Characterization of Northern California Petroleum by stable carbon isotopes
[paper edition]

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Introduction

The purpose of this study is to characterize natural occurrences of petroleum at the surface and in the subsurface within northern California in order to define and map petroleum systems for U.S. Geological Survey energy resource assessments. Furthermore, the chemical characterization and mapping of natural petroleum occurrences could also be used to discriminate natural occurrences from accidental oil spills during the activities of extraction or transportation of petroleum. Samples include petroleum from exploratory well tests, producing fields, natural seeps, and oil-stained rocks, and condensates from gas wells. Most of the sample localities are in northern California but a few samples from central and southern California are included for comparison (table 1). Even though other analyses were performed, only stable carbon isotope ($\delta^{13}C$) data are presented here for brevity and because $\delta^{13}C$ values are one of the most discriminating characteristics of California petroleum.

Magoon and others (1995) identified four hydrocarbon types in northern California based on stable carbon isotopic compositions of 16 oil and 6 condensate samples (figure 1). Stanley and others (1996) presented additional data and focused on the oil types found in the San Francisco Bay area of northern California. Lillis and Stanley (1999) identified three oil types (two Miocene and one Eocene) in the La Honda basin (northern California) and presented oil-source rock correlations for each oil type. This report redefines and subdivides the petroleum types based on the isotope data from these studies as well as from new data.

Methods

For oil-stained rocks, the oil was extracted from the rock sample by soaking the sample in chloroform for about one hour at room temperature. Filtered extracts were vacuum evaporated to about 3 milliliters (ml) using a rotary evaporator with moderate vacuum and water bath temperature of about 35° C, and transferred to a volumetric flask for a gravimetric determination of concentration. An aliquot of known concentration was placed in a vial and the volume was reduced to approximately 1 ml in a stream of nitrogen gas at room temperature. About 2 ml of iso-octane was added and mixed with a vortex mixer on low speed, and gently evaporated in a stream of nitrogen gas to about 1 ml. The iso-octane addition and evaporation step was repeated at least three times until the chloroform was completely displaced by iso-octane precipitating the asphaltene fraction of the oil out of solution. The asphaltenes were removed by filtration and the remaining solution (maltene fraction) was gently evaporated in a stream of nitrogen to about 1 ml in preparation for column chromatography.

For petroleum samples, about 50 milligrams of oil sample was mixed with about 2 milliliters (ml) iso-octane (1:40 weight/volume ratio) with a vortex mixer on low speed. The asphaltene fraction of the oil precipitated out of solution and was removed by filtration. The maltene fraction (prepared from both oil-stained rocks and from petroleum samples) was separated into saturated hydrocarbon, aromatic hydrocarbon, and resin fractions by column chromatography using alumina/silica columns and elution solvents of increasing polarity (iso-octane, benzene, and benzene-methanol). Elution solvents and light hydrocarbons (less than C_{15}) were removed from each fraction by evaporation using a nitrogen gas stream under a fume hood or a rotary vacuum evaporator.

Stable carbon isotope ratios were determined for the C_{15}+ saturated and aromatic hydrocarbon fractions, and in a few cases, the entire oil sample. Two methods were utilized that are believed to have comparable results. Prior to 1997 all isotope measurements were determined by placing an aliquot of each sample in a quartz tube with cupric oxide and a silver strip. The tubes were sealed under a vacuum and combusted at 840°C for 4 hours. The evolved CO_2 was collected in a liquid nitrogen trap, and further purification and dehydration of the gas was accomplished by cryogenic distillation under vacuum. Carbon isotope ratios of the CO_2 were measured on a Finnigan MAT 251 dual-inlet isotope ratio mass spectrometer. During 1997 a change in instrumentation occurred and during the transition both old and new methods were used. After 1997 all samples were analyzed with a Carlo Erba elemental analyzer (EA) interfaced with a Micromass Optima continuous-flow isotope ratio mass spectrometer (IRMS). Sample aliquots were heated to approximately 1800°C in the EA quartz combustion tube filled with oxygen. The evolved CO_2 passed through chromium oxide (to complete oxidation), copper granules (reducing agent), and anhydrone (to remove water) before being swept into the IRMS with a helium carrier gas. The results are expressed in the delta (δ) notation that represents the deviation of the $^{13}C/^{12}C$ ratio in parts per thousand (per mil, or ‰) relative to the Peedee belemnite (PDB) standard.

Results and Discussion

Results of the stable carbon isotopic analyses ($\delta^{13}C$) are listed on table 1 and shown on figure 2 along with a line proposed by Sofer (1984) that separates waxy oils from non-waxy oils. Waxy oils are usually derived from terrigenous organic matter, whereas non-waxy oils are usually derived from marine organic matter. Nearly all of the samples plot on the marine side of the Sofer line (figure 2). Polygonal boundaries that are roughly parallel to the Sofer line trend are placed around data groups (table 2). Unclassified samples are individually labeled on figure 2.

Classification of condensate samples into oil types using the $\delta^{13}C$ values of the C_{15}+ hydrocarbon fractions is problematic for two reasons. First, condensates are predominately composed of volatile hydrocarbons and the C_{15}+ fraction of the saturated and aromatic hydrocarbons constitutes only a small weight percentage of the total sample. Thus, the C_{15}+ stable carbon isotope values of condensates are not as representative as are the values for normal crude oil. Second, the saturate/aromatic hydrocarbon ratio is usually so high (greater than 10) that the C_{15}+ aromatic fraction weight is too small to measure the $\delta^{13}C$ value. In many cases, column chromatography was not performed and the isotope measurement was made on the C_{15} + whole oil. In addition to these methodology problems, there is some question as to whether condensates should be compared with crude oils; that is, condensates are not crude oils but rather are the minor liquid fraction that condenses out of gas during natural gas production. For these reasons, the condensates are classified as separate groups.

Cretaceous (K) Oil Group

K1 Subgroup

The K1 samples were collected from the Wilbur Springs area east of Clear Lake and include several oil seeps and an oil sample from an exploratory well. Although the source is unknown, K1 oils are speculated to be derived from Cretaceous source rocks based on the age of the rocks in which the oil is found (Early Cretaceous). Furthermore, Peabody (1990) found that petroleum from the Wilbur Springs quicksilver district has a chemical composition compatible with the Tithonian to Valanginian Stony Creek Formation as their primary source. Magoon and others (1995, 1996) considered oil samples from the Arbuckle and Bunker gas fields (Oils 26-28, table 1) to be part of this group, but are here classified with K4 oils discussed below. The

McLaughlin Mine (Oil 103) and Rathbun (Oil 105) seeps are isotopically heavier than the other K1 seeps, possibly due to mixing of Miocene with Cretaceous sources.

K2 Subgroup

Many of the mercury deposits of the California Coast Ranges have small quantities of oil, solid bitumen, and hydrocarbon minerals that are genetically associated with the mercury ore (Bailey, 1959; Peabody, 1990, 1993; Peabody and Einaudi, 1992). The K2 samples are oils genetically associated with mercury deposits and have an isotopic composition similar to the other Cretaceous oils. However, three samples associated with mercury ore are isotopically distinct from the K2 subgroup: (1) the oil in vugs of the mercury ore from the Mirabel Mine (Oil 107), (2) the curtisite sample (a hydrocarbon mineral) from the Mirabel Mine (Oil 108), and (3) an oil-coated silica gel in mercury-bearing silica-carbonate rock from near the Helen mine (Oil 109).

K3 and K4 Subgroups

The K3 and K4 samples are liquid hydrocarbons produced from gas fields along the west side of the Sacramento basin. The K3 samples are clear to straw-yellow liquids with insufficient C_{15}+ aromatic hydrocarbons to measure $\delta^{13}C$ values, whereas the K4 samples are yellow, red, and brown liquids and have measurable $\delta^{13}C$ aromatic hydrocarbon values. All of K3 and some of K4 samples are assumed to be condensates based on their light color, high saturated/aromatic hydrocarbon ratio (greater than 10) and their origin from gas fields. The K4 samples from Arbuckle, Bunker, and Winters gas fields have a darker color and lower saturated/aromatic hydrocarbon ratio (less than 8) and are reported to be oils; the Winters gas field has had minor oil production (California Division of Oil and Gas, 1983). The K3 and K4 samples are speculated to be derived from Cretaceous source rocks based on their intimate association with natural gas accumulations that, in turn, are believed to be derived from Cretaceous source rocks (Magoon and others, 1994). Although K4 and K1 samples have similar isotopic compositions, they are considered separate groups because K4 samples have an association with gas production. Sherman Island (Oil 106) and Concord (Oil 101) gas field condensate samples are located in the same area (west side of Sacramento basin) as the K3 and K4 samples, but are isotopically distinct possibly due to mixing of Eocene and Cretaceous sources.

Eocene Oil Group

The Eocene oil group includes crude oil samples from three northern California oil fields: Brentwood, Livermore, and Oil Creek. Several oils analyzed from central and southern California fall into the Eocene group, including samples from Coalinga, North Antelope Hills, and Antelope Hills oil fields. These oils are believed to be derived from Eocene source rocks based on similar isotopic composition with other proposed Eocene oils in California (Sofer, 1984; Kornacki and McNeil, 1996) and based on oil-source rock correlation studies (Peters and others, 1994; Lillis and Stanley, 1999). The produced oil from Cymric field (Oil 102) is probably a mixture of Eocene and Miocene oils based on correlations of other Cymric oils to either Eocene or Miocene sources (Peters and others, 1994).

Miocene Oil Group

M1 Subgroup

The M1 oil group consists of four crude oils from the Half Moon Bay field, San Mateo County. Lillis and Stanley (1999) show that the source of these oils is the lower Miocene Lambert Shale, and that these oils are isotopically heavier than oils derived from middle and upper Miocene source rocks. Similarly, oils from lower Miocene source rocks in central

California are isotopically heavier than the middle and upper Miocene Monterey oils (Kornacki, 1988; Lillis, 1988; Lillis, 1994; Peters and others, 1994; Kornacki, 1996).

M2 Subgroup

The M2 oil group includes oil seeps and stains from Marin, Mendocino, Santa Cruz and San Mateo Counties and most of the northern California oil field samples including Petrolia, Petaluma, Pinole Point, La Honda, South La Honda and Sargent fields (table 1). Nearly all oils analyzed from central and southern California oil fields fall into the M2 group, including South Belridge, Edison, Hollister, King City, San Ardo, Kern Front, and portions of Antelope Hills. Magoon and others (1995) defined the Miocene oil group boundaries with saturated hydrocarbons being -22.9 ± 0.6‰ and the aromatic hydrocarbons being -22.1 ± 0.5‰ (figure 1). We redefine the boundaries as shown on figure 2 and listed in table 2. These oils are likely derived from middle and upper Miocene marine source rocks (mostly Monterey Formation but also including some other units) based on similar isotopic composition with other Miocene oils in California (Magoon and Isaacs, 1983; Sofer, 1984; Crain and others, 1985; Curiale and others, 1985; Orr, 1986; Zumberge, 1987; Kornacki, 1988; Lillis, 1988; Lundell and Gordon, 1988; Sofer, 1988; Jeffrey, and others, 1991; Lillis, 1994; Peters and others, 1994; Kornacki, 1996).

M3 Subgroup

Two condensate samples from the Tompkins Hill gas field are classified as a separate subgroup (M3) because of their distinct isotopic composition, although we consider them to be genetically related to the Petrolia oils (subgroup M2). We speculate that the Tompkins Hill condensate $\delta^{13}C$ saturated hydrocarbon values are lower (isotopically lighter) because the source rock has higher amounts of Miocene vascular plants and/or pre-Miocene organic matter. However, the $\delta^{13}C$ aromatic hydrocarbon values may be lower due to low sample weights. The composition of the oil from Table Bluff gas field (Oil 110) is suspiciously different from the Tompkins Hill condensates although both fields share the same stratigraphy and producing formation and are in close proximity (less than 5 miles). The Table Bluff sample was donated from the Chevron oil collection and we speculate that the sample may be mislabeled.

M4 Subgroup

The M4 samples are mudstones and sandstones with a kerosene odor (the so-called "stink muds") exposed in the sea cliffs in the False Cape and Bear River areas of Humboldt County. Gas chromatography and $\delta^{13}C$ hydrocarbon data suggest that these oils are genetically related to the Tompkins Hill (M3) and Petrolia oils (M2). However, most of these samples plot farther from the Sofer line than the other Miocene oils. This shift is possibly due to low aromatic hydrocarbon sample weights that may yield lower the $\delta^{13}C$ aromatic hydrocarbon values. Because these “stink muds” are an unusual sample type and have slightly different isotopic characteristics, they are excluded from the Miocene boundary box. Sample 104 is compositionally distinct from all other oil-stained rocks collected in Humboldt County (M4 oils), and may be derived from sources older than Miocene.

Conclusions

Naturally occurring petroleum in northern California can be classified into Cretaceous, Eocene, or Miocene oil groups based on $\delta^{13}C$ hydrocarbon composition. Cretaceous subgroups include oil seeps from the Wilbur Springs area (K1), oil associated with mercury deposits (K2), and condensates and oils associated with natural gas production (K3 and K4). Miocene subgroups include lower Miocene oils (M1), middle and upper Miocene oils (M2), Tompkins Hill condensate (M3), and Humboldt County oil seeps (M4).

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Table 1. Stable carbon isotope composition of crude oils, oil seeps and oil-stained rocks from northern and central California

Group	Oil#	Field (Area)	Sample Identification	API Number	Comments[a]	Latitude[b]	Longitude[b]	SecTwnRng[c]	County	Depth or Elev[d]	Producing Formation/Zone	Formation Age	$\delta^{13}C$ Sats[e]	$\delta^{13}C$ Arom[e]	$\delta^{13}C$ Oil-T[e]	$\delta^{13}C$ Oil-W[e]	Sample Donator	Information Source[f]
K1	1	seep - Culver Ranch	Culver Ranch AJ-0997		Heavily biodegraded.	39.05149	-122.40040	22-14N-5W	Colusa			Lower Cretaceous	-25.85	-24.87			Elison & Mackevett	LL-5
K1	2	seep - Gibson Gusher	Gibson Gusher 2		Heavily biodegraded.	39.05231	-122.41023	21-14N-5W	Colusa		Knoxville	Lower Cretaceous	-26.31	-24.57			Reynolds, Sarge	LL-5, Fm-7, Age-7
K1	3	seep - Gibson Gusher	Gibson Gusher AJ-0996		Severely biodegraded.	39.05231	-122.41023	21-14N-5W	Colusa		Knoxville	Lower Cretaceous	-26.33	-24.58			Elison & Mackevett	LL-5, Fm-7, Age-7
K1	4	seep - Salt Creek	Salt Creek AJ-0999		Heavily biodegraded.	39.10261	-122.33649	31-15N-4W	Colusa			Upper Cretaceous	-26.99	-26.05			Elison & Mackevett	LL-5
K1	5	seep - Thompson	Thompson Seep AJ-0995		Heavily biodegraded.	39.15731	-122.34898	7-15N-4W	Colusa				-26.47	-25.56			Elison & Mackevett	LL-5
K1	6	seep - Thompson	Thompson Seep 2		Heavily biodegraded.	39.15731	-122.34898	7-15N-4W	Colusa				-26.62	-25.64			Reynolds, Sarge	LL-5
K1	7	wildcat well	Amalgamated 1	04011002530000	Drill stem test. Aromatics degraded.	39.03119	-122.40415	27-14N-5W	Colusa		Knoxville	Lower Cretaceous	-26.96	-25.78			Reynolds, Sarge	LL-2
K1	8	wildcat well	Amalgamated AJ-0998	04011002530000	Drill stem test. Aromatics degraded.	39.03119	-122.40415	27-14N-5W	Colusa		Knoxville	Lower Cretaceous	-26.85	-25.74			Elison & Mackevett	LL-2
K2	9	seep - Abbott Mine	Abbott Seep		Severely biodegraded.	39.02015	-122.44482	32-14N-5W	Lake				-26.81	-25.24			Reynolds, Sarge	LL-5
K2	10	stain - Contact mine	Contact mine		Oil extract from silica carbonate Hg ore.	38.75917	-122.76333	5-10N-8W	Sonoma	Elev. 2920			-27.21	-24.22			Lillis & others (USGS)	LL-5
K2	11	stain - Culver Baer mine	Culver Baer mine		Oil-filled vugs in silica carbonate Hg ore.	38.78069	-122.81883	24-11N-9W	Sonoma				-26.70	-24.02			Lillis & others (USGS)	LL-5
K2	12	stain - Helen mine	Helen mine		Oil extract in silica carbonate Hg ore.	38.74111	-122.69944	1-10N-8W	Lake	Elev. 2640			-26.22	nd			Lillis & others (USGS)	LL-5
K2	13	stain - New Almaden Mine	New Almaden Mine		Oil extract from mecury mine ore.	37.18083	-121.84389	3-9S-1E	Santa Clara		Franciscan	Jurassic-Cretaceous	-26.58	-24.34		-24.70	Stanley, Rick (USGS)	LL-5
K3	14	Dutch Slough (Bethel Island)	TransAmer. Development 3	04013001000101	Condensate.	38.00806	-121.64919	21-2N-3E	Contra Costa	7520-7580	Martinez/First Massive sand	Paleocene	nd	nd	-25.84	-25.15	Reed, Gary (Amer.Expl.Co)	LL-2
K3	15	Knightsen	Cecchini 1-32, RD 2	04013203140000	Condensate. Deep pool S. of Dutch Slough field.	37.97117	-121.67057	32-2N-3E	Contra Costa	8767-8873	Mokelumne River/3rd Massive	Upper Cretaceous	nd	nd	-26.76		Hector, Scott (Baker Oil & Gas)	LL-2
K3	16	Lindsey Slough	Kroutch 16-1	04095209310000	Condensate.	38.18652	-121.75010	16-4N-2E	Solano	5736-5752	Capay/Margaret Hamilton sand	Eocene	nd	nd	-26.29		Hector, Scott (Baker Oil & Gas)	LL-1
K3	17	Maine Prairie	Liberty Farms 1	04095201290000	Condensate.	38.29078	-121.71157	11-5N-2E	Solano	6163-6165	H&T sand	Upper Cretaceous	-27.00	nd			Chevron	LL-2, STR-2
K3	18	Maine Prairie	WZU 3 (Edward Wineman 2)	04095001560001	Condensate. Moderately degraded.	38.33738	-121.73071	27-6N-2E	Solano	4755-4795	Basal Capay	Eocene	-25.76	nd			Chevron	LL-2, API-2, STR-2
K3	19	Pleasant Creek	Shell-Pleasant Creek Unit 5-1	04113000650000	Condensate. Moderately degraded.	38.54603	-122.00356	17-8N-1W	Yolo				-25.28	nd			Chevron	LL-2, API-2, STR-2, SmID 2
K3	20	Rio Vista (East Midland)	RVGU 12	04067000490000	Moderately degraded condensate. Formerly Brannon Island 3.	38.14835	-121.64501	33-4N-3E	Sacramento	4450-4495	Mokelumne River/Midland sand	Upper Cretaceous	nd	nd	-25.90	-25.38	Amerada Hess	LL-2
K3	21	Rio Vista (East Midland)	RVGU 137	04067000640000	Condensate. Well formerly Kuhn Community 3.	38.12064	-121.66852	8-3N-3E	Sacramento	5290-5390	Capay/Margaret Hamilton sand	Eocene	nd	nd	-26.27	-26.07	Amerada Hess	LL-2
K3	22	Rio Vista (West Midland)	RVGU 158 (2 Twitchell Fee)	04067001060000	Condensate. Mildly degraded.	38.10930	-121.66224	17-3N-3E	Sacramento	5049-5115	Capay/Margaret Hamilton sand	Eocene	-26.30	nd			Amerada Hess	LL-2
K3	23	Rio Vista (West Midland)	Trigueiro 4	04095208620000	Condensate.	38.16744	-121.70349	25-4N-2E	Solano	9562-9638	Mokelumne River/Peterson	Upper Cretaceous	nd	nd	-26.07	-26.02	Amerada Hess	LL-1
K3	24	Suisun Bay	Suisun Community 7	04095004080000	Condensate.	38.13972	-121.99284	5-3N-1W	Solano	4405-4470	Domengine	Eocene	-26.07	nd			Chevron	LL-2, API-2, STR-2
K3	25	W. Thornton-Walnut Grove	Maberto 1	04077002170000	Condensate.	38.22059	-121.44265	4-4N-5E	Sacramento				-26.66	nd			Chevron	LL-2, API-2, STR-2, Field-3
K4	26	Arbuckle	Marsh 1	04011000490000	Heavily biodegraded oil from gas field.	39.00498	-122.08030	4-13N-2W	Colusa	6363-6381	Forbes/ F Zone sand	Cretaceous	-26.94	-25.96			Reynolds, Sarge	LL-2
K4	27	Bunker	O'Keefe 1	04095205810100	Mildy degraded oil from gas field.	38.36390	-121.78449	17-6N-2E	Solano	6702-6718	Mokelumne River	Upper Cretaceous	-25.59	-25.13			Boyd, Richard (Capitol Oil)	LL-2
K4	28	Bunker	O'Keefe 1	04095205810000	Mildly degraded oil from gas field.	38.36390	-121.78449	17-6N-2E	Solano	6700-6730	Mokelumne River/Lower sand	Upper Cretaceous	-26.61	-25.29			MacKevett, Nat	LL-2
K4	29	Kirby Hill	Wagenet 2	04095000780000	Condensate.	38.16997	-121.91100	19-4N-1E	Solano	5398-5650	Martinez	Paleocene	-26.57	-25.42			Chevron	LL-2, STR-2
K4	30	Ryer Island	Ryer 3	04095000300000	Condensate. Mildly degraded.	38.07681	-122.01122	30-3N-1W	Solano	4300-5000	Nortonville/Domengine	Eocene	-26.55	-24.53			Haglund, Dave (Shell)	LL-2
K4	31	Winters	McCune 1	04095207160000	Condensate(?) Mildly degraded.	38.49065	-121.88715	32-8N-1E	Solano	5576-5585	Winters/McCune?	Upper Cretaceous	-26.73	-25.14			Haglund, Dave (Shell)	LL-2
K4	32	Winters	McCune 1	04095207160000	Condensate(?) Mildly degraded.	38.49065	-121.88715	32-8N-1E	Solano	5600-5600	Winters	Upper Cretaceous	-26.44	-25.16			Chevron	LL-2
K4	33	Winters	Winters Unit 4-1 (?)	04095004910000	Condensate. Well ID uncertain. Moderately degraded.	38.53123	-121.89718	19-8N-1E	Solano	4845-4885	Winters/McCune sand	Upper Cretaceous	-26.40	-27.12			Chevron	SampID-4, LL-2, API-2, STR-2,
E	34	Antelope Hills	Hopkins A 56X	04029134410000	Moderately biodegraded.	35.53185	-119.85739	31-27S-20E	Kern	2045-2132	Point of Rocks sandstone	Upper Eocene	-29.20	-28.93			MacKevett, Nat	LL-1
E	35	Antelope Hills	Hopkins A 62X	04029134430000		35.53974	-119.85468	31-27S-20E	Kern	2412-2429	Phacoides sand	Lower Miocene	-29.06	-28.14			MacKevett, Nat	LL-1
E	36	Antelope Hills, North	Fussel Fee 2-14	04030015870000	Moderately biodegraded.	35.57393	-119.90219	14-27S-19E	Kern	1560-1636	Phacoides sand	Lower Miocene	-28.43	-27.75			MacKevett, Nat	LL-1
E	37	Brentwood (East area)	Ginochio 1	04013000750202		37.93694	-121.74488	15-1N-2E	Contra Costa	4100-4200	Mokelumne River/3rd Massive	Upper Cretaceous	-29.40	-27.73			Reed, Gary (Amer.Expl.Co)	LL-2
E	38	Coalinga	Fee 122-13D	04019027420000	Heavily biodegraded. Mixed light saturated hydrocarbons.	36.18475	-120.39792	13-20S-14E	Fresno		Temblor sand	Miocene	-27.85	-27.46			Peters, Ken (Chevron)	LL-2
E	39	Livermore	Nissen 3	04001200120000	Mildly biodegraded.	37.69359	-121.68289	7-3S-3E	Alameda	1410-1420	Cierbo/Greenville sand	Upper Miocene	-28.37	-27.20			Reed, Gary (Amer.Expl.Co)	LL-2
E	40	Livermore	Schenone 1	04001200440000	Mildly biodegraded.	37.69519	-121.68423	6-3S-3E	Alameda	1500-1510	Cierbo/Greenville sand	Upper Miocene	-28.34	-27.21			Reed, Gary (Amer.Expl.Co)	LL-2
E	41	Oil Creek	Costa 7-A	04081200200000		37.23927	-122.16484	14-8S-3W	San Mateo	1940-2040	Butano/Costa	Eocene	-28.71	-27.51			Haglund, Dave (Shell)	LL-2
M1	42	Half Moon Bay (Verde)	Cowell 1 (Wilshire)	04081000080000	Deepest well in field - TD 7982 ft.	37.39722	-122.40471	21-6S-5W	San Mateo	1373-2724	Purisima	Pliocene	-22.80	-21.60			Chevron	LL-2, API-2, DE-3, Fm-3, Age-3
M1	43	Half Moon Bay (Verde)	Cowell Estate 3 (Zia Oil Corp.)	04081200430000	Operator now Midcoast Oil LTD. Partnership.	37.39650	-122.40228	22-6S-5W	San Mateo	1732-2242	Purisima	Pliocene	-22.25	-21.35			Chevron	SampID-4, LL-API-2, DE-3, Fm-3, Age-3
M1	44	Half Moon Bay (Verde)	DeBenedetti 1	04081001620000		37.40156	-122.40795	21-6S-5W	San Mateo	1405-1420	Purisima	Pliocene	-22.11	-21.74			Chevron	LL-2, DE-3, Fm-3, Age-3
M1	45	Half Moon Bay area	Cowell 1 (Mid-St Consolidated)	04081000900000	Northwest of Verde producing area of field.	37.42199	-122.43236	8-6S-5W	San Mateo				-22.49	-21.10			Chevron	SampID-4, LL-API-2,STR-2
M2	46	Antelope Hills	Phippen 18	04029618790000	Moderately biodegraded.	35.51158	-119.84815	8-28S-20E	Kern	2295-2460	Button Bed (IB) sand	Middle Miocene	-22.99	-22.34			MacKevett, Nat	LL-1
M2	47	Belridge, South	Sec 13 88-A	04029297650000	Moderately biodegraded.	35.48505	-119.76203	13-28S-20E	Kern	0-1500	Etchegoin/Gusher	Pliocene	-22.88	-22.22			Peters, Ken (Chevron)	Field-2, LL-1, API-1
M2	48	Edison	Ryan Brown 4B	04029065460000	Heavily biodegraded.	35.37200	-118.86729	28-29S-29E	Kern		Chanac	Pliocene	-23.09	-22.73			Peters, Ken (Chevron)	LL-1, API-1
M2	49	Half Moon Bay (Purisima Ck.)	Layne 2 (John Tedesco)	04081000160000		37.41511	-122.39804	15-6S-5W	San Mateo	710	Purisima	Pliocene	-23.67	-23.08			Haglund, Dave (Shell)	LL-2
M2	50	Hollister- Flint Hills area	Justo 1	04069000500000	Petrolex Inc operator.	36.86477	-121.41718	28-12S-5E	San Benito		Etchegoin (?)	Pliocene (?)	-22.24	-20.63			Chevron	Field-2, LL-2, API-2, STR-2, Fm-7, Age-7
M2	51	Kern Front	Fee 10-11	04029106620000	Heavily biodegraded.	35.45659	-119.04887	27-28S-27E	Kern		Chanac	Pliocene	-23.37	-22.52			Peters, Ken (Chevron)	LL-1, API-1
M2	52	King City	BCB Doud 4-32	04053009970000	Heavily biodegraded.	36.15286	-121.12717	32-20S-8E	Monterey	2000	Monterey/Thorup zone	Miocene	-22.99	-22.43			Abel, Pat (CDOGG)	LL-2
M2	53	La Honda	Lane Union Oil 4	04081000730000	Well name formerly Neaves Union Lane 4.	37.32188	-122.31536	17-7S-4W	San Mateo	1800-2277	Butano/Costa	Eocene	-23.14	-22.19			Chevron	SampID-2, LL-2, DE-3, Fm-3, Age-3
M2	54	La Honda, South	Neaves Union Burns 8	04081000610000	Moderately biodegraded. Producing formation is informal name.	37.30524	-122.29546	21-7S-4W	San Mateo	1358-1468	Burns sand	Lower Miocene	-22.42	-21.86			Haglund, Dave (Shell)	LL-2, Age-7
M2	55	La Honda, South	Neaves-Burns		Well # unknown, location center of sec 21. Heavily biodegraded.	37.3076	-122.3042	21-7S-4W	San Mateo		Burns sand (?)	Lower Miocene (?)	-22.64	-22.49			Chevron	Field-4, LL-5, Fm-3
M2	56	Petaluma	tank battery oil in NE1/4 of sec 30	04097000080000	Specific well unknown, use Petaluma Community 5-2 location.	38.25549	-122.55575	30-5N-6W	Sonoma	920 avg.	Petaluma	Pliocene	-22.96	-22.23			Magoon, Les (USGS)	LL-2
M2	57	Petrolia	Hidden Valley 1	04023200270000	Well shut in.	40.37421	-124.29039	21-1S-2W	Humboldt	1185-1363	Franciscan	Eocene to Cretaceous	-23.51	-22.56			McLaughlin, Robert (USGS)	LL-6
M2	58	Petrolia	Hidden Valley 1	04023200270000	Well shut in.	40.37421	-124.29039	21-1S-2W	Humboldt	1185-1363	Franciscan	Eocene to Cretaceous	-23.30	-23.31			Lillis & others (USGS)	LL-6
M2	59	Petrolia	Shelby Woods 1	04023000970000	Well shut in.	40.37369	-124.28996	21-1S-2W	Humboldt	700-1394	Franciscan	Eocene to Cretaceous	-23.31	-23.28			Lillis & others (USGS)	LL-6
M2	60	Petrolia	Shelby Woods 1	04023000970000	Chevron sample collection.	37.37369	-124.28996	21-1S-2W	Humboldt	1365-1394	Franciscan	Eocene to Cretaceous	-23.31	-23.19			Chevron	SampID-4, LL-6, Fm-7, Age-7
M2	61	Petrolia	Whitchurch 1A	04023200650000	Sample 1 of 3. Well shut in.	40.37596	-124.28962	16-1S-2W	Humboldt	726-760	Franciscan	Eocene to Cretaceous	-23.37	-23.18			Lillis & others (USGS)	LL-6
M2	62	Petrolia	Whitchurch 1A	04023200650000	Sample 3 of 3. Well shut in.	40.37596	-124.28962	16-1S-2W	Humboldt	726-760	Franciscan	Eocene to Cretaceous	-23.27	-23.22			Lillis & others (USGS)	LL-6
M2	63	Pinole Point	Bethlehem 1	04013200430000		37.99988	-122.34032	19-2N-4W	Contra Costa	6400	Neroly/lower zone	Upper Miocene	-22.36	-21.53			Tedesco, Larry (Chevron)	LL-2
M2	64	San Ardo	Alexander 23	04053206600000	Heavily biodegraded.	35.94882	-120.81090	8-23S-11E	Monterey		Monterey/Aurignac sand	Miocene	-23.38	-22.74			Abel, Pat (CDOGG)	LL-2
M2	65	San Ardo	Hambey 46-18	04053001620000	Heavily biodegraded.	35.93439	-120.82957	18-23S-11E	Monterey	2300	Monterey/Lombardi sand	Miocene	-23.40	-22.21			Abel, Pat (CDOGG)	LL-2
M2	66	Sargent	10 (no lease name)	04085000370000	Moderately biodegraded.	36.93113	-121.58987	36-11S-3E	Santa Clara		Etchegoin (?)	Pliocene (?)	-24.26	-23.57			Chevron	LL-2, API-2, Fm-7, Age-7
M2	67	Sargent	Gulf-James W. Rea Jr. et. al. M-1	04085000480001	Well formerly named McMillan M-1. Heavily biodegraded.	36.92974	-121.58526	36-11S-3E	Santa Clara		Etchegoin (?)	Pliocene (?)	-24.52	-23.93			Chevron	LL-2, API-2, STR-2, Fm-7, Age-7
M2	68	Sargent	tank battery oil	04085200330000	Moderately biodegraded. Specific well known, use Sargent #2.	36.92923	-121.58663	36-11S-3E	Santa Clara	600 avg	Etchegoin (?)	Pliocene (?)	-24.10	-23.64			Abel, Pat (CDOGG)	LL-2, SampID-7, DE-7, Fm-7, Age-7
M2	69	seep - Tarwater Creek	Tarwater Creek Seep		Severely biodegraded.	37.26823	-122.23937	6-8S-3W	San Mateo		Purisima	Pliocene	-22.62	-21.88			Magoon & Lorenson (USGS)	LL-5, Fm-8, Age-8
M2	70	stain - Majors Creek	Majors Creek		Oil-stained sandstone. Severely biodegraded.	36.98278	-122.14216	12-11S-3W	Santa Cruz	Elev. 160	Santa Cruz Mudstone	Miocene	-23.30	-22.10			Lillis, Paul (USGS)	LL-5
M2	71	stain - Majors Creek area	98SM-1 Point Quarry		Bituminous sandstone. Projected SecTwnRng.	37.00681	-122.10889	6-11S-2W	Santa Cruz	Elev. 880	Santa Cruz Mudstone	Miocene	-22.77	-22.05			Stanley, Rick (USGS)	LL-5
M2	72	stain - Majors Creek area	98SM-2 Point Quarry		Asphalt in fractured mudstone. Projected SecTwnRng.	37.00681	-122.10889	6-11S-2W	Santa Cruz	Elev. 880	Santa Cruz Mudstone	Miocene	-23.05	-22.06			Stanley, Rick (USGS)	LL-5
M2	73	stain - Majors Creek area	98SM-3 Coast Road		Asphalt in fractured dolomite concretion. Projected SecTwnRng.	36.98417	-122.14750	11-11S-3W	Santa Cruz	Elev. 120	Santa Cruz Mudstone	Miocene	-22.91	-22.69			Stanley, Rick (USGS)	LL-5
M2	74	stain - Majors Creek area	98SM-4 Back Ranch Rd		Bituminous sandstone. Projected SecTwnRng.	36.99042	-122.13722	12-11S-3W	Santa Cruz	Elev. 520	Santa Cruz Mudstone	Miocene	-23.02	-22.09			Stanley, Rick (USGS)	LL-5
M2	75	stain - Majors Creek area	98SM-5 Hwy 1/Back Ranch Rd		Bituminous sandstone. Projected SecTwnRng.	36.98292	-122.14222	12-11S-3W	Santa Cruz	Elev. 160	Santa Cruz Mudstone	Miocene	-22.85	-22.10			Stanley, Rick (USGS)	LL-5
M2	76	stain - Yellow Bank Creek	98SM-6 Yellow Bank Creek		Oil?-stained sandstone. Projected SecTwnRng.	36.99139	-122.16806	10-11S-3W	Santa Cruz	Elev. 20	Santa Cruz Mudstone	Miocene	-24.01	-23.26			Stanley, Rick (USGS)	LL-5
M2	77	stain - Point Arena	Point Arena Cove		Oil-stained sandstone. Severely biodegraded.	38.91639	-123.71139	11-12N-17W	Mendocino	Elev. 25	Point Arena Formation	Miocene	-23.40	-22.70			Stanley, Rick (USGS)	LL-5
M2	78	stain - Point Montara	CS -1		Oil-stained sandstone. Severely biodegraded.	37.53733	-122.51767	33-4S-6W	San Mateo	Elev. 25	marine terrace	Pleistocene	-21.35	-20.57			Stevens, Cal (San Jose State)	LL-5
M2	79	stain - Pt Reyes	PR-1 Palomarin Beach		Sandstone dike, 7cm, visible oil, strong HC odor.	37.92638	-122.73667	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.54	-22.37			Stanley, Rick (USGS)	LL-6
M2	80	stain - Pt Reyes	PR-2 Palomarin Beach		Sandstone dike, 18in , visible oil.	37.92681	-122.73750	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.46	-22.21			Stanley, Rick (USGS)	LL-6
M2	81	stain - Pt Reyes	PR-3 Palomarin Beach		Thin ""braided"" sandstone dike, visible.	37.92694	-122.73806	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.55	-22.29			Stanley, Rick (USGS)	LL-6
M2	82	stain - Pt Reyes	PR-4 Palomarin Beach		Sandstone dike, visible oil, HC odor.	37.92917	-122.74167	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.72	-22.20			Stanley, Rick (USGS)	LL-6
M2	83	stain - Pt Reyes	PR-6 Wildcat Beach		Sandstone sill or bed, visible oil, HC odor.	37.95278	-122.78236	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-23.17	-22.50			Stanley, Rick (USGS)	LL-6
M2	84	stain - Pt Reyes	PR-7 Wildcat Beach		Sandstone sill or bed, visible oil, HC odor.	37.95569	-122.78319	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-23.08	-22.41			Stanley, Rick (USGS)	LL-6
M2	85	stain - Pt Reyes	PR-8 Wildcat Beach		Sandstone sill or bed, visible oil, HC odor.	37.95778	-122.78403	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.90	-22.52			Stanley, Rick (USGS)	LL-6
M2	86	stain - Pt Reyes	PR-9 Wildcat Beach		Sandstone sill or bed with visible oil.	37.96125	-122.78625	##-1N-8W	Marin	Elev. 20	Santa Cruz Mudstone	Miocene	-22.93	-22.20			Stanley, Rick (USGS)	LL-6
M2	87	stain - Pt Reyes	PR-27 Wildcat Beach		Sandstone, oil-stained.	37.97500	-122.79500	36-2N-9W	Marin	Elev. 20	Monterey Formation	Miocene	-23.15	-22.37			Lillis & Stanley (USGS)	LL-5
M2	88	unnamed field	Dr. Peck's well		Production from Dr. Peck's well.Heavily biodegraded.	37.24514	-121.95832	10-8S-1W	Santa Clara	125(?)	Monterey (?)	Miocene	-23.65	-23.14		-23.32	Stanley, Rick (USGS)	LL-5
M2	89	wildcat well	Etter 1	04023000540000		40.24844	-124.13554	36-2S-1W	Humboldt	1800-1900	Franciscan (?)	Eocene to Cretaceous	-23.30	-22.87			Chevron	LL-2, Fm-7, Age-7
M2	90	wildcat well	Pearson USL 1-B	04053211700000	Indian Valley area east of San Ardo field.	36.04636	-120.63676	1-22S-12E	Monterey	1982-1997			-23.82	-23.11			Chevron	LL-2
M3	91	Tompkins Hill	Holmes Eureka 16	04023000450000	Condensate. Aromatic data questionable.	40.63436	-124.16260	22-3N-1W	Humboldt	3908-4422	Rio Dell	Middle Pliocene	-24.06	-24.37			Haglund, Dave (Shell)	LL-2
M3	92	Tompkins Hill	tank battery oil		Condensate, specific well unknown, use sec22 location.	40.63	-124.16	22-3N-1W	Humboldt				-24.28	-24.51			Lorenson, Thomas (USGS)	LL-2
M4	93	seep - Bear River	97PGL-22		Sandstone, oil stained, HC odor.	40.45000	-124.40306	22-1N-3W	Humboldt	Elev. 20			-24.06	-24.50			Lillis & others (USGS)	LL-6
M4	94	seep - Bear River	97PGL-23		Fractured rock, 2 oil stains/seeps about 6 ft apart.	40.44667	-124.40472	27-1N-3W	Humboldt	Elev. 20			-24.76	-23.24			Lillis & others (USGS)	LL-6
M4	95	seep - False Cape	97PGL-10		Limestone, Oil stained vugs, HC odor.	40.50361	-124.38583	3-1N-3W	Humboldt	Elev. 20			-22.36	-22.87			Lillis & others (USGS)	LL-6
M4	96	seep - False Cape	97PGL-7		Sandstone, HC odor.	40.51556	-124.38250	35-2N-3W	Humboldt	Elev. 20			-23.17	-23.42			Lillis & others (USGS)	LL-6
M4	97	seep - False Cape	97PGL-3		Mudstone, HC odor.	40.52444	-124.37611	26-2N-3W	Humboldt	Elev. 20			-24.10	-26.05			Lillis & others (USGS)	LL-6
M4	98	seep - False Cape	97PGL-4		Sandstone, w oil stained veins, HC odor.	40.52144	-124.37909	26-2N-3W	Humboldt	Elev. 20			-23.41	-24.44			Lillis & others (USGS)	LL-6
M4	99	seep - False Cape	97PGL-5		Sandstone, HC odor.	40.51922	-124.38149	26-2N-3W	Humboldt	Elev. 20			-22.72	-24.25			Lillis & others (USGS)	LL-6
M4	100	seep - False Cape	97PGL-6		Sandstone, HC odor.	40.51639	-124.38222	35-2N-3W	Humboldt	Elev. 20			-23.47	-24.36			Lillis & others (USGS)	LL-6
X	101	Concord	Boylan 1	04013000900000	Condensate.	38.00334	-122.02547	24-2N-2W	Contra Costa	2936-3044	F1 zone	Upper Cretaceous	-28.13	-26.00			Chevron	LL-2
X	102	Cymric	Sauer Dough 25	04029746080000		35.38320	-119.68833	23-29S-21E	Kern		Phacoides sand	Miocene	-25.26	-24.07			Peters, Ken (Chevron)	LL-1
X	103	seep - McLaughlin Mine	McLaughlin Gold Mine		Heavily biodegraded. Located in NE NE of sec 1.	38.83556	-122.35974	1-11N-5W	Napa	Elev. 1590	volcanic rock - brecciated zone	Pleistocene	-25.58	-23.91			Enderlin, Dean (Homestake Mine)	LL-5, Comments-4
X	104	seep - Oil Creek north	97PGL-2		Sandstone, black, HC odor.	40.52528	-124.37556	26-2N-3W	Humboldt	Elev. 20			-27.91	-26.82			Lillis & others (USGS)	LL-6
X	105	seep - Rathbun	Rathbun AJ-1000		Severely biodegraded.	39.01970	-122.37758	35-14N-5W	Colusa			Lower Cretaceous	-25.18	-24.07			Elison & Mackevett	LL-5
X	106	Sherman Island	Signal-Upham 1	04067002560000	Condensate.	38.07804	-121.72989	27-3N-2E	Sacramento	6300	Martinez/Anderson	Paleocene	-28.22	-25.56			Haglund, Dave (Shell)	LL-2
X	107	stain - Mirabel mine	Mirabel mine		Oil-filled vugs in silica carbonate Hg ore.	38.69917	-122.59611	23-10N-7W	Lake	Elev. 1360			-24.50	-23.17			Lillis & others (USGS)	LL-5
X	108	stain - Mirabel mine	Mirabel mine curtisite		Curtisite - hydrocarbon mineral.	38.69917	-122.59611	23-10N-7W	Lake	Elev. 1360			nd	nd		-23.13	Lillis & others (USGS)	LL-5
X	109	stain - near Helen mine	unnamed mine "Paul's mine"		Oil-coated gel in silica carbonate Hg ore.	38.73944	-122.69778	1-10N-8W	Lake	Elev. 2640			-25.10	-25.59			Lillis & others (USGS)	LL-5
X	110	Table Bluff (?)	Leon-Oro-Blanco T-1 (?)	04023000190000	Questionable sample identification.	40.66742	-124.21832	6-3N-1W	Humboldt	4800-4810			-25.74	-24.84			Chevron	LL-2
X	111	water well	Granny Creek H2O		Near confluence w/ Mattole River. Possible distillate.	40.26229	-124.19300	28-2S-1W	Humboldt				-27.30	-27.43			Lillis & Lorenson (USGS)	LL-6
X	112	wildcat well (?)	Etter 1 (?)	04023000540000	Questionable sample from Etter's barn. Possible distillate cut.	40.24844	-124.13554	36-2S-1W	Humboldt				-23.51	nd			Mary Etter	SampID-4, LL-2, rest-7

a. Comments by authors. Biodegradation interpretation based on unpublished gas chromatography data:
  Mild = n-alkane concentration low or not detected
  Moderate = acyclic isoprenoid (for example, pristane) concentration low or not detected
  Heavy = aromatic hydrocarbons (for example, dimethyl napthalenes, methyl phenanthrenes) low or not detected
  Severe = hopane and sterane concentration low or not detected
b. Latitude and Longitude values are based on NAD 27 datum.
c. SecTwnRng = Section Township Range
d. Production Depth or Outcrop Elevation in feet.
e. $\delta^{13}C$ Sats = saturated hydrocarbons, Arom = aromatic hydrocarbons, Oil-T = oil topped (C_{15}+), Oil-W = whole oil. Reported per mil PDB.
  nd = not determined due to low concentration
f. The source of sample information is the donator except as noted:

Data Type
LL = latitude and longitude
API = API Number
DE = Depth/Elevation
Fm = Producing Formation/Zone
Age = Formation Age
SampID = Sample Identification
STR = SecTwnRng

Data Source
1 = IHS Energy
2 = California Division of Oil, Gas and Geothermal Resources website ftp://ftp.consrv.ca.gov/pub/oil/maps/
3 = California Division of Oil, Gas and Geothermal Resources records
4 = authors modified donator information
5 = authors calculated LL from topographic map
6 = authors measured LL with GPS receiver
7 = authors
8 = California Division of Oil, Gas and Geothermal Resources TR 26

Table 2. Stable carbon isotope boundaries of petroleum types from northern and central California. Values refer to corners of boxes shown on figure 2.

	$\delta^{13}C$ Sats C_{15}+	$\delta^{13}C$ Arom C_{15}+
Boundary for Cretaceous	-25.70	-24.90
	-26.80	-23.70
	-27.90	-24.90
	-27.00	-26.40
Boundary for Eocene	-27.70	-27.47
	-28.60	-26.46
	-30.00	-28.00
	-29.20	-29.12
Boundary for Miocene	-21.20	-20.60
	-22.00	-20.00
	-24.80	-24.00
	-24.30	-24.70

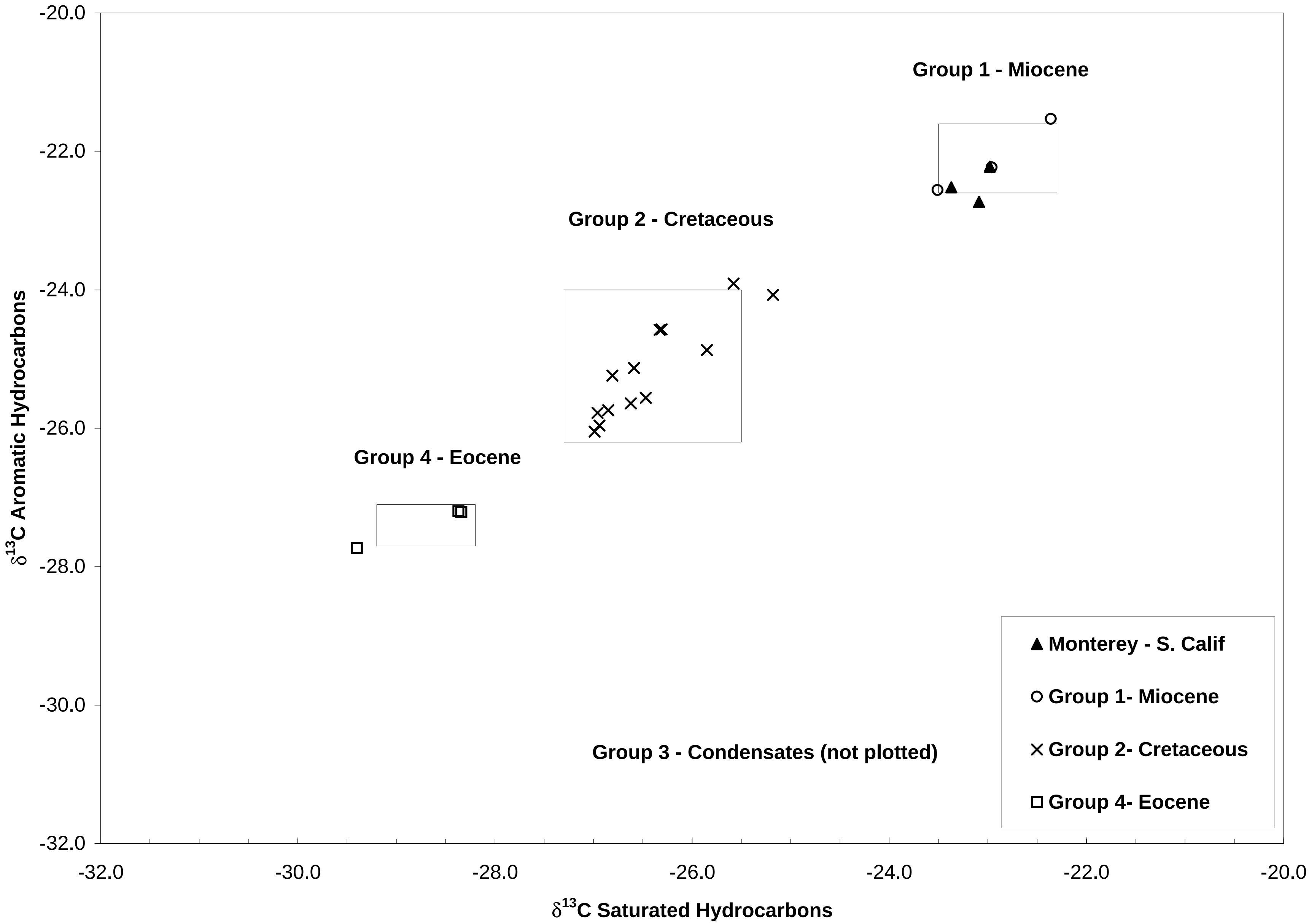

Figure 1. Hydrocarbon types in northern California (after Magoon and others, 1995)

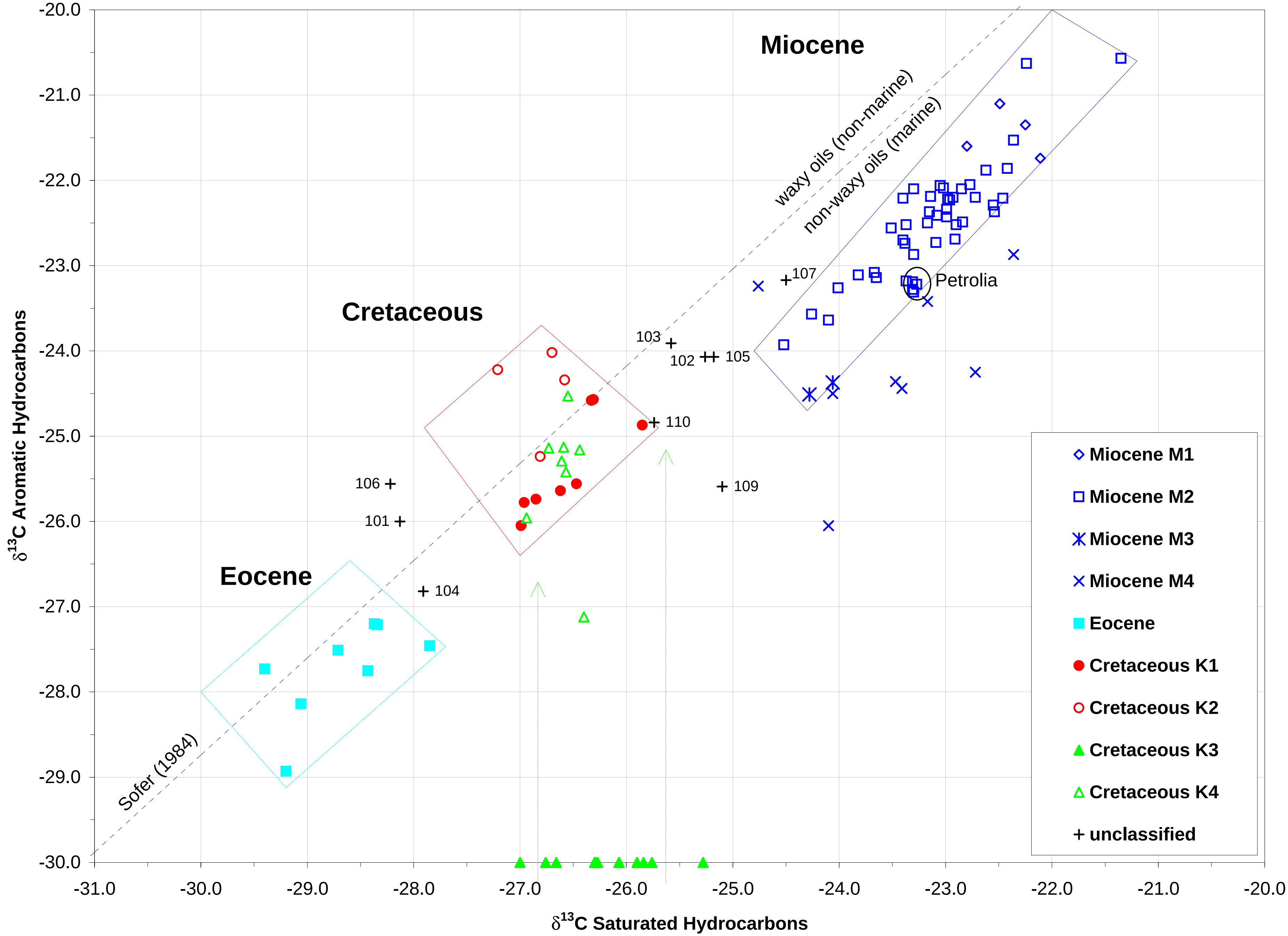

Figure 2. Isotopic composition of oils, oil seeps, and oil stains, northern California. See table 2 for oil boundary coordinates.