U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

Preliminary report on petroleum source potential and thermal maturity of the Lospe Formation (lower Miocene) near Point Sal, onshore Santa Maria basin, California

by

Richard G. Stanley[1], Mark J. Pawlewicz[2], David R. Vork[3], Samuel Y. Johnson[2], and Zenon C. Valin[1]

Open-File Report 95-530

[1]U.S. Geological Survey, Menlo Park, California 94025
[2]U.S. Geological Survey, Denver, Colorado 80225
[3]Unocal Corporation, Houston, Texas 77210

1995

Preliminary report on petroleum source potential and thermal maturity of the Lospe Formation (lower Miocene) near Point Sal, onshore Santa Maria basin, California

By Richard G. Stanley, Mark J. Pawlewicz, David R. Vork,
Samuel Y. Johnson, and Zenon C. Valin

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The Lospe Formation is an 830-m-thick sequence of sedimentary and minor volcanic rocks at the base of the onshore Neogene Santa Maria basin of central California. Eighteen outcrop samples (14 from lacustrine and shallow-marine mudstones of the Lospe Formation, and 4 from bathyal marine shales of the overlying Point Sal Formation) were collected from a measured stratigraphic section at North Beach (informal name) near Point Sal, and analyzed using Rock-Eval pyrolysis and vitrinite reflectance. The Rock-Eval data indicate that mudstones of the Lospe are low in organic carbon (range 0.18 to 0.80 weight percent, mean about 0.35 percent), and therefore are generally poor potential source rocks of petroleum. In contrast, shales of the Point Sal Formation exhibit much higher total organic carbon (range 1.47 to 3.63 weight percent, mean about 2.4 percent), and therefore are good to very good potential source rocks. These results should be regarded as preliminary because only a small number of samples were analyzed, and because interpretation of the data is complicated by weathering effects, relatively high thermal maturity, and evidence of migrated bitumen in some samples.

Vitrinite reflectance values (range 0.68 to 1.56 percent R_o, mean 1.29 percent R_o) and calculated maximum burial temperatures (range 106 °C to 192 °C, mean 172 °C) of the Lospe and Point Sal Formations in the North Beach section are the highest ever reported for Neogene rocks of the onshore Santa Maria basin. These high values can be explained by a combination of burial heating plus a local heat source such as a nearby gabbro sill and (or) a high-temperature hydrothermal system. The local heating event is poorly dated but probably late early or early middle Miocene, and may have stimulated thermal generation of oil and gas from organic-rich strata of the Point Sal Formation.

INTRODUCTION

The onshore part of the Santa Maria basin is an important petroleum-producing region in coastal California (fig. 1). Since the first commercial discovery in 1901, more than 820 million barrels of oil and 810 billion cubic feet of associated gas have been produced from this area (California Division of Oil and Gas, 1993). Most of the hydrocarbon accumulations are trapped in anticlines bounded by reverse faults, but a major stratigraphic trap occurs in the western Santa Maria Valley field (Dunham and others, 1991). The most important producing reservoirs are fractured siliceous rocks and dolomites of Miocene age, and sandstones of Miocene and Pliocene age (Woodring and Bramlette, 1950; Dryden and others, 1968; Crawford, 1971; Redwine, 1981; Roehl, 1981; California Division of Oil and Gas, 1991).

The principal petroleum source rocks in the Santa Maria basin are believed to be organic-rich strata within the Miocene Monterey Formation (Woodring and Bramlette, 1950; Crawford, 1971; Isaacs and Petersen, 1987; Dunham and others, 1991; Lillis and King, 1991). However, some geologists have speculated privately that stratigraphic units beneath the Monterey--including the Lospe Formation--might be

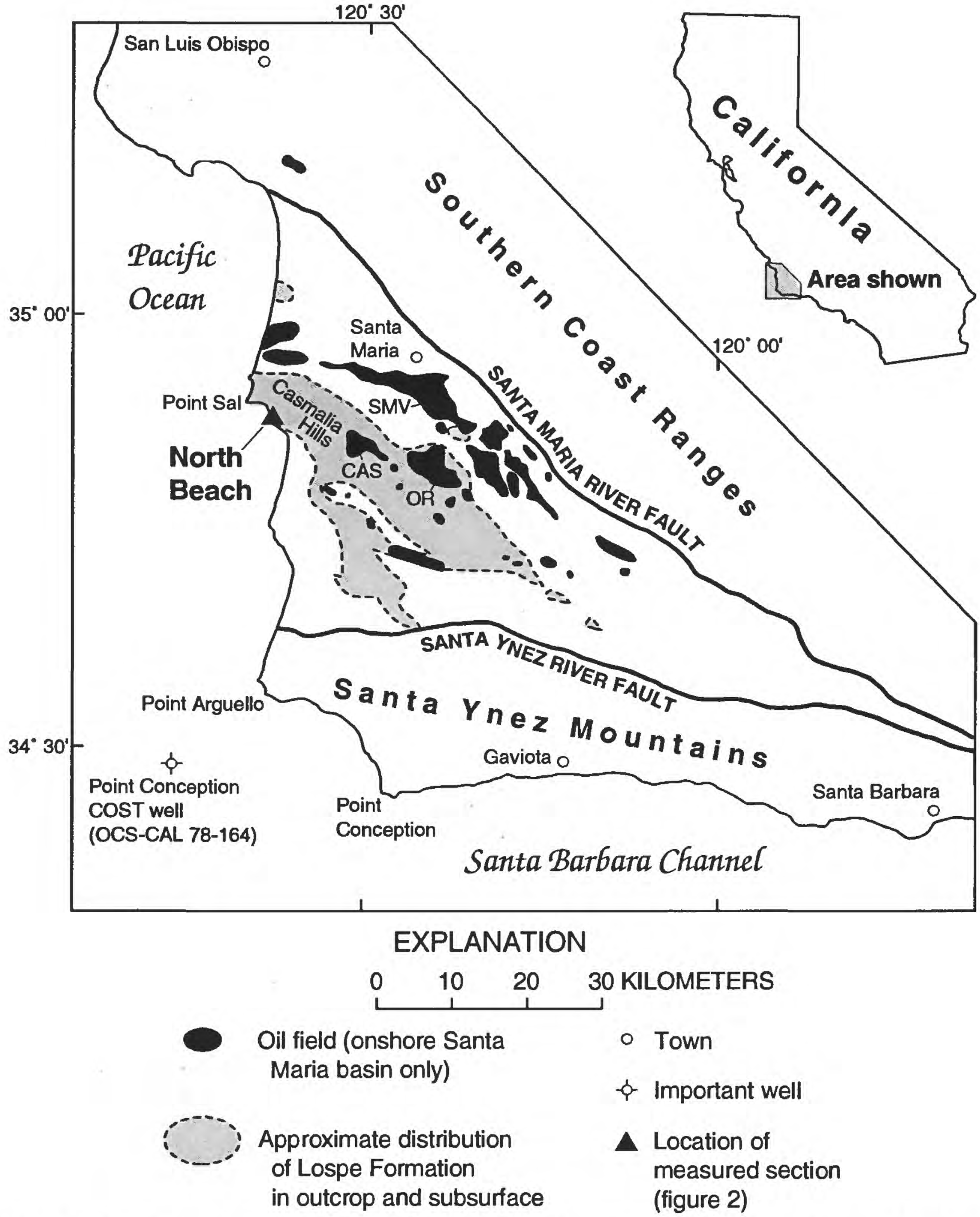

Figure 1. Location map. Generally, the onshore Santa Maria basin is the triangular area bounded by the Santa Maria River fault (Hall, 1978a) and the Santa Ynez River fault (Sylvester and Darrow, 1979). The shaded area shows the extent of the Lospe Formation in the subsurface onshore according to Hall (1982) with modifications from McLean (1991). Onshore oil fields in the Santa Maria area are shown in black and include the Casmalia (CAS), Orcutt (OR), and Santa Maria Valley (SMV) fields.

minor sources of hydrocarbons. The purpose of this report is to present the results and implications of a reconnaissance study, using Rock-Eval pyrolysis and vitrinite reflectance, of the petroleum source potential and thermal maturity of the Lospe Formation in a measured stratigraphic section at North Beach (informal name) near Point Sal (figs. 1, 2). The Rock-Eval data show that mudstones of the Lospe are organically lean and unlikely to be significant sources of oil or gas. The vitrinite reflectance results indicate that both the Lospe and Point Sal Formations at North Beach are thermally mature to overmature with respect to the oil-generative window. These thermal maturities are the highest ever reported for Neogene rocks of the onshore Santa Maria basin and probably record heating associated with emplacement of a gabbro sill and (or) a local high-temperature hydrothermal system.

STRATIGRAPHIC AND SEDIMENTOLOGIC SETTING

The Lospe Formation (Tolman, 1927; Wissler and Dreyer, 1943) consists of nonmarine and shallow-marine sedimentary rocks and minor rhyolitic tuffs that crop out sporadically in the Casmalia Hills near Point Sal (fig. 1). The Lospe also is present in the subsurface of the Santa Maria basin, where it has been penetrated by numerous exploratory wells (Woodring and Bramlette, 1950; Hall, 1978a, 1982; McLean, 1991; California Division of Oil and Gas, 1991). Sandstones of the Lospe Formation are minor producing reservoirs in the Casmalia and Orcutt oil fields (Woodring and Bramlette, 1950; California Division of Oil and Gas, 1991).

The Lospe Formation records initial tectonic subsidence of the Neogene Santa Maria basin during an episode of crustal extension or transtension beginning about 18 Ma (Stanley and others, 1992a; McCrory and others, in press). In its type area in the Casmalia Hills, the Lospe is as much as 830 m thick, rests unconformably on the Jurassic Point Sal ophiolite (Hopson and Frano, 1977), and is of late early Miocene age (Saucesian Stage of Kleinpell, 1938 and 1980) on the basis of microfossils and radiometric dates (Stanley and others, 1991, 1992a). The Lospe is conformably overlain by the Point Sal Formation (Canfield, 1939, p. 66-67; Wissler and Dreyer, 1943, p. 237; Woodring and others, 1943, p. 1344), which also is of late early Miocene age (Saucesian and Relizian Stages of Kleinpell, 1938 and 1980) on the basis of microfossils (Stanley and others, 1991, 1992).

In the North Beach section (fig. 2) the Lospe is about 410 m thick, but the section is cut by numerous normal(?) faults of unknown displacement, so the original thickness may have been greater. Alluvial fan and fan-delta facies within the basal part of the Lospe consist mainly of reddish-brown and greenish-gray conglomerate and sandstone derived from nearby fault-bounded uplifts of Mesozoic sedimentary and igneous rocks (Stanley and others, 1990, 1991; Johnson and Stanley, 1994; McLean and Stanley, 1994). The alluvial fan and fan-delta deposits grade upward into a sequence of interbedded mudstone and sandstone that accumulated in a lake with possible intermittent connections to the ocean (Stanley and others, 1991). The mudstones are gray-brown when fresh, weather gray-green, are bioturbated to laminated, and locally display scattered mud cracks that indicate infrequent desiccation. Primary and secondary gypsum occurs locally in the lake

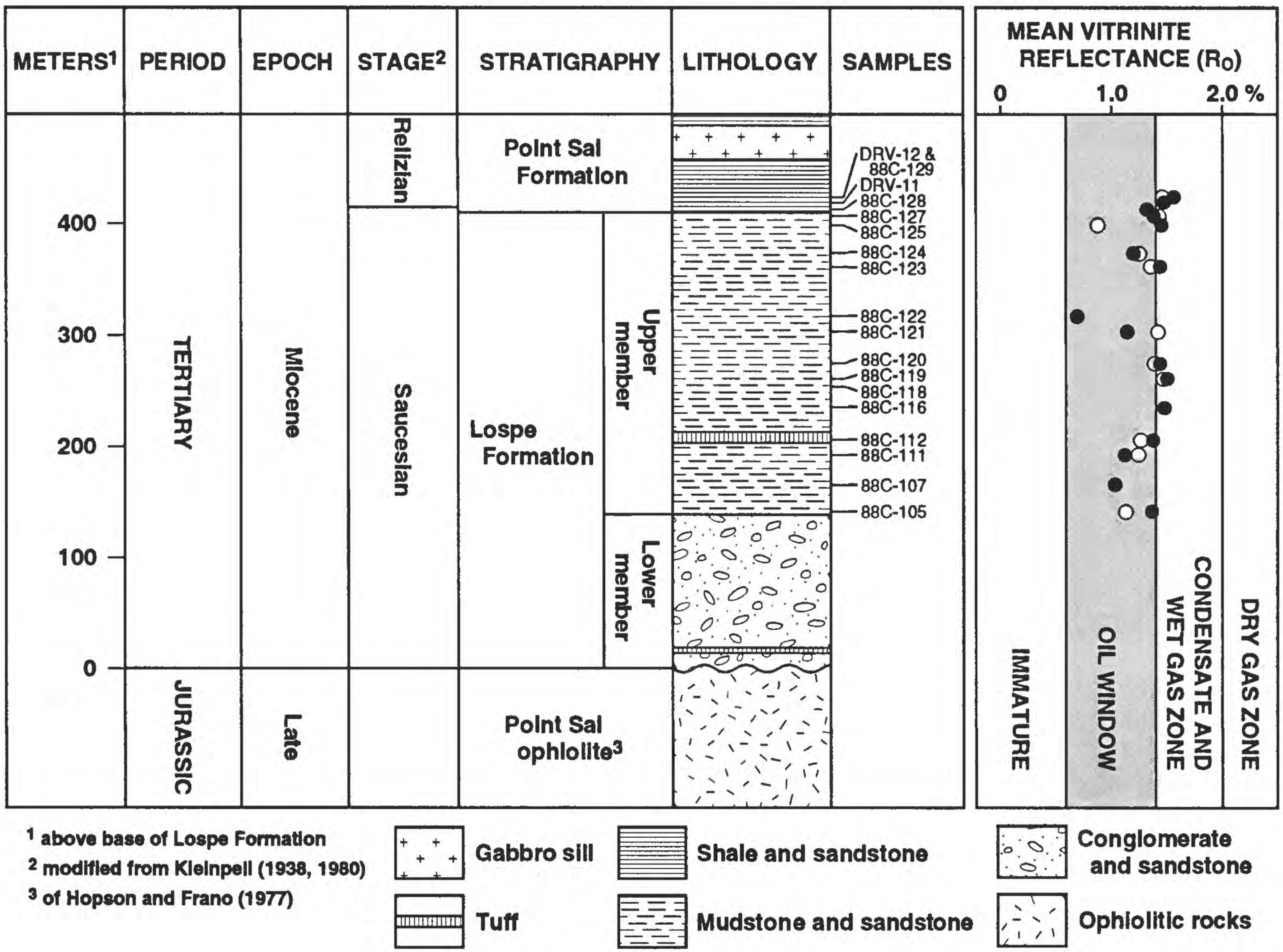

Figure 2. Generalized stratigraphy of the North Beach section, showing sample locations and mean values of vitrinite reflectance (on a linear scale) for run 1 (circles) and run 2 (dots). Top and base of oil-generative window from Peters (1986); base of condensate and wet gas zone from Tissot and Welte (1984). Numerous normal(?) faults of unknown displacement are present in the outcrops, but are not shown on this figure.

deposits; isotopic studies suggest that the sulfur in this gypsum was derived from hydrothermal springs on the floor of the lake (M.L. Tuttle, U.S. Geological Survey, oral communication, 1991; Stanley and others, 1992a). Lenses of non-welded rhyolitic tuff as much as 20 m thick are interspersed throughout this interval, and were deposited primarily as subaqueous pyroclastic flows and high-concentration turbidites that may have originated from eruptive centers in the vicinity of the Santa Ynez River fault (Cole and others, 1991a, 1991b; Cole and Stanley, 1994).

The uppermost 30 m of the Lospe consists of storm-deposited, plane-laminated to bioturbated sandstone and bioturbated mudstone containing shallow-marine microfossils. These shallow-marine deposits are abruptly overlain by the Point Sal Formation, indicating rapid deepening from shelf to bathyal marine environments (Stanley and others, 1991).

In the Point Sal area, the Point Sal Formation is more than 450 m thick and consists mainly of dark gray to black silty shale with interbeds of turbidite sandstone. Generally, the shale is hard, fissile, and calcareous, with fine laminations and calcareous microfossils that suggest deposition in oxygen-poor environments at bathyal water depths (Stanley and others, 1991). At some localities, freshly-broken surfaces of the shale smell strongly of petroleum. Permeable sandstone beds of the Point Sal Formation are petroleum reservoirs in the Orcutt, Casmalia, and Santa Maria Valley fields (Woodring and Bramlette, 1950; California Division of Oil and Gas, 1991).

Sedimentary rocks of the Point Sal Formation are intruded by basic igneous intrusions mapped as "augite teschenite" by Fairbanks (1896) and as "diabase" by Woodring and Bramlette (1950) and Dibblee (1989). In the North Beach area, one such intrusion is a sill about 25-30 m thick that occurs about 40-50 m stratigraphically above the base of the Point Sal Formation (fig. 2). According to Fairbanks (1896), contact metamorphism has turned shales of the Point Sal Formation to slate for a distance of about 3 m beyond the margin of the sill. The sill rock is composed mainly of plagioclase, pyroxene, and altered olivine, and has a silica (SiO_2) content of 47.64, corresponding to a basic (gabbroic or basaltic) composition (Cole and Basu, 1995). No radiometric date has been obtained from this sill, but it intrudes strata of the Point Sal Formation that contain benthic foraminifers of the lower part of the Relizian Stage (Woodring and Bramlette, 1950) and therefore can be no older than latest early Miocene (Bartow, 1992). The youngest radiometrically-dated igneous rocks in the Santa Maria province occur in the Obispo Formation of Hall and others (1966), and yield potassium-argon ages of about 15-18 Ma (ages from Turner, 1970, corrected using the technique of Dalrymple, 1979). On the basis of these regional ages, we suggest that the sill in the North Beach area was most likely emplaced during the late early or early middle Miocene.

METHODS

Eighteen rock samples (14 from the Lospe Formation and, for comparison, 4 from the Point Sal Formation) were collected from the North Beach section along the sea cliff about 3.5 km southeast of Point Sal (figs. 1, 2). The rock samples were taken from about 10 cm to 30 cm back from the outcrop faces in order to obtain the freshest available material. All 18 samples were analyzed using a Rock-Eval II pyroanalyzer, and 16 of these were examined for vitrinite reflectance, in the laboratories of the U.S. Geological Survey, Branch of Petroleum Geology, in Denver, Colorado. Duplicate vitrinite slides were prepared and analyzed from 14 of the samples. Organic carbon was measured on all 18 samples in the laboratories of the U.S. Geological Survey, Branch of Pacific Marine Geology, in Palo Alto, California. The results of the Rock-Eval pyrolysis, vitrinite reflectance, and organic carbon analyses are shown in tables 1, 2, and 3, and summarized in table 4. Processing and examination of samples for palynomorphs were conducted in the laboratories of Unocal Oil and Gas Division in Ventura, California.

Rock-Eval pyrolysis is a widely used method of rapidly evaluating the quality and thermal maturity of prospective petroleum source rocks (Espitalié and others, 1977, 1984; Clementz and others, 1979; Tissot and Welte, 1984; Peters, 1986). The procedure mimics, in some respects, the natural hydrocarbon-generation processes that occur at much slower rates within the earth when sediments containing kerogen (sedimentary organic matter) are buried progressively deeper and subjected to increasing temperatures (Waples, 1985). Pulverized samples of rock are held at 250 °C for 3 minutes (the so-called "isothermal period"), then gradually heated from 250 °C to 600 °C at 25 °C per minute in an oxygen-free atmosphere, causing the release of water, carbon dioxide, and hydrocarbons from the rock. Several parameters are measured automatically by the Rock-Eval apparatus (table 1). The quantity S1 is the amount of hydrocarbons (HC), measured in milligrams HC per gram of rock, that is released upon initial heating to 250 °C; this quantity includes the bitumen (free organic compounds, including gas and oil) already present in the rock. The quantity S2 (also measured in milligrams HC per gram of rock) is the amount of hydrocarbons generated by pyrolytic degradation (or "cracking") of the remaining organic matter in the rock and is an indicator of the potential of the rock to generate additional oil and gas. T_{max} is the temperature--generally about 400 °C to 500 °C--at which S2 is at a maximum and is regarded as a rough indicator of thermal maturity. S3 is the amount of carbon dioxide (in milligrams of CO_2 per gram of rock) generated during pyrolysis, and is thought to be related to the amount of oxygen in the pyrolyzed organic matter. Calculated Rock-Eval parameters include (1) the total organic carbon (TOC), in weight percent; (2) the hydrogen index (HI), defined as the product 100(S2/TOC) and sometimes expressed as mg HC/g C; (3) the oxygen index (OI), defined as the product 100(S3/TOC) and sometimes expressed as mg CO_2/g C; and (4) the production index (PI), defined as the ratio S1/(S1 + S2).

Vitrinite reflectance (R_o) is a common method of determining thermal maturity and is obtained by measuring the percentage of light reflected by vitrinite, a type of kerogen formed from woody terrestrial plant material (Tissot and Welte, 1984; Waples, 1985). Higher values of vitrinite reflectance correspond to higher levels of thermal maturity. The maturation of vitrinite is irreversible and related to maximum burial temperature (Barker and Pawlewicz, 1986) and perhaps also to elapsed heating time (P.G. Lillis, U.S. Geological Survey, written communication, 1992).

Table 1. Rock-Eval pyrolysis data from the Lospe and Point Sal Formations in the North Beach section. T_{max} values for samples with S2 less than 0.2 mg HC/g rock were rejected as unreliable, following the recommendation of Peters (1986)

[Rock-Eval parameters are discussed in the text. mdst = mudstone]

Sample number	Formation	Meters above base[1]	Rock type	Depositional environment	Sample weight (mg)	TOC (weight percent)	S1 (mg HC/ g rock)	S2 mg HC/ g rock)	S3 (mg CO_2/ g rock)	S2/S3	PI (S1/ S1+S2)	HI	OI	T_{max} (°C)
88C-129	Point Sal	426.65	shale	Bathyal marine	72.1	1.47	1.10	0.58	0.76	0.76	0.65	39	51	374
DRV-12	Point Sal	426.30	shale	Bathyal marine	51.2	1.81	2.42	2.22	1.44	1.54	.52	122	79	395
DRV-11	Point Sal	423.70	shale	Bathyal marine	56.3	3.57	3.35	2.96	1.77	1.67	.53	82	49	454
88C-128	Point Sal	416.15	shale	Bathyal marine	49.9	2.67	2.28	2.94	1.44	2.04	.44	110	53	447
88C-127	Lospe	409.55	mdst	Shallow marine	191.8	.24	.15	.51	.31	1.64	.23	212	129	493
88C-125	Lospe	401.25	mdst	Shallow marine	187.7	.46	.04	.37	.18	2.05	.10	80	39	442
88C-124	Lospe	378.05	mdst	Lacustrine	202.3	.39	.25	.44	.48	.91	.37	112	123	334
88C-123	Lospe	364.55	mdst	Lacustrine	234.9	.41	.48	.84	.54	1.55	.36	204	131	346
88C-122	Lospe	319.65	mdst	Lacustrine	204.5	.68	.01	.41	.21	1.95	.02	60	30	423
88C-121	Lospe	305.95	mdst	Lacustrine	192.0	.37	.96	1.42	.77	1.84	.40	383	208	364
88C-120	Lospe	277.30	mdst	Lacustrine	185.7	.26	.01	.08	.12	.66	.12	30	46	
88C-119	Lospe	260.45	mdst	Lacustrine	211.2	.20	0	.02	.08	.25	0	10	40	
88C-118	Lospe	255.65	mdst	Lacustrine	221.6	.34	0	.08	.18	.44	0	23	52	
88C-116	Lospe	237.90	mdst	Lacustrine	220.9	.34	.02	.13	.16	.81	.14	38	47	
88C-112	Lospe	209.80	mdst	Lacustrine	201.3	.43	.09	.42	.25	1.68	.18	97	58	363
88C-111	Lospe	196.30	mdst	Lacustrine	206.5	.18	.07	.42	.09	4.66	.15	233	50	401
88C-107	Lospe	167.95	mdst	Lacustrine	206.7	.24	.08	.19	.23	.82	.31	79	95	
88C-105	Lospe	142.95	mdst	Lacustrine	145.3	.30	.16	.91	.26	3.50	.15	303	86	

[1]Above base of Lospe Formation in the measured stratigraphic section at North Beach. Numerous normal(?) faults of unknown displacement probably have removed parts of the section (Johnson and Stanley, 1994).

Table 2. Total carbon obtained by dry combustion, carbonate carbon obtained by coulometric titration, and organic carbon determined by the difference between total carbon and carbonate carbon, for samples from the Lospe and Point Sal Formations in the North Beach section. Also shown, for comparison with organic carbon results, are values of Rock-Eval TOC (from table 1). See text for discussion

Sample number	Formation	Total carbon (weight percent)	Carbonate carbon (weight percent)	Organic carbon (weight percent)	Rock-Eval TOC (weight percent)
88C-129	Point Sal	3.76	1.48	2.28	1.47
DRV-12	Point Sal	2.85	1.03	1.82	1.81
DRV-11	Point Sal	4.79	1.16	3.63	3.57
88C-128	Point Sal	2.76	1.07	1.69	2.67
88C-127	Lospe	0.52	0.32	0.20	0.24
88C-125	Lospe	.61	.16	.45	.46
88C-124	Lospe	.74	.27	.47	.39
88C-123	Lospe	.73	.36	.37	.41
88C-122	Lospe	1.05	.24	.80	.68
88C-121	Lospe	0.49	.26	.23	.37
88C-120	Lospe	.44	.17	.27	.26
88C-119	Lospe	.62	.40	.22	.20
88C-118	Lospe	.64	.29	.35	.34
88C-116	Lospe	.48	.13	.35	.34
88C-112	Lospe	.52	.16	.36	.43
88C-111	Lospe	.21	.03	.18	.18
88C-107	Lospe	.27	.06	.21	.24
88C-105	Lospe	.41	.13	.28	.30

Table 3. Vitrinite reflectance (R_o) data from the Lospe and Point Sal Formations in the North Beach section

Sample number	Formation	Vitrinite reflectance (R_o) run 1:				Vitrinite reflectance (R_o) run 2:			
		Number of meas-urements	Range of R_o (percent)	Mean R_o (percent)	Standard deviation	Number of meas-urements	Range of R_o (percent)	Mean R_o (percent)	Standard deviation
88C-129	Point Sal	16	1.02-1.73	1.46	0.18	5	1.52-1.60	1.56	0.04
DRV-12	Point Sal								
DRV-11	Point Sal	25	1.26-1.72	1.47	.11	4	1.40-1.62	1.47	.10
88C-128	Point Sal					3	1.25-1.45	1.32	.12
88C-127	Lospe	14	0.98-1.89	1.43	.23	5	1.25-1.44	1.38	.08
88C-125	Lospe	8	0.74-1.28	.87	.18	3	1.43-1.47	1.44	.03
88C-124	Lospe	12	1.03-1.46	1.24	.12	1	1.20-1.20	1.20	.00
88C-123	Lospe	27	1.00-1.62	1.37	.16	21	1.15-1.65	1.43	.12
88C-122	Lospe	11	0.60-0.82	.68	.07	25	0.58-0.87	.69	.06
88C-121	Lospe	20	1.15-1.53	1.41	.11	1	1.14-1.14	1.14	.00
88C-120	Lospe	31	1.17-1.54	1.37	.10	51	1.17-1.63	1.43	.10
88C-119	Lospe	23	1.28-1.65	1.43	.09	45	1.28-1.66	1.49	.08
88C-118	Lospe								
88C-116	Lospe	35	1.23-1.71	1.48	.11	51	1.17-1.76	1.47	.12
88C-112	Lospe	27	1.03-1.57	1.27	.13	41	1.20-1.66	1.38	.10
88C-111	Lospe	24	0.98-1.58	1.23	.14	1	1.59-1.59	1.11	.00
88C-107	Lospe					55	.89-1.17	1.03	.07
88C-105	Lospe	2	1.06-1.19	1.13	.09	7	1.21-1.52	1.36	.11

Table 4. Summary of Rock-Eval pyrolysis, organic carbon, and vitrinite reflectance (R_o) data from the Lospe and Point Sal Formations in the North Beach section

Subset	Number of Rock-Eval/ organic carbon/ R_o analyses	Rock -Eval TOC (wt. pct.)	Organic carbon (wt. pct.)	S1 (mg HC/ g rock)	S2 (mg HC/ g rock)	S3 (mg HC/ g rock)	S2/S3	PI	HI	OI	T_{max} (° C)	Mean R_o (percent) (run 1)	Mean R_o (percent) (run 2)	Mean R_o (percent) (runs 1 & 2)
All samples	18/18/30[1]													
minimum		0.18	.18	0	0.02	0.08	0.25	0	10	30	334	0.68	0.69	0.68
maximum		3.57	3.63	3.35	2.96	1.77	4.66	.65	383	208	493	1.48	1.56	1.56
mean		.80	.79	.64	.83	.52	1.60	.26	123	76	403	1.27	1.31	1.29
Point Sal Fm.	4/4/5[2]													
minimum		1.47	1.69	1.10	.58	.76	.76	.44	39	49	374	1.46	1.32	1.32
maximum		3.57	3.63	3.35	2.96	1.77	2.04	.65	122	79	454	1.47	1.56	1.56
mean		2.38	2.36	2.29	2.18	1.35	1.50	.54	88	58	418	1.47	1.45	1.46
Lospe Fm.	14/14/25[3]													
minimum		.18	.18	0	.02	.08	.25	0	10	30	334	.68	.69	.68
maximum		.68	.80	.96	1.42	.77	4.66	.4	383	208	493	1.48	1.49	1.49
mean		.35	.34	.17	.45	.28	1.63	.18	133	81	396	1.24	1.27	1.26

[1]Includes 14 R_o analyses for run 1 and 16 R_o analyses for run 2.
[2]Includes 2 R_o analyses for run 1 and 3 R_o analyses for run 2.
[3]Includes 12 R_o analyses for run 1 and 13 R_o analyses for run 2.

Carbon was measured by methods described by Jackson and others (1987). Total carbon was determined by dry combustion with a Coulometrics, Inc. Model 5020 Total Carbon Apparatus. Carbonate carbon was measured by automated coulometric titration of carbon dioxide (Huffman, 1977) using a Coulometrics, Inc. Model 5010 Carbon Dioxide Coulometer. Organic carbon was then determined by the difference between total carbon and carbonate carbon.

Although the Rock-Eval, vitrinite reflectance, and organic carbon techniques are widely used and accepted, there is a high degree of variability in the sample preparation steps, analytical procedures, and units of measurement employed in various laboratories. Therefore, caution must be used when comparing source rock data from different laboratories (Dembicki, 1984).

QUANTITY OF ORGANIC MATTER

The quantity of organic matter in the samples is indicated by the Rock-Eval TOC (total organic carbon, in weight percent), organic carbon determined from combustion and coulometry, and the Rock-Eval quantities S1 and S2. The Rock-Eval TOC of mudstones in the Lospe Formation ranges from 0.18 to 0.68 percent with a mean of about 0.35 percent (tables 1 and 4); these results are generally close to the amounts of organic carbon determined from combustion and coulometry (tables 2 and 4). Only one of the 14 Lospe samples exhibits a Rock-Eval TOC or organic carbon value greater than 0.5 percent (table 2), which is regarded as the lower limit for potential source rocks of petroleum by Tissot and Welte (1984). Comparison with table 5 shows that, on the basis of Rock-Eval TOC and organic carbon, 13 of the 14 Lospe samples have poor hydrocarbon generative potential, while one sample has fair generative potential. In contrast, the Rock-Eval TOC values for mudstones of the Point Sal Formation range from 1.47 to 3.57 percent and average 2.38 percent (tables 1 and 4); these results are comparable to the amounts of organic carbon measured by combustion and coulometry (tables 2 and 4), and indicate that the Point Sal samples have good to very good hydrocarbon generative potential (table 5). The Rock-Eval TOC and organic carbon results from both the Lospe and Point Sal Formations should be viewed with caution, however, because the amount of organic material in rocks can be significantly reduced by oxidation during outcrop weathering (Leythaeuser, 1973; Clayton and Swetland, 1978; Peters, 1986; Stanley, 1987) and, in thermally mature and overmature rocks, by losses due to hydrocarbon generation and expulsion (Daly and Edman, 1987). Vitrinite reflectance results (discussed later in this report) from the North Beach samples suggest thermal maturities within the oil-generative window and the upper part of the condensate and wet gas zone (table 3 and figure 2); organic carbon reductions at such levels of thermal maturity are generally small (10-20 percent) for type III and IV kerogens, which are common in samples from the Lospe and Point Sal Formations, but may be as much as 50 percent for type II kerogens (A.R. Daly and J.D. Edman, Exlog and Brown and Ruth Laboratories, Englewood, Colorado, written communication to D.W. Houseknecht, 1987). A further complication is that organic carbon can be increased by contamination due to migrated bitumen (K.E. Peters, Chevron, written

Table 5. Geochemical parameters describing source rock generative potential, from Peters (1986)

Potential	TOC (weight %)	S1 (mg HC/g rock)	S2 (mg HC/g rock)
Poor	0-0.5	0-0.5	0-2.5
Fair	0.5-1.0	0.5-1.0	2.5-5.0
Good	1.0-2.0	1.0-2.0	5.0-10.0
Very good	2.0+	2.0+	10.0+

Table 6. Geochemical parameters describing type of hydrocarbon generated, from Peters (1986)

Type	Hydrogen Index (HI)	S2/S3
Gas	0-150	0-3
Gas and oil	150-300	3-5
Oil	300+	5+

communication, 1992), which may be significant in some of our Point Sal samples, as noted below.

Values of S1 for mudstones from the Lospe Formation range from 0 to 0.96, with a mean of about 0.17 (tables 1 and 4). Thirteen of the 14 Lospe samples exhibit values of S1 less than 0.5 (table 1), suggesting poor generative potential (table 5). All Lospe samples exhibit values of S2 of less than 2.5 (table 1), also indicating poor generative potential (table 5). Samples from the Point Sal Formation exhibit S1 values ranging from 1.10 to 3.35 (table 1), suggesting good to very good hydrocarbon generative potential (table 5); however, these high values most likely reflect the presence of indigenous or migrated oil, which is also indicated by the strong oily odor emitted by freshly-broken surfaces of these rocks. Values of S2 from the Point Sal Formation range from 0.58 to 2.96 (table 1), are generally higher than from the Lospe, and indicate poor to fair generative potential for the Point Sal (table 5).

We suggest that the generally low values of S1 and S2 in the Lospe samples indicate initially poor generative potential due to a large proportion of woody (humic) and oxidized (inertinitic and recycled) kerogens, as discussed below in the section on "Types of Organic Matter." The values of S1 and S2 in the Lospe also may have been lowered by oxidation of organic matter during surface weathering of the sampled outcrops, by adsorption on clay minerals of the hydrocarbons produced during pyrolysis, and by hydrocarbon generation and expulsion during thermal maturation (Peters, 1986; Daly and Edman, 1987), but the amounts of such losses are unknown.

Both the quantity of organic matter and the inferred hydrocarbon generative potential in the samples appear to correlate with depositional environment. Mudstones of the Point Sal Formation that were deposited in bathyal, oxygen-poor marine environments have generally higher values of TOC, S1, and S2 than mudstones of the Lospe Formation that accumulated in a lacustrine setting (table 1). The reasons for this are unclear but may include one or more of the following: (1) Rates of consumption of organic matter by bottom-dwelling invertebrates and microorganisms may have been higher in the Lospe lake than the Point Sal sea; this hypothesis is consistent with our field observation that burrowed intervals are more common in the Lospe than in the Point Sal Formation, while laminated intervals are more common in the Point Sal. (2) Accumulation rates of terrigenous debris (silt and clay) may have been higher than accumulation rates of organic matter during deposition of the Lospe Formation, resulting in relatively greater dilution of organic material in the Lospe than in the Point Sal. (3) Rates of organic productivity may have been higher in the bathyal marine setting of the Point Sal Formation than in the lacustrine setting of the Lospe, perhaps because coastal upwelling made the marine environments more nutrient-rich and therefore more fertile.

TYPES OF ORGANIC MATTER

Plots of hydrogen index (HI) versus oxygen index (OI) on a modified van Krevelen diagram (fig. 3) show a range of kerogen compositions in samples from the Lospe and Point Sal Formations, and also indicate considerable overlap between the two formations. Most of the Lospe and Point Sal samples are types III and IV,

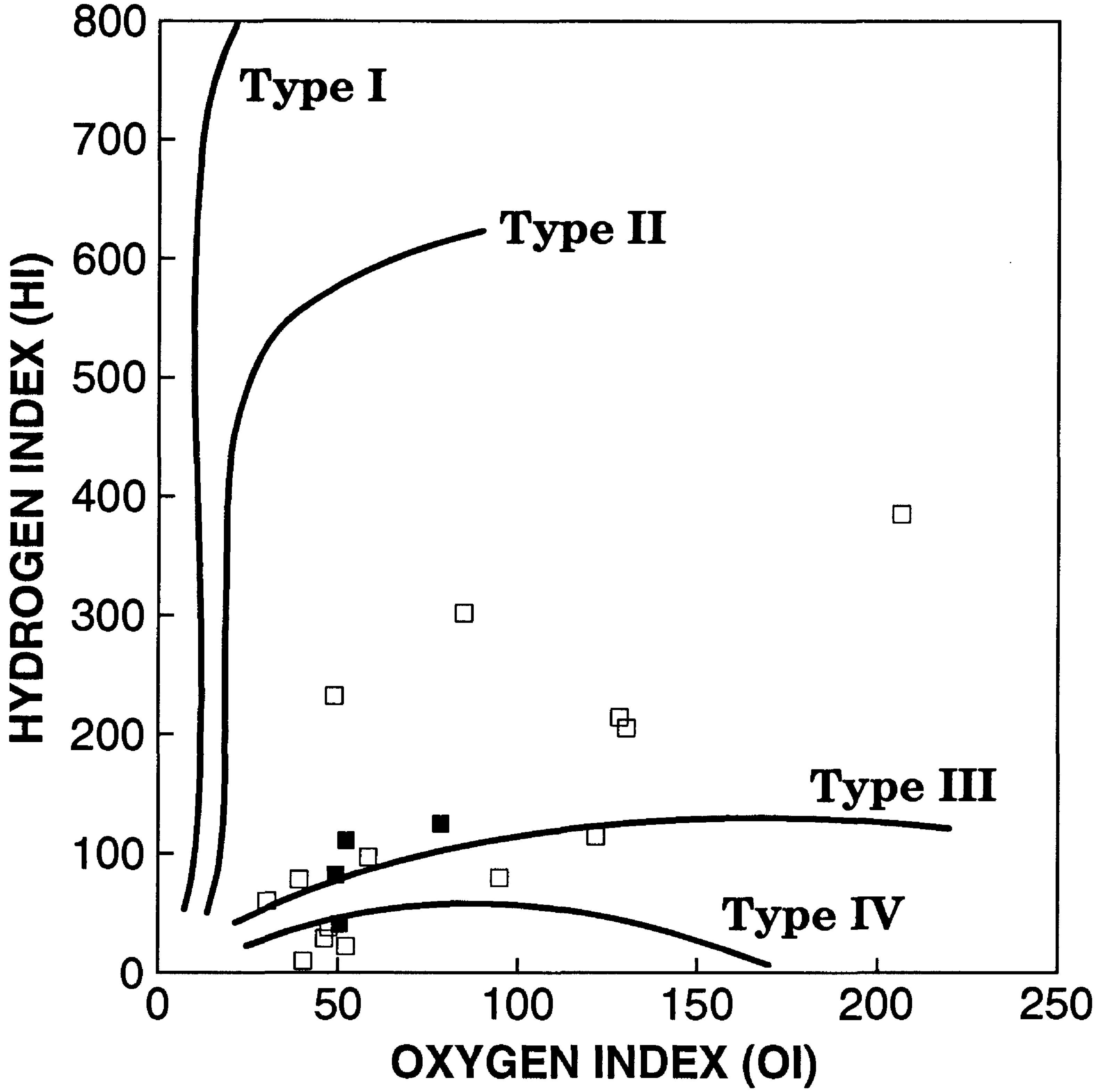

Figure 3. Modified van Krevelen diagram (Peters, 1986) showing idealized kerogen types (solid lines) and results for samples from the Lospe Formation (empty squares) and the Point Sal Formation (filled squares) from the North Beach section (table 1). Type I and type II kerogens are oil-prone, type III kerogens are gas-prone, and type IV kerogens are inert (Peters, 1986).

but some appear to be intermediate between types II and III. Type II kerogens are generally considered to be potential sources of both oil and gas, while type III kerogens are sources mainly of gas (Tissot and Welte, 1984; Peters, 1986). Type IV kerogens are generally regarded as inert, with little or no hydrocarbon source potential (Peters, 1986; K.E. Peters, written communication, 1992).

A wide range in kerogen compositions also is suggested by variations in the values of HI and the ratio S2/S3. HI ranges from 39 to 122 in the Point Sal Formation, and from 10 to 383 in the Lospe Formation (tables 1 and 4). All 4 samples from the Point Sal Formation and 9 of the 14 Lospe samples exhibit HI less than 150 and values of S2/S3 less than 3 (table 1), suggesting gas generative potential (table 6). These results should be viewed with caution because both HI and S2/S3 can be reduced by (1) thermal maturation accompanied by generation and subsequent escape of hydrocarbons, (2) adsorption of pyrolytic organic compounds onto the clay mineral matrix during pyrolysis, and (3) oxidation of organic matter during transport, sedimentation, diagenesis, or outcrop weathering (Peters, 1986). Taken at face value, however, the Rock-Eval data suggest that kerogens in the Lospe Formation are variable in composition, and mostly gas-prone. Two Lospe samples are clearly anomalous, with HI greater than 300 and S2/S3 between 3 and 5 (table 1). The reasons for these anomalously high values are unknown, but may reflect the presence of migrated bitumen.

Analysis of palynomorphs in samples from the North Beach section suggests that much of the organic matter in the Lospe is of terrestrial (humic and herbaceous) origin. (Four samples from the Point Sal Formation were processed for palynomorphs but were barren.) The palynomorphs from the Lospe show signs of oxidation, but yield evidence of a diverse terrestrial vascular plant flora including *Carya* (hickory), *Quercus* (oaks), *Juglans* (walnuts), *Ulmus* (elms), *Betula* (birch), Pinaceae (pines), *Alnus* (alder), *Pterocarya* (trees related to walnut and hickory), Bombacaceae (tropical trees, including baobab and balsa), *Ilex* (holly), *Ephedra* (Mormon tea), *Salix* (willows), Malvaceae (mallow family; e.g., cotton), and Astereaceae (sunflower family). This assemblage suggests a deciduous hardwood forest and temperate climate with wet summers. Also found were palynomorphs of the Chenopodiaceae (goosefoot family; e.g., spinach, beets, and saltbush), which may indicate alkaline soil. Several Lospe samples contained reworked pollen of Late Cretaceous and Paleogene age. A few samples yielded sparse marine dinocysts, which may indicate that the Lospe lake was at times marine-influenced; alternatively, the dinocysts may have been reworked from older marine strata.

One of the samples from the Lospe Formation (table 1, sample 88C-121) shows an oxygen index (OI) value of 208. Values over 150 are unusually high (Katz, 1983), and can be caused by oxidation of organic matter in the samples during outcrop weathering (Peters, 1986; Stanley, 1987) or by generation of carbon dioxide during pyrolysis by thermal degradation of carbonate minerals such as calcite, dolomite, and siderite (Katz, 1983; Peters, 1986). Either or both of these problems may have affected our data, because the samples were collected from surface exposures susceptible to weathering and because the samples were not treated with acid to remove carbonate before pyrolysis.

THERMAL MATURITY

The thermal maturity of organic matter in our samples is indicated by the vitrinite reflectance (percent R_o); however, these results should be viewed with caution because of the low numbers of vitrinite reflectance measurements in some samples (table 3). The vitrinite reflectance of samples from the Lospe Formation ranges from 0.68 to 1.49 percent R_o, with a mean of 1.26 percent R_o (tables 3 and 4). Comparison of these values with the thermal maturity range chart (table 7) indicates that the thermal maturity of Lospe samples falls within the oil-generative window and the upper part of the condensate and wet gas zone (fig. 2). The vitrinite reflectance of samples from the Point Sal Formation ranges from 1.32 to 1.56 percent R_o with a mean of 1.45 percent R_o (tables 3 and 4), falling within the lower part of the oil-generative window and the upper part of the condensate and wet gas zone (fig. 2). Thus, on the basis of the ranges and mean values of vitrinite reflectance, it appears that the thermal maturity of the Point Sal Formation is about the same to somewhat higher than the underlying Lospe Formation. Inspection of fig. 2 shows that the relationship between vitrinite reflectance and stratigraphic position is not a simple linear trend, and that there is an apparent increase in vitrinite reflectance in the part of the section above 225 m from the base of the Lospe.

The vitrinite in most samples is consistent in appearance, with some plant structure visible and some evidence of weathering. No obviously recycled vitrinite was noted. In most of our samples, histograms of the reflectance measurements exhibit unimodal populations with well-defined peaks. None of the histograms show the bimodal distribution expected from samples that contain both primary and recycled vitrinite (e.g., Hunt, 1979).

Nevertheless, the vitrinite reflectance values for sample 88C-122 are anomalously low compared to the other samples (fig. 2). The reason for this is unknown, but may be related to retardation of vitrinite maturation due to the absorption of thermally-generated bitumen into the vitrinite, as proposed by Peters and others (1978) for a similar anomaly noted in samples of Cretaceous rocks from the Atlantic Ocean. Another possibility is that this sample was somehow shielded from the high temperatures that affected the other samples. If the high temperatures were related to migrating hot fluids in the subsurface, shielding may have been provided by local permeability barriers such as faults, clayey intervals, or zones of early cementation in the surrounding strata.

Six of the 14 Lospe samples and 2 of the 4 Point Sal samples exhibit T_{max} less than 435 °C (table 1), suggesting that these rocks are thermally immature with respect to the oil-generative window (table 7)--a result that is inconsistent with the high thermal maturities indicated by the vitrinite reflectance data. Anomalously low T_{max} can be caused by the occurrence of resinite (fossil tree resin), and by oil that has been generated in place or migrated into the rock (Peters, 1986). The presence of oil is an obvious explanation for low T_{max} in some samples (88C-121, 88C-123, 88C-124, 88C-129, DRV-11, and DRV-12) that also exhibit high production index (PI) values. Further organic geochemical analysis--for example, organic petrography, and extraction prior to Rock-Eval pyrolysis (Peters, 1986)--may resolve the problem

Table 7. Geochemical parameters describing level of thermal maturation (from Peters 1986), and corresponding estimated burial temperatures (T_{burial}) calculated from vitrinite reflectance using the following equation (Barker, 1988): $\ln(R_o) = 0.0096\,(T_{burial}) - 1.4$

Maturation	Production Index (PI)[1] [S1/(S1 + S2)]	T_{max}[1] (° C)	Vitrinite reflectance (percent R_o)	T_{burial} (°C)
Top oil window	ca. 0.1	ca. 435-445	ca. 0.6	ca. 93
Bottom oil window	ca. 0.4	ca. 470	ca. 1.4	ca. 181

[1] T_{max} and PI are crude measurements of thermal maturation and are partly dependent on other factors, including the type of organic matter (Peters, 1986).

Table 8. Maximum burial temperatures (T_{burial}) calculated from vitrinite reflectance results using the following equation (Barker, 1988): $\ln(R_o) = 0.0096\,(T_{burial}) - 1.4$. See text for discussion

Subset	Mean R_o (%) (from table 3)	T_{burial} (°C)
All samples		
minimum	0.68	106
maximum	1.56	192
mean	1.29	172
Point Sal Fm.		
minimum	1.32	175
maximum	1.56	192
mean	1.46	185
Lospe Fm.		
minimum	.68	106
maximum	1.49	187
mean	1.26	170

of anomalously low values of T_{max} relative to vitrinite reflectance in the other samples.

INFERRED PALEOTEMPERATURES IN THE NORTH BEACH SECTION

Vitrinite reflectance data can be used to estimate maximum burial temperatures using the following equation (Barker, 1988):

$$\ln(R_o) = 0.0096(T_{burial}) - 1.4 \quad (1)$$

where R_o is the vitrinite reflectance (in percent), and T_{burial} is the maximum burial temperature in °C. Potential errors may be as great as ± 30 °C (Laughland and others, 1990). Using equation 1 and the observed vitrinite reflectance values from the Point Sal area, we calculate maximum burial temperatures for the Lospe Formation ranging from 106 °C to 187 °C, with a mean of 170 °C (table 8). The calculated temperatures for the Point Sal Formation are generally higher, ranging from 175 °C to 192 °C, with a mean of 185 °C. Recent work by Barker and Pawlewicz (1994) suggests that maximum temperatures may have been as much as 20 °C higher if one assumes that the vitrinite reflectance values reflect peak heating during hydrothermal metamorphism, rather than burial heating.

These results are noteworthy for two reasons. First, our vitrinite reflectance values and calculated paleotemperatures are, to the best of our knowledge, the highest ever reported for rocks of Miocene and younger age in the Santa Maria province. Second, our results suggest an inverted thermal maturity profile, in which the Lospe Formation appears to be less thermally mature than the overlying Point Sal Formation. This is contrary to the usual case in which rocks that are stratigraphically and/or structurally lower exhibit higher levels of thermal maturity because they have been buried deeper and experienced correspondingly higher temperatures (e.g., Hunt, 1979; Tissot and Welte, 1984). These issues are further discussed below.

COMPARISON WITH PREVIOUS THERMAL MATURITY RESULTS FROM THE SANTA MARIA BASIN

For several reasons, little information is available to the public on the thermal maturity of strata in the Santa Maria basin. Research done by the petroleum industry is largely unpublished (Isaacs and Petersen, 1987). Most studies have focused on the Monterey Formation, but experience suggests that conventional techniques of measuring thermal maturity--including vitrinite reflectance, Rock-Eval T_{max}, Thermal Alteration Index (TAI, a measurement of kerogen on a color scale), and others--may be unreliable or difficult to interpret in the Monterey (Isaacs and Petersen, 1987; Isaacs, 1988). Another problem is that vitrinite particles are sparse or absent from the Monterey in many areas (Isaacs and Petersen, 1987). Some evidence suggests that the Monterey Formation in some areas generates oil at lower than expected levels of thermal maturity, perhaps at vitrinite reflectance values less than 0.4 percent R_o (McCulloh, 1979; Petersen and Hickey, 1987; Isaacs and Petersen, 1987; Isaacs, 1987, 1988). Low-temperature generation of petroleum in the Monterey, if it occurs, may be related to the unusual chemistry of some Monterey kerogens, particularly the high sulfur content (Orr, 1984; Petersen and Hickey, 1987; Isaacs, 1988; Baskin and Peters, 1992). The notion of low-temperature generation of petroleum in the Monterey is not universally accepted, however (for example, see Dunham and others, 1991, p. 442-443).

Currently available information, summarized here, indicates that the Monterey Formation and other Neogene strata in the Santa Maria basin and surrounding areas are thermally immature to mature with respect to the conventional oil-generative window (table 7). Studies of silica diagenesis in the Santa Maria basin and surrounding areas show that, in places, siliceous strata of the Monterey Formation have been buried at least as deep as the zone of transformation of opal-CT to quartz, which corresponds to temperatures of about 75 to 85 °C (Isaacs, 1988, and references therein), slightly less than the top of the oil-generative window at about 93 °C (table 7). In some parts of the Santa Maria basin, the Monterey Formation presently is situated at depths where temperatures exceed 120 °C, well within the conventional oil window (Dunham and others, 1991, p. 443). Studies of illite/smectite geothermometry of the Monterey Formation in a well in the Orcutt field (fig. 1) suggest temperatures greater than 100 to 105 °C (Pollastro, 1990), which fall within the oil-generative window (table 7). In the Point Arguello oil field about 10 km southwest of Point Arguello (fig. 1), the highest measured temperature was about 128.8 °C at a depth of about 2,255 m (Williams and others, 1994, p. F6; Colin Williams, oral communication, 1995), also within the oil window (table 7). A reconnaissance study of 43 well and outcrop samples from the Miocene Point Sal and Monterey Formations and the Miocene and Pliocene Sisquoc Formation of the onshore Santa Maria basin and the Miocene Monterey Formation of the Santa Barbara coast showed vitrinite reflectance values of 0.21 to 0.6 percent R_o and TAI values of 1.1 to 2.5, indicating that these rocks are thermally immature to marginally mature (Isaacs and Magoon, 1984; Isaacs and Tomson, 1990). A regional study of more than 200 outcrop and subsurface samples from the Santa Maria and Ventura basins concluded (on the basis of TAI, R_o, Rock-Eval pyrolysis T_{max}, sapropel fluorescence, and silica diagenetic grade) that the Point Sal and Monterey Formations are generally immature to marginally mature but are fully mature in certain areas such as subthrust sections and deep synclines (Global Geochemistry Corporation, 1985). In a study of the Monterey Formation, Keller (1984) reported that 16 outcrop samples from the Santa Barbara coast and 2 subsurface samples from the onshore Santa Maria basin showed Rock-Eval pyrolysis T_{max} values ranging from 397 to 436 °C, or immature to marginally mature (table 7). Six outcrop samples of the Monterey Formation along the Santa Barbara coast showed several organic geochemical characteristics consistent with thermal immaturity (G.E. Claypool *in* Taylor, 1976, p. 25). Also from the Santa Barbara coast, unpublished analyses of atomic hydrogen/carbon ratios in organic matter in 37 samples indicate that the Monterey Formation in this area is thermally immature (C.M. Isaacs, written communication, 1991). A sample of the Monterey Formation collected from near Gaviota (fig. 1) showed a vitrinite reflectance of 0.38 percent R_o (Pytte, 1989). The lower Miocene Rincon Shale of the Santa Barbara coast also is thermally immature, on the basis of Rock-Eval pyrolysis T_{max} values (Stanley and others, 1992b, 1993). In the Point Conception COST well (fig. 1), the highest average vitrinite reflectance values reported were 0.68 percent R_o for Mesozoic rocks near the bottom of the well, and 0.34 percent R_o for the oldest Neogene rocks (Bostick, 1979). In the same well, similarly low levels of thermal maturity also were suggested by studies of molecular composition of saturated hydrocarbons, pyrolysis characteristics, elemental analysis of solid organic matter, TAI values, and thermal history modeling (Claypool and others, 1979; Petersen and Hickey, 1987). In the San Luis Obispo area (fig. 1), samples of the Monterey Formation from outcrops and wells are immature to marginally mature on the basis of Rock-Eval T_{max} ranging from 410 to 429 °C (Frizzell and Claypool, 1983), and TAI results that correspond to vitrinite reflectance values of about 0.3 to 0.7 percent R_o (Surdam and Stanley, 1984). Kablanow and Surdam (1984) and Isaacs and Tomson (1990) reported additional pyrolysis results (using techniques other than Rock-Eval) indicating that the Monterey Formation is thermally immature in the San Luis Obispo and Santa Maria areas.

Higher levels of thermal maturity occur sporadically in the Santa Maria area in rocks older than Miocene. In the Santa Ynez Mountains and southern Coast Ranges (fig. 1), TAI results from 115 outcrop samples and 20 core samples show that Mesozoic and Paleogene rocks are thermally immature to mature with respect to the oil-generative window (Frederiksen, 1985). Also in the Santa Ynez Mountains, vitrinite reflectance values from 20 outcrop samples and 25 subsurface samples of Mesozoic and Paleogene rocks range from 0.23 to 2.44 percent R_o, or thermally immature to overmature with respect to the oil-generative window (Helmold, 1980; Helmold and van de Kamp, 1984). Frizzell and Claypool (1983) reported Rock-Eval pyrolysis results from 17 samples of Mesozoic and Paleogene strata in the San Luis Obispo and Cuyama River gorge areas (fig. 1); however, only two of these samples showed S2 peaks greater than 0.2 mg HC/g (Peters, 1986), and these had T_{max} values of 430 °C and 444 °C, or immature to marginally mature with respect to the oil-generative window (table 7). Howell and Claypool (1977) suggested, on the basis of pyrolysis data (technique of Claypool and Reed, 1976), that three mudstone samples from the Lower Cretaceous of the southern Coast Ranges had reached maximum paleotemperatures of 230 to 200 °C, or overmature with respect to the oil-generative window; however, these estimates of paleotemperature may not be reliable because all three samples had low pyrolytic hydrocarbon yields (Howell and Claypool, 1977).

In summary, previous investigations have found that Neogene strata in the Santa Maria basin and surrounding region are thermally immature to marginally mature, while Mesozoic and Paleogene strata range from immature to overmature. Our vitrinite reflectance results (range 0.68 to 1.56 percent R_o, mean 1.29 percent R_o) and inferred paleotemperatures (range 106 to 192 °C, mean 172 °C) for the Lospe and Point Sal Formations in the North Beach section appear to include the highest ever reported from Neogene rocks in the Santa Maria area.

GEOLOGIC SIGNIFICANCE OF HIGH THERMAL MATURITIES AND PALEOTEMPERATURES

To better understand the possible geologic significance of the high thermal maturities and corresponding high paleotemperatures in the North Beach section, we compared our observed vitrinite reflectance values with those predicted by a commercial computer program, BasinMod version 2.95 (Platte River Associates, 1992). The BasinMod program constructs geological models of thermal maturity from stratigraphic and geothermal data provided by the user, and relies on a variety of assumptions regarding physical parameters such as compaction, thermal conductivity, heat capacity, and kinetics that are built into the program.

We used BasinMod to construct three models that predict vitrinite reflectance versus stratigraphic position for the North Beach section (figure 4). All three models incorporate data on lithology, thickness, age, and paleobathymetry from McCrory and others (in press, their table A3). Present-day geothermal gradients in the Santa Maria basin are markedly variable from place to place and from formation to formation, but generally in the range of 45-60 °C/km for the Foxen Mudstone and older units, and 20-40 °C/km for the Careaga Sandstone and units younger than the Careaga (Williams and others, 1994, p. F6). The three predictive models in figure 4 were calculated by BasinMod from the minimum (curve A), mean (curve B), and maximum (curve C) geothermal gradients reported by Williams and others (1994).

Inspection of figure 4 shows that most of the observed values of vitrinite reflectance in the upper part of the Lospe Formation and in the Point Sal Formation are higher than predicted by BasinMod for even the maximum geothermal gradients. Furthermore, the observed values suggest an inverted thermal maturity profile (mentioned earlier in this report), which contrasts with BasinMod's prediction of a smooth increase in thermal maturity with depth (figure 4). We suggest that the anomalously high observed values of vitrinite reflectance and the apparent inverted thermal maturity profile at North Beach resulted from a local heat source such as the gabbro sill in the lower part of the Point Sal Formation (figure 2), or a zone of high-temperature hydrothermal waters in the lower part of the Point Sal Formation and upper part of the Lospe. The temperatures and thermal effects presumably were greatest in the rocks immediately adjacent to the heat source and decreased with distance away from it, resulting in the apparent inverted thermal maturity profile. Figure 4 also shows that the observed and predicted values of vitrinite reflectance (assuming mean and maximum geothermal gradients) seem to converge about 250 m below the base of the gabbro sill. On the basis of this convergence, we suggest that the observed values of vitrinite reflectance in the middle of the Lospe Formation reflect thermal maturation during burial at present-day geothermal gradients.

Most basic magmas crystallize at temperatures of about 900 to 1200 °C (Macdonald, 1972; Hyndman, 1985). High levels of thermal maturity and unusual thermal maturity profiles in mudrocks and coals that have been invaded by hot igneous intrusions have been widely reported (Briggs, 1935; Dapples, 1939; Dutcher and others, 1966; Schopf and Long, 1966; Bostick, 1971; Dow, 1977; Peters and others, 1978, 1983; Simoneit and others, 1978, 1981; Dypvik, 1979; Perregaard and Schiener,

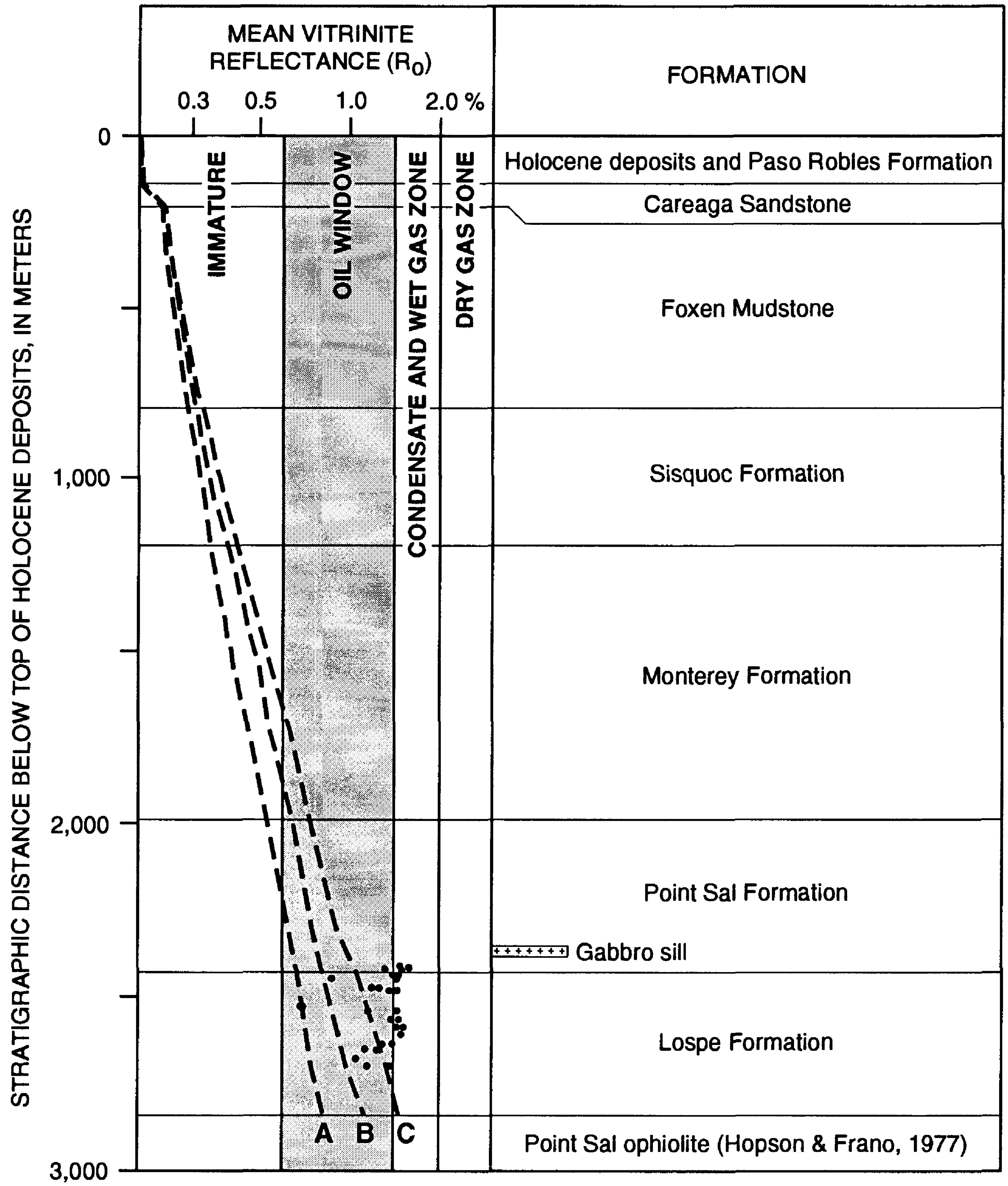

Figure 4. Values of vitrinite reflectance (on a logarithmic scale) calculated by the commercial computer program BasinMod in the North Beach area (dashed lines), for three different sets of assumed geothermal gradients: A, 20 °C/km for the Careaga Sandstone and younger units, and 45 °C/km for the Foxen Mudstone and older units; B, 30 °C/km for the Careaga Sandstone and younger units, and 52.5 °C/km for the Foxen Mudstone and older units; and C, 40 °C/km for the Careaga Sandstone and younger units, and 60 °C/km for the Foxen Mudstone and older units. Compare the calculated values with actual observed values of vitrinite reflectance from table 2 (dots). See text for discussion.

1979; Bostick and Pawlewicz, 1984; Clayton and Bostick, 1985; Niem and Niem, 1985). Igneous intrusions can cause a large increase in the vitrinite reflectance of the intruded rocks by providing high temperatures over short time ranges (Hunt, 1979). Reflectance values above 3 percent R_o are common in contact metamorphism, but decrease with increasing distance away from the intrusive (Dow, 1977; Peters and others, 1978, 1983; Hunt, 1979; Bostick and Pawlewicz, 1984; Clayton and Bostick, 1985). A traditional rule of thumb is that contact metamorphism affects the intruded rocks for a distance of about one to two times the thickness of the intrusive body (Dow, 1977; K.E. Peters, oral communication, 1992). The actual distance, however, depends on the size of the intrusive, the temperature difference between the magma and the intruded rock, the rate of cooling, the depth at which the intrusive was emplaced, the amount of volatiles emitted from the magma, the amount of pore water in the intruded rocks, and the thermal conductivity of the intruded rocks (Dow, 1977; Hunt, 1979, Simoneit and others, 1981; Peters and others, 1983).

In the North Beach section, the observed values of vitrinite reflectance differ significantly from the ones predicted by BasinMod for a distance of about 250 m below the gabbro sill (assuming maximum present day geothermal gradients, represented by curve C on figure 4). This may mean that contact metamorphism extended as far as 250 m from the sill. However, the rule of thumb noted above predicts that the zone of contact metamorphism should extend only about 25-60 m from the sill, which is about 25-30 m thick. Perhaps the width of the apparent zone of contact metamorphism was enhanced by hot hydrothermal waters that either accompanied the gabbro intrusion or circulated during a separate event before or after the intrusion. Hot fluids may have found conduits along the ubiquitous faults and fractures in the area, and also along permeable horizons of sandstone within the Point Sal and Lospe Formations. Hydrocarbons may have been thermally generated in organic-rich strata of the Point Sal Formation, and may have circulated with the hydrothermal waters. High-temperature hydrothermal systems associated with volcanism have been recognized in many parts of the world, and are known to have resulted in geologically rapid thermal maturation of sedimentary strata over thicknesses of hundreds of meters (see, for examples, Barker and Pawlewicz, 1990; Summer and Verosub, 1992; and references therein).

It is possible that geothermal gradients in the Santa Maria basin were higher in the geologic past. Several tectonic and thermal models invoking subcrustal slabless windows, with asthenospheric upwelling resulting in high heat flow and high geothermal gradients, have been proposed for the Santa Maria area (Heasler and Surdam, 1983, 1985, 1989; Compton, 1991; Howie, 1991). It is also possible that higher temperatures could have been reached during deep burial beneath one or more thrust sheets during late Cenozoic compressional tectonism in the area, but we believe this is unlikely because available structural cross-sections show that the Casmalia Hills (including the North Beach section) are on the structurally highest block in the Santa Maria Basin (Woodring and Bramlette, 1950), and not in the lower plate beneath any recognized thrust fault. While tectonic models invoking higher ancient geothermal gradients or deeper burial may help explain some aspects of the high thermal maturity observed at North Beach, our analysis using BasinMod and modern geothermal gradients suggests that such models are not needed. Furthermore, the inverted thermal maturity profile found at North Beach can only be explained by a local thermal anomaly such as an igneous intrusion or hydrothermal system.

SUMMARY AND IMPLICATIONS FOR PETROLEUM EXPLORATION

Worldwide experience indicates that certain lakebed sediments can be prolific petroleum source rocks (Fouch and Dean, 1982; Powell, 1986; Katz, 1990). Nevertheless, results from Rock-Eval pyrolysis of a limited number of outcrop samples suggest that, at least locally, lacustrine and shallow-marine mudstones of the Lospe Formation contain too little organic matter (organic carbon generally less than 0.5 percent) to be potential source rocks of petroleum. In contrast to the Lospe, the amount of organic carbon in the Point Sal Formation ranges from about 1.5 to more than 3.5 percent (tables 2 and 4). In the Monterey Formation, the principal source rock in the Santa Maria basin, organic carbon content averages about 5 percent and is as high as 23 percent in individual beds (Isaacs and Petersen, 1987). Kerogens in the Lospe are mainly gas-prone Type III and inert(?) Type IV. Monterey kerogens, however, are mostly oil-prone Type II, and of mixed marine algal and terrestrial origin (Isaacs and Petersen, 1987; Isaacs, 1988).

The data set from the North Beach section is small and may not be representative of the Lospe Formation everywhere. It is possible that organic-rich mudstones occur in the Lospe elsewhere in the Santa Maria basin. Our preliminary conclusions can be tested by further investigations, including regional studies of subsurface cores and cuttings (rather than outcrop samples, which are susceptible to weathering), by using samples that are less thermally mature than those from the North Beach section, and by additional geochemical analyses such as hydrous pyrolysis (e.g., Lewan, 1985; Peters and others, 1990), and kerogen elemental composition (e.g., Tissot and Welte, 1984, and references therein).

Previous work by Lillis and King (1991) suggested two major periods of oil generation and migration in the Santa Maria basin: one during the late Miocene, in which low-gravity, high-sulfur oil was generated in the Monterey Formation and migrated into existing stratigraphic and structural traps; and a later episode in which high-gravity, low-sulfur oil generated at higher levels of thermal maturity moved into folds of Pliocene and Quaternary age. Our thermal maturity results from the North Beach section suggest the hypothesis that a third, earlier, and volumetrically less significant episode of oil generation (most likely in the Point Sal Formation) occurred locally near early to middle Miocene igneous intrusions and (or) hydrothermal systems.

Heat from igneous intrusions and high-temperature hydrothermal waters can cause thermal transformation of organic matter in petroleum source rocks near the intrusion, and generation of oil and gas (Simoneit and others, 1978, 1981; Peters and others, 1983; Tissot and Welte, 1984; Kvenvolden and Simoneit, 1990). The exact time-temperature history of these processes are unknown, but one scenario suggests that petroleum can form by intense heating (at about 300-350 °C) during periods as short as about 100 years (Kvenvolden and others, 1988; Simoneit and

Kvenvolden, 1994). We suggest that at least some of the oil detected in our samples from the North Beach section could have been generated in organic-rich strata of the Point Sal Formation by heating during early or middle Miocene intrusion or hydrothermal activity. We further speculate that, if similar intrusions or hydrothermal systems occur elsewhere in the Santa Maria basin, they may have caused generation of limited quantities of oil and gas in small areas. Subsequently, some of this petroleum may have accumulated in early-formed fault and stratigraphic traps (e.g., Namson and Davis, 1990; Lillis and King, 1991) in strata overlying the intrusions. Hydrocarbons may also have accumulated beneath thick, laterally extensive sills like the one near North Beach; such sills may have served not only as heat sources, but also as seals that trapped oil and gas generated in organic-rich shales of the Point Sal Formation.

Basic igneous dikes and sills of Miocene age have been recognized in outcrop along the fringes of the Santa Maria basin in the San Luis Obispo area (Hall, 1973; Hall and others, 1979), in the nearby Southern Coast Ranges (Hall and Corbató, 1967; Hall, 1978b, 1981a, 1981b; Vedder and others, 1988) and in the Santa Ynez Mountains (Robyn, 1980), but we know of no Miocene intrusions in the subsurface in the onshore Santa Maria basin. However, organic geochemical studies suggest that parts of the basin, including the Casmalia and Orcutt fields, may have experienced higher heat flow in the past (King and Lillis, 1990); the elevated heat flow may have resulted from crustal thinning and/or emplacement of yet-unrecognized Miocene igneous intrusions or hydrothermal systems in the subsurface. Oil generated near such thermal anomalies might occur along the Santa Ynez River fault at the southern margin of the Santa Maria basin, where clockwise tectonic rotation of the Santa Ynez Mountains during the early and middle Miocene (Hornafius, 1985; Luyendyk, 1991) may have caused the creation of small triangular crustal gaps that were the sites of mantle upwelling (Cole and others, 1991b). These speculative ideas can be tested by further drilling, geophysical investigations, organic geochemical studies, and radiometric dating of intrusions.

ACKNOWLEDGMENTS

We thank the United States Air Force for permission to work on Vandenberg Air Force Base. Much of the laboratory work was ably performed by T.A. Daws and G.M. Frost. We also thank K.J. Bird, R.B. Cole, T.A. Daws, D.W. Houseknecht, C. E. Katherman, D.G. McCubbin, and K.E. Peters for stimulating discussions. Comments by P.M. Lillis and M.E. Tennyson were helpful in revising an early draft of this report.

REFERENCES CITED

Barker, C.E., 1988, Geothermics of petroleum systems: implications of the stabilization of kerogen thermal maturation after a geologically brief heating duration at peak temperatures, *in* Magoon, L.B., ed., Petroleum systems of the United States: U.S. Geological Survey Bulletin 1870, p. 26-29.

Barker, C.E., and Pawlewicz, M.J., 1986, The correlation of vitrinite reflectance with maximum temperature in humic organic matter, *in* Bunterbarth, G., and Stegena, L., eds., Paleogeothermics: Berlin, Springer-Verlag, Lecture Notes in Earth Sciences, v. 5, p. 79-93.

Barker, C.E., and Pawlewicz, M.J., 1990, Vitrinite reflectance as an exploration tool in defining areas of recent and ancient heating: a case study of the Cerro Prieto geothermal system, Mexico, *in* Nuccio, V.F., and Barker, C.E., eds., Applications of thermal maturity studies to energy exploration: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 161-166.

———1994, Calculations of vitrinite reflectance from thermal histories and peak temperatures (Chapter 14), *in* Mukhopadhyay, P.K., and Dow, W.G., eds., Vitrinite reflectance as a maturity parameter--applications and limitations: Washington, D.C., American Chemical Society, p. 216-229.

Bartow, J.A., 1992, Paleogene and Neogene time scales for southern California: U.S. Geological Survey Open-File Report 92-212, 2 sheets.

Baskin, D.K., and Peters, K.E., 1992, Early generation characteristics of a sulfur-rich Monterey kerogen: American Association of Petroleum Geologists Bulletin, v. 76, no. 1, p. 1-13.

Bostick, N.H., 1971, Thermal alteration of clastic inorganic particles as an indicator of contact and burial metamorphism in sedimentary rocks: Geoscience and Man, v. 3, p. 83-92.

———1979, Vitrinite reflectance, *in* Cook, H.E., ed., Geologic studies of the Point Conception deep stratigraphic test well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-218, p. 125-128.

Bostick, N.H., and Pawlewicz, M.J., 1984, Paleotemperatures based on vitrinite reflectance of shales and limestones in igneous dike aureoles in the Upper Cretaceous Pierre Shale, Walsenburg, Colorado, *in* Woodward, Jane, Meissner, F.F., and Clayton, J.L., eds., Hydrocarbon source rocks of the greater Rocky Mountain region: Denver, Colorado, Rocky Mountain Association of Geologists, p. 387-392.

Briggs, Henry, 1935, Alteration of coal-seams in the vicinity of igneous intrusions, and associated problems: Transactions of the Institution of Mining Engineers, v. 89, part 4, p. 187-219.

California Division of Oil and Gas, 1991, California oil and gas fields, Volume II, southern, central, and coastal California [3rd edition]: Sacramento, California, California Department of Conservation, Publication TR12, 689 p.

———1993, 78th Annual Report of the State Oil and Gas Supervisor, 1992: Sacramento, California, California Department of Conservation, Publication PR06, 159 p.
Canfield, C.R., 1939, Subsurface stratigraphy of Santa Maria Valley oil field and adjacent parts of Santa Maria Valley, California: American Association of Petroleum Geologists Bulletin, v. 23, no. 1, p. 45-81.
Claypool, G.E., Baysinger, J.P., Lubeck, C.M., and Love, A.H., 1979, Organic geochemistry, *in* Cook, H.E., ed., Geologic studies of the Point Conception deep stratigraphic test well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-218, p. 109-124.
Claypool, G.E., and Reed, P.R., 1976, Thermal-analysis technique for source-rock evaluation: quantitative estimate of organic richness and effects of lithologic variation: American Association of Petroleum Geologists Bulletin, v. 60, no. 4, p. 608-626.
Clayton, J.L., and Bostick, N.H., 1985, Temperature effects on kerogen and on molecular and isotopic composition of organic matter in Pierre Shale near an igneous dike: Organic Geochemistry, v. 10, nos. 1-3, p. 135-143.
Clayton, J.L., and Swetland, P.J., 1978, Subaerial weathering of sedimentary organic matter: Geochimica et Cosmochimica Acta, v. 42, no. 2, p. 305-312.
Clementz, D.M., Demaison, G.J., and Daly, A.R., 1979, Well site geochemistry by programmed pyrolysis: Proceedings, Eleventh Annual Offshore Technology Conference, v. 1, p. 465-470.
Cole, R.B., and Basu, A.R., 1995, Nd-Sr isotopic geochemistry and tectonics of ridge subduction and middle Cenozoic volcanism in western California: Geological Society of America, v. 107, no. 2, p. 167-179.
Cole, R.B., and Stanley, R.G., 1994, Sedimentology and origin of subaqueous pyroclastic sediment gravity flows in the Neogene Santa Maria basin, California: Sedimentology, v. 41, p. 37-54.
Cole, R.B., Stanley, R.G., and Johnson, S.Y., 1991a, Origin of tuff deposits in the lower Miocene Lospe Formation, Santa Maria basin, California [abs.]: Association of Petroleum Geologists Bulletin, v. 75, no. 2, p. 359-360.
Cole, R.B., Stanley, R.G., and Basu, A.R., 1991b, Stratigraphy and origin of lower Miocene volcanic rocks, onshore and offshore Santa Maria province, California [abs.]: Geological Society of America, Abstracts with programs, v. 23, no. 5, p. A476.
Compton, J.S., 1991, Porosity reduction and burial history of siliceous rocks from the Monterey and Sisquoc Formations, Point Pedernales area, California: Geological Society of America Bulletin, v. 103, no. 5, p. 625-636.
Crawford, F.D., 1971, Petroleum potential of Santa Maria province, California, *in* Cram, I.H., ed., Future petroleum provinces of the United States--their geology and potential: American Association of Petroleum Geologists Memoir 15, p. 316-328.
Dalrymple, G.B., 1979, Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558-560.

Daly, A.R., and Edman, J.D., 1987, Loss of organic carbon from source rocks during thermal maturation [abs.]: American Association of Petroleum Geologists Bulletin, v. 71, no. 5, p. 546.

Dapples, E.C., 1939, Coal metamorphism in the Anthracite-Crested Butte quadrangles, Colorado: Economic Geology, v. 34, no. 4, p. 369-398.

Dembicki, Harry, Jr., 1984, An interlaboratory comparison of source rock data: Geochimica et Cosmochimica Acta, v. 48, p. 2641-2649.

Dibblee, T.W., Jr., 1989, Geologic map of the Point Sal and Guadalupe quadrangles, Santa Barbara County, California: Santa Barbara, California, Dibblee Geological Foundation, scale 1:24,000.

Dow, W.G., 1977, Kerogen studies and geological interpretations: Journal of Geochemical Exploration, v. 7, p. 79-99.

Dryden, J.E., Erickson, R.C., Off, T., and Yost, S.W., 1968, Gas in Cenozoic rocks in Ventura-Santa Maria basins, California, *in* Beebe, B.W., ed., Natural gases of North America: American Association of Petroleum Geologists Memoir 9, v. 1, p. 135-148.

Dunham, J.B., Bromely, B.W., and Rosato, V.J., 1991, Geologic controls on hydrocarbon occurrence within the Santa Maria basin of western California, *in* Gluskoter, H.J., Rice, D.D., and Taylor, R.B., eds., Economic Geology, U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. P-2, p. 431-446.

Dutcher, R.R., Campbell, D.L., and Thornton, C.P., 1966, Coal metamorphism and igneous intrusives in Colorado, *in* Given, P.H., ed., Coal science: American Chemical Society, Advances in Chemistry Series, v. 55, p. 708-723.

Dypvik, Henning, 1979, Major and minor element chemistry of Triassic black shales near a dolerite intrusion at Sassenfjorden, Spitsbergen: Chemical Geology, v. 25, p. 53-65.

Espitalié, J., Madec, M., Tissot, B., Mennig, J.J., and Leplat, P., 1977, Source rock characterization method for exploration: Proceedings, Ninth Annual Offshore Technology Conference, v. 3, p. 439-444.

Espitalié, J., Marquis, F., and Borsony, I., 1984, Geochemical logging, *in* Voorhees, K.J., ed., Analytical pyrolysis: London, Butterworth and Co., Ltd., p. 276-304.

Fairbanks, H.W., 1896, The geology of Point Sal: University of California, Bulletin of the Department of Geology, v. 2, no. 1, p. 1-92.

Fouch, T.D., and Dean, W.E., 1982, Lacustrine and associated clastic depositional environments, *in* Scholle, P.A., and Spearing, Darwin, eds., Sandstone depositional environments: American Association of Petroleum Geologists Memoir 31, p. 87-114.

Frederiksen, N.O., 1985, Map showing thermal-alteration indices in roadless areas and the Santa Lucia Wilderness in the Los Padres National Forest, southwestern California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1655-F, scale 1:250,000.

Frizzell, V.A., Jr., and Claypool, G.E., 1983, Petroleum potential map of Mesozoic and Cenozoic rocks in roadless areas and the Santa Lucia Wilderness in the Los Padres National Forest, southwestern California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1655-D, scale 1:250,000, 18 p.

Global Geochemistry Corporation, 1985, The geochemical and paleoenvironmental history of the Monterey Formation--sediments and hydrocarbons: Canoga Park, California, unpublished report, v. 1 (data synthesis and text), 459 p.

Hall, C.A., Jr., 1973, Geology of the Arroyo Grande 15-minute quadrangle, San Luis Obispo county, California: California Division of Mines and Geology Map Sheet 24, scale 1:48,000.

———1978a, Origin and development of the Lompoc-Santa Maria pull-apart basin and its relation to the San Simeon-Hosgri strike-slip fault, western California, *in* Silver, E.A., and Normark, W.R., eds., San Gregorio-Hosgri fault zone, California: California Division of Mines and Geology Special Report 137, p.

———1978b, Geologic map of Twitchell Dam and parts of Santa Maria and Tepusquet Canyon quadrangles, Santa Barbara county, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-963, 2 sheets, scale 1:24,000.

———1981a, San Luis Obispo transform fault and middle Miocene rotation of the Western Transverse Ranges, California: Journal of Geophysical Research, v. 86, no. B2, p. 1015-1031.

———1981b, Map of geology along the Little Pine fault, parts of the Sisquoc, Foxen Canyon, Zaca Lake, Bald Mountain, Los Olivos, and Figueroa Mountain quadrangles, Santa Barbara county, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1285, two sheets, scale 1:24,000.

———1982, Pre-Monterey subcrop and structure contour maps, western San Luis Obispo and Santa Barbara Counties, south-central California: U.S. Geological Survey Miscellaneous Field Studies Map MF-1384, six sheets, scale 1:62,500.

Hall, C.A., Jr., and Corbató, C.E., 1967, Stratigraphy and structure of Mesozoic and Cenozoic rocks, Nipomo quadrangle, Southern Coast Ranges, California: Geological Society of America Bulletin, v. 78, p. 559-582.

Hall, C.A., Jr., Ernst, W.G., Prior, S.W., and Wiese, J.W., 1979, Geologic map of the San Luis Obispo-San Simeon region, California: U.S. Geological Survey Miscellaneous Investigations Series Map I-1097.

Hall, C.A., Jr., Turner, D.L., and Surdam, R.C., 1966, Potassium-argon age of the Obispo Formation with *Pecten lompocensis* Arnold, southern Coast Ranges, California: Geological Society of America Bulletin, v. 77, p. 443-446.

Heasler, H.P., and Surdam, R.C., 1983, A thermally-subsiding basin model for the maturation of hydrocarbons in the Pismo basin, California, *in* Isaacs, C.M., and Garrison, R.E., eds., Petroleum generation and occurrence in the Miocene Monterey Formation, California: Los Angeles, California, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 69-74.

———1985, Thermal evolution of coastal California with application to hydrocarbon maturation: American Association of Petroleum Geologists Bulletin, v. 69, no. 9, p. 1386-1400.

———1989, Thermal and hydrocarbon maturation modeling of the Pismo and Santa Maria basins, coastal California, *in* Naeser, N.D., and McCulloh, T.H., eds., Thermal history of sedimentary basins: methods and case histories: New York, Springer-Verlag New York, Inc., p. 297-309.

Helmold, K.P., 1980, Diagenesis of Tertiary arkoses, Santa Ynez Mountains, California [Ph.D. dissertation]: Stanford, California, Stanford University, 225 p.

Helmold, K.P., and van de Kamp, P.C., 1984, Diagenetic mineralogy and controls on albitization and laumontite formation in Paleogene arkoses, Santa Ynez Mountains, California, *in* McDonald, D.A., and Surdam, R.C., eds., Clastic diagenesis: American Association of Petroleum Geologists Memoir 37, p. 239-276.

Hopson, C.A., and Frano, C.J., 1977, Igneous history of the Point Sal ophiolite, southern California, *in* Coleman, R.G., and Irwin, W.P., eds., North American ophiolites: Oregon Department of Geology and Mineral Industries Bulletin 95, p. 161-183.

Hornafius, J.S., 1985, Neogene tectonic rotation of the Santa Ynez Range, Western Transverse Ranges, California, suggested by paleomagnetic investigation of the Monterey Formation: Journal of Geophysical Research, v. 90, no. B14, p. 12,503-12,522.

Howell, D.G., and Claypool, G.E., 1977, Reconnaissance petroleum potential of Mesozoic rocks, Coast Ranges, central California, *in* Howell, D.G., Vedder, J.G., and McDougall, K.A., eds., Cretaceous geology of the California Coast Ranges, west of the San Andreas fault: Los Angeles, California, Society of Economic Paleontologists and Mineralogists, Pacific Section, Pacific Coast Paleogeography Field Trip Guide 2, p. 85-90.

Howie, J.M., 1991, Time-transgressive evolution of the Pacific-North American transform plate boundary in central California: constraints from crustal structure, chap. 3 *of* Howie, J.M., Seismic studies of crustal structure and tectonic evolution across the central California margin and the Colorado Plateau margin [Ph.D. dissertation]: Stanford, California, Stanford University, p. 113-165.

Huffman, E.W.D., Jr., 1977, Performance of a new automatic carbon dioxide coulometer: Microchemical Journal, v. 25, p. 567-573.

Hunt, J.M., 1979, Petroleum geochemistry and geology: San Francisco, W.H. Freeman and Company, 617 p.

Hyndman, D.W., 1985, Petrology of igneous and metamorphic rocks (3d ed.): New York, McGraw-Hill Book Company, 786 p.

Isaacs, C.M., 1987, Sources and deposition of organic matter in the Monterey Formation, south-central coastal basins of California, *in* Meyer, R.F., ed., Exploration for heavy crude oil and natural bitumen: American Association of Petroleum Geologists Studies in Geology, v. 25, p. 193-205.

———1988, Marine petroleum source rocks and reservoir rocks of the Miocene Monterey Formation, California, U.S.A., *in* Wagner, H.C., Wagner, L.C., Wang, F.F.H., and Wong, F.L., eds., Petroleum resources of China and related subjects: Houston, Texas, Circum-Pacific Council for Energy and Mineral Resources Earth Science Series, v. 10, p. 825-848.

Isaacs, C.M., and Magoon, L.B., 1984, Thermal indicators of organic matter in the Sisquoc and Monterey Formations, Santa Maria basin, California [abs.]:

Abstracts, Annual Midyear Meeting, San Jose, California, August 10-13, 1984, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 40.
Isaacs, C.M., and Petersen, N.F., 1987, Petroleum in the Miocene Monterey Formation, California, *in* Hein, J.R., ed., Siliceous sedimentary rock-hosted ores and petroleum: New York, Van Nostrand Reinhold Company, p. 83-116.
Isaacs, C.M., and Tomson, J.H., 1990, Reconnaissance study of petroleum source-rock characteristics of core samples from the Sisquoc and Monterey Formations in a north-south subsurface transect across the onshore Santa Maria basin and in surface sections along the Santa Barbara-Ventura coast, southern California: U.S. Geological Survey Open-File Report 89-108, 43 p.
Jackson, L.L., Brown, F.W., and Neil, S.T., 1987, Major and minor elements requiring individual determination, classical whole rock analysis, and rapid rock analysis: U.S. Geological Survey Bulletin 1770-G, p. G1-G23.
Johnson, S.Y., and Stanley, R.G., 1994, Sedimentology of the conglomeratic lower member of the Lospe Formation (lower Miocene), Santa Maria basin, California: U.S. Geological Survey Bulletin 1995-D, p. D1-D21.
Kablanow, R.I., III, and Surdam, R.C., 1984, Diagenesis and hydrocarbon generation in the Monterey Formation, Huasna basin, California, *in* Surdam, R.C., ed., Stratigraphic, tectonic, thermal, and diagenetic histories of the Monterey Formation, Pismo and Huasna basin, California: Society of Economic Paleontologists and Mineralogists, Guidebook No. 2, p. 53-68.
Katz, B.J., 1983, Limitations of Rock-Eval pyrolysis for typing organic matter: Organic Geochemistry, v. 4, no. 3/4, p. 195-199.
———ed., 1990, Lacustrine basin exploration--case studies and modern analogs: American Association of Petroleum Geologists Memoir 50, 340 p.
Keller, M.A., 1984, Silica diagenesis and lithostratigraphy of the Miocene Monterey Formation of the northwestern Ventura basin, California, including biostratigraphy, pyrolysis results, chemical analyses, and a preliminary temperature zonation of the opal-CT zone: U.S. Geological Survey Open-File Report 84-368, 79 p.
King, J.D., and Lillis, P.G., 1990, Thermal modeling using biomarkers in the Santa Maria basin, California [abs.]: American Association of Petroleum Geologists Bulletin, v. 74, no. 5, p. 695.
Kleinpell, R.M., 1938, Miocene stratigraphy of California: Tulsa, Oklahoma, American Association of Petroleum Geologists, 450 p.
———1980, The Miocene stratigraphy of California revisited: Tulsa, Oklahoma, American Association of Petroleum Geologists Studies in Geology 11, p. 1-53.
Kvenvolden, K.A., Rapp, J.B., Hostettler, F.D., King, J.D., and Claypool, G.E., 1988, Organic geothermometry of petroleum from Escanaba Trough, offshore northern California: Organic Geochemistry, v. 13, nos. 1-3, p. 351-355.
Kvenvolden, K.A., and Simoneit, B.R.T., 1990, Hydrothermally derived petroleum: examples from Guaymas basin, Gulf of California, and Escanaba Trough, northeast Pacific Ocean: American Association of Petroleum Geologists Bulletin, v. 74, no. 3, p. 223-237.
Laughland, M.M., Underwood, M.B., and Wiley, T.J., 1990, Thermal maturity, tectonostratigraphic terranes, and regional tectonic history: an example from

the Kandik area, east-central Alaska, *in* Nuccio, V.F., and Barker, C.E., eds., Applications of thermal maturity studies to energy exploration: Rocky Mountain Section, Society of Economic Paleontologists and Mineralogists, p. 97-111.

Lewan, M.D., 1985, Evaluation of petroleum generation by hydrous pyrolysis experimentation: Philosophical Transactions, Royal Society of London, series A, v. 315, p. 123-134.

Leythaeuser, Detlev, 1973, Effects of weathering on organic matter in shales: Geochimica et Cosmochimica Acta, v. 37, no. 1, p. 113-120.

Lillis, P.G., and King, J.D., 1991, Controls on the variation of crude oil quality, Santa Maria basin, California [abs.]: American Association of Petroleum Geologists Bulletin, v. 75, no. 2, p. 372.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, no. 11, P. 1528-1536.

Macdonald, G.A., 1972, Volcanoes: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 510 p.

McCrory, P.A., Ingle, J.C., Jr., Wilson, D.S., and Stanley, R.G., in press, Neogene tectonic evolution of Santa Maria province, California, and transfer of central California to the Pacific plate: U.S. Geological Survey Bulletin 1995.

McCulloh, T.H., 1979, Implications for petroleum appraisal, *in* Cook, H.E., ed., Geologic studies of the Point Conception deep stratigraphic test well OCS-CAL 78-164 No. 1, outer continental shelf, southern California, United States: U.S. Geological Survey Open-File Report 79-218, p. 26-42.

McLean, Hugh, 1991, Distribution and juxtaposition of Mesozoic tectonic elements in the basement of the Santa Maria basin, California: U.S. Geological Survey Bulletin 1995-B, 12 p.

McLean, Hugh, and Stanley, R.G., 1994, Provenance of sandstone clasts in the lower Miocene Lospe Formation near Point Sal, California: U.S. Geological Survey Bulletin 1995-E, p. E1-E7.

Namson, Jay, and Davis, T.L., 1990, Late Cenozoic fold and thrust belt of the southern Coast Ranges and Santa Maria basin, California: American Association of Petroleum Geologists Bulletin, v. 74, no. 4, p. 467-492.

Niem, A.R., and Niem, W.A., 1985, Oil and gas investigation of the Astoria basin, Clatsop and northernmost Tillamook counties, northwest Oregon: Oregon Department of Geology and Mineral Industries, Oil and Gas Investigation OGI-14, scale 1:100,000, 8 p.

Orr, W.L., 1984, Sulfur and sulfur isotope ratios in Monterey oils of the Santa Maria basin and Santa Barbara Channel area [abs.]: Abstracts, Annual Midyear Meeting, San Jose, California, August 10-13, 1984, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 62.

Perregaard, J., and Schiener, E.J., 1979, Thermal alteration of sedimentary organic matter by a basalt intrusive (Kimmeridgian shales, Milne Land, East Greenland): Chemical Geology, v. 26, p. 331-343.

Peters, K.E., 1986, Guidelines for evaluating petroleum source rock using programmed pyrolysis: American Association of Petroleum Geologists Bulletin, v. 70, no. 3, p. 318-329.

Peters, K.E., Moldowan, J.M., and Sundaraman, P., 1990, Effects of hydrous pyrolysis on biomarker thermal maturity parameters: Monterey phosphatic and siliceous members: Organic Geochemistry, v. 15, no. 3, p. 249-265.

Peters, K.E., Simoneit, B.R.T., Brenner, Shmuel, and Kaplan, I.R., 1978, Vitrinite reflectance-temperature determinations for intruded Cretaceous black shale in the eastern Atlantic, *in* Oltz, D.F., ed., Low temperature metamorphism of kerogen and clay minerals: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 53-58.

Peters, K.E., Whelan, J.K., Hunt, J.M., and Tarafa, M.E., 1983, Programmed pyrolysis of organic matter from thermally altered Cretaceous black shales: American Association of Petroleum Geologists Bulletin, v. 67, no. 11, p. 2137-2146.

Petersen, N.F., and Hickey, P.J., 1987, California Plio-Miocene oils: evidence of early generation, *in* Meyer, R.F., ed., Exploration for heavy crude oil and natural bitumen: American Association of Petroleum Geologists Studies in Geology, v. 25, p. 351-359.

Platte River Associates, Inc., 1992, BasinMod, a modular basin modeling system, version 2.95: Available from Platte River Associates, Inc., 2000 West 120th Avenue, Suite 10, Denver, Colorado 80234.

Pollastro, R.M., 1990, Geothermometry from smectite and silica diagenesis in the diatomaceous Monterey and Sisquoc Formations, Santa Maria basin, California [abs.]: American Association of Petroleum Geologists Bulletin, v. 74, no. 5, p. 742.

Powell, T.G., 1986, Petroleum geochemistry and depositional setting of lacustrine source rocks: Marine and Petroleum Geology, v. 3, no. 3, p. 200-219.

Pytte, M.H., 1989, Organic geochemistry of the Miocene Monterey and equivalent formations in five California basins, *in* MacKinnon, T.C., ed., Oil in the California Monterey Formation: American Geophysical Union Field Trip Guidebook T311, p. 11-27.

Redwine, L. E., 1981, Hypothesis combining dilation, natural hydraulic fracturing, and dolomitization to explain petroleum reservoirs in Monterey Shale, Santa Maria area, California, *in* Garrison, R.E., and Douglas, R.O., eds., The Monterey Formation and related siliceous rocks of California: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 221-248.

Robyn, E.S., 1980, A description of the Miocene Tranquillon volcanics and a comparison with the Miocene Obispo tuff [M.A. thesis]: Santa Barbara, University of California, 110 p.

Roehl, P.O., 1981, Dilation brecciation--a proposed mechanism of fracturing, petroleum expulsion, and dolomitization in the Monterey Formation, California, *in* Garrison, R.E., and Douglas, R.O., eds., The Monterey Formation and related siliceous rocks of California: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 285-315.

Schopf, J.M., and Long, W.E., 1966, Coal metamorphism and igneous associations in Antarctica, *in* Given, P.H., ed., Coal science: American Chemical Society, Advances in Chemistry Series, v. 55, p. 156-195.

Simoneit, B.R.T., Brenner, Shmuel, Peters, K.E., and Kaplan, I.R., 1978, Thermal alteration of Cretaceous black shale by basaltic intrusions in the eastern Atlantic: Nature, v. 273, no. 5663, p. 501-504.

———1981, Thermal alteration of Cretaceous black shale by basaltic intrusions in the eastern Atlantic--II: effects on bitumen and kerogen: Geochimica et Cosmochimica Acta, v. 45, p. 1581-1602.

Simoneit, B.R.T., and Kvenvolden, K.A., 1994, Comparison of ^{14}C ages of hydrothermal petroleums: Organic Geochemistry, v. 21, no. 5, p. 525-529.

Stanley, R.G., 1987, Effects of weathering on petroleum-source evaluation of coals from the Suntrana Formation near Healy, Alaska, *in* Hamilton, T.D., and Galloway, J.P., eds., Geologic studies in Alaska by the U.S. Geological Survey during 1986: U.S. Geological Survey Circular 998, p. 99-103.

Stanley, R.G., Johnson, S.Y., Cole, R.B., Mason, M.A., Swisher, C.C., III, Cotton Thornton, M.L., Filewicz, M.V., Vork, D.R., Tuttle, M.L., and Obradovich, J.D., 1992a, Origin of the Santa Maria basin, California [abs.], *in* Carter, L.M.H., ed., USGS Research on Energy Resources--1992 Program and Abstracts, Eighth V.E. McKelvey Forum on Mineral and Energy Resources: U.S. Geological Survey Circular 1074, p. 73.

Stanley, R.G., Johnson, S.Y., Obradovich, J.D., Tuttle, M.L., Cotton Thornton, M.L., Vork, D.R., Filewicz, M.V., Mason, M.A., and Swisher, C.C., III, 1990, Age, facies, and depositional environments of the lower Miocene Lospe Formation, Santa Maria basin, central California [abs.], *in* Carter, L.M.H., ed., USGS Research on Energy Resources--1990 Program and Abstracts, Sixth V.E. McKelvey Forum on Mineral and Energy Resources: U.S. Geological Survey Circular 1060, p. 78-79.

Stanley, R.G., Johnson, S.Y., Tuttle, M.L., Mason, M.A., Swisher, C.C., III, Cotton Thornton, M.L., Vork, D.R., Filewicz, M.V., Cole, R.B., and Obradovich, J.D., 1991, Age, correlation, and origin of the type Lospe Formation (lower Miocene), Santa Maria basin, central California [abs.]: American Association of Petroleum Geologists Bulletin, v. 75, no. 2, p. 382.

Stanley, R.G., Valin, Z.C., and Pawlewicz, M.J., 1992b, Rock-Eval pyrolysis and vitrinite reflectance results from outcrop samples of the Rincon Shale (lower Miocene) collected at the Tajiguas Landfill, Santa Barbara County, California: U.S. Geological Survey Open-File Report 92-571, 27 p.

Stanley, R.G., Valin, Z.C., and Pawlewicz, M.J., 1993, Rock-Eval pyrolysis and vitrinite reflectance results from lower Miocene strata in the onshore Santa Maria basin and Santa Barbara coastal area, California [abs.]: American Association of Petroleum Geologists Bulletin, v. 77, no. 4, p. 716-717.

Summer, N.S., and Verosub, K.L., 1992, Diagenesis and organic maturation of sedimentary rocks under volcanic strata, Oregon: American Association of Petroleum Geologists Bulletin, v. 76, no. 8, p. 1190-1199.

Surdam, R.C., and Stanley, K.O., 1984, Diagenesis and migration of hydrocarbons in the Monterey Formation, Pismo syncline, California, *in* Surdam, R.C., ed., Stratigraphic, tectonic, thermal, and diagenetic histories of the Monterey Formation, Pismo and Huasna basin, California: Society of Economic Paleontologists and Mineralogists, Guidebook No. 2, p. 84-94.

Sylvester, A.G., and Darrow, A.C., 1979, Structure and neotectonics of the western Santa Ynez fault system in southern California: Tectonophysics, v. 52, p. 389-405.

Taylor, J.C., 1976, Geologic appraisal of the petroleum potential of offshore southern California: the borderland compared to onshore coastal basins: U.S. Geological Survey Circular 730, 43 p.

Tissot, B.P., and Welte, D.H., 1984, Petroleum formation and occurrence [2d ed.]: Berlin, Springer-Verlag, 699 p.

Tolman, C.F., 1927, Biogenesis of hydrocarbons by diatoms: Economic Geology, v. 22, no. 5, p. 454-474.

Turner, D.L., 1970, Potassium-argon dating of Pacific coast Miocene foraminiferal stages, *in* Bandy, O.L., ed., Radiometric dating and paleontologic zonation: Geological Society of America Special Paper 124, p. 91-129.

Vedder, J.G., Howell, D.G., McLean, Hugh, and Wiley, T.J., 1988, Geologic map of Los Machos Hills and Caldwell Mesa quadrangles and part of Tar Spring Ridge quadrangle, California: U.S. Geological Survey Open-File Report 88-253, scale 1:24,000.

Waples, D.W., 1985, Geochemistry in petroleum exploration: Boston, International Human Resources Development Corporation, 232 p.

Williams, C.F., Galanis, S.P., Jr., Grubb, F.V., and Moses, T.H., Jr., 1994, The thermal regime of Santa Maria province, California: U.S. Geological Survey Bulletin 1995-F, p. F1-F25.

Wissler, S.G., and Dreyer, F.E., 1943, Correlation of the oil fields of the Santa Maria district, *in* Jenkins, O.P., ed., Geologic formations and economic development of the oil and gas fields of California: California Division of Mines Bulletin 118, p. 235-238.

Woodring, W.P., and Bramlette, M.N, 1950, Geology and paleontology of the Santa Maria district, California: U.S. Geological Survey Professional Paper 222, 185 p.

Woodring, W.P., Bramlette, M.N., and Lohman, K.E., 1943, Stratigraphy and paleontology of Santa Maria district, California: American Association of Petroleum Geologists Bulletin, v. 27, no. 10, p. 1335-1360.