Petroleum migration in the Miocene Monterey Formation, California, USA: constraints from fluid-inclusion studies

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Abstract

The Miocene Monterey Formation constitutes a fracture-controlled petroleum reservoir, with intercalated calcareous and fine-grained siliceous rocks serving as both the source and reservoir for oil accumulations. Petroleum is produced from macroscopic fractures, and numerous tar and asphalt seeps at the surface attest to the present-day movement of hydrocarbons through fractures in the Monterey Formation. Many fractures are filled with carbonate (mostly calcite and dolomite), quartz, baryte and anhydrite. These same fractures often contain tar or oil filling openings, and occasionally a thin layer of oil can be seen coating growth surfaces between two generations of vein-filling minerals.

Evidence for migration of fluids through these fractures in the geological past is provided by aqueous and petroleum fluid inclusions contained within vein-filling minerals. Vein-filling dolomite from Jalama Beach contains three different types of primary petroleum inclusions (based on fluorescence characteristics)—indicating that oils with significantly different API gravities flowed through the fractures. Petrographic and microthermometric analyses of oil and coexisting aqueous inclusions indicate that the fracture-filling minerals precipitated from aqueous solutions of seawater salinity at ~75–100 °C, and that oil was introduced into the fracture system episodically during mineral growth. A sample from the Lion's Head area consists of early calcite and late quartz, both of which contain aqueous inclusions with seawater salinity. Inclusions in quartz homogenize at slightly higher temperatures than those in calcite. These data are consistent with calcite deposition during an early heating event, followed by quartz deposition during cooling. No petroleum inclusions were observed in the Lion's Head sample.

KEYWORDS: petroleum, migration, fluid inclusions, Monterey Formation, California.

Introduction

THE Miocene Monterey Formation in the Santa Maria and Santa Barbara–Ventura areas of California, U.S.A., is a major oil reservoir (Fig. 1), with about 2 billion barrels of reserves discovered since 1969 (Isaacs and Petersen, 1987). The Monterey Formation constitutes a fracture-controlled petroleum reservoir, with permeability derived from fractures rather than from matrix porosity (cf. Belfield *et al.*, 1983; La Pointe *et al.*, 1984), and is composed of intercalated calcareous and fine-grained siliceous rocks serving as both the *source* and *reservoir* for oil accumulations. Petroleum is produced from macroscopic fractures, and numerous tar and asphalt seeps at the surface attest to the present-day movement of hydrocarbons through fractures in the Monterey. Reservoir models envisage similar mechanisms of petroleum migration in the present-day subsurface (Pisciotto, 1978; Dunham and Blake, 1987).

In recent years, the use of fluid-inclusion techniques to study mineral diagenesis and petroleum generation and migration in sedimentary basins has become common (Aulstead and Spencer, 1985; Bodnar, 1989; Bone and Russell, 1988; Broomhall and Allan, 1985; Burley *et al.*, 1989; Burruss, 1981, 1985; Burruss *et al.*, 1983; Haszeldine *et al.*, 1984*a*, *b*; Horsfield and McLimans, 1984; Jensenius and Burruss, 1990; Malley *et al.*, 1986; McLimans, 1985; 1987; Narr and Burruss, 1984; O'Hearn and Moore, 1985; Pagel *et al.*, 1986; Roedder, 1979, 1984 [Chapter 11]; Tsui and Jordan, 1985; Visser, 1982). Primary aqueous fluid inclusions in overgrowths on detrital grains,

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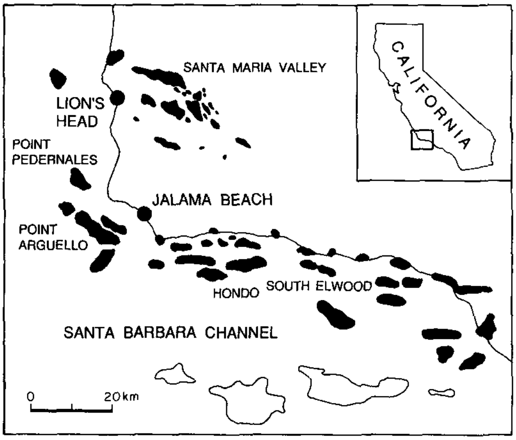


FIG. 1. Oil and gas fields in the Santa Maria and Santa Barbara–Ventura areas, California, and adjacent offshore areas. Also shown are Jalama Beach and Lion's Head sample locations (from Isaacs and Petersen, 1987).

in cements in clastic rocks and in fracture-filling minerals, can provide valuable information on the *P–T* conditions of mineral formation, as well as compositions of diagenetic fluid(s). Furthermore, the presence of hydrocarbon (petroleum) inclusions provides definitive evidence that petroleum has migrated through the rock at some time in the past, and by relating the paragenesis of the oil inclusions to other structural and diagenetic features, the timing of oil migration relative to these events may be determined.

Petroleum generation, maturation and migration history in the Monterey Formation is much more amenable to study using fluid inclusions as compared to most petroleum reservoir environments for several reasons. First, as noted above, the Monterey is a fracture-controlled reservoir. Aqueous fluids migrating through these fractures precipitated various minerals in response to changing physical and chemical conditions, and samples of the aqueous solutions and petroleum that flowed through the fractures were trapped as primary fluid inclusions during crystal growth. The sequential manner in which fractures filled, as described below, and crosscutting relationships of fractures of different ages make determination of the fluid paragenesis relatively simple compared to studies of petroleum reservoirs in which permeability is due to matrix porosity rather than fractures. Thus, fluid evolution associated with petroleum generation and migration in the Monterey Formation may be studied using techniques that have been developed and applied so successfully for many years to define fluid evolution histories of hydrothermal ore deposits. Additionally, fluid inclusions in fracture-filling minerals in the Monterey are very large and abundant, compared to inclusions from other petroleum reservoir environments. Inclusions >50 μm in maximum dimension are not uncommon, and typical inclusions are in the 10–30 μm size range, greatly facilitating microthermometric analysis of these inclusions. Finally, because the Monterey Formation is both the *source* and the *reservoir* for the hydrocarbons, migration distances and the concomitant chemical changes often associated with migration, such as water-washing, oxidation and biodegradation, are expected to be minimal.

In this paper I describe results of a fluid inclusion study of veins from the Jalama Beach and Lion's Head areas (Fig. 1) of the Santa Maria Basin in California. The Jalama Beach sample is a ~1 cm wide dolomite vein contained within massive dolostone. The fracture is associated with tar-bearing, dolomite-cemented breccias which Belfield *et al.* (1983) suggest were generated by high pore (hydrocarbon) fluid pressures which fractured the rocks. The Jalama Beach outcrops are just east of the large offshore Point Arguello oil field (Fig. 1; Crain *et al.*, 1985), and Winter and Knauth (1990) have suggested that fractures in the oil field and in the Jalama Beach area had similar origins and developed at similar temperatures and depths. Thus, studies of the Jalama Beach sample might provide information on the conditions attending hydrocarbon accumulation in the Point Arguello field.

The Lion's Head sample is a ~3 cm wide calcite and quartz vein cutting dolostones, collected approximately 100 yards south of the fault contact between the Monterey Formation and ultramafic crystalline rocks of the Jurassic age Point Sal Ophiolite. Early vein filling is by calcite, followed by quartz. Based on lithology, silica-diagenetic grade (quartz) and structural features, Pisciotto (1978) suggested that the Lion's Head section might be a good analogue for fractured Monterey Formation reservoirs in the subsurface, and recent drilling has confirmed Pisciotto's hypothesis (Dunham and Blake, 1987).

The purpose of this study was to examine fluid inclusion characteristics of these two samples to determine the physical and chemical nature of fluids migrating through the fractures and to begin to develop a temporal and spatial framework for fluid evolution in the Monterey Formation. This study is part of a larger, continuing multi-disciplinary project to study diagenesis in the Monterey Formation in the vicinity of the Santa Maria Basin in California.

Geological setting

The geology of the Monterey Formation, and its relationship to petroleum generation and migration in the Santa Barbara–Santa Maria areas, has been summarized in several recent publications (Isaacs, 1984; Crain *et al.*, 1985; Dunham and Blake, 1987; Isaacs and Petersen, 1987). The following summary of the geology in the vicinity of the Santa Maria Basin is taken from the recent review paper by Isaacs and Petersen (1987).

The Miocene Monterey Formation is lithologically complex and regionally variable, and includes diatomite, diatomaceous shale and mudstone, chert, porcellanite, siliceous mudstone and shale, chalk, marl, phosphatic shale, dolostone, limestone, shale and sandstone. Overall, the rocks are unusually siliceous. The Monterey Formation is thought to have been deposited on the slopes or bottoms of basins associated with an active continental margin, similar to the present Gulf of California. Input of terrigenous material was restricted as a result of tectonic basin formation associated with plate readjustments in the Oligocene and marine transgression during a period of globally elevated sea level.

Most petroleum production in the Santa Maria and Santa Barbara areas is from fractured reservoirs. Only certain fractures are important for hydrocarbon migration, and these fractures occupy very specific temporal and spatial positions with respect to *diagenetic, lithologic* and *structural* characteristics of the Monterey. Thus, fractures formed prior to silica diagenesis do not play a major role in hydrocarbon accumulation. Chert, porcellanite and dolomite are the most intensely fractured lithologies, and only fractures orientated orthogonal to bedding and striking parallel to major folds are important oil conduits (Belfield *et al.*, 1983). It should also be noted that average matrix porosity in Monterey reservoirs is of the order of 10–35% (Isaacs, 1981) and that fracture porosity, which is $\leqslant 3\%$, provides a relatively small contribution to the total reservoir porosity. However, these fractures are important because they connect the pore spaces, and fracture permeabilities can be very high—of the order of 10's of darcys.

Fracture-fillings (veins) in the Monterey Formation generally exhibit features which suggest that, once the fractures opened, they remained open during the entire vein formation history and that there was little or no differential movement along the fracture during vein filling. These conclusions are supported by the observation that vein-filling minerals are almost always symmetrically zoned about the centre of the vein—suggesting that the crystals grew contemporaneously from each wall into the interior of the fracture as shown in Fig. 2. Minor features, such as fluid inclusions (Fig. 2) and solid phases (clay minerals?) outlining growth surfaces on one side of the vein can always be found at the identical stratigraphic position on the opposite side of the vein. Also, the crystals are unbroken and undeformed, which would not be the case if there had been differential movement along the fracture after vein-filling began. Dunham and Blake (1987) have suggested, based on observations of veins in drill core, that fractures were partially to completely filled in the subsurface, and this is supported by isotopic evidence (Winter and Knauth, 1990) which indicates that dolomite veins at Jalama Beach (which are presently at the surface) formed at depths of 800–1635 m below the seafloor.

Fluid inclusions

Methodology. Vein samples from Jalama Beach and Lion's Head were cut and polished on low-speed saws and polishing wheels using water as the lubricant. Doubly-polished sections were examined with a petrographic microscope equipped with both plain white and ultraviolet (UV) light sources. Vertical UV illumination for fluorescence analysis was provided by a high-pressure mercury arc lamp and filters that allowed only the long-wavelength UV (transmission maximum at 366 nm) to reach the sample. The occurrence of aqueous and petroleum-bearing inclusions (as indicated by fluorescence under UV illumination) and their distribution within individual samples and crystals were noted. Microthermometric data were collected using a USGS-type gas-flow heating/cooling stage (Werre *et al.*, 1979) calibrated at $-56.6°$, $0.0°$ and $374\,°C$ using synthetic fluid inclusions (Sterner and Bodnar, 1984). Ice-melting and homogenization temperatures reported below are accurate to at least $\pm 0.1\,°C$ and $\pm 0.5\,°C$ respectively.

Jalama Beach. Petrographic examination of a dolomite-filled fracture collected from Jalama Beach (Fig. 1) reveals the presence of two distinct types of fluid inclusions—aqueous and petroleum-bearing. The aqueous inclusions occur isolated or along growth zones and are undoubtedly primary. At room temperature the inclusions contain an aqueous liquid and a vapour bubble that occupies <10 volume percent of the inclusion (Fig. 3). The second type of inclusion contains a liquid petroleum phase. These inclusions always occur along growth surfaces (Fig. 4) and, in most cases, the growth surface is defined by the presence of the

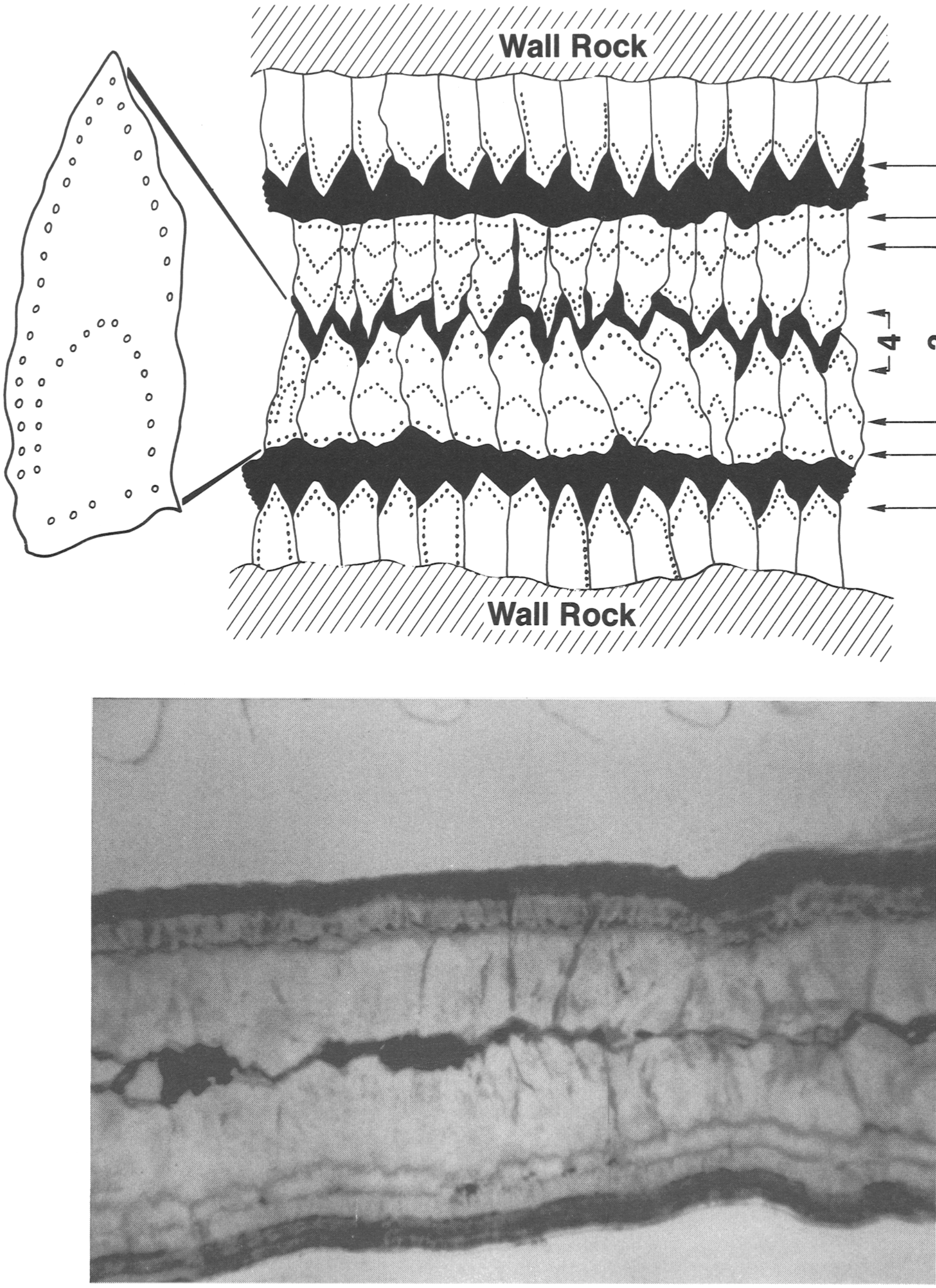


FIG. 2. (Top) Schematic representation of the style of vein-filling in Monterey fractures. Note the symmetry across the vein and unbroken and undeformed nature of crystals. Numbers 1–4 represent four different growth zones outlined by petroleum fluid inclusions, with 1 being earliest and 4 being latest. The different generations of inclusions are symmetrically distributed about the centre of the vein. (Bottom) Photomicrograph of a thin section of a carbonate vein from Jalama Beach. The vein is approximately 1 cm wide.

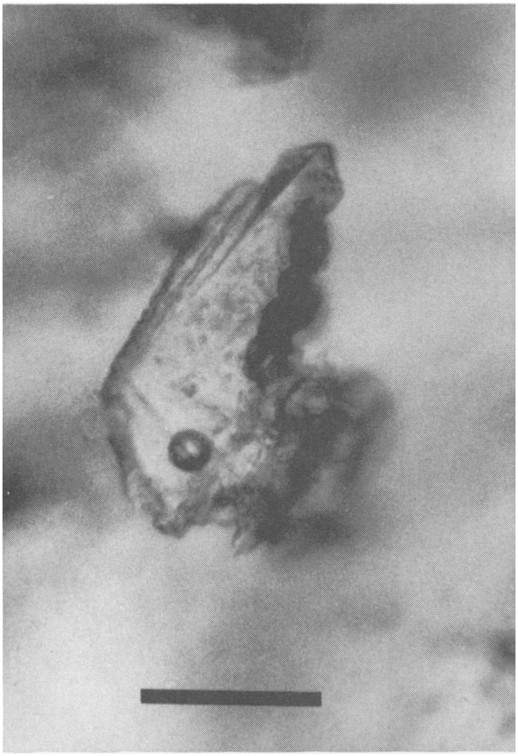


FIG. 3. Aqueous fluid inclusion in dolomite vein from Jalama Beach. Scale bar equals 25 μm.

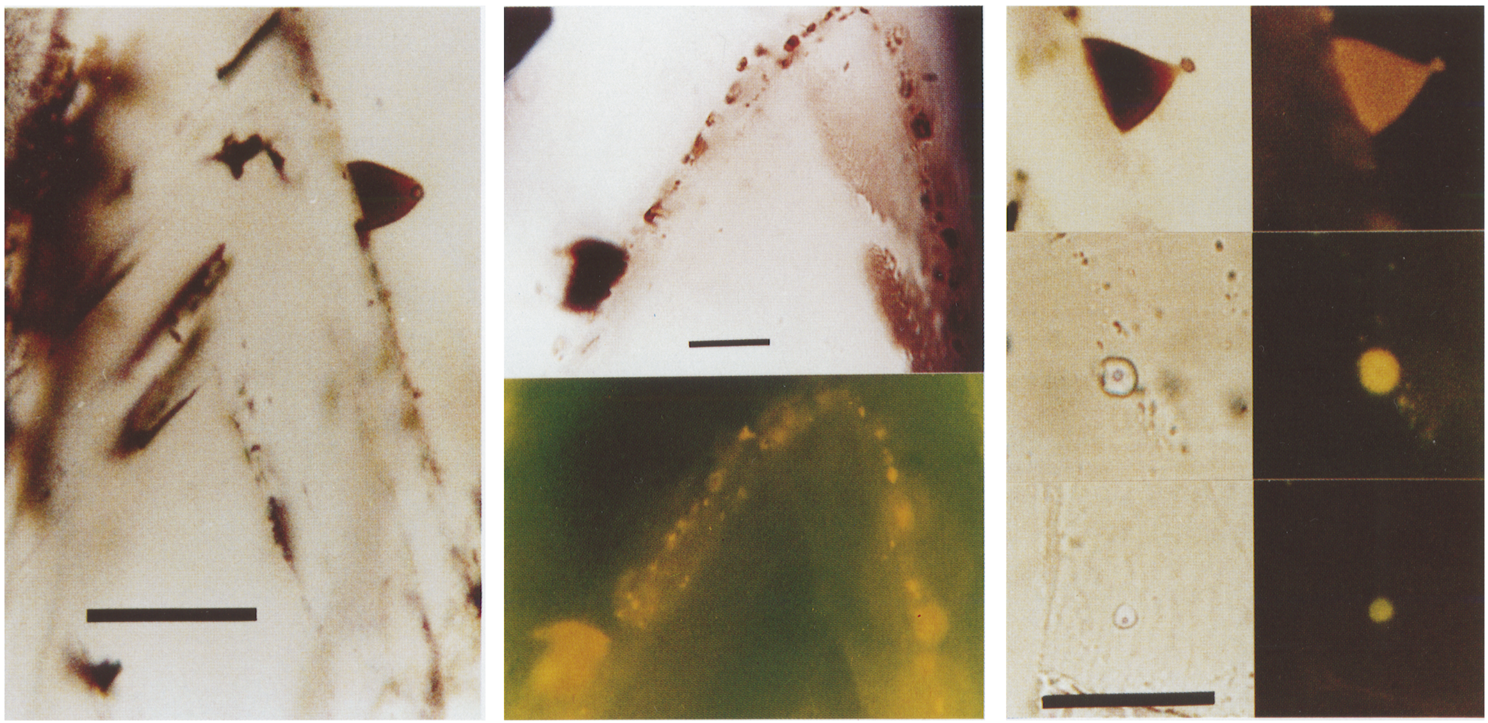
petroleum fluid inclusions (Fig. 5). This type of inclusion may be further subdivided based on optical characteristics under both normal white light and UV illumination. Some of the inclusions appear clear and colourless under white light, while others are dark brown. Under UV illumination, some of the clear inclusions display greenish fluorescence and others fluoresce yellow–gold (Fig. 6). The inclusions that are brown in white light fluoresce a dull brownish-orange under UV illumination (Fig. 6).

The three different sub-types of petroleum inclusions are not randomly distributed in the vein but, rather, occupy distinct zones. Specifically, the inclusions which fluoresce green occur nearest to the vein wall, those that fluoresce yellow–gold occur further out in the vein, and the inclusions that fluoresce brownish-orange occur near the vein centre. This distribution, and the fact that the inclusions are interpreted as being primary, suggests that the composition of petroleum migrating through the fracture was changing with time. Although a variety of changes in the composition of the oils may lead to different fluorescence characteristics, the property most often related to variation in fluorescence color and intensity is API gravity* (Henry and Donovan, 1984; McLimans, 1987). Higher API gravity oils (light oils) fluoresce in the blue end of the spectrum, whereas heavier oils (lower API gravity) fluoresce in the red region (Fig. 7). This suggests that the oils flowing through the fractures at Jalama Beach were becoming progressively heavier (lower API gravity) as the vein formed. Such behaviour may be interpreted in one of two ways. Heavy oils may represent either immature oils, or oils that have experienced considerable water-washing and degradation by bacterial action (see Isaacs and Petersen, 1987, and references therein). The heavier oils occur late in the vein-filling history, and one might, therefore, assume that they represent degraded oils that were transported by, and in contact with, water (causing degradation) longer than oils trapped in the early hydrocarbon inclusions. Note, however, that biological markers (Curiale *et al.*, 1985) and other chemical characteristics (Isaacs and Petersen, 1987) suggest that heavy Monterey oils are immature, and not degraded.

Homogenization temperatures of both aqueous and petroleum fluid inclusions from the Jalama Beach sample are shown in Fig. 8. Aqueous inclusions homogenize to the liquid phase over the range 60–110 °C, with the large majority between 70 and 90 °C. Ice melting temperatures range from -3.0 to -1.6 °C and indicate salinities of 2.7–4.9 wt.% NaCl equivalent, compared to a seawater salinity of ~3.5 wt.%. Petroleum inclusions homogenize to the liquid phase over the range 55–135 °C, with early green-fluorescing inclusions homogenizing at ~55–65 °C, later yellow-fluorescing inclusions homogenizing at ~110–135 °C, and latest orange–brown inclusions homogenizing at ~55–90 °C (Fig. 8).

If it is assumed that the aqueous inclusions and

*The density of a crude oil is often reported in API-degrees (API = American Petroleum Institute) and is referred to as the API gravity of the oil, given by the equation: API gravity [°API] = (141.5/d − 131.5, where d is the density in grams/cm^3 at 60 °F (15.56 °C).



FIGS. 4–6. Fig. 4 (*left*) Large, orange–brown petroleum inclusion trapped on growth surface of carbonate crystal from Jalama Beach. Scale bar equals 25 µm. Fig. 5. (*centre*) Growth surface in carbonate crystal outlined by late, orange–brown petroleum inclusions shown in plain white light (top) and under UV illumination (bottom) showing fluorescence. Scale bar equals 100 µm. Fig. 6 (*right*). Petroleum fluid inclusions as seen under plain white light (left) and under UV illumination (right). All three types of inclusions occur in the same carbonate vein from Jalama Beach. The green-fluorescing inclusion at the bottom occurs closest to the vein wall and is oldest; the orange–brown fluorescing inclusion at top occurs near vein centre and is youngest; the yellow-fluorescing inclusion in middle is of intermediate age. Scale bar equals 25 µm.

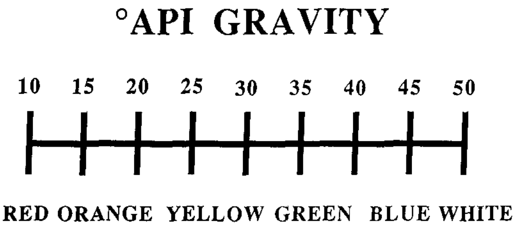


FIG. 7. Relationship between °API gravity and colour of fluorescence under UV illumination for crude oils. Modified from Lang and Gelfand (1985).

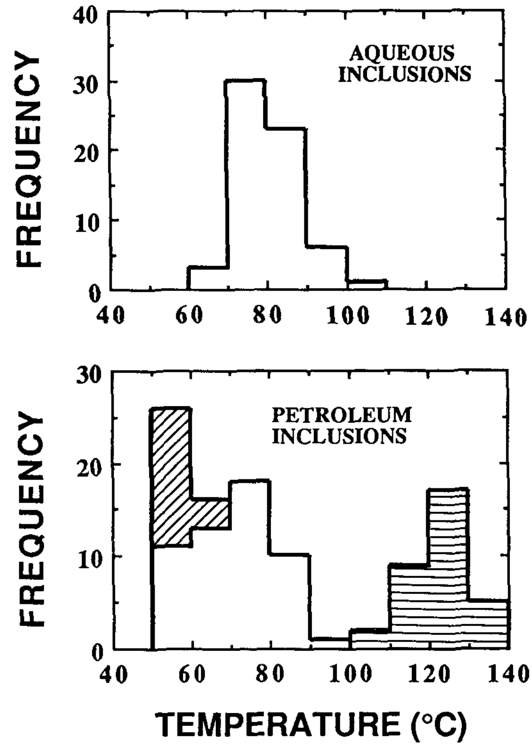


FIG. 8. Histograms of homogenization temperatures of fluid inclusions from a carbonate vein from Jalama Beach. Top histogram represents aqueous inclusions and bottom histogram represents petroleum inclusions. Diagonal pattern indicates early, green-fluorescing petroleum inclusions; intermediate age, yellow-fluorescing inclusions are indicated by horizontal pattern; open pattern indicates late, orange-brown-fluorescing inclusions.

the late, orange-brown petroleum inclusions* were trapped at the same time (i.e. at the same temperature and pressure conditions), and that the water and petroleum are essentially pure phases at these conditions (i.e. their mutual solubilities are low), we may use the intersecting isochore technique (Roedder and Bodnar, 1980) to approximate the trapping conditions. The bubble-point/dew-point curve and isochores for the petroleum inclusions (Fig. 9) were obtained using *PVTX* data for a typical heavy (20.6 °API) Monterey oil calculated using a semi-theoretical equation of state (Peng and Robinson, 1976). Data from Potter and Brown (1977) were used to approximate the isochores for aqueous inclusions (Fig. 9).

Normally, when the intersecting isochore technique is applied to coexisting aqueous and oil inclusions, the isochores intersect at a high angle, owing to the much higher compressibility of the oils as compared to the aqueous phase (e.g. Narr and Burruss, 1984; Aulstead and Spencer, 1985; McLimans, 1987). However, owing to the low API gravity (high density) of typical Monterey oils, the slopes of the isochores in *P–T* space for these oils are very similar to the slopes of the aqueous isochores (Fig. 9). As a result, the isochores do not intersect to define a unique or limited area of *P–T* space in which the inclusions must have been trapped. Rather, the fields defined by the aqueous and petroleum isochores overlap to define a region of *P–T* conditions that extends from the oil bubble-point curve to higher temperatures and pressures. The intersecting isochore technique, therefore, does not provide rigid constraints on the *P–T* conditions of formation of the coexisting inclusions. The minimum temperature and pressure of formation are defined by the region of overlap of the aqueous inclusion isochores and the oil isochores along the Monterey oil bubble-point curve (Fig. 9). That is, the inclusions must have been trapped at pressures equal to or greater than those along the bubble-point curve for the oil. For the inclusions considered here, this represents a temperature range from ~75–100 °C at a pressure of ~200 bars

* Although all three types of petroleum inclusions coexist with the aqueous inclusions, the late orange-brown inclusions were chosen for the calculation because they are by far the most abundant type, outnumbering the other two types combined by at least ten to one. Further, the orange-brown inclusions were the latest to be trapped and are least likely to have experienced any post-trapping compositional or volume changes. Finally, the orange-brown inclusions are thought to most closely approximate the compositions of oils found in active seeps and being produced from the Monterey Formation in this area. Abundant analytical, experimental, and theoretical data on the compositions and properties of these oils are available in the literature, and these data may be used to help constrain trapping conditions of the inclusions.

(Fig. 9). This temperature range is consistent with temperatures obtained from isotopic measurements (53–103 °C; Winter and Knauth, 1989). Further, a pressure of 200 bars would correspond to depths of ~2000 m (assuming hydrostatic conditions with an average fluid density of ~1 g/cm^3). Winter and Knauth (1989) report depths ranging from 800 to 1635 m *below the seafloor* for vein filling at Jalama Beach. Thus, a depth of formation corresponding to 200 bars, i.e. about 2000 m, is consistent with Winter and Knauth's data assuming a water depth of 365–1200 m. Isaacs and Petersen (1987) report that inferred water depths of basins in the Santa Barbara–Ventura area ranged from 50 to >2000 m, so the required water depths (365–1200 m) are considered to be reasonable.

Lion's Head. A second sample collected from Lion's Head (Fig. 1) consists of a ~3 cm thick vein containing early calcite and late quartz filling the vein centre. The majority of the inclusions in calcite occur along growth surfaces and are clearly primary. The remainder of the inclusions in calcite and nearly all inclusions in quartz were not obviously related to any growth feature and are considered of indeterminate origin. Aqueous inclusions in both calcite and quartz from Lion's Head have salinities similar to those from Jalama Beach—i.e. they are essentially of seawater salinity. Homogenization temperatures of inclusions in calcite range from ~50 to 120 °C with the majority between 60 and 110 °C (Fig. 10). Inclusions in quartz homogenize between 70 and 150 °C, with the majority between ~90 and 110 °C (Fig. 10). Petrographic examination of the Lion's Head vein failed to resolve any petroleum fluid inclusions. The lack of petroleum inclusions in the Lion's Head sample suggests that these fractures were not conduits for petroleum migration during fracture filling. The lack of any visible hydrocarbons in these fractures today further indicates that these fractures are not part of the 'production permeability' of the Monterey reservoirs currently being exploited. As noted above, not all fractures in the Monterey are important for petroleum migration—northeasterly striking fractures at high angles to bedding preferentially transport oil (LaPointe *et al.*, 1984). Unfortunately, the structural orientation of the Lion's Head vein studied was not determined when collected, and it can only be assumed that it is not one of the northeasterly striking fractures which contribute to petroleum migration and production in the Monterey Formation today. This assumption is, however, consistent with the fact that little or no tar is observed in open spaces in this and similar veins at Lion's Head and there are few active tar seeps

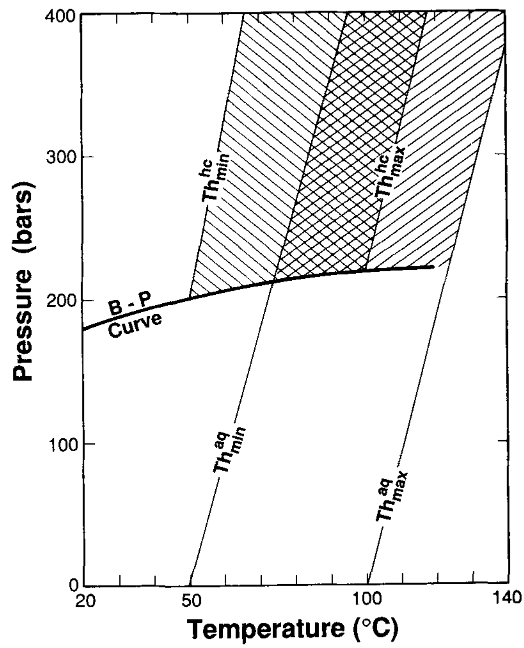


FIG. 9. Pressure–temperature conditions of formation of late, orange–brown fluorescing oil inclusions and coexisting aqueous inclusions defined by the intersection of inclusion isochores. The cross-hatched pattern represents the area of overlap defined by the isochores representing the minimum temperature of homogenization (Th) of the aqueous inclusions and the maximum Th of the oil inclusions.

in the area where the sample was collected, unlike the Jalama Beach locality where active seeps and vugs filled with oil and tar are very common.

The Lion's Head sample described above contains early calcite and later quartz. This paragenetic relationship is ubiquitous in the Monterey Formation when both minerals occur in the same fracture and suggests variations in the chemistry of the fluids during vein filling. Gross chemical characteristics of the aqueous fluid, represented by the ice-melting temperatures and calculated NaCl equivalent salinities, do not reflect this change in fluid chemistry. However, it is obvious that the chemical (or physical) properties must have changed to some extent, because early fluids were in equilibrium with and precipitating calcite, while later fluids were in equilibrium with quartz. The change from carbonate to quartz deposition in the fracture systems might reflect that point in time when the fluids flowing through the fracture reached their thermal maximum and began to cool. Calcite, which exhibits retrograde solubility, would be deposited during heating to the

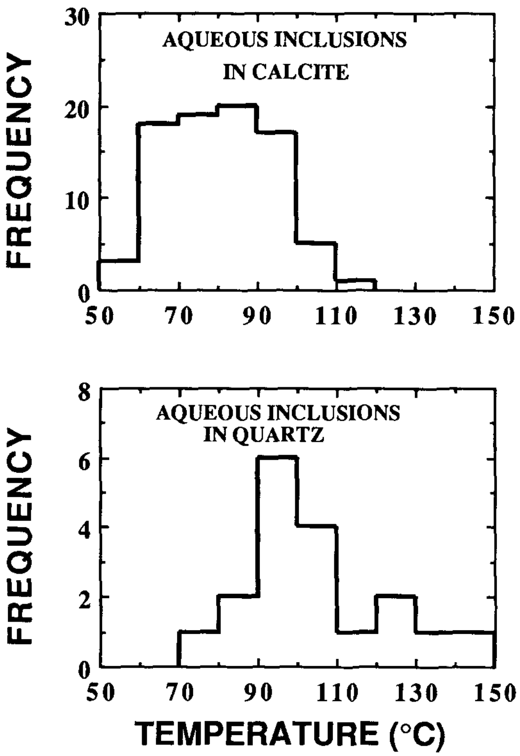


FIG. 10. Histograms of homogenization temperatures of aqueous fluid inclusions from a single vein containing early calcite (top) and later quartz (bottom) from Lion's Head.

maximum temperature, while quartz would precipitate during cooling. Microthermometric data presented here are consistent with this scenario, but do not preclude other mechanisms.

Summary

The Miocene Monterey Formation in the vicinity of the Santa Maria Basin in California represents an ideal location to study fluid evolution associated with the development of an economic hydrocarbon occurrence at an active plate margin. The Monterey Formation constitutes a fracture-controlled petroleum reservoir, with intercalated calcareous and fine-grained siliceous rocks serving as both the source and reservoir for oil accumulations. Petroleum is produced from macroscopic fractures, and numerous tar and asphalt seeps at the surface attest to the present-day movement of hydrocarbons through fractures in the Monterey.

Preliminary fluid inclusion analyses of samples from Jalama Beach indicate that vein-filling minerals were deposited at ~75–100 °C and that petroleum was introduced into the fracture system episodically. The composition of the oil changed as vein-filling progressed, with early oils being light and later oils being heavy and similar to oils produced from the Monterey today. At Lion's Head, the early vein-filling mineral is calcite, followed by later quartz. Temperatures during calcite precipitation may have increased from ~60 to 110 °C, and then decreased during later quartz precipitation. The Lion's Head sample contains no evidence that petroleum is presently flowing or has in the past flowed through the fracture. This observation is consistent with previously published reports that not all fractures are important for petroleum migration.

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