Mineralization, fluid flow, and sealing properties associated with an active thrust fault: San Joaquin basin, California

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ABSTRACT

Petrographic observations indicate that the distribution of cement and porosity within a Quaternary-age thrust fault in the subsurface of the Wheeler Ridge oil field in California is a function of depth and temperature and varies spatially. At depths shallower than 2.5 km (1.6 mi), porosity increases because of the abundance of open microfractures and plagioclase dissolution. At depths greater than 2.5 km (1.6 mi), the porosity in the fault zone decreases because of calcite cementation in microfractures that ultimately form vein networks. Based on δ18O data, we distinguished veins cemented by intraformational (lateral) flow into the fault from veins cemented by ascending fluids along the fault. Ascending, cementing fluids traveled at least 75–750 m (246–2460 ft) vertically. The petrography suggests that oil migration was the last event following dissolution and calcite cementation in the fault zone. Based on oil chemistry, whole-oil δ13C, API gravity, and petrographic data, we propose that hydrocarbons, presently in shallow and deep reservoirs, flowed laterally into the fault zone. Whereas hydrocarbons in shallow reservoirs flowed across the fault into the hanging wall, hydrocarbons in deep reservoirs were trapped against the fault in the footwall. The increase of API gravity with depth and lack of evidence for retrograde condensation indicate a limited vertical migration and reaccumulation of hydrocarbon, suggesting that below 2.5 km (1.6 mi), the thrust behaves as a vertical seal. The sealing properties of the thrust vary spatially and may be controlled by calcite cementation.

INTRODUCTION

Dissolution and precipitation along faults and fractures play a critical role in diagenesis, reservoir quality, and petroleum migration.
and accumulation in sedimentary basins. Predictive models of water-rock interactions associated with faults, however, are extremely difficult to evaluate. Several assumptions are needed, specifically pertaining to fracture and fault architecture and conductivity.

Our poor understanding of fractures as open systems is further complicated, because along faults, P-T-C conditions, water composition, flow velocities, and shear stresses change at unknown rates. One viable way to evaluate the interplay between faulting and fracturing, fluid flow, and mineralization is through direct petrologic observation. For petroleum geologists, it is critical to create conceptual models that include (1) the magnitude of fluid movement along and across faults, (2) the resulting precipitation and dissolution reactions, and (3) the effects of diagenesis on the fault's ability to conduct hydrocarbon or form seals. These are the main topics addressed in this paper.

Shear is a significant aspect of the fault conductivity, but it is not part of this study. Shear zones generally result in chemically altered material, which reversibly decreases the conductivity across faults (e.g., Goddard and Evans, 1995), whereas diagenesis may decrease or increase, reversibly, fault permeability by dissolution or precipitation of mineral reactions. Additionally, diagenetic cements may yield information of fluid chemistry and thermal anomaly events associated with faults that are critical for our study.

Published studies on faults offer excellent conceptual models of fault-zone permeability (Antonellini and Aydin, 1994), fault-zone architecture (Caine et al., 1996; Sibson, 1996; Heynekamp et al., 1999), and fault-zone hydrology (Lopez and Smith, 1995, 1996; Meilloux et al., 1999). These studies are heavily based on detailed observations of fractured porous sandstones in outcrops and numerical models; however, they lack insights into the physical-chemical mechanism controlling fault cementation. However, diagenetic studies of fault cements, which intrinsically yield insights into water-rock interactions and fault cementation mechanisms, have been limited to surface or outcrop sample suites (e.g., Goddard and Evans, 1995; Mozley and Goodwin, 1995; Eichhubl and Boles, 2000; Ghisetti et al., 2002). Few diagenetic studies, with exceptions (e.g., Burley et al., 1989; Losh, 1998), include subsurface core sampling, probably because of the poor recovery in highly fractured zones. Fault outcrops may certainly offer unlimited sampling capabilities and good two-dimensional visualization, but outcrops may also represent a limited and incomplete section of the total fault length. Within long faults, some sections could behave as seals, whereas others could act simultaneously as barriers, and furthermore, they may evolve over time differently.

Based on the reasons explained above, we chose a subsurface study that includes petrologic observations in shallow sections as well as deep sections of a single fault. Our study is based on the premise that diagenetic effects are a direct result of water-rock interactions and are indirect evidence of fluid movement. Our approach involves contrasting diagenetic effects observed in unfaulted intervals with those observed in the fault zone, from depths of 0.3 to 3 km (0.2 to 2 mi). We infer from the diagenetic cement magnitudes of fluid movement, and additionally, we investigate the effect of diagenesis on the fault quality or ability to conduct and trap hydrocarbons at different depths.

We chose a thrust fault located in the subsurface of the Wheeler Ridge oil field (Figure 1), which has been active since the Quaternary. Previous work has divided the fault zone into a central gouge zone, containing slip surfaces, clay-rich gouge, and cataclasite (Caine et al., 1996), and bounding damaged zones. The damaged zone commonly contains subsidiary structures that bound the fault core, including veins, fractures, and joints. In this particular setting, the fault zone extends about 15 m (49 ft) away from the fault surface (30 m [100 ft] total). Our sampling included sandstone (within and outside the fault zone), waters, and hydrocarbons present in both the hanging wall and footwall. The Wheeler Ridge fault offers an unusual opportunity to study an actively deforming or recently deformed system because of the good quality of the subsurface control around the fault and a well-documented structural reconstruction (i.e., Medwedeff, 1988; Keller et al., 1998).

GEOLOGIC SETTING

The east-west-trending Wheeler Ridge oil field is located between the boundary of the Transverse Ranges and the southern edge of the San Joaquin Valley, along the northern flank of the San Emigdio Mountains (Figure 1). The San Emigdio Mountains are part of the east-west-trending western Transverse Ranges, which are bounded on the north and south by fold and thrust belts (Keller et al., 1998). The Wheeler Ridge anticline represents the frontal fold of the northern edge of the Transverse Ranges thrust system (Mueller and Suppe, 1997), which developed in response to
shortening across a restraining bend of the San Andreas fault (Keller et al., 1998). The San Emigdio Mountains have accommodated about 7 km (4.4 mi) of shortening since the late Pliocene, during which the San Joaquin basin has been actively subsiding (Davis, 1983). Active uplift has occurred along the southward-dipping Pleito-Wheeler Ridge thrust fault system and along the White Wolf fault, which merges with the thrust system (Figure 1).

A Mesozoic and older crystalline basement forms the core of the San Emigdio Mountains and is exposed south of the Wheeler Ridge oil field. The northern flank of the mountains is overlain by a north-dipping sedimentary sequence of marine shale and sandstone, as well as terrestrial sandstone and conglomerate units (Nilsen et al., 1973). The north-dipping strata are Eocene to Miocene age and flatten toward the San Joaquin Valley.

**Figure 1.** (A) The Wheeler Ridge oil field is located between the San Joaquin Valley and Transverse Ranges, north of the San Emigdio Mountains. (B) Structural elements in the Wheeler Ridge area. Modified after Dibblee (1973), Davis (1983), Medwedeff (1992), and Keller et al. (1998, 2000). (C) Map illustrating oil-field production areas (dashed lines), surface locations of sampled wells, and location of the AA' cross section illustrated in Figure 9. Courtesy of Vintage Petroleum, Inc.
In the Wheeler Ridge oil field, the Tertiary strata are 3.6 km (2.2 mi) thick, underlay less than 300 m (1000 ft) of Quaternary sedimentary rocks, and represent shallow-marine deposits accumulated on a Jurassic igneous basement (Figure 2). All sedimentary rocks in Wheeler Ridge have undergone continual compaction from the time of deposition until present; however, shortening in the oil field caused between 200 and 300 m (660 and 1000 ft) of uplift in the last 0.4 m.y. The sandstone-to-shale ratio averages 1:4, based on our analysis of spontaneous-potential, gamma-ray, and resistivity logs.

The sedimentary sequences near the Wheeler Ridge oil field have been well studied, and different nomenclatures and correlations have been proposed (e.g., Hluza, 1960; Barnes, 1964; Dibblee, 1973; Nilsen, 1973, 1987; Keller et al., 1998, 2000). For our purposes, we use official subsurface unit names and stratigraphic nomenclature first published by Hluza (1960) and Barnes (1964) and later by the Correlation of Stratigraphic Units of North America (1984) and California Oil and Gas Division (1985), because they contain more lithologic detail of the subsurface units.

Structurally, the Wheeler Ridge thrust fault has been interpreted as an actively growing fault-bend fold (Medwedeff, 1992; Mueller and Talling, 1997) propagating eastward along its axis (Keller et al., 1998). The folding, faulting, and uplift most likely began during the late Pleistocene to Holocene (0.185–0.400 Ma) and have continued until the present (Zepeda et al., 1986). Medwedeff (1992) interpreted the thrust to be of Quaternary age based on the restoration of pre-deformational stratigraphy and fault array. Present-day uplift rates (based on radiocarbon and uranium series ages of geomorphic surfaces) divided by the total amount of uplift yield similar ages of deformation, further supporting previous interpretations (Keller et al., 1998).

Cross sections of the Wheeler Ridge area reveal a north-dipping steep front limb and a shallowly inclined back limb (e.g., Medwedeff, 1992; Mueller and Suppe, 1997; Keller et al., 1998). Our subsurface structural cross section, located in the central area of the field about 3 km (2 mi) west from previous interpretations (Figure 1), reveals the same geometry and indicates that the fault surface intersects Eocene strata at 3.5-km (2.2 mi) depth and has a total slip of 760 m (2500 ft).

**Figure 2.** The Wheeler Ridge thrust fault cuts all the Tertiary strata, which is greater than 3.6 km (2.2 mi) thick. The stratigraphic column was compiled from Hluza (1960), Barnes (1964), Correlation of Stratigraphic Units of North America (1984), and California Oil and Gas Division (1985). See also cross section (Figure 9) for formation thickness.

**ANALYTIC METHODS**

We collected more than 90 core samples and 11 fluid samples from 27 different well locations (Figure 1). The sample depth ranged from 1 to 3.8 km (0.6 to 2.4 mi), spanning the Santa Margarita Sandstone to the...
Tejon Formation. To discriminate between structures of different ages present in the oil field and surrounding areas, we located our samples with respect to the Wheeler Ridge thrust fault using structural maps and cross sections as well as fault surface maps, all generated by Vintage Petroleum, Inc. Available structural cross sections and subsurface maps from the literature (e.g., Hluza, 1960; Barnes, 1964; Medvedeff, 1988, 1992) were also used. From the most cohesive and complete cored intervals, we obtained 60 thin sections, which we stained for potassium feldspar and carbonate, counted 400 points per slide, and studied the calcite veins under a cathodoluminescence microscope.

The elemental composition of calcite is based on electron microprobe analysis using a Cameca SX50, set with an acceleration voltage of 15 kV, a beam current of 10 nA, and a beam diameter of 10 μm. Results were normalized to 1 mol of Fe, Mn, Mg, and Ca. From core material, we extracted and pulverized 18 intergranular and fracture-filling calcite cements for carbon and oxygen isotope analysis. The stable isotope laboratory at Southern Methodist University (in Dallas, Texas) conducted these measurements.

The sampled fluids included subsurface waters and hydrocarbons obtained from producing oil wells, following the techniques of Fisher and Boles (1990) and Franks et al. (2001). The formation waters were analyzed for 818O, 8D, and dissolved metals using an inductively coupled plasma-atomic emission spectrometer (ICP-AE) ARL model 3510 ICP.

PTS Laboratories analyzed the hydrocarbons through bulk oil-gas chromatographs of the C2 to the C34 fraction. In light hydrocarbons, the C2 – C34 fraction generally contains paraffinity and aromaticity ratios, which we used to estimate evaporative fractionation that may be associated with oil leakage through faults (cf. Carpenter et al., 1996).

SANDSTONE PETROGRAPHY

Cores used in this study ranged from the Santa Margarita Sandstone to the Tejon Formation. All sandstones are feldspathic (Table 1). The main authigenic phase is calcite. Quartz overgrowth, kaolinite, and illite are present in minor amounts. In thin section, the rock porosity is low, ranging as high as 16%, but averaging less than 5%. The intergranular volume varies with depth from 30% at 0.8 km (0.5 mi) to 6% at 3.2 km (1.2 mi).

For comparative purposes, we divided the sandstones in two groups: sandstone at least 15 m (50 ft) beyond the fault surface and sandstone present in the fault zone. Each group has distinctive diagenetic imprints, leading us to describe the diagenesis of the first group separately from the second.

Diagenesis of Sandstone Away from Fault Zone

Mechanical compaction reduced the intergranular volume, squeezed ductile grains, and crushed sand particles. At shallow depths (<2.5 km; <1.6 mi), the lack of cementation enables us to observe grain packing and reduction of primary porosity caused by grain-scale microfractures, whereas in the deep section of the column (>2.5 km; >1.6 mi), the grain-scale microfractures in quartz are annealed and only visible under cathodoluminescence.

Early calcite cement occurs locally with high intergranular volumes (29 to 35%) and fills most of the pore space in sandstone. Microprobe analysis of 40 spots in this cement reveals a relatively pure composition that averages Ca0.96Mg0.04(Fe + Mn)0.95CO3 (Figure 3). This intergranular cement has a δ13C_PDB (PDB = Pee Dee belemnite) that ranges from -6.1 to -6.6% and an δ18O_PDB that ranges from -5.81 to -0.44%.

Away from the fault zone, Kspar and plagioclase dissolution is common at depths between 0 and 1.5 km (0.9 mi). Dissolution represents 16 and 75% of the total porosity. Below 2.8-km (1.7-mi) depth, late calcite cement fills low intergranular volumes (between 14 and 7%), indicating a second phase of cementation. The late calcite cement has an average composition of Ca0.955Mg0.025(Fe + Mg)0.015CO3 (Figure 3) and a δ13C_PDB and δ18O_PDB ranging from +0.6 to -2.8% and from -10.6 to -11.1%, respectively. Below 3.2-km (2-mi) depth, illite is the dominant diagenetic clay mineral, and based on point counts, it ranges from 2 to 3%. Quartz overgrowths are present in relatively minor amounts (1–3%). Previous studies in the San Joaquin basin (i.e., Wilson et al., 2000) demonstrate that quartz cement is not volumetrically important because of the short time and low temperature of burial.

Diagenesis in the Fault Zone

At shallow depths (<2.5 km; <1.6 mi), the sandstones are characterized by the presence of open centimeter-scale fractures, crushed and sheared grains, and dissolved plagioclase and lithic fragments. At depths between 2.1 and 2.5 km (1.3 and 1.6 mi), some siltstone and very fine-grained sandstone contain veins.
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*Based on 400 point counts per thin section. Hyp. = hypabyssal rock fragments; Plag. = plagioclase; Volc. = volcanic; Qtz. = quartz.

**Sandstones with calcite cemented veins and residual bituminite.
Figure 3. Normalized molar composition of calcite cements outside and within the fault zone. N = number of samples. Data suggest that calcite compositions are relatively constant throughout the stratigraphic column within and away from the fault zone. Differences in carbonate cement are revealed mainly by carbon and oxygen isotopic data.

Partially filled by euhedral calcite crystals and solid bituminite. At greater depths, sandstones in the fault zone contain microfaults filled exclusively with calcite cement. These observations suggest that the degree of cementation along the fault zone is a function of depth and thus, a function of temperature. In the following section, we describe, through petrography and geochemistry, the effects of cementation and dissolution on the fault-sealing properties.

 Depths Shallower than 2.5 km (1.6 mi)

Centimeter-Scale Fractures
These fractures were observed in calcite-cemented sandstone and in sandstone with more than 20% of intergranular clay matrix. The fracture width ranges from 1 to 11 mm (0.039 to 0.43 in.). Open microfractures enhance the porosity and represent as much as 70% of the total porosity. Open-mode microfractures surrounded by crushed and chemically altered fine grains suggest a period of shear and consolidation followed by a period of dilation or opening (Figure 4A). Microfractures are less than 1 mm wide and form fracture networks that enhance the rock porosity (Figure 4A).

Grain Crushing
The degree of grain crushing and fragmentation caused by shearing increases toward the fault zone (Figure 4B). The degree of crushing appears to be more intense in coarse-grained sandstone than in medium-grained or fine-grained sandstone; however, the chemical alteration (catalyzed by shearing) is volumetrically higher in lithic fine-grained sandstone than in any other grain size. Consequently, the porosity reduction caused by chemical alteration of sheared grains in the fault zone is greater in lithic fine-grained sandstone and lower in clean, coarse-grained sandstone, similar to experimental observations (Chuhan et al., 2002).

Plagioclase and Lithic Fragment Dissolution
The dissolution porosity in the fault zone is higher than the dissolution porosity in unfaulted rocks. Plagioclase dissolution, similar to lithic fragment dissolution, is as much as four times greater near the fault zone and increases the total secondary porosity (Figure 5A, B). Quantification of dissolution products in thin section (i.e., kaolinite as a product of plagioclase dissolution) is difficult because of the abundance of clay and sheared rock. It is possible that fluids (probably of meteoric origin) unsaturated with respect to plagioclase and lithic fragments flowed along the shallow fault zone and caused the dissolution. A marked increase in the total reactive surface area caused by microfractures and fragmentation may have also enhanced the dissolution reaction rates relative to nonfractured material (cf. Oelkers, 1996). Diluted, marine pore-water fluids,
Figure 4. Photomicrographs of sandstone in the fault zone. (A) Sample from well KCL-1 at 1350-m (4429-ft) depth, exposing extensive grain fracturing and cataclasis, and open mode I uncemented, centimeter-scale fractures increasing porosity; (B) sample from well KCL 63-29, at 865 m (2838 ft) illustrating intragranular, uncemented fractures and porosity caused by dissolution of grains; and (C) sample from well SB-1 at 3748-m (12,296-ft) depth revealing calcite-cemented microfaults. At depths shallower than 2.5 km (1.6 mi), the fault zone is highly conductive; at greater depths, the fault zone is sealed by calcite cementation. Wells are operated by Vintage Petroleum.
Figure 5. (A) Thin-section porosity variation in relation to faulting. Left side: Total porosity increases toward fault zone because of extensive microfracturing, plagioclase, and lithic fragment dissolution. Right side: Porosity decreases toward fault zone because of postfracturing calcite cement. Samples vary in grain size. (B) Grain dissolution variation relative to fault. At depths shallower than 2.5 km (1.6 mi), the porosity increases toward the fault zone. mbsl = meters below sea level.
which suggest meteoric influence, have been found in shallow reservoirs. For example, the total dissolved solids value in Vintage Petroleum well 434-28 at 1036 m (3400 ft) is 11,018 mg/L, and its $\delta^{18}$O$_{SMOW}$ (SMOW = standard mean ocean water) is $-6.40\%$.

We compared thin-section total porosity as well as plagioclase and lithic fragment dissolution of samples in the fault zone with samples away from the fault (Figure 5). The data were derived from two different Vintage Petroleum wells, KCL-2 and KCL 87-22. The fault zone in these wells is located at 2393 and 1440 m (7851 and 4724 ft), respectively. In well KCL-2, plagioclase dissolution increases from 1 to 4%, and the lithic fragments dissolution increases from 1.5 to 3% toward the fault zone. In well KCL G 87-22, the porosity increases toward the fault zone from 16 to almost 21% and in well KCL-2 from 5 to 13%. Although we sampled the most cohesive sections of the fault zone, the porosity may be highly variable. However, the available data clearly indicate a porosity increase toward the fault zone at shallow depths.

 Depths between 2.1 and 2.5 km (1.3 and 1.6 mi)

Calcite-Bituminite-Filled Veins
Veins filled with solid hydrocarbon bituminite are present in siltstone and very fine-grained sandstone, which have thin-section porosity of 1–3%. The veins are partially cemented by large calcite crystals and bituminite and range in thickness between 1 and 3 mm (0.04 and 0.12 in.). Isolated crystals may have formed pore bridges that presumably maintained open fractures for hydrocarbon filling. The calcite morphology and orientation indicate growth into open-pore space from the vein walls to the center. The average value of $\delta^{13}$C$_{PDB}$ for individual calcite crystals is $-1.30 \pm 0.2\%$, whereas the $\delta^{18}$O$_{PDB}$ within the same vein ranges from $-11.7$ to $-13.9\%$ (Figure 6). The absence of oil fluid inclusions and presence of euhalic calcite crystals indicates that carbonate precipitation predated oil migration. Unfortunately, the porosity could not be measured in thin sections because the cores presented a low degree of cohesion and a high frequency of fractures.

 Depths Greater than 2.5 km (1.6 mi)

Calcite-Cemented Microfaults
Spotty calcite-cemented microfaults are typically present in sandstone in the fault zone at depths greater than 2.5 km (1.6 mi) (Figure 4C). Microfaults range in thickness from 1 to 17 mm (0.039 to 0.67 in.), and their total slip is 0.1–4 cm (0.039 to 1.57 in.), based on core measurements. Euhedral calcite crystals increase in size toward the center of the fracture zone (Figure 4C). The

\[
\delta^{18}O_{PDB} \text{ vs. } \delta^{13}C_{PDB}
\]


\[
\delta^{13}C_{PDB} \text{ Calcite}
\]

\[
\delta^{18}O_{PDB} \text{ Calcite}
\]

**Figure 6.** Carbon and oxygen isotopic data from intergranular and vein carbonate filling cements. Below the lower axis, we show a simplified carbonate source model for the carbonate samples present in the Wheeler Ridge oil field (Wood and Boles, 1991). Near-zero and light $\delta^{13}$C$_{PDB}$ values may reflect deep, mixed-marine thermogenic sources and/or mixture of oxidation of light hydrocarbon chains, suggesting deep carbonate sources during carbonate cementation associated with fault.
crystals form a pseudolamination parallel to the fracture walls, indicating that the growth occurred in open, fluid-filled fracture space.

Microprobe analysis reveals that the cements are close to pure calcite (Figure 3), and their cathodoluminescence is uniformly bright orange, with no apparent zoning. The δ13C_PDB values for these veins range from −7.19 to −26.6‰, and the δ18O_PDB ranges from −14.30 to −9.67‰ (Figure 6). In some cases, the porosity decreases to less than 1% toward the fault zone; the decrease is caused by the abundance of vein networks (Figures 4, 5). For example, in well SB-1, the fault zone is located at about 3.1-km (1.9-mi) depth. Around that depth, the total porosity away from the fault averages 8%, whereas within the fault, it is reduced to less than 3% (right side of Figure 5A).

**Calcite Cement in Crushed Sandstones**

Late-stage calcite cement fills the intergranular volume of sandstone left by the grain crushing and compaction toward the fault zone (right side of Figure 5A). Comparing deep samples with the fault zone located at 3124 m (10,248 ft), we observed that the total porosity away from the fault averages 8%, whereas within the fault, it is reduced to less than 1%. The calcite composition is Ca$_{0.95}$Fe$_{0.05}$(CO$_3$), which is similar to intergranular cements present in sandstone away from the fault (Figure 3). The dissimilarities between carbonate cements that precipitated away and within the fault zone at depths greater than 2.5 km (1.6 mi) are revealed in their isotopic signatures. The calcite in unfaulted sandstone has a δ13C_PDB range from −11 to −4‰ and a δ18O_PDB range from +0.6 to −2.76‰. However, the intergranular calcite in the fault zone has a heavier δ13C_PDB, between +0.7 and −0.4‰, and lighter δ18O_PDB, within −15.6 ± 0.2‰ (Figure 6). The following discussion explains differences in δ13C compositions and the origin of the cementing fluids based on δ18O data.

**DISCUSSION**

**δ13C Sources**

The early-stage intergranular calcite in sandstone away from the fault zone has δ13C_PDB values of −6.4 ± 0.3‰, whereas the late-stage calcite has δ13C_PDB from +0.6 to −2.8‰ (Figure 6). Both cement types completely filled the pore space in the sandstone. We estimated their precipitation temperatures by matching the occupied intergranular volume with compaction curves from the basin (Ziegler and Spotts, 1977) and assuming a geothermal gradient of 26°C/km (126.8°F/mi) (Wilson et al., 2000). The calculated values ranged from 15 to 40°C (59 to 104°F) for the early-stage calcite and between 70 and 90°C (158 and 194°F) for the late-stage calcite. An estimate of the temperatures and depths of carbonate precipitation helps us to infer possible carbon sources.

A δ13C_PDB value of −6.4 ± 0.3‰ at 15–40°C (59–104°F) probably reflects a mixed marine-meteoric water with marine dominance of carbon (Lee and Boles, 1996). Our interpretation is supported by the early-stage calcite δ18O_PDB = −6 to −1‰ (Figure 6), which reflects fluids with δ18O_Smow = −1 to −7‰ at 15 and 40°C (59 and 104°F) during precipitation. Given the shallow depth and temperature of precipitation, it would be tempting to presume meteoric dominance. Meteoric waters in the Wheeler Ridge oil field and its surrounding areas have δ18O_Smow values between −13 and −10‰ (Mellier, 2001). If precipitation temperatures are calculated using our calcite δ18O and Mellier’s (2001) data, values between −14 and −1°C (6.8 and 30.2°F) are obtained, which are clearly too low.

Near-zero δ13C_PDB values in late-stage intergranular calcite and calcite crystals in bituminitic veins away and within the fault zone may reflect a process related to the presence of hydrocarbons in the reservoirs. A study of a large δ13C data set from late-stage carbonate cements confirms calcite precipitation at temperatures more than 70°C (158°F) in oil reservoirs from the San Joaquin basin (Boles, 1998). Additionally, evidence for positive δ13C_PDB values (−12.8 to +8‰) of carboxyl carbon in reservoir fluids of the San Joaquin basin has been shown (Franks et al., 2001). As pointed out by Boles (1998) and Franks et al. (2001), dissolution-precipitation of biogenic shells (δ13C_PDB ~ 0), and microbial methanogenesis or fermentation (δ13C_PDB ~ +15‰) may not be the only sources for positive carbon (e.g., Curtis and Coleman, 1986).

The sparry calcite veins in sandstone have δ13C_PDB ratios between −7.9 and −26.6‰ (Figure 6). These carbon values have been traditionally associated with precipitation in the sulfate-reduction zone, within less than 1 m (3 ft) of the sediment-water interface (e.g., Nisensbaum et al., 1972; Curtis and Coleman, 1986). However, because veins are present in the fault zone at depths greater than 2.5 km (1.6 mi), the calcite probably precipitated at temperatures greater than 80°C.
(176°F); therefore, we interpret these values to be derived from mixed marine-thermogenic carbon sources. Furthermore, in deep burial settings, the thermal maturation of kerogen yields organic carbon that shifts the δ13C_PDB composition of calcite cements to values as low as −25 ‰ (Curtis and Coleman, 1986). The bulk δ13C_PDB of Wheeler Ridge oil averages −23 ± 0.1 ‰, and the C1–C4 carbon group is commonly lighter than the bulk δ13C_PDB (Kaplan et al., 1988; Peters et al., 1994). Light δ13C, as in late-stage fault-related calcite veins, may represent a mixture of oxidation of light hydrocarbon chains. So far, we have suggested tentative carbon sources present in the fluids during cementation; however, the δ18O values of the calcite veins deserve special consideration because they ultimately reflect thermal anomalies associated with faulting.

**Magnitude of Fluid Movement and Fault Cementation Model Based on δ18O**

As explained in the previous discussion, the sealing properties of the fault are affected by calcite precipitation at depths greater than 2.5 km (1.6 mi). Calcite precipitates by decompression and mixing of fluids (e.g., Boles and Ramseyer, 1987), changes in temperature, and/or by diffusion caused by chemical potential gradients (e.g., Thyne, 2001). These mechanisms differ mainly in the scale of mass transport associated with them. Consequently, the sequence of steps in our fault cementation hypothesis starts with (1) an estimation of the mass-transfer distance, followed by (2) determination of cementation mechanisms.

We begin the model sequence by framing the oxygen isotopic composition of all the subsurface waters in the oil field that could have been associated with the cementation (shaded area in Figure 7). We also include isotopic data from reservoir brines situated far from the oil field (Fisher and Boles, 1990). Because veins occur at temperatures more than 90°C (194°F), we limit the isotopic field to fluids that are presently at temperatures higher than 75°C (167°F). Separately, we calculate the δ18O_SMOW values for the possible cementing fluids, which we call calculated δ18O_water, using the veins’ maximum burial temperatures and their δ18O from the calcite. We perform all the calculations using the Friedman and O’Neil (1977) equation,

![Calcite δ18O_PDB vs. Water δ18O_SMOW](image)

**Figure 7.** Calcite δ18O_PDB from veins versus δ18O_SMOW from oil-field waters. Isotopic data suggest that cementing fluids flowed upward to the fault from sources at least 75 to 750 m (246 to 2460 ft) below the sample depth. The shaded area represents the δ18O_SMOW range of subsurface waters, Wheeler Ridge oil field. The ∆δ reflect thermal anomalies caused by ascending cooling fluid flow and recorded in carbonate cements in fault zone (see text). The ∆δ calculation is translated into vertical flow distance in Table 2.

1306 Mineralization, Fluid Flow, and Sealing Properties of a Thrust Fault
which assumes a calcite-water equilibrium fractionation (per mil) of $2.78 \times \left(10^6/T^2\right)$ – 2.89, where $T$ is temperature in Kelvin.

If the calculated $\delta^{18}O_{\text{water}}$ data points fall in the measured $\delta^{18}O_{\text{water}}$ range (shaded area, Figure 7), we assume that the veins were cemented either by a small-scale diffusion mechanism, lateral (intraformational) flow into the fault zone, or by ascending fluids that reached thermal equilibrium with the host rock. If the calculated $\delta^{18}O_{\text{water}}$ data points fall out of the measured $\delta^{18}O_{\text{water}}$ range, we search for the minimum $\Delta\delta$ required (by the calculated $\delta^{18}O_{\text{water}}$) to fall in the measured $\delta^{18}O_{\text{water}}$ box (Figure 7). These $\Delta\delta$ values are translated into $\Delta T$ through the Friedman and O’Neil’s equation. Finally, by dividing $\Delta T$ by the thermal gradient, which is 26°C/km (126.8°F/mi) in the footwall, we obtain a vertical distance that represents the minimum distance traveled by the cementing fluid before precipitating calcite in the vein. Our model requires three basic assumptions.

**Assumption 1:** Constant thermal gradient during the past 0.2 m.y. equals to 26°C/km (Boles and Ramsey, 1987; Lee and Boles, 1996; Boles, 1998; Wilson et al., 2000). This assumption is supported by a paleo-thermal study of the San Joaquin basin, which concluded that the heat flux in the basin has remained constant at 55 mW/m² for the last million years (Fischer et al., 1988).

**Assumption 2:** The $\delta^{18}O$ signature of the reservoir fluids, presently at temperatures more than 75°C (167°F), has remained constant from the onset of the faulting until the present. It is well known that long timescales (millions of years), increasing temperature, and recrystallization are the main factors controlling positive $\delta^{18}O$ shifts in reservoir fluids (Dickinson, 1986).

The cementation along the Quaternary Wheeler Ridge fault must have started, at the earliest, coeval with faulting, between 0.2 and 0.4 m.y. (Keller et al., 1998, 2000). The extrapolation regarding the $\delta^{18}O$ evolution of Miocene waters from the San Joaquin basin (cf. Fisher and Boles, 1990) indicates that 0.2 and 0.4 m.y. could lead to small positive shifts between 0.05 and 0.1% only if sediments and waters were subject to burial and increasing temperatures. However, at an uplift rate between 1 and 4 mm/yr (0.04 and 0.16 in./yr) (Keller et al. 1998, 2000), the net 300 m (984 ft) of folding and uplift certainly would not increase the temperature of the sediments and fluids. In actuality, it may decrease it. Thus, a decrease in temperature caused by uplift and a short time for water-rock interaction (0.2–0.4 m.y.) led us to validate our assumption that $\delta^{18}O$ of brines at temperatures more than 75°C (167°F) may have remained constant from the beginning of the faulting until the present.

**Assumption 3:** Equilibrium isotopic fractionation.

Our results (Table 2) show that 5 out of 10 of the calculated $\delta^{18}O_{\text{water}}$ values are consistent with the isotopic range from the formation waters (circles inside shaded box in Figure 7). Furthermore, they are consistent with waters of equal stratigraphic level at which the veins are found today. The calculations also reveal that the remaining five calculated $\delta^{18}O_{\text{water}}$ fall outside the range and are 0.3–2.3% lighter (in the SMOW scale) than any formation water in the oil field or surrounding areas (points outside shaded area in Figure 7). From O’Neil’s equation, a 0.3–2.3% $\Delta\delta$ results in a 2–21° $\Delta T$, which represents 75–750 m (246–2460 ft) of vertical distance for a thermal gradient of 26°C/km (126.8°F/mi) (Table 2). In other words, 5 out of 10 $\delta^{18}O$ ratios in veins clearly suggest

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**Table 2. Calculation of the Minimum Flow Distance of Cementing Waters from $\delta^{18}O$ of Vein Cements and Reservoir Waters**

<table>
<thead>
<tr>
<th>Well Name</th>
<th>Fault and Vein Depth (m)</th>
<th>Calcite $\delta^{18}O$ (PDB)</th>
<th>Calcite $\delta^{18}O$ (SMOW)</th>
<th>MBT (°C)</th>
<th>Calculated Water $\delta^{18}O$ (SMOW)</th>
<th>ID $\Delta\delta$</th>
<th>New Temperature (°C)</th>
<th>DT (°C)</th>
<th>Vertical distance (m)**</th>
</tr>
</thead>
<tbody>
<tr>
<td>KCLD-87-22</td>
<td>2514.2</td>
<td>−14.3</td>
<td>16.12</td>
<td>96.7</td>
<td>−1.46</td>
<td>0.3</td>
<td>99</td>
<td>2.5</td>
<td>87</td>
</tr>
<tr>
<td>KCL-1 52-25</td>
<td>2418</td>
<td>−13.93</td>
<td>16.5</td>
<td>93</td>
<td>−1.6</td>
<td>0.4</td>
<td>96</td>
<td>3</td>
<td>113</td>
</tr>
<tr>
<td>KCL-1 52-25</td>
<td>2418</td>
<td>−13.92</td>
<td>16.61</td>
<td>93</td>
<td>−1.5</td>
<td>0.3</td>
<td>95</td>
<td>2</td>
<td>75</td>
</tr>
<tr>
<td>PR 2-25</td>
<td>2420.6</td>
<td>−15.68</td>
<td>14.7</td>
<td>93.1</td>
<td>−3.47</td>
<td>2.2</td>
<td>113</td>
<td>19.9</td>
<td>792</td>
</tr>
<tr>
<td>KCL 35-36</td>
<td>1716</td>
<td>−9.67</td>
<td>20.89</td>
<td>66</td>
<td>−0.52</td>
<td>1.22</td>
<td>74</td>
<td>8</td>
<td>307</td>
</tr>
</tbody>
</table>

*MbT = maximum burial temperature; ID = minimum isotopic difference between calculated $\delta^{18}O_{\text{water}}$ and $\delta^{18}O_{\text{water}}$ Wheeler Ridge oil field; DT = calculated temperature difference.

**Vertical distance obtained by dividing DT by the present-day thermal gradient (26°C/km).
the presence of thermal anomalies, with a 2–21° higher temperature in the vein cement compared with the ambient value in the host rock. According to our calculations, ascending fluids that traveled vertical distances of at least 75–750 m (246–2460 ft) may have caused these anomalies. The remaining five veins could have been cemented by lateral flow or diffusion. We emphasize that, during fluid flow, different sinks (i.e., convection, conduction, and heat of reactions) remove a fraction of the heat, and true ΔT and distances could potentially be greater than the ones we are calculating.

The order of magnitude in our calculations is consistent with several other studies. For instance, Eichhubl and Boles (1997, 2000) calculated upward flow distances of 200–400 m (660–1300 ft) using δ18O in dolomite veins and 700 m (2300 ft) using strontium isotopes in calcite veins that cut the Monterey Formation. Based on δ18O in calcite veins from Losh (1998), we calculated a temperature anomaly of 7°C (44.6°F) in a major growth fault from offshore Louisiana. The temperature anomaly, if caused by fluid flow along the fault, would correspond to a vertical flow distance of about 300 m (1000 ft), assuming a thermal gradient of 25°C/km (124°F/ml). Additionally, modeling of decomposition indicates that temperature anomalies caused by decompressing flow range from 5 to 20° (Roberts and Nunn, 1995).

Regardless of the decomposition mechanism, we presume that fluid expulsion and the upward vertical flow may have caused the thermal anomalies along the fault zone. The relatively short, vertical distances represent minimum values and may depend directly on excess pressure. Fluid expulsion requires quick and short-lived decompressions that occur by fracturing of seals surrounding the geopressured sediments (Roberts and Nunn, 1995; Sibson, 1996). Furthermore, fluid decompression causes a pressure drop and a subsequent $P_{CO_2}$ decrease, which ultimately controls calcite saturation. In an H2O-CO3-Me+ system, carbonate cementation is controlled by changes in temperature and $P_{CO_2}$. Carbonate tends to dissolve with decreasing temperature under constant $P_{CO_2}$; however, it tends to precipitate with decreasing $P_{CO_2}$ at constant temperature. Whereas formation waters move laterally into the fault and later flow upward through the fault, the dissolved CO2 goes into the lower pressure regime of the fault. This change in pressure may have caused carbonate cement (i.e., CaCO3) to precipitate along the fault zone in the veins. A similar phenomenon is observed in gas anchors from wells in the San Joaquin basin, in which the pressure inside the tubing was less than the ambient formation pressure, causing calcite scaling (Boles and Ramseyer, 1987).

Calcite dissolution-precipitation is not evident in petrography, and the negative δ13C values in fault cements are more related to thermogenic sources than to dissolution of biogenic material. Ca2+ may have been derived, at least partially, from plagioclase albization, which is a transformation occurring in the San Joaquin basin at temperatures between 100 and 150°C (212 and 302°F) (Boles and Ramseyer, 1988). Assuming Ca2+ conservation during plagioclase albization, the 7% of oligoclase that is present in the sandstone would yield 0.7 vol.% of calcite (Boles, 1984). This amount is about 10% of the total volume of calcite cement observed in the fractured rocks; however, we do not know the fluid/rock ratio with precision to test this calculation further.

So far, we have documented that the degree of cementation along the fault zone varies with depth. In addition, evidence of upward fluid flow indicates that the deep section of the fault behaved initially as a permeable path, and the cementation transformed it into a barrier. Furthermore, as we will explain in the following section, the distribution of hydrocarbon in the oil field with respect to the fault suggests that the deep section of the Wheeler Ridge thrust evolved over time into a low, permeable, vertical barrier, whereas the shallow section remained as a pathway.

Evidence in Support of Conductivity Distribution along the Fault Zone

We sampled oils that were present in footwall and hanging-wall reservoirs and performed isotopic and crude-oil correlations. The crude-oil correlation enabled us to test indirectly and independently our thrust's conductivity model, i.e., decreasing conductivity with depth by grouping hydrocarbons with similar chemical composition trapped against or across the fault.

Our results indicate that the whole-oil isotopic values, δ34C_PDB = 23.4 ± 0.3‰, are consistent with Miocene petroleum source rocks typically associated with the Antelope or the Monterey Formation (Fischer et al., 1988). The detailed examination of selected hydrocarbon gas-chromatograph peaks, from the n-C8 to n-C19, and the heavy biomarker fraction n-C25 to n-C32 suggests the existence of two oil groups, generated by two different sources. There is poor correlation between peak ratios from the light distillation fraction probably because of incipient biodegradation (right side of Figure 8A). However, the presence of two groups
is confirmed by (1) a clear grouping or family appearance in the correlation of peak ratios from the diesel fraction (left side of Figure 8A) and (2) a good peak ratio correlation of heavy hydrocarbons from the biomarker fraction n-C_{25} to n-C_{32} (Figure 8B). In summary, group 1 consists of hydrocarbon present in the Santa Margarita Sandstone, Fruitvale and Vedder formation, whereas group 2 consists of oil present in the Oligocene-lower Miocene reserve sand and in the Valv sands (Figure 9). From these two hydrocarbon groups, we can infer, from their location and distribution with respect to the fault, barrier and pathways present along the length of the fault zone.

Lateral Oil Migration Confirms that the Fault is a Path at Shallow Depths and a Barrier at Deep Levels

Miocene to Eocene shales at the Wheeler Ridge field have low total organic carbon as well as high oxygen and low hydrogen indices, suggesting poor oil-generation potential (Kaplan et al., 1988). Thus, the hydrocarbons, at least from group 1, were probably generated 2–3 km (1.2–2 mi) north of the field, where oil kitchens have been present in the past million years (Heasler and Surdam, 1985; Fischer et al., 1988). Primary migration may have occurred laterally from the north, up north-dipping water-saturated sands, driven by buoyancy (England, 1994). In order for the hydrocarbons from group 1, presently in Santa Margarita and Fruitvale reservoirs, to be trapped in the hinge of the fold formed in the hanging wall, they must have migrated laterally into the fault zone across the shallow section of the thrust (Figure 9). Hydrocarbons presently in the Vedder formation (also from group 1) migrated in the same fashion, but were trapped in the footwall, against the deep section of the fault. In the former case of oil migration into Santa Margarita and Fruitvale reservoirs, the fault zone behaved as a pathway, whereas in the latter case of oil migration into the Vedder sands, the fault behaved as a seal.

Traditionally, shear and the juxtaposition of formations with contrasting permeability have been thought to control fault conductivity (e.g., Meilou et al., 1999). However, our petrographic observations suggest that calcite cementation must have enhanced, at least partially, the sealing capacity of the fault zone, preventing further lateral flow. Neither the lateral nor vertical migration of the oil from group 2 can be evaluated because of insufficient data. However, we might speculate that the hydrocarbons from group 2 must have been generated from a different location than group 1, judging from the differences in compositions mentioned previously.

**Figure 8.** Polar plots based on selected ratios from gas chromatographs showing crude-oil correlation. The data suggest two oil families. Right half of (A) illustrates ratios from the light distillation fraction, revealing little correlation. Left half of (A) shows ratios from the diesel fraction, exposing good correlation and the possibility of two sources. The figure in (B) graphs ratios from the heavy biomarker fraction (without the normal paraffins) and also reveals that oils fall into two distinctive families.

Perez and Boles 1309
Limited Vertical Oil Migration Supports the Concept of Poor Fault Conductivity at Depths between 1 and 2.5 km (0.6 and 1.6 mi)

One way to determine hydrocarbon remigration from deep reservoirs and reaccumulation in shallow reservoirs is through (1) the correlation of API gravity and δ^{13}C ratios with depth and (2) the evaluation of evaporative fractionation effects. Typically, a physical separation of gas condensates from its associated oils results in an API gravity decrease with depth, a whole-oil δ^{13}C fractionation of as much as 1‰, and a decrease in the paraffinicity versus aromacity index (PAI) with depth (Thompson, 1987; Carpentier et al., 1996; Magnier and Trindade, 1999).

Figure 10 illustrates representative whole-oil chromatographs of hydrocarbons from groups 1 and 2. Chromatographs from Vintage Petroleum wells 232-28, 144-28, and 82-29 evidence biodegradation with relative high concentration of aromatics, and only the sample from well 21-28 indicates some evaporative loss.
Furthermore, oil distributed along the stratigraphic column has whole-oil δ\(^{13}\)C\(_{\text{PDB}}\) that averages 23.4 ± 0.3 % and a gravity increase with depth from 23.4° API at 260 m (850 ft) to 35° API at 2738 m (8983 ft) (Table 3). Both parameters suggest that remigration and fractionation, if any, have been limited, indicating indirectly that the thrust, in its intermediate zone between 1- and 2.5-km (0.6- and 1.6-mi) depth, behaved as a vertical seal instead of a conduit. Our interpretation is supported by the PAI correlation (Figure 11). Although the PAI correlation of group 2 is not conclusive because of lack of sufficient data, the PAI of group 1 yields important information: the toluene/n-C\(_7\) vs. nC\(_7\)/methycyclohexane ratios do not decrease with depth (Figure 11), possibly indicating (1) that a true fractionation has not occurred, and (2) that the fault zone between 1 and 2.5 km (0.6 and 1.6 mi) behaved as a vertical seal.

In summary, it is unlikely that significant amounts of hydrocarbon remigrated from deep reservoirs and reaccumulated in shallow reservoirs along the thrust fault. Hence, hydrocarbon present in Santa Margarita and Fruitvale reservoirs was not derived from deeper hydrocarbon in the Vedder zone, although they have the same composition, and are connected vertically through the fault. The limited migration from deep reservoirs suggests a fault-sealing behavior at depths between 1 and 2.5 km (0.6 and 1.6 mi), which supports our petrographic observations of calcite cementation along the fault zone.

**CONCLUSIONS**

Mineralization along the Wheeler Ridge thrust varies spatially along and across the fault and is a function of depth and temperature. At shallow depths (<2.5 km; <1.6 mi), the plagioclase and lithic fragment dissolution increases laterally toward the fault zone, increasing the fault conductivity. Similarly, at greater depths (>2.5 km; >1.6 mi), postfracture calcite cement is the
Table 3. Stable Isotopes, API Gravity, and Toluene/n-C5 ratios versus Toluene/n-C7 Ratios from Wheeler Ridge Oils*

<table>
<thead>
<tr>
<th>Well Name and Number</th>
<th>Sample Depth (m)</th>
<th>Reservoir Age</th>
<th>Whole-Oil δ13C (PDB)</th>
<th>Saturated δ13C (PDB)</th>
<th>Aromatic δ13C (PDB)</th>
<th>API Gravity (%)</th>
<th>n-C7/MCH Ratio</th>
<th>Toluene/n-C7 Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>82-29</td>
<td>262</td>
<td>Miocene</td>
<td>-23.3 ND</td>
<td>ND ND</td>
<td>23.4 1.45</td>
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<td>-23.6 ND</td>
<td>ND ND</td>
<td>~20-25** 0.98</td>
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<td>2738</td>
<td>Miocene-Oligocene</td>
<td>ND ND</td>
<td>ND ND</td>
<td>~35** 0.82</td>
<td>0.57</td>
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<td>Miocene</td>
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<td>22.99†</td>
<td>19 ND</td>
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<td>3142-3285</td>
<td>Eocene</td>
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<td>-22.82†</td>
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*Oil groups based on the analysis of Figure 9. ND = not determined; MCH = methylcyclohexane; Und. = undifferentiated.
**Estimated from peak heights on chromatographs.
†Data from Kaplan et al. (1988).

The main diagenetic phase and increases laterally toward the fault zone; however, it decreases the fault conductivity in the direction of the fault, possibly creating local seals.

The fact that the main fault extends from less than 200 m (660 ft) (Keller et al., 1998) to below 3.7 km (2.3 mi) allowed us to observe that open microfractures were once present at all depths near the fault zone. At shallow depths, open microfractures (in the fault zone) enhanced the porosity, but at greater depths, they were cemented, and the porosity decreased relative to depth-equivalent nonfractured intervals.

Five out of ten δ18O ratios in veins indicate the presence of thermal anomalies, which suggest vertical

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Figure 11. Paraffinicity versus aromaticity index (PAI) for oils from groups 1 and 2, suggesting that if there has been leakage, it has not been sufficient to considerably fractionate crude oils. Supporting data in Table 3.

**EVAPORATIVE FRACTIONATION INDEX**

![Graph showing EVAPORATIVE FRACTIONATION INDEX]

Oil group 1

Oil group 2

1312 Mineralization, Fluid Flow, and Sealing Properties of a Thrust Fault
ascending flow in the range of 75–800 m (250–2600 ft). These results are consistent with other fault studies (i.e., Eichhubl and Boles, 1997, 2000), with data published by Losh (1998) and modeling results from Roberts and Nunn (1995). Thus, we conclude that fluids and heat were transported along the thrust fault from a vertical distance of at least 75–800 m (246–2600 ft). Short-scale fluid flow and diffusion are equally important mechanisms to explain fault cementation at Wheeler Ridge.

The organic geochemical data enabled us to trace hydrocarbon-migration pathways, determine traps, as well as to indirectly test our petrographic observations that indicate a vertical variation of conductivity in the fault zone. The deep section of the fault behaves as a seal to hydrocarbons, whereas the shallow section behaved as a lateral pathway for fluid migration. Paraffinity versus aromaticity index, API gravity distribution, and lack of a significant whole-oil δ13C_{PDB} fractionation evidenced either against hydrocarbon remigration or in favor of a seal in the intermediate zone of the fault.

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