PETROLEUM GEOLOGY OF THE MONTEREY FORMATION IN THE SANTA MARIA AND SANTA BARBARA COASTAL AND OFFSHORE AREAS

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INTRODUCTION

Spectacular outcrops of the Monterey Formation are exposed along the coast between Santa Barbara and Santa Maria (Figure 1). These exposures are direct analogues to reservoir and source rocks in nearby oil fields both on and offshore.

Excellent exposure, easy access, and association with petroleum have attracted a great deal of geologic study of the coastal outcrops. In particular, the work of Isaacs (1981a, 1981b, 1982, 1983, 1984, 1985, 1987) along the Santa Barbara coast has helped clarify some long standing questions on rock composition, sedimentation rates, and stratigraphy. Other recent work including references to important earlier work includes: studies of the Santa Maria area by Pisciotto (1981) and Grivetti (1982); a field guide to the Santa Maria coastal outcrops by Dunham and Blake (1987); structural studies by Belfield and others (1983) and Snyder (1987); and petroleum geology studies by Ogle and other (1987), Crain and others (1987) and Isaacs and Petersen (1987). Classic early reports on regional geology include Woodring and Bramlette (1950) on the Santa Maria area, and Dibblee (1950, 1966) on the Santa Barbara coastline and Santa Ynez Range.

In this paper, Monterey Formation geology as gleaned mainly from coastal outcrops is summarized and related to nearby oilfields. This includes correlation of outcrops to wells and discussion of reservoir characteristics and models.

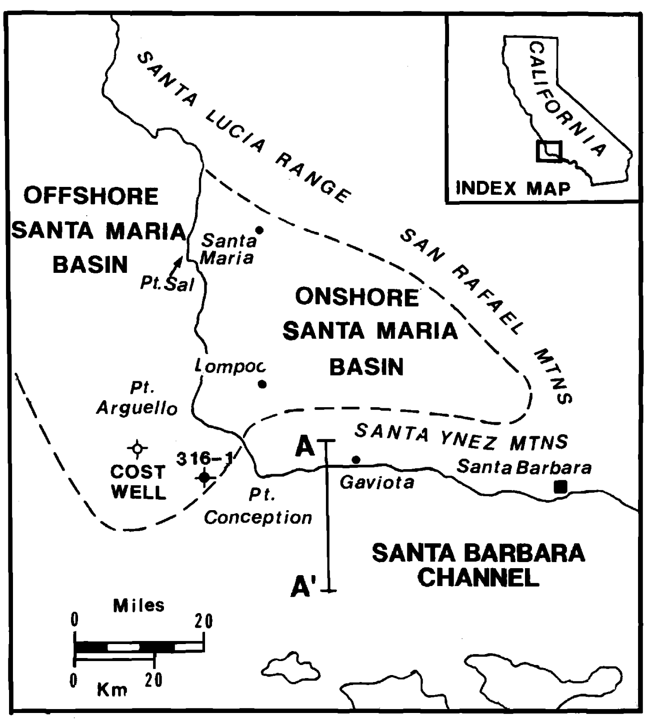

Figure 1. Location map of the Santa Barbara-Santa Maria area. See Figure 4 for cross section A-A'.

STRATIGRAPHIC AND STRUCTURAL SETTING

Prior to Oligocene times, the Santa Barbara and Santa Maria area was part of a subduction-forearc basin system that had been in place along California, albeit with some interruptions, since late Jurassic time. The Santa Maria area was the site of subduction as represented by the basement rock there - the highly deformed and in-part metamorphosed sedimentary and volcanic rocks of the Franciscan Complex. The Santa Barbara area was the site of forearc basin sedimentation as represented by a thick (6100 m; 20,000 ft) nearly uninterrupted sequence of sedimentary rocks of Late Jurassic to Oligocene age, well exposed in the Santa Ynez Mountains (Figures 1 and 2).

A change from subduction to a transform margin occurred during the Oligocene-Early Miocene and resulted in extension of the borderland and formation of new marine basins. In the Santa Barbara area, the last phase of forearc sedimentation, as represented mainly by non-marine deposition (Sespe Fm), was replaced by shallow marine (Vaqueros Fm.) then deep marine (Rincon Fm.) sedimentation in the newly formed basins. In the Santa Maria area, the Franciscan was overlain by the non-marine and shallow-marine(?) Lospe Formation during this period.

Monterey Formation deposition began in the Late Early Miocene and continued into the Late Miocene. As Monterey deposition proceeded, the Transverse Ranges were apparently rotated clockwise as shown by paleomagnetic studies (Luyendyk and others, 1987). The rotation apparently began approximately 16 to 18 Ma and resulted in the present east-west orientation of the Transverse Ranges. This changed the original parallel arrangement of forearc belts to the present arrangement where subduction basement in the Santa Maria area is now wedged between belts of forearc basin rocks (Figure 3).

Monterey deposition ceased approximately 6.0 Ma when a major tectonic disturbance uplifted parts of the margins of both the Santa Barbara and Santa Maria areas, resulting in an increase in detritus and deposition of the Sisquoc Formation. The uplift is marked by an unconformity between the Monterey and Sisquoc Formations in many areas (Woodring and Bramlette, 1950: Dibblee, 1966). Tectonism continued through the Pliocene and Early Pleistocene and both

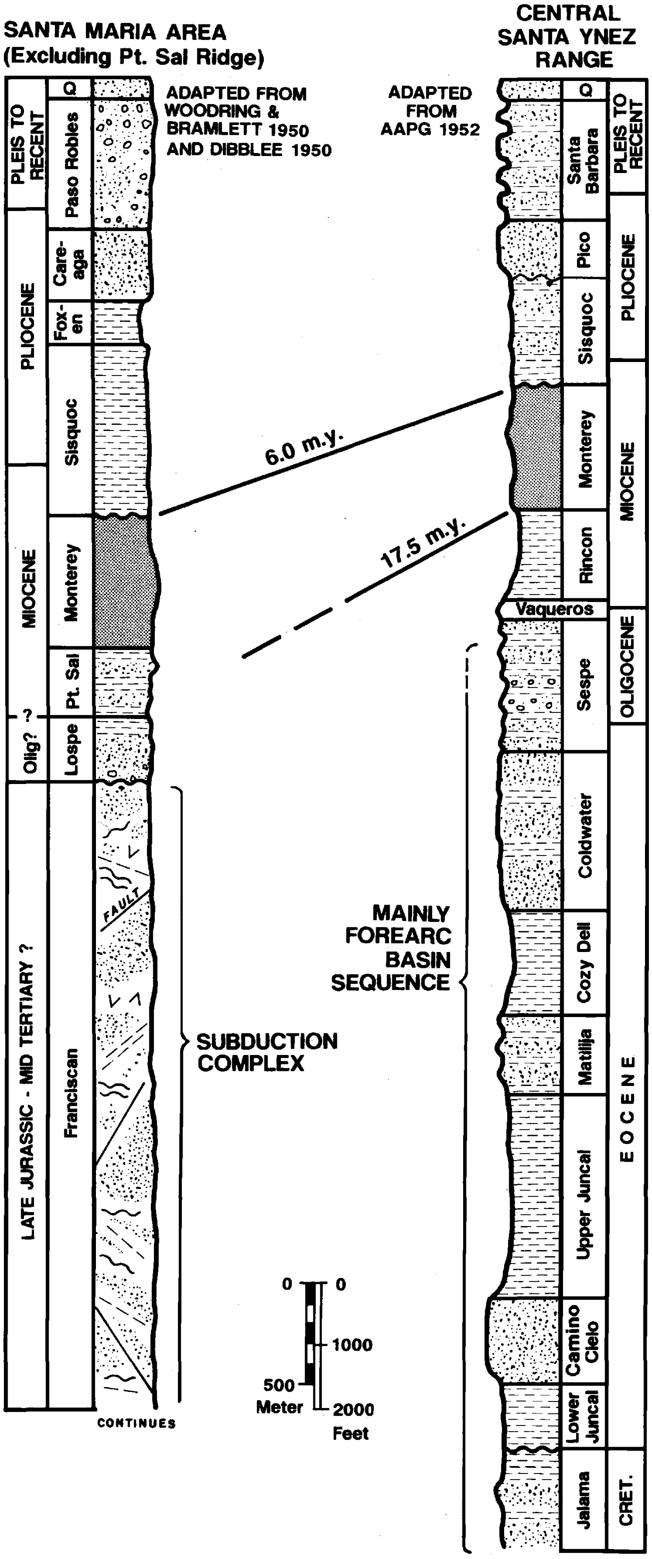

Figure 2. Typical geologic columns from the Santa Barbara and Santa Maria areas.

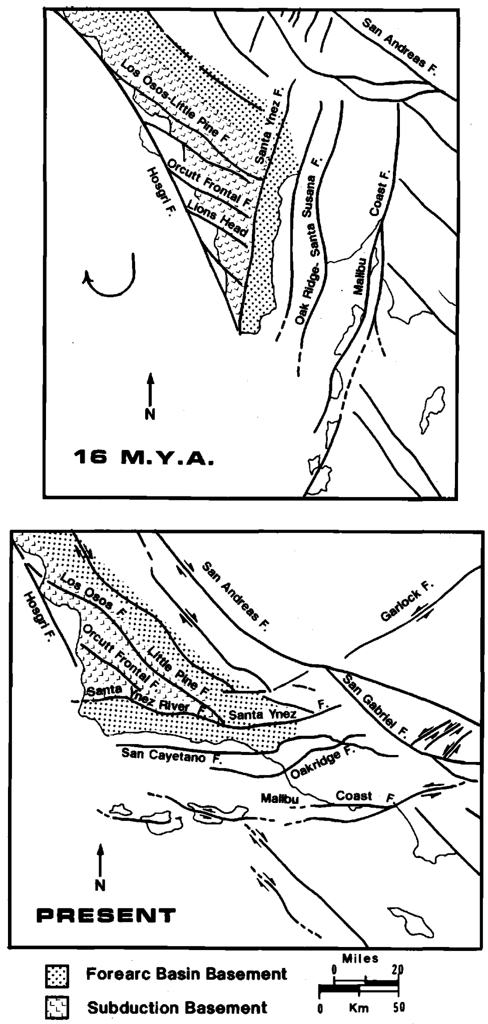

Figure 3. Model for clockwise rotation of the Transverse Ranges, after Hornafius and others (1986).

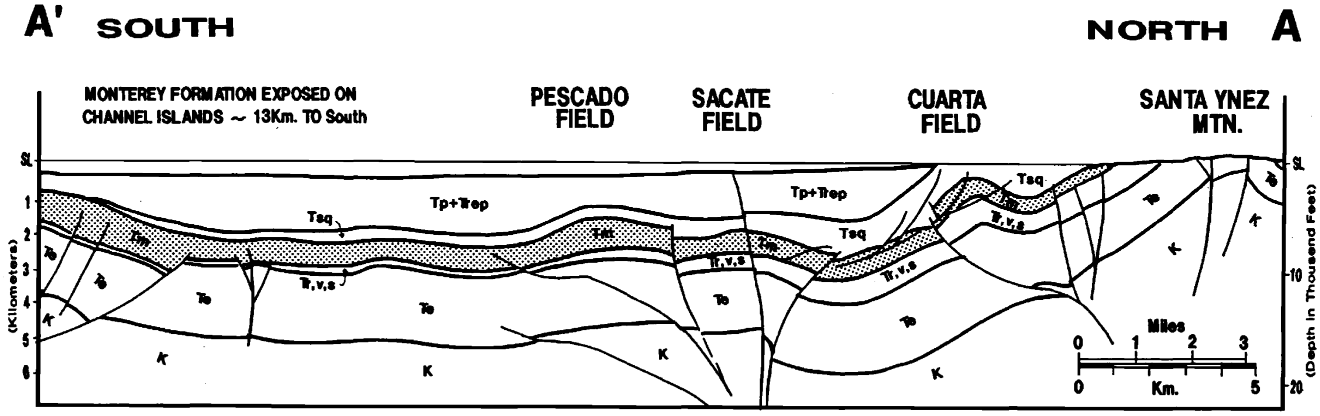

Figure 4. Cross section through the western Santa Barbara Channel; drawn by J. C. Phelps. Location shown in Figure 1. Trep = Repetto; Tp = Pico; Tsq = Sisquoc Fm.; Tm = Monterey Fm.; Tr,v,s = Rincon, Sespe, and Vaqueros Fms.; Te = Eocene Fms.; K = Cretaceous.

the Santa Barbara Channel area and the Santa Maria basin remained as deep basins and continued to fill with sediment while basin margins were uplifted. In Mid and Late Pleistocene times, roughly north-south compression accelerated, and resulted in the formation or enhancement of most of the structures we see today, such as the Santa Ynez Mountains and many of the anticlinal traps that form present-day oil fields (Figure 4) (Woodring and Bramlette, 1950; Dibblee, 1966; Yeats, 1987). Rapid uplift still continues in some areas, ranging up to 7 mm (.3 in)/yr in the Santa Barbara-Ventura area based on studies of marine terraces (LaJoie and others, 1982).

The intense tectonism that has characterized the Santa Barbara-Santa Maria area since the deposition of the Monterey Formation provided the elements necessary for oil field formation. First, rapid subsidence and basin margin uplift resulted in extremely rapid deposition in some areas, burying the Monterey Formation to hydrocarbon generating depths (Figure 4). As rapid sedimentation proceeded, folding accompanied by reverse faulting formed traps and helped create fractured reservoir rocks, particularly along the edges of basins, into which deep generated hydrocarbons could easily migrate.

MONTEREY FORMATION STRATIGRAPHY

Various stratigraphic subdivisions of the Monterey Formation have been recognized in the Santa Maria and Santa Barbara Basin as summarized by Pisciotto (1981). At Chevron and in this guidebook, we use four subdivisions following features of the Issacs (1981a) and Pisciotto (1981) schemes. These are, from youngest to oldest, the clayey-siliceous, the upper calcareous-siliceous, phosphatic, and lower calcareous-siliceous members.

The four members can be recognized along both the Santa Barbara and Santa Maria coastlines. Along the Santa Maria coastline the complete sequence averages approximately 1100 m (3400 ft) thick (Figure 5). Along the Santa Barbara coastline near Gaviota the sequence is much thinner, averaging approximately 400 m (1300 ft) in thickness (Isaacs, 1981a).

The siliceous rocks in most exposures have been diagenetically altered to opal CT or quartz phase. Generally it is not possible to determine between opal CT and quartz phase in outcrop and therefore outcrop descriptions of diagenetically altered siliceous rocks, as given below, apply equally to both phases.

The LOWER CALCAREOUS-SILICEOUS MEMBER is composed of dolostone and dolomitic or calcareous porcelanite and mudstone (Figure 6). Phosphatic beds are present locally, particularly in the upper part of this member. Chert is rare. Bedding thickness is variable but most beds are less than 20 cm (8 in) thick. The thickest beds are generally 2 to 3 m (6 to 10 ft) thick and are typically dolostone. Some dolostone nodules are present locally. The lower calcareous-siliceous member rests conformably on the Tranquillon volcanics in the Point Arguello area. There is some intermixing of volcanic material and biogenic material at the contact. Further east along the Santa Barbara coastline, the the Monterey Formation rests conformably on the Rincon Formation. Locally a tuff bed(s), probably of Tranquillon origin, is present at or just above the Monterey-Rincon contact. North of Point Conception near Pt Sal, the Monterey Formation rests conformably on the Pt Sal Formation, a deep-marine clastic sequence of mudstone and subordinate sandstone that is coeval with part of the lower calcareous-siliceous member.

The PHOSPHATIC MEMBER, where best developed, is composed primarily of carbonate-rich phosphatic mudstone (Figure 7). Dolostone nodules and beds make up approximately 10% of typical sections. Phosphatic mudstone is dark brown when fresh and is usually laminated. Phosphatic material most commonly occurs as small, isolated, pea-sized blebs or as finely dispersed material along laminations. In some places, phosphatic material occurs as thumb-sized nodules, concentrated along bedding planes. In many areas the phosphatic member contains abundant porcelanite, dolostone and chert interbedded with phosphatic mudstone. This is typically the case for the upper part of the phosphatic member, and in such cases the transition to the upper calcareous-siliceous member is gradational. The contact with the lower calcareous-siliceous member is not well exposed along the Santa Maria coastline. Along the Santa Barbara coast, the lower contact is marked by an abrupt down-section increase in resistance to erosion due to a higher biogenic silica content in the underlying lower calcareous-siliceous member.

The UPPER CALCAREOUS-SILICEOUS MEMBER contains a greater proportion of porcelanite and chert versus mudstone than the other members (Figure 8). Dolostone beds and nodules are also conspicuous and phosphatic mudstone is present locally, particularly near the base. Many of the beds are finely laminated. Thick-bedded, highly contorted chert beds are a conspicuous component in the Santa Maria coastal outcrops. The range in bed thickness is similar to that for the lower calcareous-siliceous member but thin

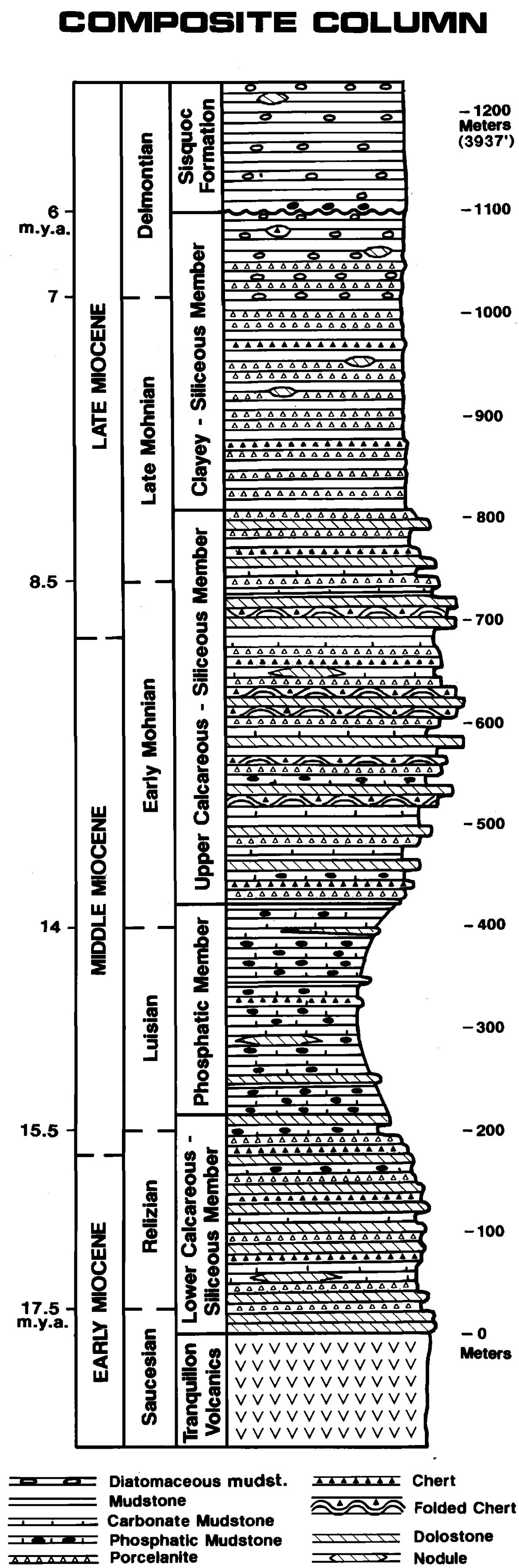

Figure 5. Composite geologic column of the Monterey Formation in the Pt. Arguello-Pt. Conception-Lompoc area. Lower contact may be younger locally. Biostratigraphic data from Grivetti (1982), Dumont (1986, and pers. comm.), Finger (pers. Comm), and unpublished Chevron reports. Absolute age of stage boundaries from Barron (1986).

beds (1 to 5 cm (.4 to 2 in) thick) are better defined and more abundant, creating a more heterogeneous appearance (compare figures 6 and 8). This member has a greater average siliceous content than the other members which, along with the dolostone beds, make it especially resistant to erosion. The spectacular cliffs at Point Arguello and the seaward-pointing fingers at Mussel Rock, two of the most prominent features along the coast north of Point Conception, are both expressions of the resistant chert, porcelanite and dolostone that make up most of this member.

The CLAYEY-SILICEOUS MEMBER typically consists of a monotonous sequence of uniformly bedded porcelanite and siliceous mudstone (Figure 9). Bed thickness typically ranges from a few to 30 cm (1 to 9 in) and many beds are laminated. The uniformity of most outcrops is occasionally broken by the presence of a few dolostone nodules ranging up to a meter (3 ft) in length. More rarely, small chert nodules and thin chert beds are present in some sections. The clayey-siliceous member is overlain by distinctly less siliceous and poorly bedded rocks of the Sisquoc Formation. The contact varies from gradational to disconformable to angular unconformable. In a few areas the contact is marked by a phosphatic conglomerate, or by a breccia composed mainly of Monterey Formation clasts.

Opal A diatomaceous rocks are present in both the Santa Barbara and Santa Maria areas. These rocks are white where weathered or dark brown where fresh and may be laminated or unlaminated. They are otherwise fairly uniform in appearance. In

Fig. 6. Lower calcareous-siliceous member; near Gaviota.

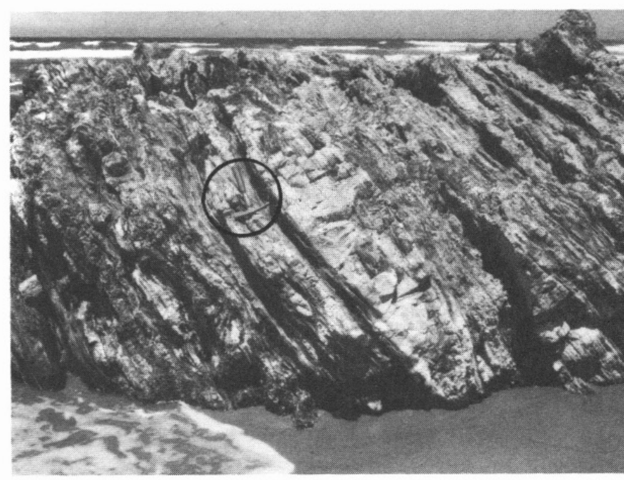

Figure 8. Upper calcareous-siliceous member, near Point Arguello. Hammer circled.

Fig. 7. Phosphatic member; near Gaviota.

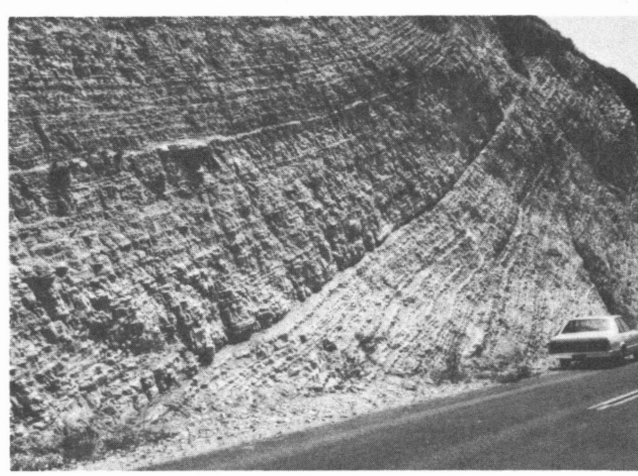

Fig. 9. Clayey-siliceous member; Sweeny Road, near Lompoc.

the Santa Maria area the upper part of the clayey-siliceous member is typically the only part of the Monterey Formation that is diatomaceous. Older diatomaceous strata are present locally such as at the Johns Manville diatomite quarry near Lompoc. In the Santa Barbara area, the entire Monterey sequence is diatomaceous near Goleta (Isaacs 1981a); but within several kilometers (a few miles) east and west, the sequence is mainly opal CT phase.

Typical Upper Monterey diatomaceous strata are finely laminated whereas the overlying Sisquoc is mainly massive or coarsely laminated. However, exceptions to these observations make this technique of differentiating the formations unreliable.

SOURCE ROCKS

Good source rocks are present throughout the Monterey Formation. Total organic carbon content is high (see Pytte, this volume) and most of the kerogen present is amorphous type II. Most of the kerogen is thought to be derived from the major marine micro-organisms - coccolithophores, dinoflagellates, diatoms and foraminifera. In addition, bacterial mats may have been important contributors (Williams and Reimers, 1983).

Organic carbon content is highest in the phosphatic member; average values along the Santa Barbara coast are 5% and range up to 34% for individual beds (Issacs, 1987). Maximum values from the Point Arguello field range up to 18% (Crain and others 1987). These values are very high, considering that an organic carbon content of 0.5 to 1.0% is considered sufficient for commercial hydrocarbon generation.

Isaacs (1987) has recently raised some interesting questions regarding the general views on distribution of organic matter in the Monterey Formation that do not agree with previous generalizations. Her data show that organic material is highest in rocks with high detrital and carbonate content, rather than in highly biogenic siliceous rocks such as chert and porcelanite. Furthermore, laminated beds apparently deposited in low oxygen environments where organic material is best preserved, have less organic carbon than unlaminated beds.

In terms of generating depths, the Monterey Formation in the COST well near Pt Arguello appears to be generating oil at 2100 m (6890 ft) at temperatures of 80° to 85° C (176° to 187° F), with a present day geothermal gradient of approximately 40° C/km (2.2° F/100 ft) (Petersen and Hickey, 1987). The generating rocks are probably at their maximum burial depth in this well and can therefore serve as a crude guide to generation depths elsewhere. For example, the range for geothermal gradients in the Santa Maria and Santa Barbara channel areas varies for the most part between 25° and 50° C/km (1.4° to 2.7° F/100 ft). This translates into approximate initial generating depths of from 1400 to 3000 m (4590 to 9840 ft), assuming similar past heat flows and sea bottom or ground temperatures of between 6° and 15° C (43° and 59° F).

CORRELATION FROM OUTCROPS TO WELLS

Correlation of Monterey Formation member boundaries by biostratigraphic means (see Dumont, this guidebook) is not always possible because in many outcrops and wells, datable microfossils have been destroyed by diagenesis. This is particularly true of the siliceous rock types. In some cases, special processing of dolostone samples can yield diatoms, but on a routine basis, paleontological correlations are often crude. Better results can often be obtained by analysis of drill cuttings and well logs.

Recognition of the four members of the Monterey Formation using drill chips can be done by estimating the percentages of siliceous and carbonate rock types using a binocular microscope, or preferably by using thin sections as shown in an example of two offshore wells near Pt Arguello (Figure 10). Using a somewhat different approach, Isaacs and others (1983) used geochemical analyses of bulk drill chips to recognize members in the COST Well, OCS-CAL-78-164.

Though variations are common, a typical downhole sequence observed in drill chips in the Western Santa Barbara Channel and Santa Maria offshore areas is as follows. The Sisquoc Formation appears as massive or coarsely laminated siliceous mudstone. The clayey-siliceous member is recognized by an increase in finely laminated porcelanite. The upper calcareous-siliceous member is marked by a sharp increase in chert and dolostone. The phosphatic member is marked by an increase in mudstone and a decrease in chert. The lower calcareous-siliceous member is recognized by an increase in siliceous content and in many areas by a strong increase in dolostone. Locally, sandstone and siltstone are present within or in place of the lower calcareous-siliceous member.

Wireline log data offers a quick method

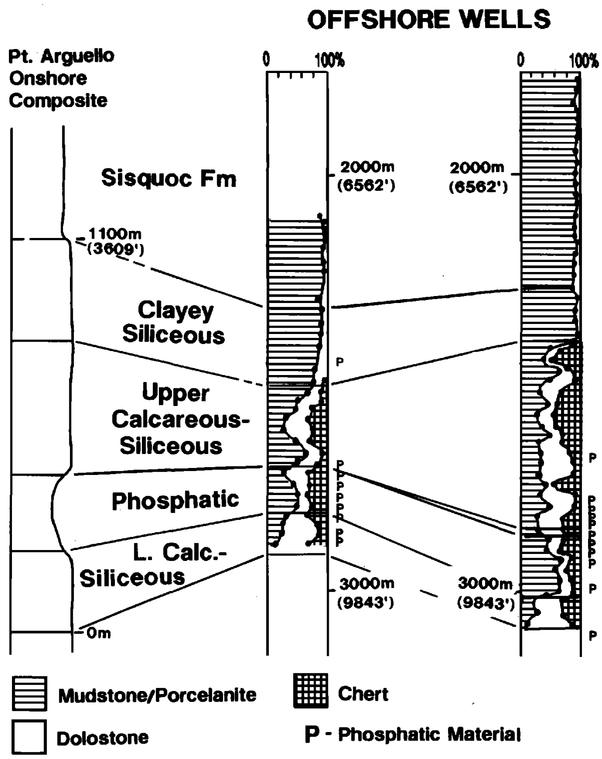

Figure 10. Correlation of members from outcrop to wells based on rock type abundance as determined from thin section.

of recognizing and correlating the four members. The gamma ray, and to a lesser extent resistivity, are the simplest and easiest tools to use at present.

In the Santa Maria and western Santa Barbara Channel areas, gamma ray response varies dramatically and appears to be a direct response to changing lithology. An analysis of several offshore wells (Bertucci, pers. comm.) showed that the Sisquoc Formation and the upper and lower calcareous-siliceous members have a low gamma response, averaging from 30 to 80 API units whereas the clayey-siliceous and phosphatic members have a high response, averaging 75 to 200 API units (Figure 11). The difference in response appears to be due mainly to differences in uranium content, which in turn appears to correlate to differences in organic content and to a lesser extent, phosphatic content. In general, the member boundaries as outlined by the gamma ray appear to correlate well with boundaries determined from drill chips and resistivity. No comparative study of gamma ray response of outcrop samples has yet been done.

Resistivity appears to be mainly related to porosity and clay content in Monterey rocks rather than to pore fluid type and content (see Fish, this volume). The OCS

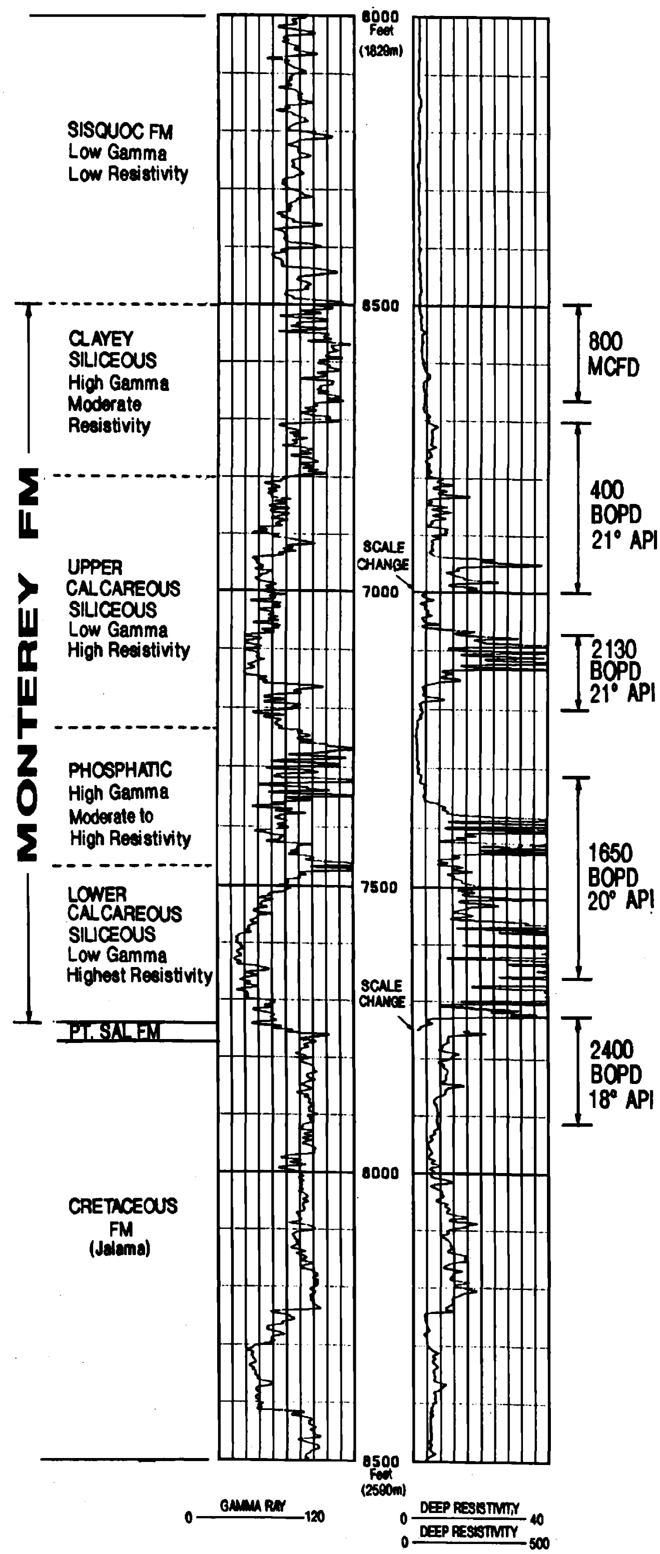

Figure 11. Resistivity (right column) and gamma ray (left column) logs from the OCS-316-1 well, Pt. Arguello Field. Responses are described in text. Flow rates from drill stem tests are shown on right. Note that all members of the Monterey tested oil.

316-1 well (Figure 11) serves as a good example of how resistivity varies downhole. Resistivity is very low in the Sisquoc Formation, typically reading 1 to 2 ohms. Resistivity increases slightly at what we believe is the Sisquoc-Monterey contact based on drill chip and gamma ray response. The increase may be due to a downhole decrease in clay content across this boundary. A further modest increase in resistivity and spikyness generally occurs within the clayey-siliceous member, 30 to 100 m (98 to 328 ft) below the inferred Sisquoc-Monterey contact. Resistivity increases greatly within the upper calcareous-siliceous member probably in response to the presence of tight chert and dolostone beds. In some wells a decrease in resistivity is seen in the phosphatic member. Resistivity increases in the lower calcareous-siliceous member, probably in response to the presence of abundant "tight" dolostone beds.

RESERVOIR PROPERTIES OF CT AND QUARTZ PHASE ROCKS

The Monterey Formation is a fractured reservoir - the name implying that without fractures, commercial production of hydrocarbons would be impossible. Fractured reservoirs are usually found in rocks with reasonable porosity, typically 10 to 30%, but very low matrix permeability (Arguilera, 1980). These fractured reservoirs have a "dual porosity system", in which hydrocarbons are largely stored in the matrix but transported to the wellbore via fractures.

Oil company estimates for fracture porosity in the Monterey Formation range from less than 1% to up to 10%. Fracture porosity of individual beds may be higher. However, most workers argue that total fracture porosity in most fractured reservoirs averages less than than one percent (e.g., Reiss, 1980).

Matrix porosity of Monterey rock types is controlled by rock type and diagenetic grade (Table 1). Results vary greatly but a general pattern in which porosity decreases from opal CT to quartz is clear (Isaacs 1981b; Chevron unpublished data). Porosities of opal CT rocks generally range from 15 to 35 percent, whereas quartz-phase rocks generally range from 2 to 25 percent. In terms of rock type, porcelanites and siliceous mudstones have the highest porosities and dolostones and some cherts have the lowest.

ROCK TYPE	POROSITY		PERMEABILITY
	CT	QTZ	
Mudstone (Siliceous)	20 - 30%	15 - 25%	< 1 md
Porcelanite	25 - 35%	10 - 25%	< 1 md
Chert	15 - 25%	2 - 15%	< 1 md
Dolostone	2 - 10%	2 - 10%	< 1 md

Table 1. Porosity and permeability values for unfractured opal CT and quartz phase rocks. Data from Isaacs (1981b) and Chevron (unpublished data).

Though matrix permeability is negligible in Monterey rock types (Table 1), fracture permeability can be very high. Flow rates in many wells have exceeded 5000 bbls/day and permeabilities of up to several darcys have been calculated from drill stem tests; (Regan and Hughes 1949; Crain and others, 1987; Ogle and others, 1987). In the Point Arguello Field, permeability determined from drill stem tests averages from less than one to over 3000 millidarcies (Crain and others, 1987). Production data suggest that this permeability is not evenly distributed but is concentrated in thin, widely spaced zones.

It has long been known that fracture abundance varies with rock type (Grivetti, 1982; Belfield and others, 1983; Snyder, 1987). In general, the more siliceous a rock is, the more likely it will be fractured (Figures 12 thru 15). Results of fracture spacing measurements from several wells and onshore outcrop areas show that the order of fracturability from most to least fractured is: chert-porcelanite-mudstone-dolostone. Average fracture spacing for each rock type is: brecciated chert - 0.4 cm (.16 in); unbrecciated chert - 2 cm (.8 in); porcelanite - 3.6 cm (1.4 in); mudstone - 6.5 cm (2.6 in); and dolostone - 8.6 cm (3.4 in) (Table 2). These results generally agree with the observations of other workers. However, some workers report that dolostone has more fractures than mudstone and, in some cases, more fractures than porcelanite. This is true locally, particularly where dolostone breccia is present; however, the most common type of dolostone present along the coast is massive and relatively unfractured.

In addition to rock type, the main factor controlling fracture density in most areas appears to be local deformation. As a

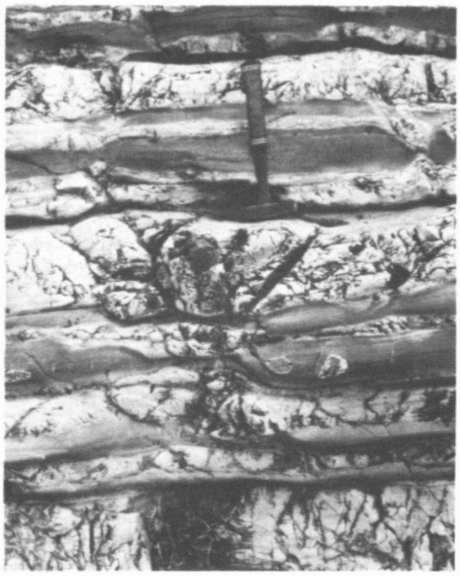

Fig. 12. Small fractures in porcelanite; interbedded mudstone is relatively unfractured.

Figure 14. Brecciated and highly contorted chert bed; such beds are generally restricted to the upper calcareous-siliceous member.

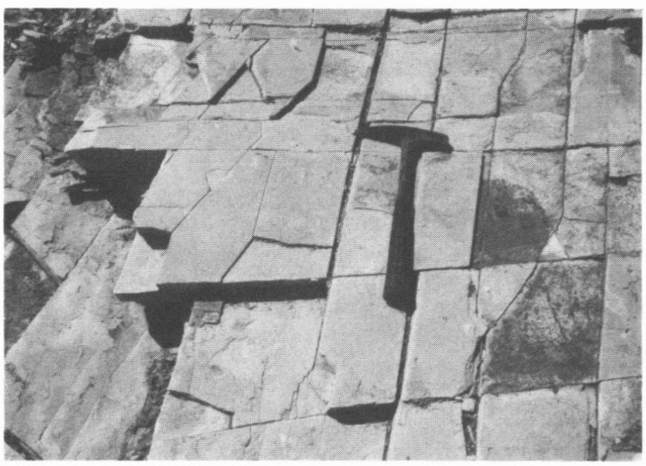

Figure 13. Bedding plane view of small fractures in porcelanite. Note the unusually regular fracture sets. Hammerhead is parallel to strike.

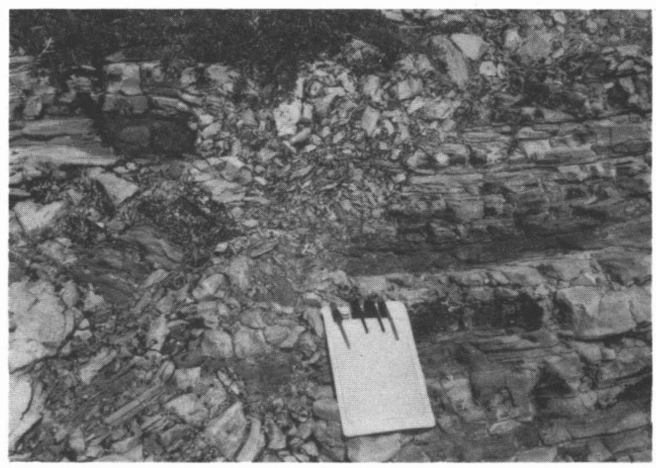

Figure 15. Fracture breccia; note how the breccia cross-cuts bedding.

general observation, fractures appear to be more common near faults and fold hinges than in less deformed areas (Grivetti, 1982).

Our data suggest that there is no apparent difference in fracture spacing between opal CT and quartz phase rocks. This observation goes against that of most previous workers. To add to the confusion, Grivetti (1982) concluded that fracture intensity was greater in opal CT rocks near Pt Arguello than in the quartz phase rocks at Lions Head. Since in many areas fracturing depends in large part on local structure, it may be difficult to prove if one phase is consistently more fractured than the other.

Fracture Types and Models

Three major types of fractures can be distinguished in outcrop: (1) small fractures usually contained within individual beds; (2) brecciated beds, usually chert; and (3) large fractures, faults and associated breccia. These fracture types are somewhat idealized and intergradational, but they serve as

Location	Chert		Porcelanite	Mudstone	Dolostone
Offshore Cores	Brecciated 0.3	Unbrecciated 1	1.5	2.7	9.7
			2		
	Brecciated 0.3	Unbrecciated 3	8	15	15
Jalama Beach	0.5		3.5	5.5	7.5
Lions Head	0.6		3.2	5.5	6.6
Various Coastal Outcrops	0.5		1.1	3.8	4.4
Average	0.3**	2**	3.6	6.5	8.6

** From Core Only

Table 2. Average fracture spacing values (in cm; 1 in = 2.5 cm) from core and outcrop. Fracture spacing represents the distance between fractures measured in a straight line running parallel to bedding. Data from unpublished Chevron reports.

convenient end members from which important generalizations can be made.

Small fractures are by far the most common fracture type (Figure 12). In most cases they are spaced a few centimeters (1 to 4 in) apart and are restricted to individual beds - that is, they do not extent across bed boundaries. These fractures are usually oriented perpendicular to bedding or nearly so. Two dominant fracture sets are recognized - one roughly parallel and one roughly perpendicular to the strike of bedding (Figure 13) (Grivetti, 1982; Belfield and others, 1983). Additional fracture sets may also be present.

Brecciated beds are almost always composed of chert (Figure 14). These beds contain closely spaced fractures that cut in every direction. The fractures cut the chert into tiny fragments, usually only a few millimeters across. The individual pieces have generally moved only slightly with respect to each other so that laminations and other bedding features can still be recognized.

Large fractures and associated breccia are differentiated from small fractures in that they cross-cut beds. Generally they cross-cut many beds and have exposed lengths of from a few to tens of meters (tens of feet +). Where large fractures are present, they are generally spaced from several to tens of meters (tens of feet +) apart. However, in some localized areas, usually associated with fold hinges or fault zones, these fractures can be abundant with fracture spacing down to a few centimeters (inches). In such situations, fracture breccias are commonly developed. These appear as bed cross-cutting zones of broken rock, from a few centimeters (1 in) or less to over a meter (3.3 ft) wide (Figure 15). They are most common in chert and porcelanite sequences. Orientation of large fractures and fracture breccia is similar to small fractures; most are roughly perpendicular to bedding and the predominant fracture sets are roughly parallel and perpendicular to strike.

Another type of fracture breccia includes dolostone breccia; it consists of brecciated dolostone, often mixed with other rock types, formed by repeated precipitation from fracture-filling solutions (Roehl, 1981; Redwine, 1981). Dolostone breccia typically occurs along the coast in zones several meters to ten's of meters (tens of feet +) wide. In most cases, dolostone breccia cross-cuts bedding in an orientation similar to large fractures and other breccia types.

Crude calculations of the permeability of the three fracture types can be made using fracture spacing and width measurements (Table 3). For example, based on a fracture width of 10 to 20 microns (typical widths from core material as seen in thin section and with the scanning electron microscope), the permeability of brecciated chert beds is several hundred millidarcies whereas beds with small fractures average approximately 2 to 50 millidarcies. For large fractures and associated breccia, permeabilities of several darcies seem likely based on the width of large fractures as measured in core and outcrop.

A simple fracture model for the clayey-

ROCK TYPE	FRACTURE SPACING (CM) (TABLE 2)	CALCULATED K FOR VARIOUS FRACTURE WIDTH 10 μ	15μ	20μ	30μ
Brecciated Chert **	0.3	56	187	445	1503
Chert *	2	4	14	33	112
Porcelanite *	4	2	7	17	56
Mudstone *	7	1	4	9	32
Dolostone *	9	1	3	7	25

** Cubic Model; * Matchstick Model

Table 3. Fracture permeability as calculated from fracture spacing and width measurements using the formulas given by Reiss (1980).

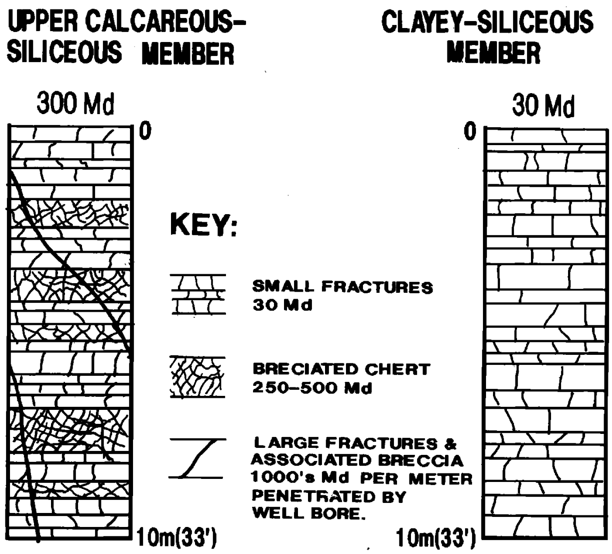

Figure 16. Fracture model for Monterey oil fields.

siliceous and upper calcareous-siliceous members is shown in Figure 16. In this model, the clayey-siliceous member is shown to have small fractures only, as it typically does in outcrop, and is assigned an average permeability of 30 millidaries based on drill stem tests and fracture spacing and width calculations (Table 3). The upper calcareous-siliceous member is shown to contain small fractures, brecciated chert, and large fractures with associated breccia; this interval is assigned an average permeability of 300 md as a conservative estimate based on drill stem test-determined permeabilities reported by Ogle and others (1987) and Crain and others (1987).

To model the upper calcareous siliceous member, one third of the section is designated as brecciated chert with an average permeability of 400 millidarcies and the remaining rock is assigned an average permeability of 30 millidarcies for small fractures; this gives an average permeability of approximately 150 millidarcies. In order to account for the 300 millidarcies suggested by drill stem tests, several large fractures and associated breccia with 1000's of millidarcies per meter (.33 ft) penetrated by the wellbore are included.

The usefulness of such calculations are debatable on many counts, the most important being the uncertainty of fracture widths in the subsurface. But if our estimates are roughly correct, they indicate that large fractures and associated breccia may be the most important contributors to permeability in wells. Alternatively, small fractures and fractures in brecciated chert beds may be held open to greater widths than we see in core material.

Fracture orientation is another factor that must be considered in reservoir modeling. It appears that fractures oriented perpendicular to the strike of bedding are held open in the subsurface whereas those oriented in other directions are relatively closed. Experiments with clay models show this clearly; under compression, clay will buckle into a doubly plunging anticline with two sets of fractures as we see in outcrop - the open ones trend perpendicular to the fold axis, or bedding strike, and the closed fractures trend parallel to it (Figure 17). Outcrop

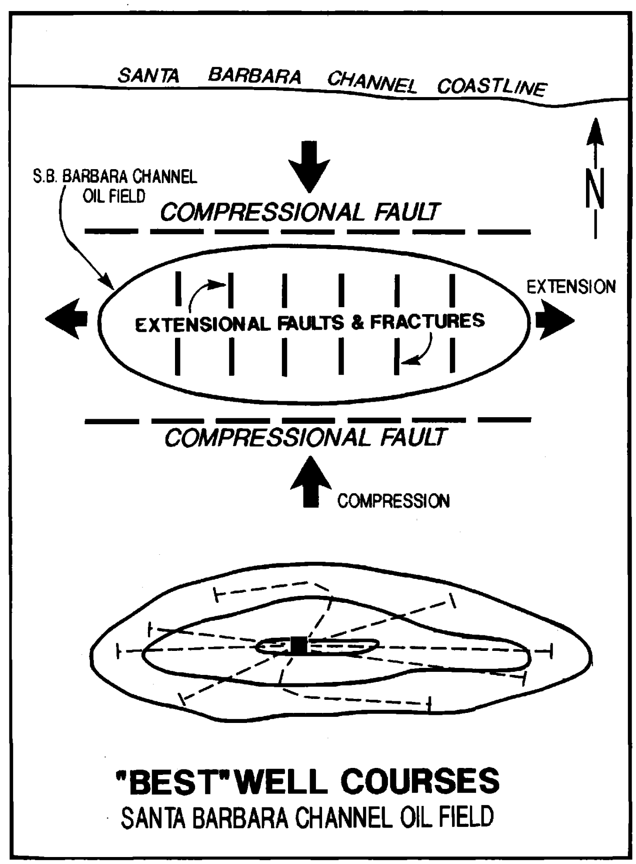

Figure 17. Most Santa Barbara Channel oil fields have elongated oval shapes that formed under roughly north-south compression. Clay models show that under such conditions two main sets of fractures will form; one set of "closed" fractures or faults perpendicular to compressional forces and one set of extensional or "open" fractures or faults parallel to compression. Since permeability should be much higher in the "open" fractures, well courses designed to intersect them may maximize production.

evidence for this was given by Belfield and others (1983) who showed that along the Santa Barbara coastline, fractures oriented subperpendicular to the strike of bedding contain more tar than those oriented in other directions. Furthermore, Belfield and others (1983) made a case, though with limited data, that productivity in wells in the Elwood field is higher in wells drilled subparallel to the axial trace of the anticline than in wells drilled normal to it (Figure 17).

HISTORY OF PETROLEUM EXPLORATION

The Santa Barbara-Santa Maria area has been an active oil province for nearly 100 years (Figure 18). Production and exploration summaries are given in Woodring and Bramlette (1950), Dibblee (1966), Yerkes and others (1969), Taylor (1976), Williams (1985), California Division of Oil and Gas (1974 and 1986) and Crain and Thurston (1987).

Petroleum resources in the Santa Barbara Channel and Santa Maria area were first recognized and utilized by the native Chumash Indians who lived in the region for many thousands of years before the arrival of the first European explorers in the 1500s. The natives used the tar from seeps and tar sands to chaulk their canoes, waterproof their baskets, and as a general adhesive. An indian village was located next to a large natural seep in Carpinteria, 20 km (12 mi) east of Santa Barbara. Another well known seep is present offshore, 12 km (7 mi) west of Santa Barbara, where an oil slick is nearly always visible. Other offshore seeps are common, as attested by tar that is present on the beaches between Santa Maria and Ventura.

Oil was discovered around the turn of the century in both the Channel region and in the Santa Maria area. In Summerland, just east of Santa Barbara, oil and gas seeps led to drilling and production of oil in the 1890's from Plio-Pleistocene strata probably sourced from the Monterey Formation. In the Santa Maria area, drilling near an outcrop of tar sand led to the discovery of the Orcutt field in 1902, with the Monterey Formation as both the source and the reservoir.

In the Santa Maria area, the initial discovery of the Orcutt Field led to an exploration program based on drilling

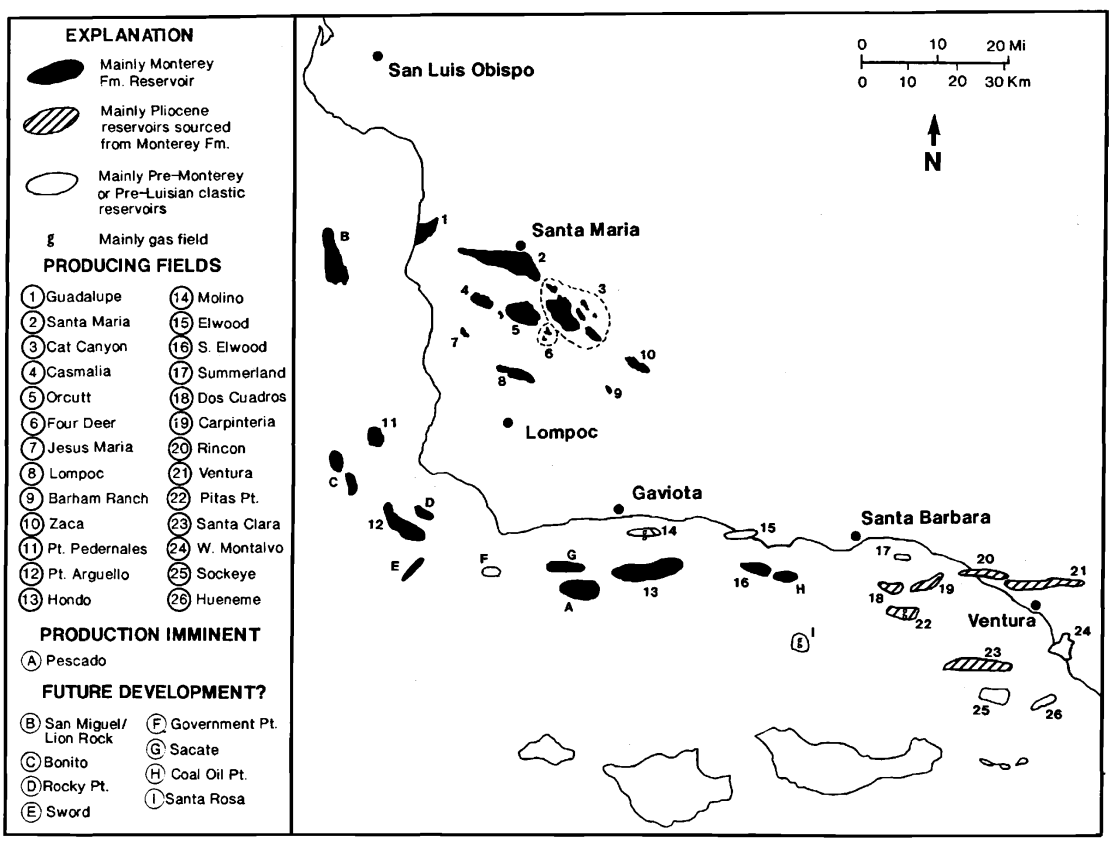

Figure 18. Location of major oil fields in the Santa Maria-Santa Barbara area. Abandoned fields not shown

anticlines that showed well developed surface expression. Subsequent discoveries included the Lompoc (1903), West and East Cat Canyon (1908 and 1909), Casmalia (1917), and Gato Ridge (1931) fields. In 1934, the giant Santa Maria field was discovered following an exploration strategy based on field observations that suggested the presence of a stratigraphic trap. Later, much smaller discoveries were made at Four Deer (1947) and Guadalupe (1948). As of 1986 the Santa Maria onshore area had produced 783 million barrels with reserve estimates of 149 million barrels.

In the eastern Santa Barbara Channel area, big early discoveries were made in the early 1900's along an 35+ km (22 mi) anticlinal trend running from Ventura to the offshore area near Rincon Point. This included the Ventura, San Miguelito and Rincon Oil Fields. Later, in the 1960's as a result of improved offshore drilling capabilities, the Carpinteria and Dos Cuadros offshore fields were discovered along this trend. Other fields in the area include the relatively small West Montalvo field discovered in 1949. Production from most of these fields is mainly from Pliocene sandstones ,with the Monterey immediately below as the source of most of the oil. As of 1986, 1.4 billion barrels of oil had been produced, with over 800 million from the Ventura field alone. Reserves are estimated at 265 million barrels.

Early exploration in the western Santa Barbara Channel concentrated on pre-Monterey sandstones, mainly in the Sespe/Alegria and Vaqueros Formations (Figure 2). Oil and gas were found in several fields located on the coast between Carpinteria and Point Conception, including Elwood (1928), Mesa (1929), La Goleta (1929) Capitan (1929), and Refugio (1946). Offshore fields were discovered and developed starting in the 1950's. These were mainly gas fields with subsea completions and like the earlier discoveries were mainly in Sespe\Alegria and Vaqueros sandstones. These included the Gaviota (1958), Conception (1959), Cuarta (1959), Caliente (1962), Molino (1962), and Naples (1960) fields. In addition, oil was discovered in pre-Monterey rocks offshore at Coal Oil Point (1961), Summerland (1958), South Elwood (1966) and Point Conception (1965).

The Monterey Formation in the Santa Barbara area was virtually ignored during early exploration despite the successes in the Santa Maria Valley. There were several reasons for this. For one, the Monterey onshore was mainly located on a homocline with no trap possibilities or if folded, was exposed at the surface. Offshore however, it did offer potential but was not taken advantage of. Monterey oil was considered heavy and uneconomic for offshore production and furthermore, well logs in the Monterey were not reliable indicators of oil.

In the Santa Barbara Channel, offshore discovery of oil in the Monterey Formation did not come until 1969 when the Hondo field and South Elwood pools were discovered. Together these fields contained reserves of 250 to 300 million barrels. These finds revealed the potential of the offshore Monterey, and within two years the Sacate, Pescado, Santa Clara, and Sockeye fields were discovered all with substantial Monterey Formation reserves. In 1982, the Coal Oil Point field was discovered with estimated reserves in the Monterey Formation of 100 million barrels. At present, oil is produced from platforms at Hondo, South Elwood, Sockeye, and Santa Clara. The Hondo field is the largest producer with an average daily production of approximately 40,000 barrels. Platform installation and production appear imminent at Pescado. Sacate awaits better economic conditions and Coal Oil Point development has stalled due to environmental concerns.

In 1981 a federal lease sale was held that opened the offshore Santa Maria area to exploration. Discoveries soon followed and included the following fields: Pt Arguello; Pt. Pedernales; San Miguel/Lion Rock; Rocky Point; Bonito; and Sword. These fields have potential reserve estimates of nearly one billion barrels. At Pt. Pedernales and Pt. Arguello, platform installation is complete and production has begun or is imminent. Development of the other fields will depend on future oil prices.

In summary, The Monterey Formation is the source and reservoir for much of the oil in the Santa Maria and Santa Barbara channel areas (Figure 18). In the Santa Maria area, virtually all of the oil is Monterey sourced and most is Monterey reservoired. In the eastern Santa Barbara Channel, oil is found mainly in Pliocene sandstone reservoirs but is probably sourced mainly from the Monterey Formation. In the western Santa Barbara Channel, the Monterey Formation is the reservoir and probable source of most of the oil in the newly discovered offshore fields.

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