

OIL-BEARING ROCKS OF THE DAVENPORT AND POINT REYES AREAS AND THEIR IMPLICATIONS FOR OFFSET ALONG THE SAN GREGORIO AND NORTHERN SAN ANDREAS FAULTS

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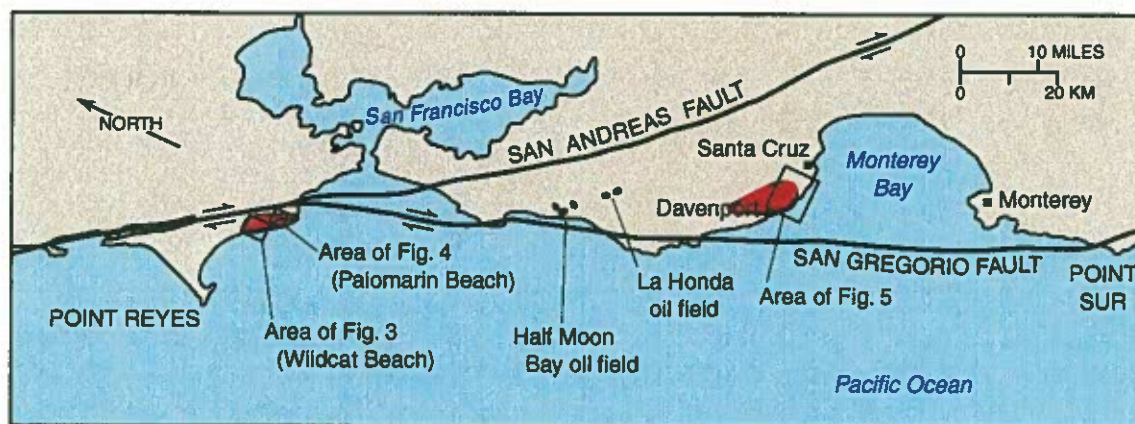
ABSTRACT

The San Gregorio fault extends about 200 km along the California coast from the Monterey Bay area to offshore Marin County, where it merges with the northern San Andreas fault. Outcrops of oil-bearing strata occur east of the San Gregorio fault near Davenport (Santa Cruz County) and west of the San Andreas fault near Point Reyes (Marin County). In both areas, much of the oil is in oil-bearing sandstone dikes and sills that intrude siliceous fine-grained strata of the upper Miocene Santa Cruz Mudstone.

Six oil samples from near Davenport, nine oil samples from near Point Reyes, and eight oil samples from the nearby Half Moon Bay and La Honda oil fields were analyzed for stable carbon isotopic composition and biomarkers. The results show that all 23 oil samples were derived from source rocks of Miocene age. The specific source rocks from which the oils were generated have not been unequivocally identified. However, source rock candidates in the Davenport and Point Reyes areas include the Santa Cruz Mudstone and Miocene Monterey Formation, whereas candidates in the Half Moon Bay and La Honda fields include the aforementioned two units as well as Miocene strata within the Lambert Shale.

Gas chromatograms of saturated hydrocarbons from the Davenport and Point Reyes oil samples show evidence of significant biodegradation, including large unresolved complex mixture humps and no identifiable n-alkanes. Furthermore, the biomarker data indicate heavy to severe biodegradation in several of the Davenport and Point Reyes oils. Analyses of biodegradation-resistant biomarkers using scatter plots and hierarchical cluster analysis indicate that the Davenport and Point Reyes oil samples are similar in composition to each other and different from Miocene oils in the Half Moon Bay and La Honda oil fields.

These remarkable similarities in geologic occurrence and organic geochemistry suggest the possibility that the oils and oil-bearing sandstone intrusions in the Davenport and Point Reyes areas share a common origin and that the two areas were formerly contiguous. We hypothesize



 Approximate area of oil-bearing sandstone intrusions in Santa Cruz Mudstone and Monterey Formation

Figure 1: Map showing San Gregorio and San Andreas faults and localities mentioned in text.

that the oils in both areas were generated from thermally mature, organic-rich Miocene strata in the vicinity of the Davenport syncline northwest of Santa Cruz, that oil migration and sandstone intrusion happened about 9–7 Ma, and that the Davenport and Point Reyes areas were subsequently separated by about 115 ± 10 km of right-lateral displacement along the San Gregorio and northern San Andreas faults.

INTRODUCTION

The San Andreas and San Gregorio faults of coastal California (Fig. 1) exhibit right-lateral strike-slip displacements of many kilometers since late Oligocene time. Detailed studies of offset sedimentary basins, deep-sea fans, volcanic fields, and other paleogeographic features show that about 300 to 330 km of right-lateral displacement has occurred along the San Andreas fault since about 25–20 Ma (Hill and Dibblee, 1953; Addicott, 1968; Clarke and Nilsen, 1973; Matthews, 1976; Stanley, 1987; Graham and others, 1989). Offset features along the San Gregorio fault include aeromagnetic and gravity anomalies, distinctive packages of crystalline and sedimentary rocks, and unusual conglomerates that together suggest about 90–180 km of right-lateral displacement since about 23 Ma (Silver, 1974; Graham and Dickinson, 1978a, b; Graham and Peabody, 1981; Clark and others, 1984; Clark, 1998; Jachens and others, 1998; Burnham, 1998).

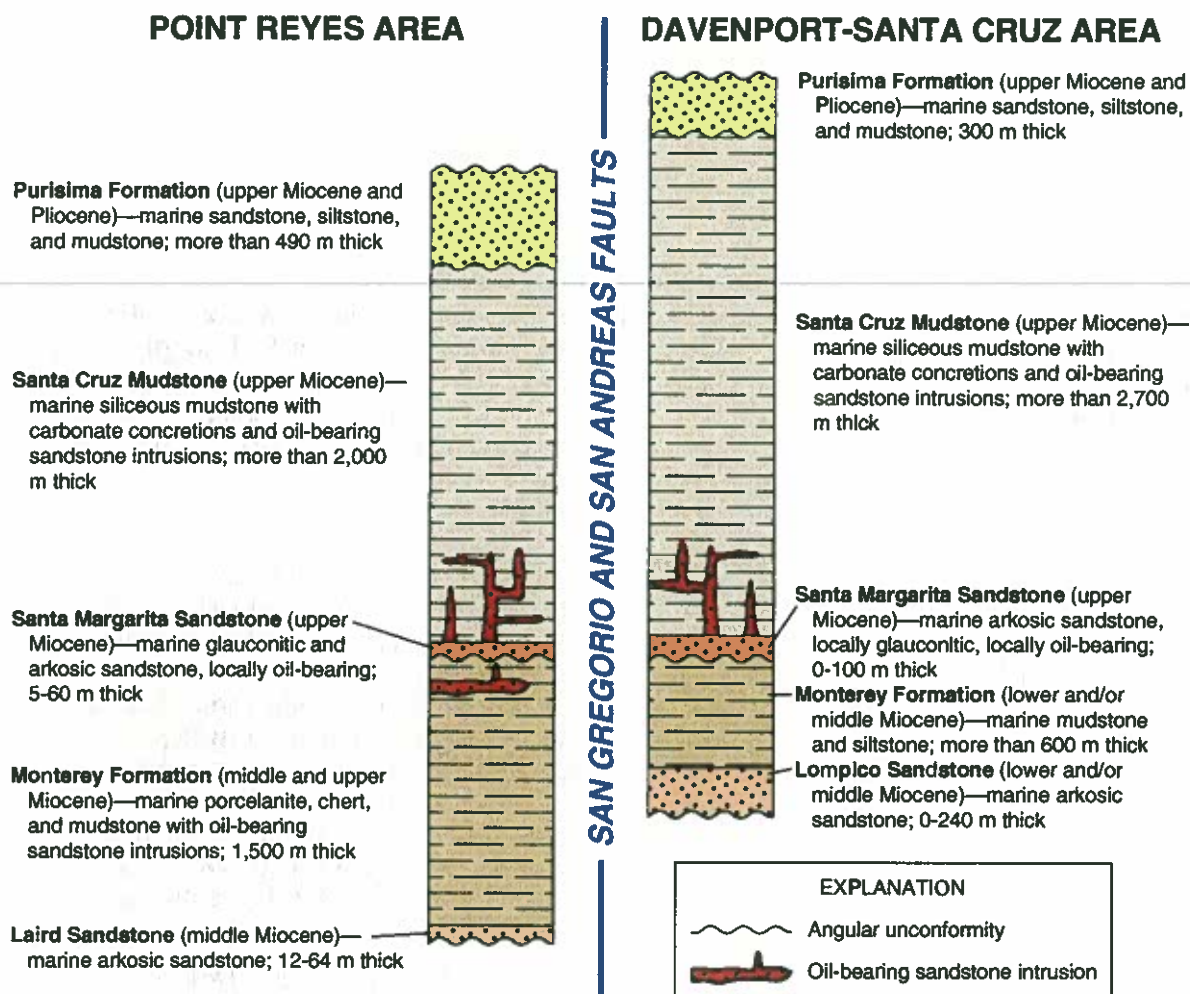


Figure 2: Schematic stratigraphic columns showing Miocene strata in the Point Reyes and Davenport areas, compiled from several sources including Clark (1981) and Clark and Brabb (1997).

During a study of natural surface occurrences of petroleum in coastal California (*Magoon and others, 1999*), we observed that oil-bearing sandstone intrusions in the Davenport and Point Reyes areas (Figs. 1–5) are similar to each other in geologic setting and organic geochemistry and are on opposite sides of the San Gregorio fault. Here we summarize these similarities and propose that the oil-bearing sandstone intrusions of the Davenport and Point Reyes areas share a common origin and were adjacent before about 115 km of right-lateral displacement along the San Gregorio and northern San Andreas faults.

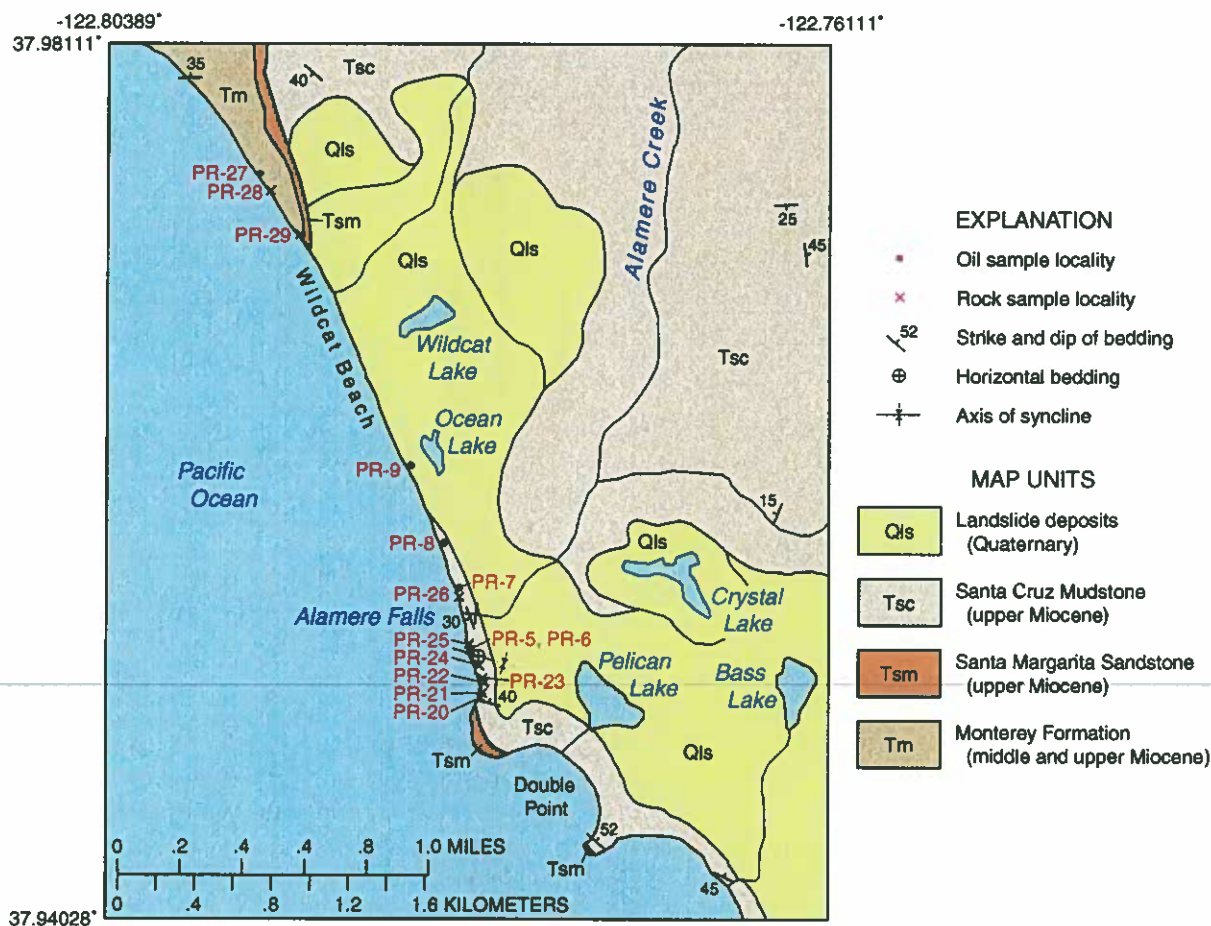


Figure 3: Geology and sample localities of the Wildcat Beach area near Point Reyes; see Fig. 1 for location. Geology modified from *Clark and Brabb (1997)*.

GEOLOGIC SETTING

Outcrops of oil-bearing strata occur east of the San Gregorio fault in the coastal area between Davenport and Santa Cruz (*Page and Holmes, 1945; Phillips, 1990*) and west of the fault at Wildcat Beach and Palomarin Beach near Point Reyes (*Galloway, 1977; Stanley, 1995; Clark and Brabb, 1997*). In these areas, the upper Miocene Santa Margarita Sandstone is oil-stained at many but not all localities, and the lower part of the upper Miocene Santa Cruz Mudstone contains numerous oil-filled fractures and oil-bearing sandstone dikes and sills that intrude siliceous fine-grained strata (Fig. 2). At Wildcat Beach, oil-filled fractures and oil-bearing sandstone intrusions are common in the Monterey Formation, but we have not observed similar oil-bearing strata in the Monterey Formation in the Davenport area (Fig. 2). About 8 km northwest of Davenport, oil-filled fractures occur in quartz diorite (*Phillips, 1990; Roberta K. Smith-Evenrden, consulting geologist, oral commun., 1999*), but oil-bearing crystalline rocks have not been reported from the Point Reyes area.

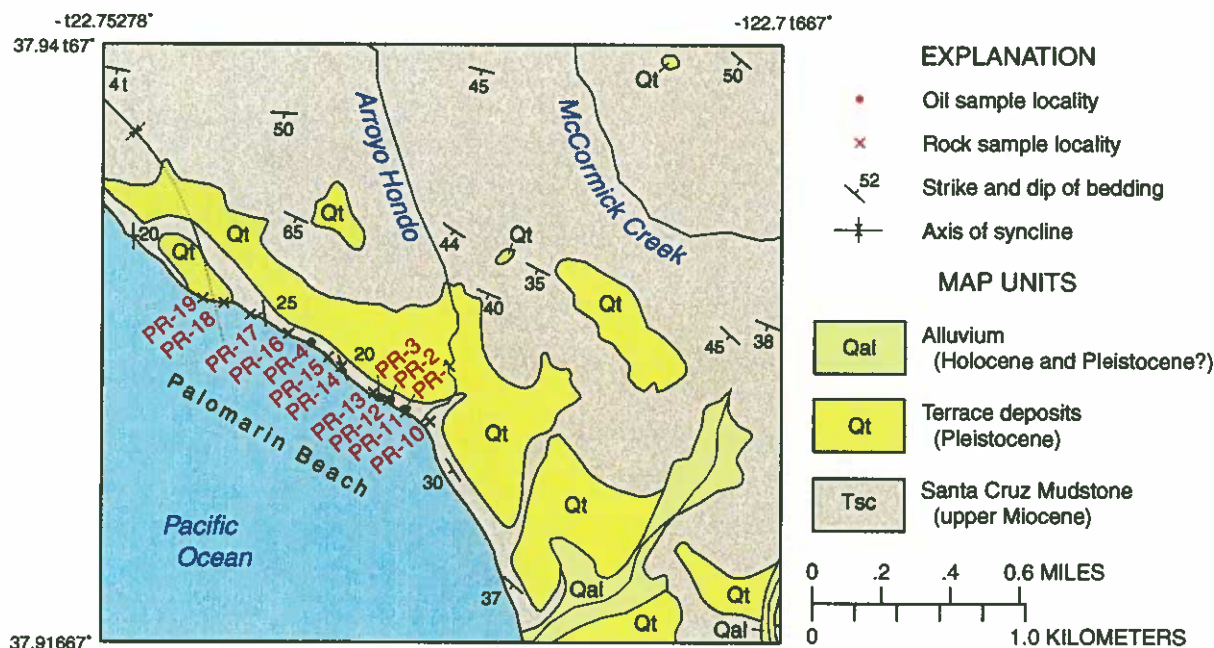


Figure 4: Geology and sample localities of the Palomar Beach area near Point Reyes; see Fig. 1 for location. Geology modified from *Clark and Brabb (1997)*.

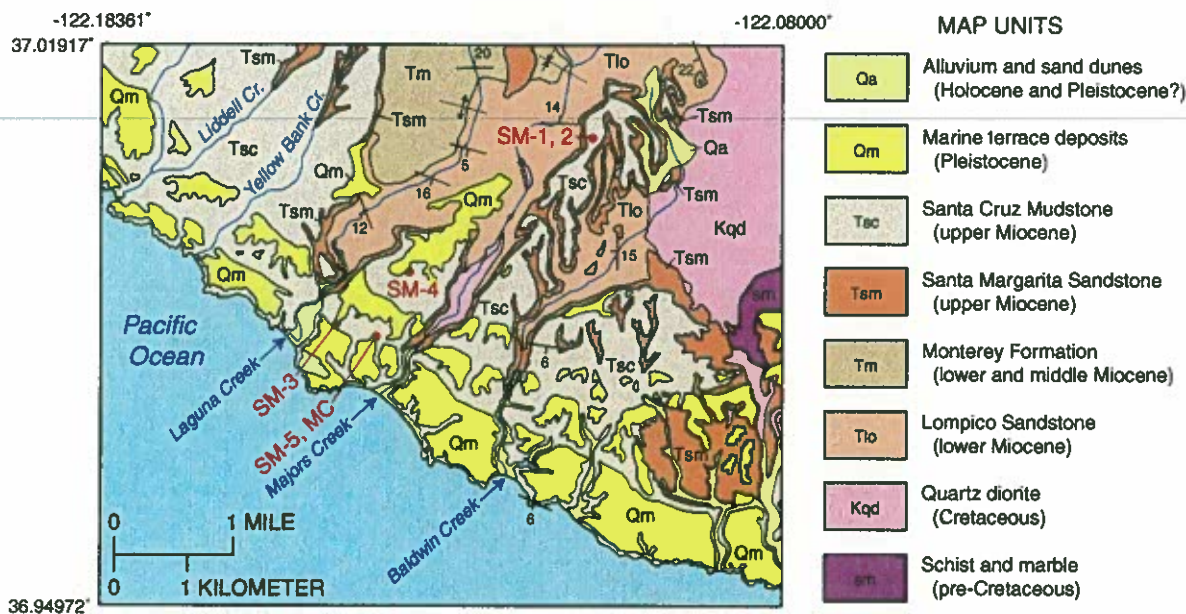


Figure 5: Geology and sample localities in an area between Davenport and Santa Cruz; see Fig. 1 for location and Figs. 3, 4 for explanation of symbols. Geology modified from *Clark (1981)*.

Sandstone intrusions in the Davenport area, many of them oil-bearing but many others apparently oil-free, are described in detail in several reports (*Eldridge, 1901; Newsom, 1903; Page and Holmes, 1945; Phillips, 1990; Thompson and others, 1999*). The sandstone intrusions of the Point Reyes area have not been described in detail, but all of the intrusions that we have

observed are oil-bearing. In both the Davenport and Point Reyes areas, the oil-bearing sandstone intrusions include dikes and sills that commonly range in width from a few millimeters to more than 5 m (Fig. 6) and persist laterally for distances of several meters to tens of meters. The largest reported intrusion near Davenport is mostly oil-free but partly oil-stained, at least 300 m wide, and traceable laterally for more than 600 m (*Thompson and others, 1999; Moore and others, 1999*).

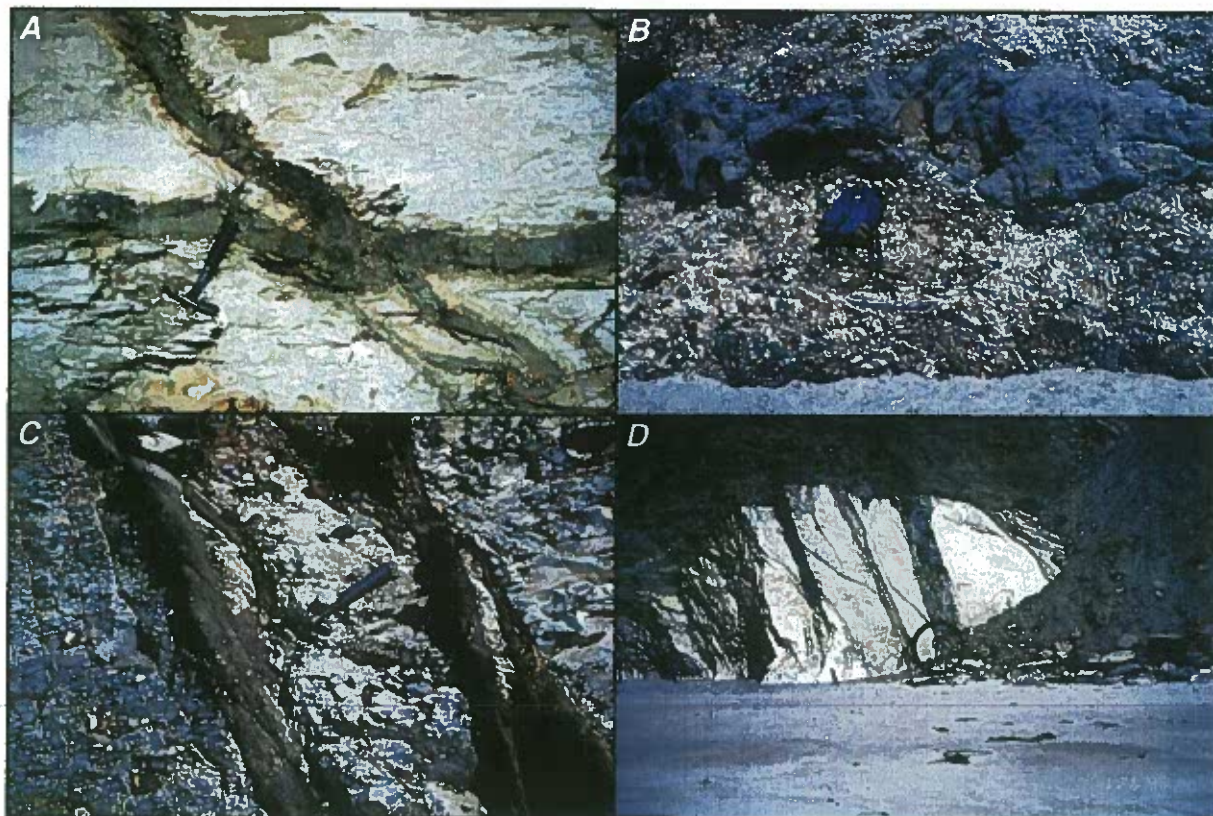


Figure 6: Outcrop photographs of oil-bearing sandstone intrusions. In photographs A, B, and C, bedding dips gently toward the camera. A, dark colored sandstone dikes and sills in lighter colored siliceous mudstone, Santa Cruz Mudstone near Davenport; rock hammer for scale. B, thick, dark colored sandstone sill in highly fractured, lighter colored siliceous mudstone, Santa Cruz Mudstone, Wildcat Beach; backpack for scale. C, dark colored sandstone dikes in siliceous mudstone, Santa Cruz Mudstone, Palomarin Beach; rock hammer for scale. D, dark colored sandstone dike (above circled figure), Monterey Formation, Wildcat Beach; bedding dips steeply toward camera; Paul Lillis for scale.

In the Davenport area, field and laboratory investigations indicate that the sandstone intrusions formed by injection of fluidized sands from the Santa Margarita Sandstone upward into fractured fine-grained strata of the Santa Cruz Mudstone (*Newsom, 1903; Page and Holmes, 1945; Phillips, 1990; Thompson and others, 1999*). Sandstone intrusions in the Santa Cruz Mudstone near Point Reyes may have formed in a similar manner, but this hypothesis remains to be tested by detailed investigations.

The precise mechanisms by which the Davenport and Point Reyes intrusions were emplaced are uncertain, but fluidization and injection of the sands may have been caused by a combination of (1) increased confining pressure created by deposition and induration of the Santa Cruz Mudstone; (2) an influx of fluids (including water, oil, and gas) from nearby, more deeply buried strata; and (3) liquefaction during seismic shaking (*Thompson and others, 1999; Boehm*

and Moore, in press). Some of the sandstone intrusions apparently were hydrocarbon-bearing at the time of emplacement (Phillips, 1990; Thompson and others, 1999), whereas other intrusions were water-saturated and hydrocarbon-free during initial emplacement and shortly thereafter were invaded by hydrocarbons and hydrocarbon-bearing sands (Thompson and others, 1999; Moore and others, 1999).

The precise times of the sandstone intrusion and hydrocarbon migration events are uncertain, but the intrusions in the lower part of the Santa Cruz Mudstone cannot be older than the strata they intrude. Biostratigraphic evidence indicates that deposition of the Santa Cruz Mudstone in both the Davenport and Point Reyes areas began about 9–8 Ma and ended about 7 Ma, prior to deposition of the lowest part of the overlying Purisima Formation about 6.7 Ma (J.A. Barron, U.S. Geological Survey, oral commun., 2000). In both the Davenport and Point Reyes areas, the sandstone intrusions are clearly older than the late Pleistocene deposits that rest in angular unconformity on the Purisima Formation and Santa Cruz Mudstone (Newsom, 1903; Clark and Brabb, 1997; Thompson and others, 1999). New, detailed field studies in the Davenport area show that at least some of the sandstone intrusions were emplaced at very shallow sediment levels and that some of the intrusions reached the sea floor and formed extrusions of sand during late Miocene deposition of the Santa Cruz Mudstone (Boehm and Moore, in press).

ORGANIC GEOCHEMICAL ANALYSES

A total of 23 oil samples from the Davenport and Point Reyes areas and the nearby Half Moon Bay and La Honda oil fields (Fig. 1) were analyzed for stable carbon isotopic composition ($\delta^{13}\text{C}_{\text{PDB}}$) and biomarkers (molecular fossils) in the Organic Geochemistry Laboratory of the Central Energy Resources Team, U.S. Geological Survey, Denver, Colorado. Five samples from near Davenport (SM-1, SM-2, SM-4, SM-5, and MC) and 8 samples from Wildcat and Palomarin Beaches near Point Reyes (PR-1, PR-2, PR-3, PR-4, PR-6, PR-7, PR-8, PR-9) were taken from sandstone intrusions in the upper Miocene Santa Cruz Mudstone. One sample (PR-27) from Wildcat Beach was taken from a sandstone intrusion in the middle and upper Miocene Monterey Formation. One sample (SM-3) was from an oil-filled fracture in a dolomite concretion in the Santa Cruz Mudstone in the Davenport area. All 5 samples from the Half Moon Bay oil field (HMB-1, HMB-3, HMB-d, HMB-m, HMB-Purisima) presumably were taken from sandstone reservoirs of Pliocene(?) age in the upper Miocene and Pliocene Purisima Formation. One sample (LH-4) from the La Honda oil field, main area, is from a sandstone reservoir in the Eocene Butano Sandstone, whereas 2 samples (LH-1, LH-8) from the La Honda oil field, south area, are from the lower Miocene "Burns sand," an unusual limestone reservoir (Stanley, 1990; El-Sabbagh and Ingle, 1990).

Fig. 7 compares the stable carbon isotopic compositions of the saturated and aromatic hydrocarbon fractions in our oil samples with the cross plot of Lillis and others (1999), which depicts the ranges of carbon isotopic values observed in California oils derived from source rocks of Eocene, Cretaceous(?), and Miocene age. The results show that (1) all 23 oil samples were derived from source rocks of Miocene age, and (2) the carbon isotopic compositions of the Davenport and Point Reyes oil samples are strikingly similar to each other but overlap with those of the Half Moon Bay and La Honda oils.

The specific source rocks from which the oils were generated have not been unequivocally identified. However, on the basis of Rock-Eval pyrolysis and other organic geochemical information (Hollander, 1984; Lillis and Stanley, 1999; Stanley and Lillis, 1999), we believe that the most likely source rock candidates in the Davenport and Point Reyes areas are the Santa Cruz Mudstone and Miocene Monterey Formation, whereas candidates in the Half Moon Bay and La Honda fields include the aforementioned two units as well as Miocene strata within the Lambert Shale.

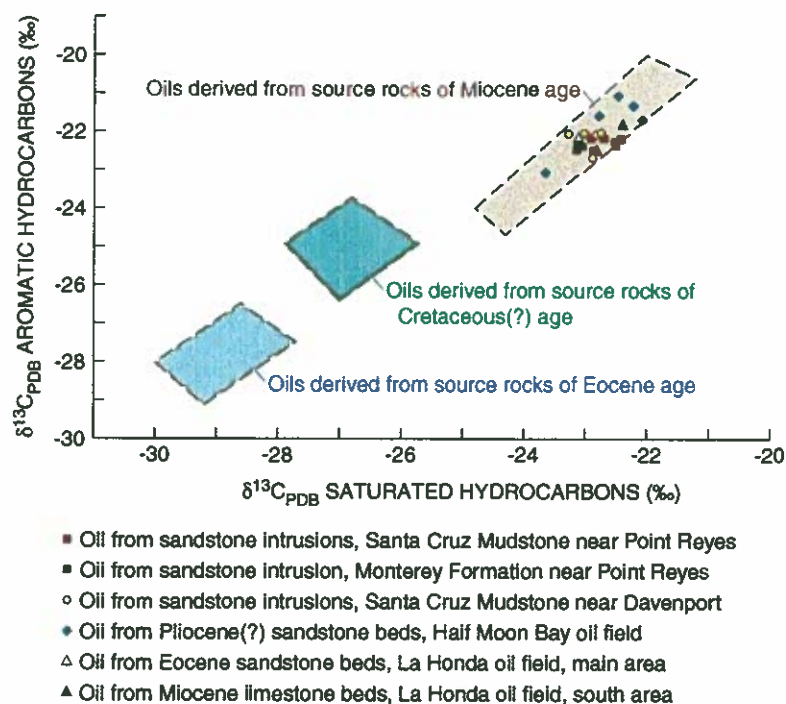


Figure 7: Stable carbon isotopic compositions of oil samples from outcrops in the Point Reyes and Davenport areas, and from wells in the Half Moon Bay and La Honda oil fields, shown on cross plot of *Lillis and others* (1999).

Gas chromatograms of saturated hydrocarbons from the Davenport and Point Reyes oil samples show evidence of significant biodegradation, including large unresolved complex mixture humps and no identifiable n-alkanes. Furthermore, the biomarker data indicate heavy to severe biodegradation in several of the Davenport and Point Reyes oils. Fig. 8A illustrates an example of a gas chromatogram of a biodegraded oil (sample SM-2, near Davenport), whereas Fig. 8B shows an example of a non-biodegraded oil (sample LH-4, La Honda oil field, main area).

Analyses of biodegradation-resistant biomarkers using 15 scatter plots (see example in Fig. 9) and hierarchical cluster analysis indicate that the Davenport and Point Reyes oil samples are similar in composition to each other and different from other Miocene oils in the Half Moon Bay and La Honda oil fields. Hierarchical cluster analysis was performed using a commercial

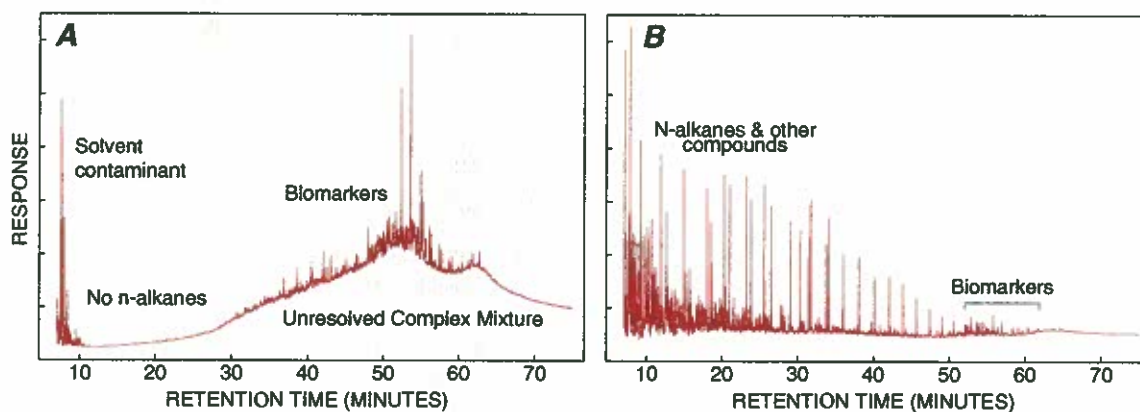


Figure 8: Examples of gas chromatograms of oils (saturated hydrocarbons only). A, Sample SM-2 from an outcrop near Davenport (Fig. 5), showing large Unresolved Complex Mixture hump. B, Sample LH-4 from the Neaves Petroleum Developments Neaves-Union-Lane No. 4 well, La Honda oil field, main area (Fig. 1).

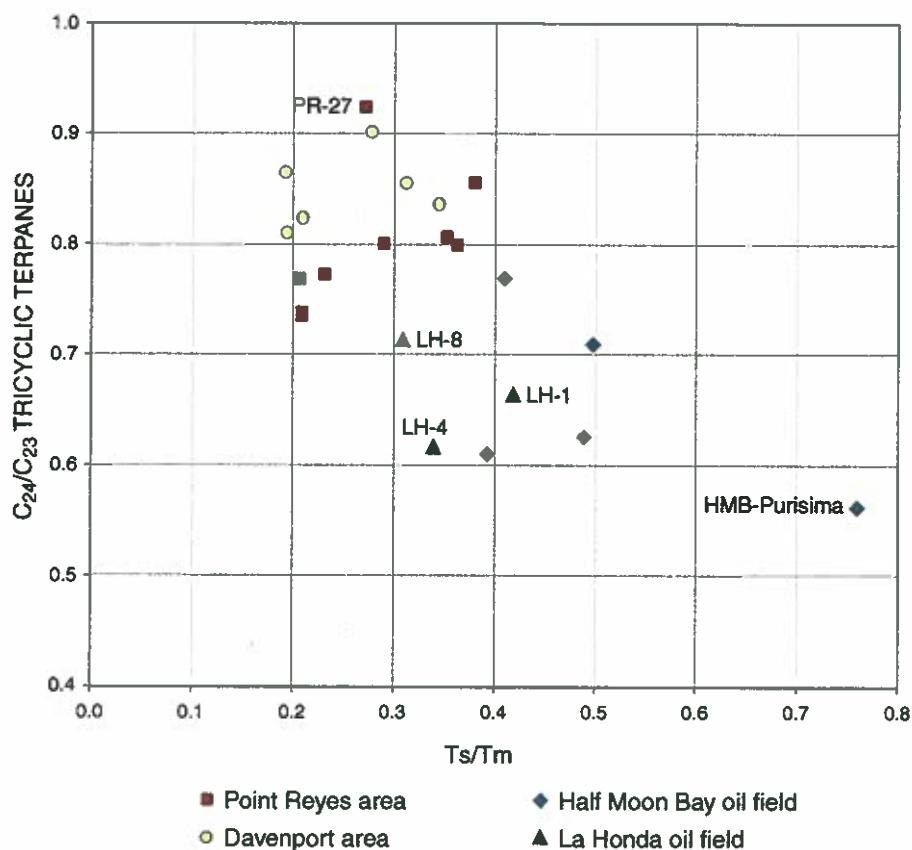


Figure 9: Plot of biodegradation-resistant biomarkers (C_{24}/C_{23} tricyclic terpanes versus Ts/Tm) showing the similar geochemical composition of oils from the Davenport and Point Reyes areas and differences from oils in the Half Moon Bay and La Honda oil fields.

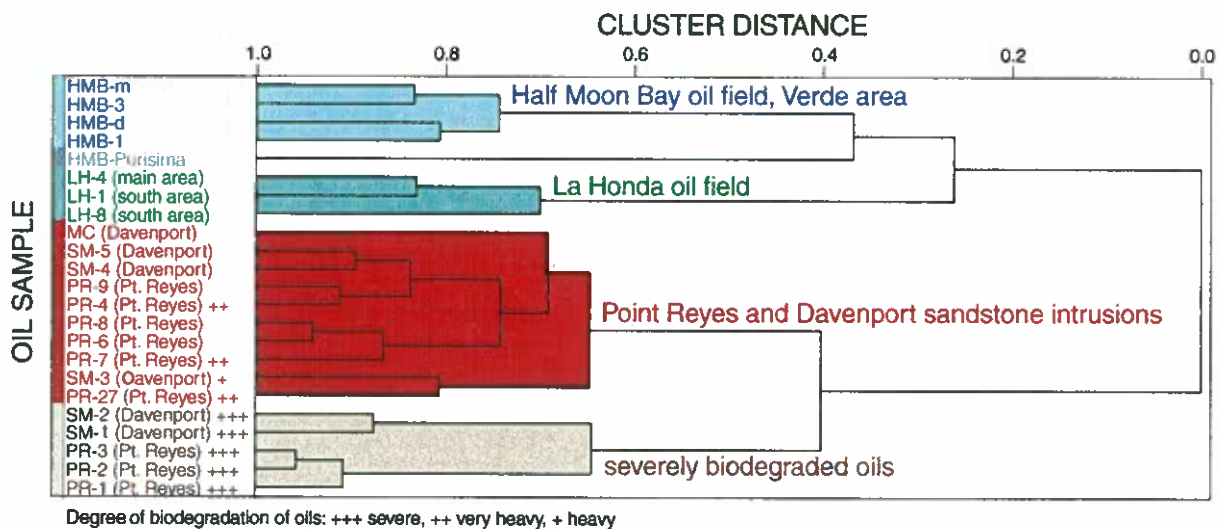


Figure 10: Dendrogram showing the genetic relationship between oils in the Davenport and Point Reyes areas based on statistical analysis of source-related geochemical data. Cluster distance is a measure of genetic similarity indicated by the horizontal distance of any two samples to their branch point.

chemometrics program, Einsight 4.04, with autoscale preprocessing, Euclidean metric distance, and incremental linkage to express sample relationships by multivariate analysis. The dendrogram (Fig. 10) shows a clear correlation between the Davenport and Point Reyes oils and distinctive differences from nearby Miocene oil fields. Specific biomarkers and ratios used in the cluster analysis include oleanane/gammacerane, C_{24}/C_{23} tricyclic terpane, C_{24} tetracyclic terpane/ C_{26} tricyclic terpane, C_{26} tricyclic terpane/Ts+Tm, C_{28} tricyclic terpane/Ts+Tm, and Ts/Tm, as well as the $\delta^{13}C_{PDB}$ aromatic hydrocarbon values. Severe biodegradation can explain the higher cluster distance of samples SM-2, SM-1, PR-3, PR-2, and PR-1 from the other Davenport and Point Reyes samples.

DISCUSSION AND CONCLUSIONS

Oil-bearing sandstone intrusions in the Davenport and Point Reyes areas resemble each other in that (1) the intrusions in both areas occur mainly in the lower part of the Santa Cruz Mudstone, (2) carbon isotopes indicate that the oils in both areas were derived from source rocks of Miocene age, and (3) biomarkers indicate that the Davenport and Point Reyes oils are similar to each other and different from other local oils. These remarkable similarities in geologic setting and organic geochemistry suggest that the oil-bearing sandstone intrusions in the Davenport and Point Reyes areas share a common origin and were adjacent to each other prior to 115 ± 10 km of right-lateral separation along the San Gregorio and northern San Andreas faults (Fig. 11). This suggestion appears to be compatible with previous estimates of right-lateral displacement along the faults of 175 km since about 23 Ma (Jachens and others, 1998), 150–160 km since about 10 Ma (Clark, 1998), and 19 km since about 3 Ma (Clark, 1998).

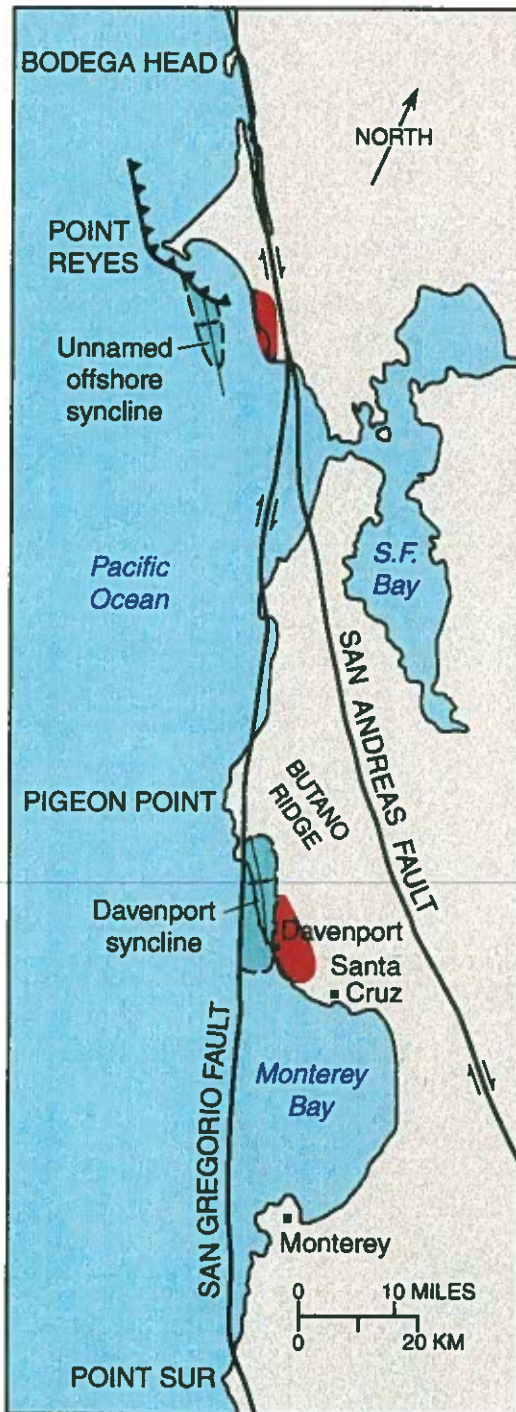
Three alternative hypotheses of the paleogeographic setting of the Davenport and Point Reyes oil-bearing sandstone intrusions are proposed below:

Hypothesis 1 (preferred)—Prior to 115 ± 10 km of right-lateral separation along the San Gregorio and northern San Andreas faults, oils in both the Point Reyes and Davenport areas were generated from thermally mature, organic-rich strata of Miocene age in the vicinity of the Davenport syncline, northwest of Davenport (Fig. 11). The oils migrated eastward into the Davenport area and westward into the Point Reyes area and contributed to the formation of sandstone intrusions in the Santa Cruz Mudstone. The timing of oil generation is uncertain, but it must have occurred during or before late Miocene emplacement of the sandstone intrusions.

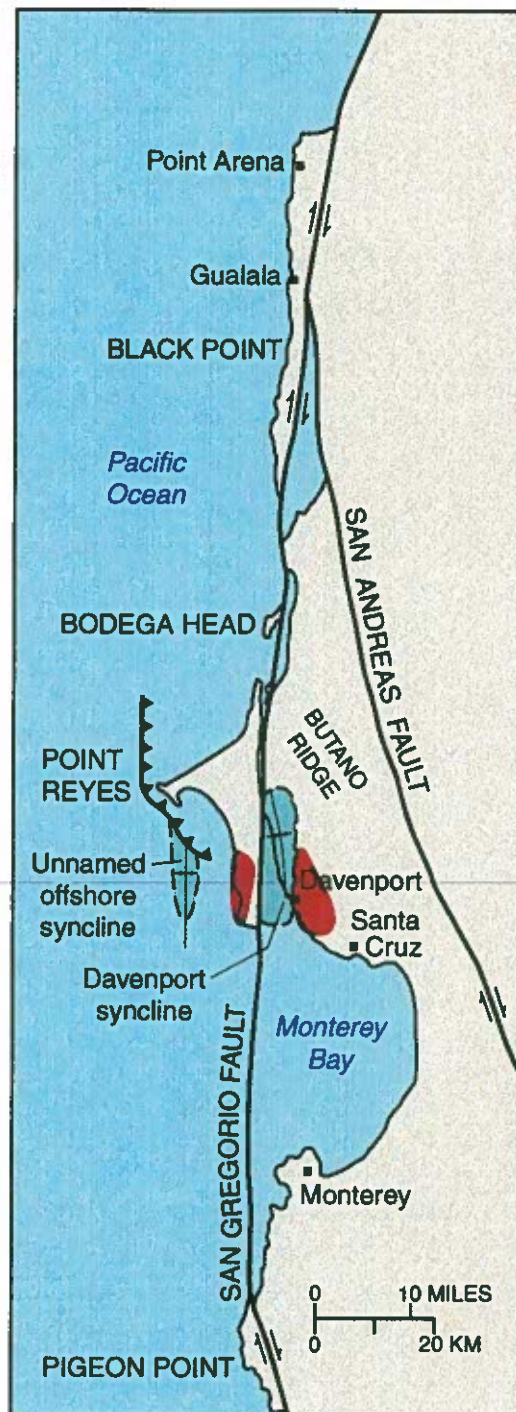
Hypothesis 2—Prior to 115 ± 10 km of right-lateral separation along the San Gregorio and northern San Andreas faults, oils in both the Point Reyes and Davenport areas were generated from thermally mature, organic-rich strata of Miocene age in an unidentified offshore area, perhaps in or near the unnamed syncline mapped by Heck and others (1990) southeast of Point Reyes (Fig. 11). This syncline corresponds to a gravity low (R.C. Jachens, oral commun., 1999) and is thought to include thick sequences of Monterey Formation and Santa Cruz Mudstone (Heck and others, 1990). The oils migrated eastward into the Point Reyes and Davenport areas and contributed to the formation of sandstone intrusions in the Santa Cruz Mudstone. As in hypothesis 1 (above), the timing of oil generation is uncertain but it must have occurred during or before late Miocene emplacement of the sandstone intrusions.

Hypothesis 3—Oils in the Point Reyes area were generated in the vicinity of the unnamed offshore syncline, whereas oils in the Davenport area were generated in the vicinity of the Davenport syncline (Fig. 11). In this scenario, the geologic and organic geochemical similarities of the oil-bearing sandstone intrusions in the two areas are unrelated and coincidental. Oil migration and sandstone intrusion in the Davenport area apparently occurred during late Miocene deposition of the Santa Cruz Mudstone, but could have occurred at the same time or at a different time in the Point Reyes area. This hypothesis permits, but does not require, large right-lateral displacement along the San Gregorio and San Andreas faults.

A. Present day:



B. About 9–7 Ma:



 Approximate area of oil-bearing sandstone intrusions in Santa Cruz Mudstone and Monterey Formation

 Hypothetical area of oil generation  Right-lateral fault, thrust fault

Figure 11: A, present day geography of part of coastal California. B, proposed paleogeographic reconstruction restoring 115 ± 10 km of right-lateral separation along the San Gregorio and northern San Andreas faults.

Fig. 12 compares the proposed 115 km of right-lateral offset of the Davenport and Point Reyes oil-bearing sandstone intrusions (hypotheses 1 and 2, above) with selected previous estimates of right-lateral separation along the San Gregorio and northern San Andreas faults. The proposed offset of the oil-bearing sandstone intrusions is of limited use in constraining long-term slip rates along the faults because the precise times of emplacement of the sandstone intrusions remain uncertain. The maximum possible age of the sandstone intrusions in the Santa Cruz Mudstone, about 9 Ma, implies slip rates along the San Gregorio and northern San Andreas faults of 40 mm/yr from 10 to 9 Ma and 16 mm/yr from 9 to 3 Ma (Fig. 12, interpretation A). Alternatively, if the sandstone intrusions formed about 6.7 Ma (the age of initial deposition of the Purisima Formation), the implied slip rates are 12.1 mm/yr from 9 Ma to 6.7 Ma and 25.9 mm/yr from 6.7 Ma to 3 Ma (Fig. 12, interpretation B). If the sandstone intrusions formed about 7.9 Ma (our preferred interpretation), the implied slip rate along the San Gregorio and northern San Andreas faults is 19.4 mm/yr from 10 Ma to 3 Ma (Fig. 12, interpretation C).

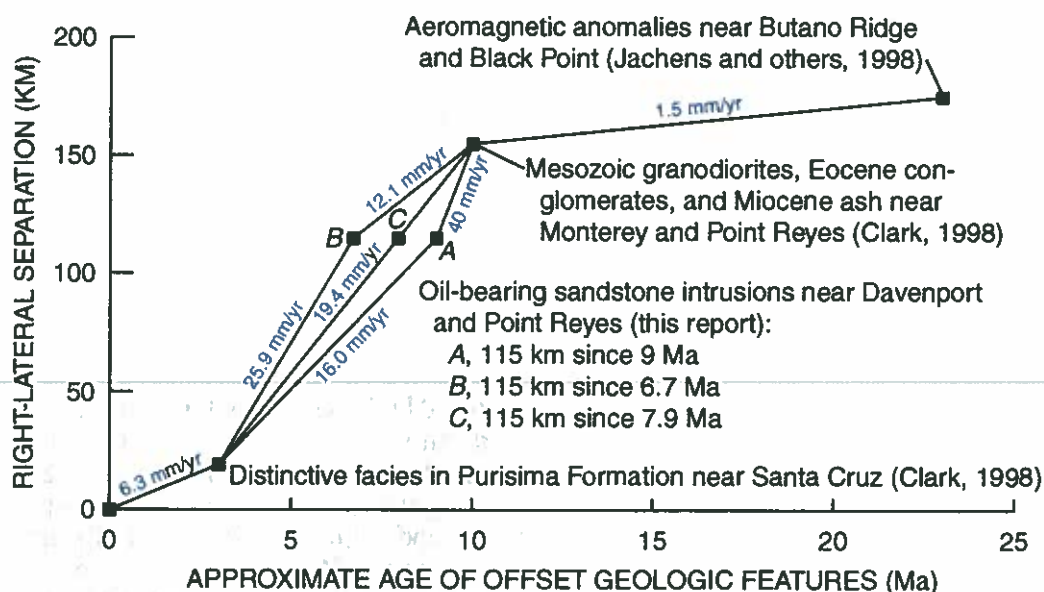


Figure 12: Graph of time (approximate age of offset geologic features) vs. displacement (right-lateral separation) along the San Gregorio and northern San Andreas faults since about 25 Ma. Filled squares represent reported ages and amounts of right-lateral separation for selected geologic features. The time of formation of the oil-bearing sandstone intrusions near Davenport and Point Reyes is uncertain; filled squares labeled A, B, and C show three possible interpretations. Lines connecting filled squares show some of the many possible interpretations of slip history along the fault; implied slip rates are shown in mm/yr.

We suggest that additional insights into the slip histories of the San Gregorio and northern San Andreas faults will arise from (1) additional geological investigations, particularly in the Point Reyes area, that lead to better understanding of the timing and mode of origin of the sandstone intrusions, and (2) additional organic geochemical studies that clarify the timing of oil generation and that yield unambiguous correlations of the Davenport and Point Reyes oils with their source rocks.

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