceous melange (R.J. McLaughlin, oral commun., 1994).

Undiscovered traps in the Tertiary rocks that depositionally overlie the Franciscan may include anticlines and stratigraphic traps similar to those in the Eel River Gas Play. Some of these traps may be hidden beneath thrust sheets of Franciscan rocks (McLaughlin and others, 1994).

**Exploration status:** Apparently, the first commercial production of petroleum in California came from the Petrolia area in 1862-1865, where many wells were drilled near oil and gas seeps (Ogle, 1953, 1956). More than 50 wells were drilled near Petrolia and along the Mattole River over the next 85 years. Some were temporary producers of light oil, and others produced gas. According to the California Division of Oil and Gas (1982), the Petrolia oil field was discovered near the older area in 1953, and produced oil of 46° API from depths of 1,570-1,620 ft. Two wells were completed, but the field was abandoned in 1971 after producing a total of 350 barrels of oil (Webster and Yenne, 1987). The nature of the reservoir and trap at the Petrolia field is unclear. Musser and Murray-Aaron (1962, p. 318-319) suggested that the trap is stratigraphic and related to the updip pinchouts of at least four steeply dipping, lenticular sandstone reservoirs of Late Cretaceous age. Alternatively, the oil may have been produced from fault-bounded inliers of the Bear River beds or Wildcat Group, or from fractured reservoirs in rocks of the Coastal, Yager, or False Cape terranes.

Unpublished well records in the files of the California Division of Oil and Gas indicate that more than a dozen wells were drilled in the Honeydew area between 1866 and 1950. Shows of oil and gas were reported from several, and at least one was completed as a gas well "for domestic use."

At least five wells have been drilled near Briceland, California, but little geological information is available. The most recent well, the Dugan Oil Co. Velma No. 1, was drilled in 1976. This well found shows of light oil from 2,000 ft to total depth of 3,154 ft, and reportedly bottomed in rocks of the Yager terrane.

Several wells have been drilled near Willits, California, with mixed results. The oldest, the Mendocino-Midway Oil Syndicate No. 1, was spudded in 1923; the well apparently penetrated fractured sandstone and shale of the Franciscan Complex, and was abandoned at total depth of 2,174 ft in 1925. Reportedly, this well encountered "a showing of gas (evidently marsh gas)" and "slight traces of oily substance" from 800 ft

to the bottom. In 1956, the L.H. Scott Percico No. 1 spudded in the Franciscan, found no shows of oil or gas, and was abandoned in Franciscan rocks at total depth of 4,080 ft. The Jewel City Exploration Hi No. 1 spudded in "Plio-Pleistocene" strata, reached the top of the Franciscan at about 1,000 ft, and bottomed in Franciscan at total depth of 2,000 ft in 1962; shows of gas were reported from 530 ft to total depth. Also in 1962, the Jewel City Smith No. 1 spudded in Franciscan rocks and reached total depth of 2,931 ft in the Franciscan; noncommercial shows of gas were found in hard shale and sandstone at several intervals from 723 to 2,475 ft. This well reportedly produced a total of 5 MCF of gas, all of which was blown into the air. In 1967, the Willits Oil and Gas Co. No. 1 spudded in the Franciscan and bottomed at total depth of 1,172 ft in hard, gray shale of the Franciscan; no shows of oil or gas were encountered.

Two wells were drilled near Ukiah, California, by W.C. Thompson Gas and Oil Exploration in 1959. Both appear to have spudded in unnamed nonmarine deposits of Pliocene and (or) Pleistocene age, but almost no geological information is available from either well. The Ukiah No. 1, drilled to total depth of 876 ft, reportedly "tested some gas and considerable water" and was later converted to a water well. The Ukiah No. 2, drilled to total depth of 630 ft, reported shows of both oil and gas but was converted to a water well.

**Resource potential:** A possible analog for the Franciscan Oil Play is the Oligocene to Miocene Hoh melange of western Washington, where there are numerous surface seeps of oil and gas (locally known as "smell muds"), and several wells near Ocean City, Washington, that reported good shows of oil and gas. The best of these wells, the Sunshine Mining Co. Medina No. 1, produced about 12,000 bbl of 39° API oil from sheared siltstone reservoirs but was abandoned because the fractured reservoirs were small and of low permeability and because shale in the Hoh tended to flow and plug casing perforations (McFarland, 1983; Petroleum Information Corp., 1985).

It appears, on the basis of limited experience in the areas near Ocean City, Washington, and Petrolia, California, that fractured reservoirs in melange are difficult to predict and find and are generally of small volume. Therefore, the accompanying data form for the Franciscan Oil Play indicates significant uncertainties associated with reservoir presence and quality, as well as trap size. I tentatively conclude that, despite the locally abundant evidence of hydrocarbons, the probability is low--less than 10 percent--that the Franciscan Oil Play includes one or more undiscovered petroleum accumulations larger than 1 MMBO.

### **0703. SARGENT-HOLLISTER OIL AND GAS PLAY**

This confirmed play is located in the southern Santa Clara Valley, about 80 mi southeast of San Francisco, California. The Sargent-Hollister Oil and Gas Play includes known and hypothetical accumulations of oil and non-associated gas in gently to moderately deformed Tertiary sedimentary rocks and fractured rocks of the Franciscan Complex. The Tertiary sequence in this area overlies the Franciscan Complex, is as thick as 16,000 ft and ranges in age from Eocene to Pliocene (Imperato and others, 1990). Very little published information is available on the stratigraphy, structure, and petroleum geology of this play. The play is bounded on the southwest by the San Andreas Fault, on the north by Franciscan rocks in outcrop and the shallow subsurface, on the east by uplifted Mesozoic and Tertiary rocks of the Diablo Range, and on the southeast by an area of closely spaced surface faults near the intersection of the San Andreas and Calaveras Fault Zones. The area of the play is about 240 sq mi.

**Reservoirs:** Known reservoirs include sandstones and diatomites in the Pliocene(?) Etchegoin Formation and fractured hard sandstones in the Franciscan assemblage. Speculatively, additional reservoirs may also occur in fractured, fine-grained rocks (mainly siliceous shales and dolomites) of early Miocene age in the informally named shale of Mount Pajaro (of Dibblee and Brabb, 1978). Other sandstones within the area of the play occur in the middle Miocene Temblor Formation and an unnamed unit of Eocene age (Dibblee and Brabb, 1978), but the reservoir potential of these rocks is unknown.

**Source rocks and hydrocarbons:** Both oil and non-associated gas are commercially produced from the Sargent-Hollister Oil and Gas Play, and surface seeps are locally prolific, but the sources of these hydrocarbons have not been identified. The oil and non-associated gas may have been derived from different sources or from a single source horizon that varies in thermal maturity from place to place. Possible local source rocks include organic-rich strata of early Miocene age in the shale of Mount Pajaro (of Dibblee and Brabb, 1978) and marine shales in the lower part of the Pliocene(?) Etchegoin Formation. An alternative hypothesis is that the oil was generated from organic-rich strata of Eocene and (or) Miocene age in the La Honda Basin west of the San Andreas Fault, prior to right-lateral displacement of about 50 mi along the fault. Another hypothesis is that the oil migrated from some unknown source east of the Calaveras Fault, which may have experienced about 100 mi of right-lateral displacement since the middle Miocene (McLaughlin and others, 1990). It is unlikely,

but possible, that some hydrocarbons were generated in unidentified organic-rich rocks within the Franciscan Complex.

Gas from the Hollister field contains no CO<sub>2</sub> or H<sub>2</sub>S, and is produced with almost no condensate (R.F. Curtin, California Division of Oil and Gas, oral commun., 1994). At this writing, I have no information on whether this gas is of thermogenic or biogenic origin.

**Traps:** Known and expected trap types include tar seals on homoclines, anticlines and fault-bounded basement highs; stratigraphic traps formed by sandstone pinchouts or permeability barriers on homoclines; and stratigraphic traps beneath the regional sub-Etchegoin unconformity. Speculatively, there may be additional traps in the footwall of the southwest-dipping Sargent Fault.

**Exploration status:** Commercial production of petroleum has been obtained from small accumulations along the Sargent fault. The Sargent field, discovered in 1906 and still active, had cumulative production of 914 MBO of 16-25 API oil and 323 MMCFG by the end of 1991. Estimates of the size of Sargent field range from 914 MMBO and 335 MMCFG (sum of cumulative production to 12/31/91 and estimated reserves, according to California Division of Oil and Gas, 1992), to 985 MBO and 333 MMCFG (NRG Associates, 1993), to nearly 2 MMBO (R.E. Bennett, Patriot Resources, oral commun., 1993). The oil is obtained from sandstone reservoirs of presumed Pliocene age (Michelin, 1943), regarded as part of the Etchegoin Formation, at depths of about 300-1,100 ft. Average pay thickness is reportedly about 130 ft; average porosity of the sandstones is about 35 percent; average permeability is about 217 mD; and the average gas/oil ratio is about 339 CF/BO (NRG Associates, 1993). The nature of the trap is unclear but may be an angular unconformity within the Etchegoin, and (or) a tar seal at the updip edge of a southeasterly-dipping homocline. Oil produced from the Sargent field is about 0.62 weight percent sulfur and is accompanied by large volumes of water.

A few miles to the southeast of Sargent field, non-associated gas and small amounts of oil have been produced from several areas collectively referred to as the Hollister field. By the end of 1991, cumulative production of non-associated gas from the Flint Hills area of the Hollister field was 7,923 MMCFG. Estimates of the size of the Flint Hills accumulation range from 8,020 MMCFG (sum of cumulative production to 12/31/91 and estimated reserves, according to California Division of Oil and Gas, 1992) to 12,369 MMCFG (NRG Associates, 1993). The gas in the Flint Hills area is produced from lenticular nonmarine and marine sandstones of the Etchegoin Formation; at least seven

separate sand horizons are productive, ranging in depth from 1,000 to 3,500 ft (Wilkinson, 1963, 1967). Average thickness of the productive sands is about 35 ft (NRG Associates, 1993). From 1956 to 1958, two wells in the Flint Hills area produced a total of about 2,300 bbl of 27° API and 36°–40° API oil from two distinct sandstone intervals within the Etchegoin Formation (Wilkinson, 1963). The trap at Flint Hills is believed to be mainly anticlinal, but some of the trapping may be stratigraphic.

In the Lomerias area of the Hollister field, abandoned in 1957, small amounts of 22°–23° API oil were produced from fractured Franciscan(?) sandstone and a basal conglomerate in the overlying Etchegoin Formation (Wilkinson, 1963, 1967).

Cumulative production of about 6 MBO was obtained from depths of 1,700–2,100 ft. The trap is poorly understood; the productive wells appear to be located on a fault-bounded block of Franciscan(?) rocks within the core of an anticline.

**Resource potential:** On the basis of two commercial discoveries, generally favorable geology, and generally light drilling density away from existing production, the chances seem good for the existence of undiscovered accumulations of both oil and gas. Future discoveries probably will be small, owing to the small geographic size of the play and its structural complexity, and likely will be concentrated along the Sargent and Calaveras Fault Zones.

The largest accumulation expected at a 5 percent chance in the Sargent-Hollister Oil and Gas Play is estimated to be about 10 MMBO by very loose analogy with the nearby Vallecitos oil field, which has a size of about 5.2 MMBO oil and 4 BCFG (sum of cumulative production to 12/31/92 and estimated reserves, according to California Division of Oil and Gas, 1993). The Vallecitos area is broadly similar in stratigraphy and structural complexity to the Sargent-Hollister area; however, production in the Vallecitos field is mainly from Paleocene and Eocene sandstones, versus Pliocene(?) sandstones in the Sargent-Hollister Oil and Gas Play. The median undiscovered accumulation size in the Sargent-Hollister Oil and Gas Play is estimated to be about 1.5 MMBO; most of the undiscovered accumulations 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 using the Checkerboard method. I counted 2 producing sections (from the Sargent and Hollister fields), 41 drilled sections, and about 180 undrilled sections. I calculated a success ratio of 0.05, and about 9 sections with undiscovered accumulations, from which I inferred a probable median of 10 undiscovered accumulations. The least number of undiscovered

accumulations is estimated at two, which is equal to the number of known accumulations. The largest number of accumulations is estimated to be about 50, or about 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 200, or about one accumulation for every undrilled section, but this struck me as overly optimistic. The numbers of undiscovered fields were split evenly between oil and non-associated gas, consistent with the distribution of known accumulations.

## **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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