

Evaluation of Hypotheses for Right-Lateral Displacement of Neogene Strata Along the San Andreas Fault Between Parkfield and Maricopa, California



Scientific Investigations Report 2017–5125

Cover. Cattle drive in Parkfield, California, looking east along Ranchita Canyon Road. The San Andreas Fault is located just beyond the hills on the skyline. Photo by Rick Stanley, U.S. Geological Survey, March 23, 2010.

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By Richard G. Stanley, John A. Barron, and Charles L. Powell, II

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Evaluation of Hypotheses for Right-Lateral Displacement of Neogene Strata Along the San Andreas Fault Between Parkfield and Maricopa, California

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Abstract

We used geological field studies and diatom biostratigraphy to test a published hypothesis that Neogene marine siliceous strata in the Maricopa and Parkfield areas, located on opposite sides of the San Andreas Fault, were formerly contiguous and then were displaced by about 80–130 kilometers (km) of right-lateral slip along the fault. In the Maricopa area on the northeast side of the San Andreas Fault, the upper Miocene Bitterwater Creek Shale consists of hard, siliceous shale with dolomitic concretions and turbidite sandstone interbeds. Diatom assemblages indicate that the Bitterwater Creek Shale was deposited about 8.0–6.7 million years before present (Ma) at the same time as the uppermost part of the Monterey Formation in parts of coastal California. In the Parkfield area on the southwest side of the San Andreas Fault, the upper Miocene Pancho Rico Formation consists of soft to indurated mudstone and siltstone and fossiliferous, bioturbated sandstone. Diatom assemblages from the Pancho Rico indicate deposition about 6.7–5.7 Ma (latest Miocene), younger than the Bitterwater Creek Shale and at about the same time as parts of the Sisquoc Formation and Purisima Formation in coastal California. Our results show that the Bitterwater Creek Shale and Pancho Rico Formation are lithologically unlike and of different ages and therefore do not constitute a cross-fault tie that can be used to estimate right-lateral displacement along the San Andreas Fault.

In the Maricopa area northeast of the San Andreas Fault, the Bitterwater Creek Shale overlies conglomeratic fan-delta deposits of the upper Miocene Santa Margarita Formation, which in turn overlie siliceous shale of the Miocene Monterey Formation from which we obtained a diatom assemblage dated at about 10.0–9.3 Ma. Previous investigations noted that the Santa Margarita Formation in the Maricopa area contains granitic and metamorphic clasts derived from sources in the northern Gabilan Range, on the opposite side of the San Andreas Fault, that have moved relatively northwestward by 254 ± 5 km of right-lateral displacement along the fault. Our new diatom ages suggest that Santa Margarita deposition and fault displacement began about 10–8 Ma and imply long-term average slip rates along the San Andreas Fault of about 25–32 millimeters per year (mm/yr),

about the same as published estimates of Quaternary average slip rates based on geologic and geodetic studies.

Introduction

The San Andreas Fault of California (fig. 1) is the most famous and perhaps the most intensively studied earthquake fault in the world. Detailed investigations of offset sedimentary basins, deep-sea fans, volcanic fields, and other geologic features show that about 330–300 kilometers (km) of right-lateral displacement has occurred along the fault since about 25–20 million years before present (Ma) (Hill and Dibblee, 1953; Dibblee, 1966; Addicott, 1968; Clarke and Nilsen, 1973; Matthews, 1976; Stanley, 1987; Graham and others, 1989). Additional right-lateral slip may have occurred along the fault before 25–20 Ma (Nilsen and Clarke, 1975; Sharman and others, 2013).

This report focuses on the suggestion of Dibblee (1966, his figure 5) that Neogene strata in the Maricopa and Parkfield areas, located on opposite sides of the San Andreas Fault, have been separated from each other by about 50 miles (mi) (80 km)¹ of right-lateral displacement (fig. 1). Dibblee (1966) did not name the stratigraphic units that he believed were displaced, so we determined their names by comparing his original map (Dibblee, 1966, his figure 5) to published 1:24,000-scale geologic maps. In the Maricopa area on the northeast side of the San Andreas Fault (fig. 2), geologic maps by Dibblee (2005a,b,c,g), Ryder and Thomson (1989), and Vedder (1970) show that the “Pliocene marine sands” at locality A (fig. 1) correspond to the upper Miocene Panorama Hills formation of Dibblee (1962), whereas the “Pliocene(?) marine siliceous mudstone” at locality B is the

¹We note that the distance along the San Andreas Fault between points B and D on the map of Dibblee (1966, his figure 5; and figure 1 of this report) is about 80 mi (130 km) when measured using the scale bar provided on his map, rather than 50 mi (80 km) as stated in Dibblee’s report. As a cross-check, we plotted the locations of points B and D on a 1:750,000-scale geologic map of California (Jennings, 1977) and verified that the distance between them is 80 mi (130 km). We suggest, but don’t know for sure, that the published estimate of 50 mi in Dibblee (1966) is a topographical error.

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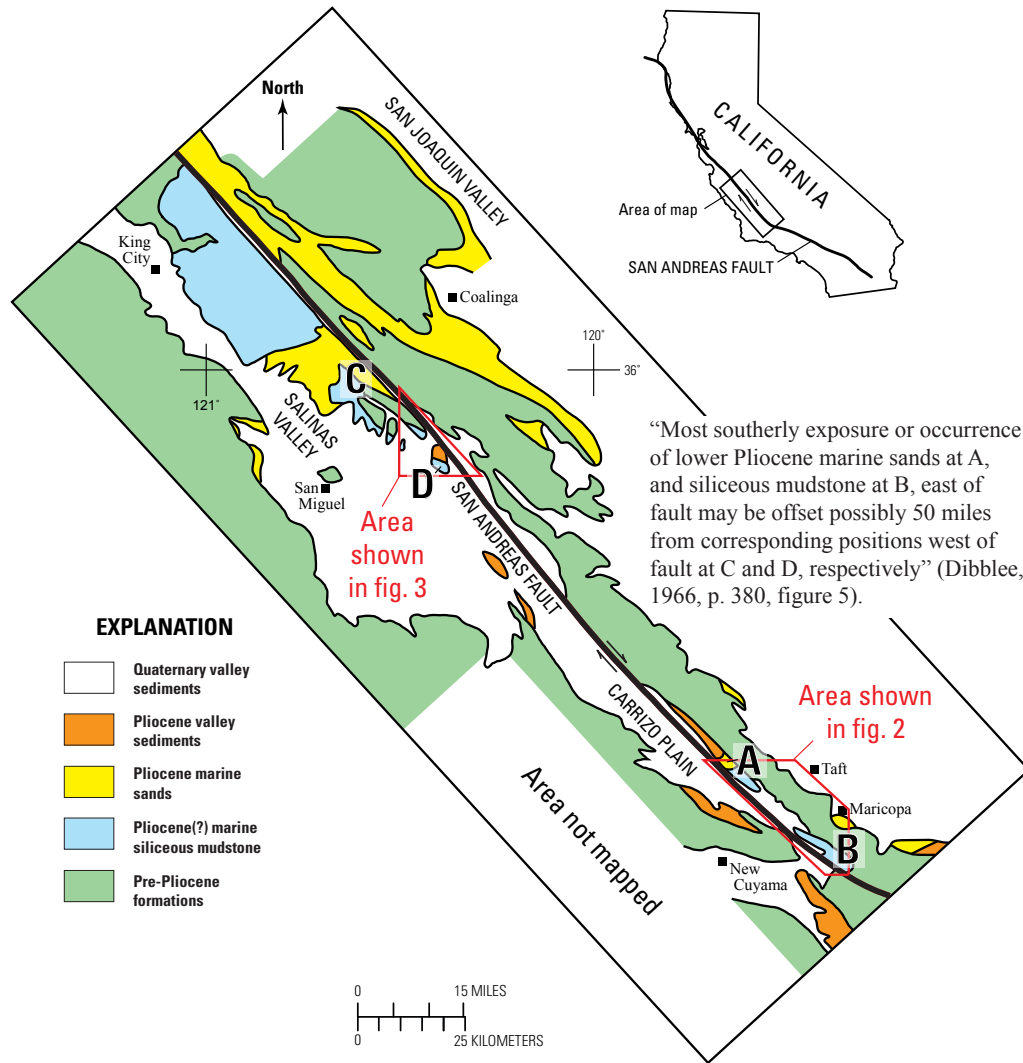


Figure 1. Redrafted version of figure 5 of Dibblee (1966) showing geologic features that may have been displaced by right-lateral offset along the San Andreas Fault. This redrafted version differs from Dibblee’s original in that it has been rotated about 43 degrees counterclockwise so that north is toward the top of the page; colors rather than patterns are used to distinguish map units; map scale and explanation of map units were moved outside the map boundary, leaving a gap labeled “area not mapped”; lines and lettering showing latitude and longitude were simplified for clarity but were otherwise unchanged; the name “Cuyama” was changed to “New Cuyama,” which is in better agreement with the location shown in the original figure; and locations of figures 2 and 3 were added.

upper Miocene Bitterwater Creek Shale.² In the Parkfield area on the southwest side of the San Andreas Fault (fig. 3), geologic maps by Dibblee (2005d,e,f) and Sims (1990) show that Dibblee’s “Pliocene(?) marine siliceous mudstone” at locality D (fig. 1) is the late Miocene lower part of the Pancho

²Prior to recalibration of the California molluscan and benthic foraminiferal stages using planktic microfossils, and prior to recognition that the boundary between the Miocene and Pliocene is about 5 Ma, the ages of the Bitterwater Creek Shale, the Panorama Hills formation of Dibblee (1962), and certain other late Miocene geologic units in California were previously considered to be Pliocene (Addicott, 1977; Marincovich, 1984a,b; Poore and others, 1984).

Rico Formation. We are uncertain about the identity of the “Pliocene marine sands” at locality C (fig. 1), but we note that they may correspond, partly or entirely, to the unnamed sandstone and conglomerate units Tuc, Tus, Tsg, Tgr, and Tsm of Dibblee (2007).

If Dibblee’s (1966) proposed cross-fault correlation of marine siliceous mudstone units at localities B and D (fig. 1) is correct, then the rocks at localities B and D should be similar in age and lithology. We tested this hypothesis by investigating the lithologies of the rocks at locality B (the Bitterwater Creek Shale in the Maricopa area) and locality D (the Pancho Rico Formation

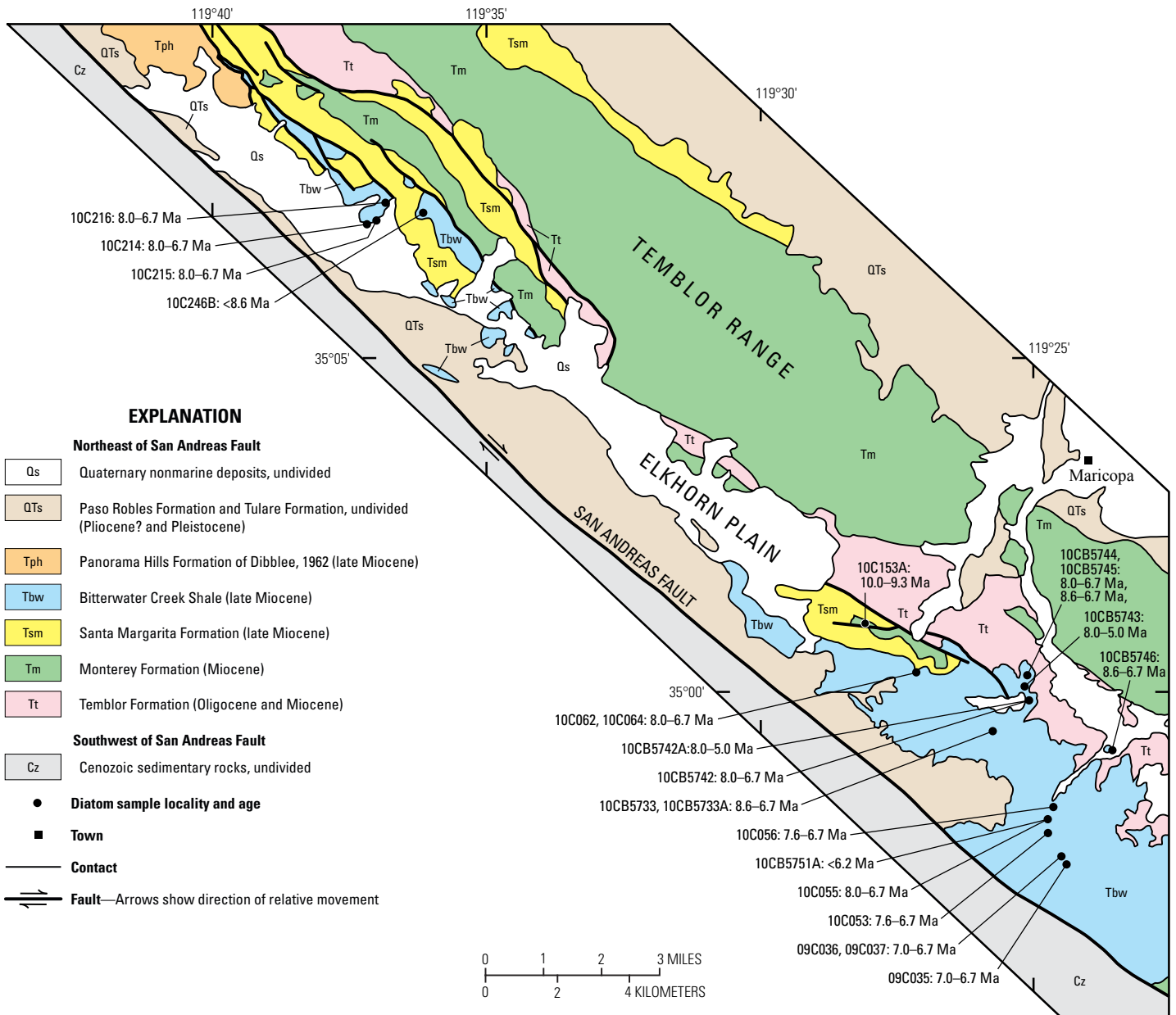


Figure 2. Generalized geologic map of the Maricopa area, modified from Ryder and Thomson (1989) and Dibblee (2005b,g), showing diatom sample localities and ages inferred from diatom biostratigraphy.

in the Parkfield area) and by collecting samples from these units and using diatom biostratigraphy to determine their ages. Our results show that rocks at localities B and D are dissimilar in age and lithology and therefore do not provide a valid cross-fault correlation that can be used to estimate right-lateral displacement along the San Andreas Fault.

In this study, we did not attempt to compare the marine sands at localities A and C (fig. 1) because—as noted above—we are uncertain about the identity of the geologic units at locality C, and because outcrops in the vicinity of locality C are poor and mostly on private property with restricted access.

Stratigraphy of the Maricopa Area

Tertiary strata on the northeast side of the San Andreas Fault near Maricopa (figs. 1, 2) are exposed on the southwest flank of the northwest-trending Temblor Range (fig. 2). The Tertiary strata are deformed by northwest-striking folds that locally are overturned and cut by northwest-striking normal and reverse faults (Ryder and Thomson, 1989).

In this area (fig. 2), the oldest exposed geologic unit is the upper Oligocene and lower Miocene Temblor Formation, which consists of marine sandstone and shale with fossil foraminifers

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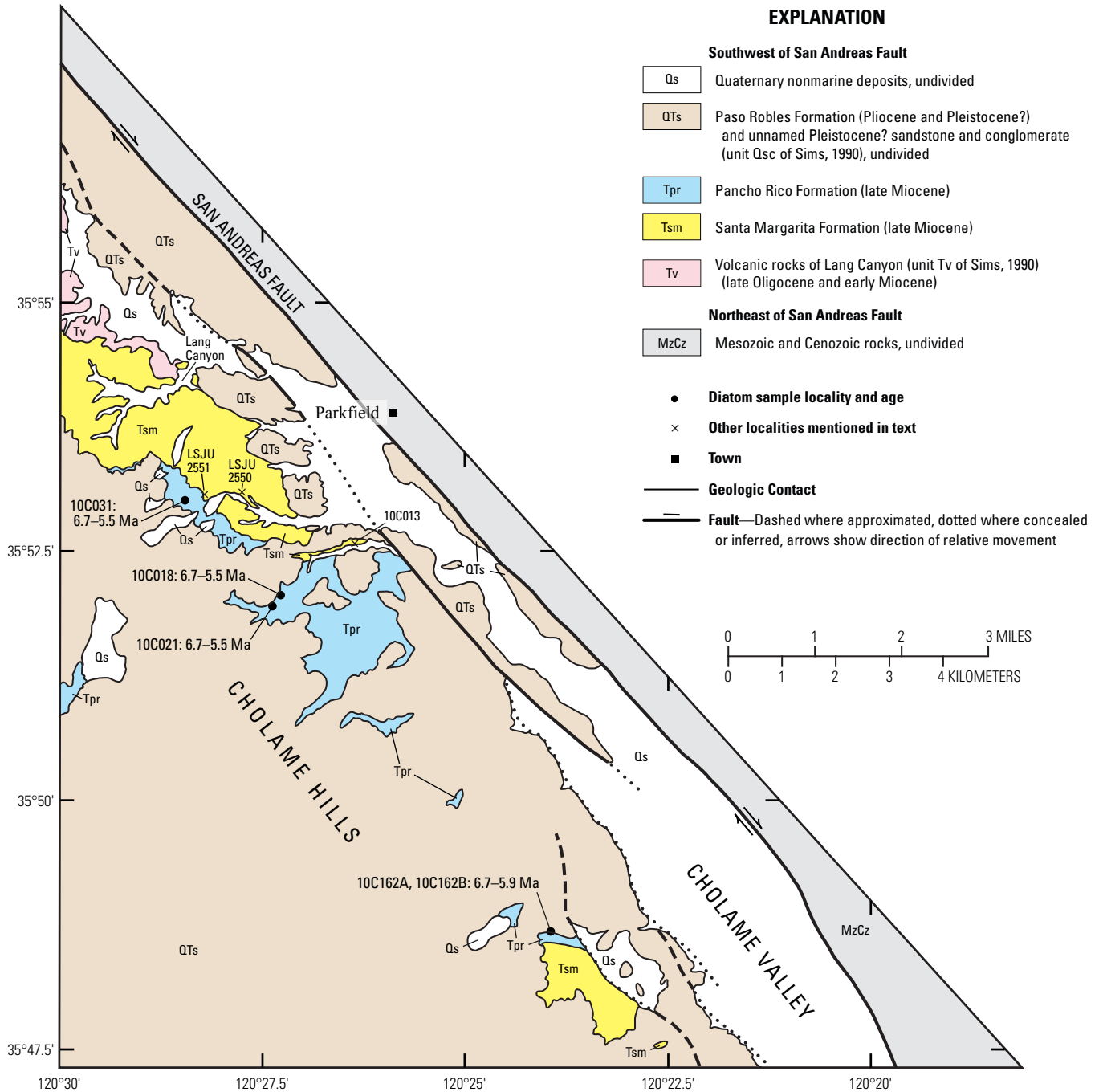


Figure 3. Generalized geologic map of the Parkfield area, modified from Dibblee (2005d,e,f) and Sims (1988, 1990), showing diatom sample localities, ages inferred from diatom biostratigraphy, and other localities mentioned in the text.

representative of the Zemorrian and Saucesian benthic foraminiferal stages (fig. 4; Kleinpell, 1938, 1980; Bent, 1985; Graham and others, 1989). Sandstones in the Temblor Formation in the area of figure 2 were derived from a granitic source terrane located west of the current position of the San Andreas Fault, which may not have existed at that time, and were deposited by sediment gravity flows at middle to lower bathyal depths on a

deep-sea fan (Graham and others, 1989).³ The thickness of the Temblor Formation in the Maricopa area is uncertain because the lower part of the unit is not exposed, but published cross sections

³In the northern Temblor Range, north of the area shown in fig. 2, the Temblor Formation includes shallow-marine sedimentary facies (Addicott, 1973; Carter, 1985), but no shallow-marine strata have been reported from the Temblor Formation in the Maricopa area (fig. 2).

TIME (Ma)	EPOCH	FORAMINIFERAL STAGE	CALIF. PROVINCIAL MOLLUSCAN STAGE ¹	UNITS IN PARKFIELD AREA	UNITS IN MARICOPA AREA	
5	Pleistocene	Late/Middle	Hallian	Quaternary, undivided	Quaternary, undivided	
		Early	Wheelerian	Paso Robles Formation and unit Qsc of Sims (1990), undivided	Paso Robles Formation and Tulare Formation, undivided	
			Venturian			
	Pliocene	Late	Repettian	"San Joaquin"	Hiatus	Hiatus
		Early	Delmontian	"Etchegoin"	Hiatus	Hiatus
	10	Late	Delmontian	"Jacalitos"	Pancho Rico Formation	Panorama Hills Fm. ²
			Mohnian	"Margaritan"	Santa Margarita Formation	Bitterwater Creek Shale
		Middle	Luisian		Hiatus	Hiatus
			Relizian			
		Early	Saucesian	"Vaqueros"	Hiatus	Hiatus
Zemorrian						
25	Oligocene	Late	Zemorrian	Volcanic rocks of Lang Canyon (Sims, 1990)		

¹California provincial molluscan stage of Addicott (1972).

²Panorama Hills formation (informal) of Dibblee (1962).

Figure 4. Stratigraphic units of the Maricopa and Parkfield areas (see figs. 1–3 for locations). Unconformities are shown as wavy lines. Geologic time scale from Orndorff and others (2010) and Cohen and others (2016). Ages of California provincial molluscan stages of Addicott (1972) shown according to Bartow (1992).⁴ Ages of benthic foraminiferal stages of Kleinpell (1938, 1980) shown according to McDougall (2007). fm., formation.

⁴The molluscan stages are based on extensive stratigraphic and faunal data that are adequate for provincial age determination and correlation, and their names are placed in quotation marks to indicate that they are informal (Addicott, 1972; Marincovich, 1984b). In some cases, the names of the molluscan stages are similar or identical to the names of lithostratigraphic units (formations), a confusing situation that could be fixed by renaming the molluscan stages (Addicott, 1972, p. 2; Marincovich, 1984b, p. 14).

suggest that the Temblor may be as thick as 2,000 meters (m) or more (Ryder and Thomson, 1989).

On the southwest side of the Temblor Range, the Temblor Formation is overlain sharply and conformably (Graham and others, 1989, p. 716 and their figure 5) by the Miocene Monterey Formation which contains fossil foraminifers representative of the Relizian, Luisian, and Mohnian benthic foraminiferal stages



Figure 5. Field photograph showing outcrop of Monterey Formation at locality 10C153A (fig. 2, southeast of Elkhorn Plain) consisting of hard siliceous shale with orange-weathering, diatom-bearing dolomitic concretions in a natural exposure on a steep hillside. Hammer (inside white circle) is 30 centimeters long.

of Kleinpell (1938, 1980). In this area, the Monterey Formation ranges in thickness from 450 to 2,700 m or more and consists mainly of marine siliceous shale and mudstone with interbeds of fine-grained sandstone (Ryder and Thomson, 1989). At locality 10C153A in the southeastern Temblor Range (fig. 2), we collected a sample of an orange-weathering dolomitic concretion (fig. 5) from the upper part of the Monterey Formation near its contact with the overlying Santa Margarita Formation. Acid digestion of this sample yielded a diatom assemblage of the late Miocene Subzone d of the *Denticulopsis lauta-D. hustedtii* Zone of Barron (1981) with an estimated age of 10.0–9.3 Ma (table 1, appendix).



Figure 6. Field photograph showing outcrop of Bitterwater Creek Shale at locality 10C214 (fig. 2, northwest of Elkhorn Plain) consisting of hard siliceous shale with orange-weathering, diatom-bearing dolomitic concretions in a natural exposure along a dry stream. Hammer (inside white circle) is 30 centimeters long.

In the Maricopa area and throughout much of central California, the Monterey Formation is unconformably overlain by the upper Miocene Santa Margarita Formation (Ryder and Thomson, 1989). On the west side of the Temblor Range, the Santa Margarita Formation is about 500 m thick (Ryder and Thomson, 1989, p. 54) and consists mostly of conglomerate and sandstone thought to have been derived from granitic, metamorphic, and volcanic rocks located west of the San Andreas Fault in the Gabilan Range, now displaced to the northwest by right-lateral slip along the San Andreas Fault (Huffman, 1972). The conglomerate and sandstone are thought to have been deposited on the subaerial and subaqueous portions of fan deltas that prograded from west to east into the marine Miocene San Joaquin basin (Ryder and Thomson, 1989). The Santa Margarita Formation was subdivided into four mappable members by Ryder and Thomson (1989), who noted the presence of many channelform bodies of conglomerate and sandstone, numerous internal unconformities, and packages of inclined strata that are tens of meters thick and resemble large-scale cross-stratification. Deposition of the Santa Margarita Formation in the Maricopa area is thought to have been coeval with strike-slip displacement along the San Andreas Fault and uplift of the Gabilan Range (Huffman, 1972; Ryder and Thomson, 1989).

The Santa Margarita Formation is overlain unconformably by the Bitterwater Creek Shale (Vedder, 1970; Ryder and Thomson, 1989), which consists mainly of gray- to white-weathering, hard, thin- to thick-bedded siliceous shale and porcelanite with orange-weathering dolomitic concretions (figs. 6, 7, 8) with interbeds of turbidite sandstone in places. The siliceous shale and porcelanite commonly exhibit conchoidal fracture and, in places, weather into pencil-like fragments (fig. 7). Sandstone dikes and sills are locally abundant. Northwest of locality 10C216 (northern part of fig. 2), the siliceous shale grades northwestward into sparsely fossiliferous, shallow marine sandstone (Vedder, 1970; Ryder and



Figure 7. Field photograph showing outcrop of Bitterwater Creek Shale near locality 10C214 (fig. 2, northwest of Elkhorn Plain) consisting of hard siliceous shale weathering to pencil-like fragments in a natural exposure along a dry stream. Hammer is 30 centimeters long.

Table 1. Ages of fossil diatom assemblages from outcrop samples of Miocene marine sedimentary rocks in the Parkfield and Maricopa areas, California.

[See figures 2 and 3 for sample locations and appendix for floral lists. Fossil identifications and age assignments by J.A. Barron with diatom zones after Barron (1981). Datum for latitude and longitude is NAD27 CONUS. Ma, millions of years before present; sp., species. Map units: Tbw, Bitterwater Creek Shale; Tpr, Pancho Rico Formation; Tm, Monterey Formation. Collectors: EEB, E.E. Brabb; RGS, R.G. Stanley]

Sample	Collector	Latitude	Longitude	Map unit	Lithology	Estimated age, Ma	Remarks
09C035	RGS	34.95677	-119.40729	Tbw	Dolomitic concretion	7.0–6.7	Late Miocene, uppermost part of Subzone a of the <i>Nitzschia reinholdii</i> Zone
09C036	RGS	34.95876	-119.40887	Tbw	Dolomitic concretion	7.0–6.7	Late Miocene, uppermost part of Subzone a of the <i>Nitzschia reinholdii</i> Zone
09C037	RGS	34.95889	-119.40901	Tbw	Dolomitic concretion	7.0–6.7	Late Miocene, uppermost part of Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C053	RGS	34.96471	-119.41282	Tbw	Dolomitic concretion	7.6–6.7	Late Miocene, Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C055	RGS	34.96839	-119.41314	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C056	RGS	34.97118	-119.41136	Tbw	Dolomitic concretion	7.6–6.7	Late Miocene, Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C062	RGS	35.00539	-119.45269	Tbw	Dolomitic concretion	8.0–6.7	Likely late Miocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C064	RGS	35.00466	-119.45322	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C214	RGS	35.11702	-119.61906	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene
10C215	RGS	35.11758	-119.61727	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene, either Subzone b of the <i>Thalassiosira antiqua</i> Zone or Subzone a of the <i>Nitzschia reinholdii</i> Zone
10C216	RGS	35.12228	-119.61398	Tbw	Dolomitic concretion	8.0–6.7	Likely late Miocene
10C246B	RGS	35.11937	-119.60252	Tbw	Dolomitic concretion	<8.6	Younger than 8.6 Ma
10CB5733	EEB	34.99021	-119.42956	Tbw	Siliceous mudstone	8.6–6.7	Late Miocene, likely Subzone a of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10CB5733A	EEB	34.99021	-119.42956	Tbw	Limestone	8.6–6.7	Late Miocene, Subzone a of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10CB5742	EEB	34.99791	-119.41866	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone. <i>Pyxilla</i> sp. reworked from the Eocene
10CB5742A	EEB	34.99791	-119.41866	Tbw	Limestone	8.0–5.0	Late Miocene to early Pliocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to the <i>Thalassiosira oestrupii</i> Zone. <i>Pyxilla</i> sp. reworked from the Eocene
10CB5743	EEB	35.00131	-119.41996	Tbw	Dolomitic concretion	8.0–5.0	Late Miocene to early Pliocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to the <i>Thalassiosira oestrupii</i> Zone. <i>Pyxilla</i> sp. reworked from the Eocene
10CB5744	EEB	35.00361	-119.41946	Tbw	Dolomitic concretion	8.0–6.7	Late Miocene, Subzone b of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone. <i>Pyxilla</i> sp. reworked from the Eocene
10CB5745	EEB	35.00441	-119.41846	Tbw	Dolomitic concretion	8.6–6.7	Late Miocene, likely Subzone a of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone. <i>Pyxilla</i> sp. reworked from the Eocene
10CB5746	EEB	34.98531	-119.39306	Tbw	Dolomitic concretion	8.6–6.7	Late Miocene, likely Subzone a of the <i>Thalassiosira antiqua</i> Zone to Subzone a of the <i>Nitzschia reinholdii</i> Zone
10CB5751A	EEB	34.96801	-119.41306	Tbw	Dolomitic concretion	<6.2	Latest Miocene to early Pliocene, Subzone b of the <i>Nitzschia reinholdii</i> Zone to the <i>Thalassiosira oestrupii</i> Zone. The silicoflagellate <i>Distephanus frugalis</i> suggests an age younger than about 6.2 Ma
10C153A	RGS	35.01664	-119.46691	Tm	Dolomitic concretion	10.0–9.3	Late Miocene, Subzone d of the <i>Denticulopsis lauta-D. hustedtii</i> Zone
10C018	RGS	35.86745	-120.45465	Tpr	Mudstone	6.7–5.5	Latest Miocene, Subzone b of the <i>Nitzschia reinholdii</i> Zone
10C021	RGS	35.86565	-120.45635	Tpr	Mudstone	6.7–5.5	Latest Miocene, Subzone b of the <i>Nitzschia reinholdii</i> Zone
10C031	RGS	35.88336	-120.47431	Tpr	Mudstone	6.7–5.5	Latest Miocene, Subzone b of the <i>Nitzschia reinholdii</i> Zone
10C162A	RGS	35.81137	-120.39917	Tpr	Siltstone	6.7–5.9	Latest Miocene, Subzone b of the <i>Nitzschia reinholdii</i> Zone
10C162B	RGS	35.81137	-120.39917	Tpr	Siltstone	6.7–5.9	Latest Miocene, Subzone b of the <i>N. reinholdii</i> Zone. Contains fragments of benthic diatoms and <i>Paralia sulcata</i> , suggesting a relatively shallow environment



Figure 8. Field photograph showing outcrop of Bitterwater Creek Shale at locality 09C036 (fig. 2, south of Maricopa) consisting of folded and faulted, thin-bedded, hard siliceous shale with a diatom-bearing dolomitic concretion located at hammer and white sample bag, exposed in a man-made cut along Klipstein Canyon Road. Hammer is 30 centimeters long.

Thomson, 1989). The thickness of the Bitterwater Creek Shale is difficult to determine owing to structural complications and poor outcrop, and also because its upper part has everywhere been removed by erosion. The thickness of the Bitterwater Creek Shale has been variously estimated as 600 m (Dibblee, 1973, p. 33), 300 m (Vedder, 1970, cross section *A–A'*), and 70 m (Ryder and Thomson, 1989, p. 11); the reasons for this large uncertainty are unclear and require further investigation.

Fossil diatoms were recovered from 21 samples of the Bitterwater Creek Shale, principally by acid digestion of dolomitic concretions (table 1, appendix). Most of the diatom assemblages represent late Miocene Subzone b of the *Thalassiosira antiqua* Zone and Subzone a of the *Nitzschia reinholdii* Zone of Barron (1981) with an estimated age range of 8.0–6.7 Ma (table 1, appendix). The diatom assemblage in sample 10CB5751A (southeastern part of fig. 2) is assigned an age younger than 6.2 Ma (table 1, appendix); however, the diatom assemblage in nearby sample 10C055 is assigned a more typical Bitterwater Creek Shale age of 8.0–6.7 Ma (table 1, appendix). Additional study is needed to determine the significance of the young age for sample 10CB5751A.

The Bitterwater Creek Shale is unconformably overlain by the informally named Panorama Hills formation of Dibblee (1962), which crops out on the west flank of the Temblor Range (fig. 2) and consists of brown, fossiliferous, and bioturbated marine sandstone and mudstone with subordinate granule-pebble conglomerate. The Panorama Hills formation contains abundant marine megafossils (Addicott, 1972; Powell and Stanley, 2011) representative of the “Jacalitos” California provincial molluscan stage of Addicott (1972), which is considered to be late Miocene (Addicott, 1977; Marincovich, 1984a,b; Smith, 1991; Bartow, 1992). The age

of the Panorama Hills formation is about 6.7–5.7 Ma on the basis of (1) diatom assemblages dated at 7.0–6.7 Ma from the underlying Bitterwater Creek Shale (table 1, fig. 2); and (2) the age of the top of the “Jacalitos” provincial molluscan stage, which is about 5.7 Ma according to Bartow (1992) and Poore and others (1984). Marine strata of the Panorama Hills formation apparently grade laterally to the northwest into nonmarine strata that are as thick as 800 m and consist of green shale, coarse-grained sandstone, and conglomerate with granitic and volcanic clasts (Ryder and Thomson, 1989, p. 12). However, this marine to nonmarine change in facies has not been mapped in detail and is poorly understood.

The Panorama Hills formation of Dibblee (1962) and Bitterwater Creek Shale are overlain in angular unconformity by the Pliocene(?) and Pleistocene Paso Robles Formation, which consists of nonmarine gravel, sand, silt, and clay derived from erosion of local bedrock sources in the Temblor Range (Vedder, 1970; Dibblee, 1973; Ryder and Thomson, 1989). The Paso Robles Formation may be as thick as 250 m on the west flank of the Temblor Range (Vedder, 1970, cross section *A–A'*).

Stratigraphy of the Parkfield Area

Outcrops of Miocene and younger strata located southwest of the San Andreas Fault in the Parkfield area and Cholame Hills (figs. 1, 3) were mapped by Dibblee (2005b,c,d) and Sims (1988, 1990). These strata are deformed by open, northwest-striking folds and cut by northwest-striking normal and reverse faults, some of which show evidence of right-lateral strike slip and historic surface rupture (Sims, 1990).

The oldest exposed rocks in the area of figure 3 are the unnamed volcanic rocks of Lang Canyon (fig. 4; Sims, 1990), which consist of rhyolite, rhyolite agglomerate, and obsidian. The thickness of the volcanic section is unclear owing to structural complications, but may be 900 m or more (Sims, 1990, cross section *B–B'*). A K-Ar whole-rock age on rhyolite of 23.8 ± 0.7 Ma (D.L. Turner, cited by Sims, 1993, p. 238) is late Oligocene (Ormdorff and others, 2010; Cohen and others, 2016). The volcanic rocks of Lang Canyon are correlative with the Neenach Volcanics and Pinnacles Volcanics (Matthews, 1973a,b, 1976; Sims, 1993). Together, these three volcanic units are thought to represent a single volcanic field of late Oligocene and early Miocene age that was tectonically disrupted by subsequent right-lateral displacement along several faults within the San Andreas Fault system (Sims, 1993).

The volcanic rocks of Lang Canyon are overlain unconformably (Sims, 1990) by the middle and upper Miocene Santa Margarita Formation, which consists of indurated to friable sandstone and conglomerate with subordinate mudstone, claystone, and vitric tuff (Sims, 1990). The sandstone is arkosic and in places contains abundant molluscan fossils indicative of a shallow marine origin, whereas the conglomerate consists mainly of angular to rounded granitic and volcanic debris (Sims, 1990, 1993). Fossils indicative of the middle and late

Miocene “Margaritan” California provincial molluscan stage were reported by Powell (2007, p. 93–94) and by Taggart and Kraetsch (1963) from two localities, LSJU 2550 and LSJU 2551 (fig. 3). At locality 10C013 (fig. 3), rocks previously mapped as Pancho Rico Formation (Dibblee, 2005b; Sims, 1990) consist of indurated sandstone and conglomerate with abundant angular clasts of granitic rocks and sparse fossil mollusks (fig. 9); these rocks closely resemble nearby outcrops of the Santa Margarita Formation, so we depict them on figure 3 as Santa Margarita. The thickness of the Santa Margarita in the Parkfield area is uncertain but may be 300–1,000 m (Sims, 1990, his cross sections *A–A'* and *B–B'*).



Figure 9. Field photograph showing outcrop of Santa Margarita Formation at locality 10C013 (fig. 3, south of Parkfield) consisting of coarse sandstone (dark rocks at hammer) and conglomerate with angular, light-colored clasts of granitic rocks in a natural exposure along a dry stream. Hammer is 30 centimeters long.

In the area of figure 3, the Santa Margarita Formation is overlain in angular unconformity by the Pancho Rico Formation, a poorly exposed unit that, in the area of figure 3, consists mainly of mudstone, siltstone, and sandstone. The mudstone and siltstone are soft to moderately indurated, tan to gray brown on fresh surfaces, and generally weather to chips that range in color from tan to white (figs. 10, 11). In most outcrops, the mudstone and siltstone are massive, poorly stratified, and apparently bioturbated, but in places the siltstone is very thinly bedded (fig. 12). In some outcrops of mudstone and siltstone, diatoms are visible in hand lens as small discs.



Figure 10. Field photograph showing outcrop of Pancho Rico Formation at locality 10C031 (fig. 3, southwest of Parkfield) consisting of diatom-bearing, chippy weathering mudstone exposed in a man-made cut along Ranchita Canyon Road. Hammer to right of white sample bag is 30 centimeters long.



Figure 11. Field photograph showing outcrop of Pancho Rico Formation near locality 10C018 (fig. 3, southwest of Parkfield) consisting of diatom-bearing, chippy weathering mudstone in a natural exposure along a dry stream. Hammer is 30 centimeters long.



Figure 12. Field photograph showing outcrop of Pancho Rico Formation near locality 10C162A (fig. 3, west of Cholame Valley) consisting of diatom-bearing, very thin bedded siltstone in a natural exposure on a steep hillside. Hammer is 30 centimeters long.

Sandstone in the Pancho Rico Formation is tan to gray brown on fresh surfaces and weathers brown, orange-brown, and tan to white. The sandstone is indurated to friable, fine to medium grained, medium to very thick bedded, and massive to bioturbated. Bioturbation is indicated by orange-brown and tan color mottling, by subtle variations in texture, and in some places by knobby weathering surfaces. No detailed information is available on sandstone mineralogy, but in hand lens the sand grains appear to be mainly of quartz and feldspar with subordinate biotite and unidentified dark lithic grains. Megafossils and shell fragments are common in some outcrops (fig. 13) and include barnacles, unidentified bivalve mollusks, and rare, unidentified gastropods.

Five samples of mudstone from the Pancho Rico Formation in the Parkfield area (table 1, fig. 3) yielded diatoms of the latest Miocene Subzone b of the *Nitzschia reinholdii* Zone with an estimated age of 6.7–5.5 Ma. This contrasts with the late Miocene and Pliocene age of the Pancho Rico Formation in the southern Salinas Valley (fig. 1) as determined mainly from fossil benthic foraminifers (Colgan and others, 2012). Additional study is needed to determine whether any part of the Pancho Rico Formation in the Parkfield area is as young as Pliocene.

Geologic mapping by Sims (1990) in the Parkfield quadrangle indicates that the volcanic rocks of Lang Canyon, the Santa Margarita Formation, and the Pancho Rico Formation are unconformably overlain by upper Cenozoic nonmarine deposits that include the Pliocene and Pleistocene(?) Paso Robles Formation and an unnamed sequence of Pleistocene(?) sandstone and conglomerate (unit Qsc of Sims, 1990). In the Cholame Hills, the Paso Robles Formation consists mainly of sand and gravel that include clasts of siliceous fine-grained rocks presumably derived from the Miocene Monterey Formation and younger units, as well as granitic and metamorphic rocks possibly derived from the La Panza Range about 100 km to the south (Sims, 1990). The thickness of the Paso Robles Formation in the Parkfield area is uncertain, but regionally the unit is more than 600 m thick (Galehouse, 1967, p. 955) and it may be as thick as 1,000–1,200 m (Colgan and others, 2012, p. 414; Dibblee, 1973, p. 39). The unnamed Pleistocene(?) sandstone and conglomerate (unit Qsc of Sims, 1990) contains clasts derived from the Franciscan Complex on the northeast side of the San Andreas Fault (Sims, 1990). The thickness of the unnamed unit is uncertain but may be 300 m or more (Sims, 1990, cross section A–A').

Comparison of Late Miocene Strata in the Maricopa and Parkfield Areas and Implications for San Andreas Fault Offset

Our study shows that the Bitterwater Creek Shale in the Maricopa area, on the northeast side of the San Andreas Fault, and the Pancho Rico Formation in the Parkfield area, on the



Figure 13. Field photograph showing outcrop of Pancho Rico Formation near locality 10C162A (fig. 3) consisting of fossiliferous and bioturbated sandstone in a natural exposure on a steep hillside. Pencil is 14 centimeters long.

southwest side of the San Andreas Fault, are lithologically unlike and of different ages. The Bitterwater Creek Shale consists mainly of hard, siliceous shale with orange-weathering dolomitic concretions and turbidite sandstone interbeds, whereas the Pancho Rico Formation on the opposite side of the San Andreas Fault consists of soft to indurated brown mudstone and siltstone with interbeds of bioturbated sandstone that locally contain abundant fossil mollusks. Diatom assemblages indicate that the Bitterwater Creek Shale was deposited about 8.0–6.7 Ma, whereas the Pancho Rico Formation was deposited about 6.7–5.5 Ma. These differences demonstrate that the Bitterwater Creek Shale and Pancho Rico Formation were not contiguous across the San Andreas Fault and therefore cannot be used as a cross-fault tie to estimate right-lateral displacement along the fault as suggested by Dibblee (1966).

The lithology and age of the Bitterwater Creek Shale are similar to the upper part of the Monterey Formation in other parts of California (Barron, 1986a,b; Barron and Isaacs, 2001). Additionally, the Bitterwater Creek Shale is similar in age and lithology to the upper Miocene Santa Cruz Mudstone in the Santa Cruz Mountains located on the opposite side of the San Andreas Fault about 300 km northwest of Maricopa (Clark and others, 1984; Stanley and Lillis, 2000). However, our current knowledge of the sedimentary facies, thickness, and paleogeography of the Bitterwater Creek Shale, Monterey Formation, and Santa Cruz Mudstone is insufficient to allow identification of specific piercing points (Crowell, 1959) that could be used to determine the amount of lateral displacement along the San Andreas Fault. Piercing points are the points of intersection of formerly contiguous linear features on opposite sides of a fault; examples of such linear features include streams, shorelines, and facies boundaries in conjunction with

structure contours (Crowell, 1959; Biddle and Christie-Blick, 1985). We suggest that future detailed studies of the Bitterwater Creek Shale and other siliceous fine-grained units of late Miocene age might reveal piercing points that, in turn, can be used to further constrain the amount and timing of right-lateral displacement along the San Andreas Fault since 8.0–6.7 Ma.

Our new diatom ages show that the Pancho Rico Formation in the Parkfield area is about the same age as the Sisquoc Formation of southern California and the Purisima Formation of northern California (Barron and Ramirez, 1992; Dumont and Barron, 1995; Powell and others, 2007; Minor and others, 2009). Additionally, the Pancho Rico Formation in the Parkfield area, on the southwest side of the San Andreas Fault, appears to be about the same age as the Panorama Hills formation of Dibblee (1962) on the opposite side of the fault near Maricopa (fig. 4). However, diatom-bearing mudstones are common in the Pancho Rico Formation but have not been found in the Panorama Hills formation, suggesting that these units were not formerly contiguous across the fault. Additional studies of the sedimentary facies, thickness, and paleogeography of these units may allow

identification of potential cross-fault ties and piercing points along the San Andreas Fault.

A potential cross-fault tie of latest Miocene age is suggested by the geographic distribution of a fossil mollusk. Powell and Stanley (2011) noted that a new species of *Forreria* (formerly referred to *F. belcheri* of Addicott, 1972, and here referred to as *Forreria* n. sp.) is found in only two places: (1) on the northeast side of the San Andreas Fault in the late Miocene Panorama Hills formation of Dibblee (1962), and (2) on the opposite side of the San Andreas Fault in the late Miocene and Pliocene Pancho Rico Formation of the Salinas Valley. On the basis of this disjunct geographic distribution, we suggest about 130–170 km of right-lateral displacement since about 6.7–5.7 Ma (fig. 14). However, we note that the present-day distribution of *Forreria* n. sp. cannot be used as a piercing point to precisely measure fault offset, because the original paleogeographic distribution of *Forreria* n. sp. is imprecisely known. For example, it is possible that significant volumes of strata containing *Forreria* n. sp. were deposited during the late Miocene but were subsequently

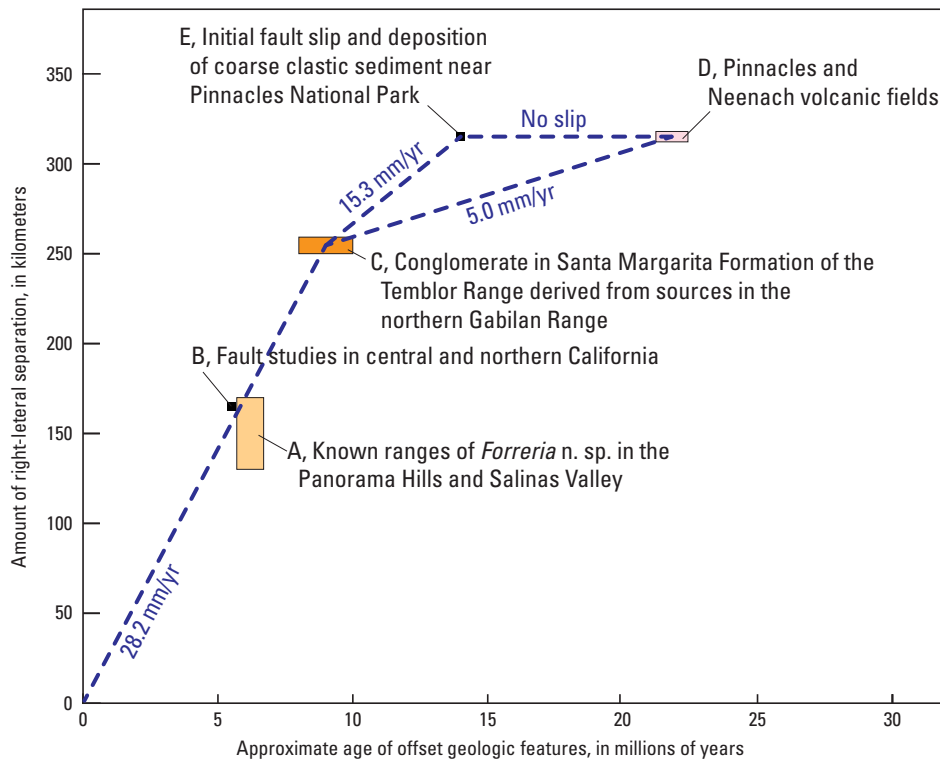


Figure 14. Graph showing age (horizontal axis) and amount of right-lateral separation (vertical axis) along the San Andreas Fault of selected geologic features (filled rectangles) that are inferred to have been offset from each other by strike-slip movement along the fault. A, offset of 130–170 kilometers (km) since 6.7–5.7 million years before present (Ma) of the known ranges of *Forreria* n. sp. in the Panorama Hills and Salinas Valley (Powell and Stanley, 2011, and this study). B, offset of 165 km since 5.5 Ma based on geologic mapping and related studies in central and northern California (Graymer and others, 2013). C, offset of 249–259 km since 10–8 Ma of upper Miocene conglomerate in the Santa Margarita Formation in the southwestern Temblor Range and presumed source areas in the northern Gabilan Range (Huffman, 1972; Graham and others, 1989; Ryder and Thomson, 1989; Stanley and others, 2013; and this study). D, offset of about 315 km since 23.55–21.3 Ma of the Pinnacles and Neenach volcanic fields (Matthews, 1973a,b, 1976) with revised ages from Weigand and Swisher (1991) and Peter Weigand (written commun. reported by Stanley and others, 2000, p. 8–9). E, deposition of coarse clastic sediment and initial slip along the San Andreas Fault near Pinnacles National Park about 14 Ma (Graymer and others, 2013). Dashed lines show implied long-term, average slip rates along the San Andreas Fault and include two of many possible alternative interpretations of slip history prior to 10 Ma. See text for discussion. mm/yr, millimeters per year.

removed by erosion; if this happened in the area along the northeast side of the San Andreas Fault and southeast of the Panorama Hills, for example, then the estimated offset of 130–170 km based on *Forreria* n. sp. may be too low. We also note that the higher end of the 130–170 km range is broadly consistent with a recent estimate of 165 km of offset since 5.5 Ma proposed by Graymer and others (2013) on the basis of geologic mapping and related investigations in central and northern California (fig. 14).

Further Discussion of San Andreas Fault Offset

Conglomeratic fan-delta deposits of the upper Miocene Santa Margarita Formation in the southwestern Temblor Range contain clasts of granitic, metamorphic, and volcanic rocks. Huffman (1972) proposed that these clasts were derived from sources located in the northern Gabilan Range on the opposite side of the San Andreas Fault, and that sediment and source were separated by about 254 ± 5 km of right-lateral displacement along the fault. Subsequent work by Ryder and Thomson (1989) supported Huffman's basic conclusions and provided additional insights into the complicated depositional history of the Santa Margarita Formation, concurrent right-lateral offset along the San Andreas Fault, and episodic uplift of the Gabilan Range.

More specifically, Ryder and Thomson (1989, p. 49 and their fig. 51C) noted that deposition of the oldest and southernmost conglomerate in the Santa Margarita Formation of the Temblor Range ended before deposition of the youngest and northernmost conglomerate began. Ryder and Thomson (1989) say that granitic, metamorphic, and dark schistose clasts in the stratigraphically lower parts of the Santa Margarita Formation in the southwestern Temblor Range (members A and B of Ryder and Thomson, 1989) were derived from sources located on the opposite side of the San Andreas Fault in the northern Gabilan Range.⁵ Flow-banded felsite clasts in a stratigraphically higher part of the Santa Margarita Formation (member C of Ryder and Thomson, 1989) were derived from uplift and erosion of the Pinnacles volcanic field in the Gabilan Range as it moved relatively northwestward along the San Andreas Fault (Ryder and Thomson, 1989, p. 49 and their fig. 51D).

Granitic and metamorphic clasts in the stratigraphically highest part of the Santa Margarita Formation (member D of Ryder and Thomson, 1989) were deposited in an area located about 20–35 km northwest of the nearest outcrops of member A and may have been derived from a northern Gabilan Range basement source located northwest of the Pinnacles volcanic field during an episode of renewed uplift and erosion of that part of the range (Ryder and Thomson, 1989, p. 53 and their fig. 51E). At that time, some unusually large blocks of granitic and metamorphic

rocks—as much as 80 m long according to Ryder and Thomson (1989) and possibly as large as 1,000 m by 250 m according to Ross (1979, p. 1; 1980, p. 153)—were transported from the elevated Gabilan Range source to the opposite side of the San Andreas Fault and deposited as part of member D of the Santa Margarita Formation. The geological processes that transported the large blocks are unknown but may have been catastrophic rockslides or sturzstroms similar to those described from regions with substantial topographic relief in Europe and California (Hsu, 1975; DeCelles, 1988; Cole and Stanley, 1995). The exact amount of right-lateral displacement on the San Andreas Fault during deposition of the Santa Margarita Formation is uncertain but was estimated by Huffman (1972) as about 8–34 km.

Previously, the age of the Santa Margarita Formation in the southwestern Temblor Range was broadly and variously estimated as 12–8 Ma (Huffman, 1972) and 14–6.5 Ma (Graham and others, 1989). However, our new diatom ages show that the stratigraphically lowest part of the Santa Margarita Formation (member A of Ryder and Thomson, 1989) in the southwestern Temblor Range is no older than 10 Ma, on the basis of the estimated age of 10.0–9.3 Ma from sample 10C153A in the uppermost part of the underlying Monterey Formation (table 1; figs. 2, 4). Furthermore, the Santa Margarita Formation is no younger than the overlying Bitterwater Creek Shale with an estimated age of 8.0–6.7 Ma based on diatom assemblages (table 1, figs. 2, 4). Thus, our new diatom ages indicate that the age of the Santa Margarita Formation in the Temblor Range is about 10–8 Ma, and imply that displacement along the San Andreas Fault of conglomerates in the Santa Margarita Formation from their sources in the northern Gabilan Range also began at about this time.

The revised age of about 10–8 Ma for the initiation of offset of the Santa Margarita Formation in the southwestern Temblor Range from its source area can be used in conjunction with selected previous estimates of San Andreas Fault offset to examine long-term, average slip rates along the San Andreas Fault in central California (fig. 14). Using the estimate of right-lateral displacement of 254 ± 5 km proposed by Huffman (1972), we calculate an average slip rate of about 28.2 millimeters per year (mm/yr) with a possible range of 24.9–32.4 mm/yr. Our estimated long-term rates are similar to (a) an implied long-term slip rate of about 30 mm/yr from San Andreas Fault studies in central and northern California that indicate 165 km of right-lateral displacement since 5.5 Ma (Graymer and others, 2013); (b) estimated slip rates of 33.9 ± 2.9 mm/yr for the past 3,700 years based on geological investigations along the San Andreas Fault (Sieh and Jahns, 1984); (c) estimated slip rates of 29.3–35.6 mm/yr from studies of fault trenches in the Carrizo plain (Noriega and others, 2006); (d) geodetic slip rates of 32.2–38.7 mm/yr along the

⁵It should be noted that Ross (1979, 1980, 1984) reported some differences between conglomerate clasts in the Santa Margarita Formation and basement rocks found by him in the Gabilan Range, but Ryder and Thomson (1989, p. 47) attributed these differences to inadequate exposures in the Gabilan Range.

San Andreas Fault between Maricopa and Parkfield based on interferometric synthetic aperture radar (InSAR) and Global Positioning System (GPS) surveys since 1996 (Tong and others, 2014, their fig. 9); (e) creep rates of 28–30 mm/yr along the creeping segment of the San Andreas Fault northwest of Parkfield from creep meters, theodolite surveys, InSAR, and GPS data (Titus and others, 2011, p. 795); and (f) slip rates of 28.2 ± 0.5 mm/yr and 33.6 ± 1 mm/yr from GPS sites that span the creeping segment of the San Andreas Fault northwest of Parkfield (Titus and others, 2006).

Slower long-term slip rates along the San Andreas Fault prior to 10 Ma are indicated by comparing the Santa Margarita-northern Gabilan offset pair with the estimated 315 km offset of the Pinnacles Volcanics from the Neenach Volcanics (Matthews, 1976). The ages of the Pinnacles Volcanics and Neenach Volcanics are believed to be about 23.55–21.3 Ma on the basis of $^{40}\text{Ar}/^{39}\text{Ar}$ incremental-heating ages (Weigand and Swisher, 1991; Peter Weigand, written commun. reported by Stanley and others, 2000, p. 8–9). These ages, when compared with the age of the Santa Margarita-northern Gabilan offset pair, imply a long-term, average slip rate of about 5.0 mm/yr along the San Andreas Fault from 22 to 10 Ma (fig. 14). An alternative interpretation, based on recent studies of the San Andreas Fault northwest of Parkfield near Pinnacles National Park by Graymer and others (2013), suggests that slip on the San Andreas Fault may have started about 14 Ma, implying no slip along the fault from 22 to 14 Ma and an average slip rate of about 15 mm/yr from 14 to 10 Ma (fig. 14). Additional study is needed to resolve the detailed slip history of the fault from 22 to 10 Ma.

Concluding Remarks

The published scientific literature includes numerous suggestions of geologic features that are thought to represent cross-fault ties that can be used to estimate the amount of displacement along the San Andreas Fault (for specific examples, see Hill and Dibblee, 1953; Dibblee, 1966; Dickinson and Grantz, 1968; Dickinson and others, 1972; Stanley, 1987; Graham and others, 1989). However, few of these suggestions are as well-constrained in age and lateral extent as the Pinnacles-Neenach and Santa Margarita-northern Gabilan offset pairs (fig. 14), nor are they true piercing points (Crowell, 1959; Biddle and Christie-Blick, 1985). Instead, many of the proposed cross-fault ties are displaced fragments of submarine fans, tabular bodies of strata, biogeographic and (or) paleobathymetric ranges, and other features that have broad geographic extent and indistinct boundaries. Additionally, some of the proposed offset features are imprecisely dated.

We believe that further insights into the slip history of the San Andreas Fault will arise from detailed geological field mapping and related stratigraphic studies combined with the use of high-resolution dating techniques such as diatom biostratigraphy and $^{40}\text{Ar}/^{39}\text{Ar}$ isotopic dating to identify offset geologic features with well-defined geometries and ages. For example, detailed geological field mapping and improved dating of the marine-to-nonmarine transition in the Panorama Hills formation of Dibblee (1962) on the northeast side of the San Andreas Fault, and its yet-to-be-identified counterpart on the southwest side of the fault, may identify a mappable shoreline that provides a new piercing point and improved understanding of the slip history of the fault.

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Appendix

Appendix. Diatom floras from sample localities mentioned in this report and listed in table 1.

See figures 2 and 3 for sample locations. All fossil identifications and age assignments by J.A. Barron. Map units: Tbw, Bitterwater Creek Shale; Tpr, Pancho Rico Formation; Tm, Monterey Formation. Collectors: EEB, E.E. Brabb; RGS, R.G. Stanley.

Sample: 09C035
 Collector: RGS
 Latitude: 34.95677
 Longitude: -119.40729
 Map unit: Tbw
 Lithology: Dolomitic concretion
 Estimated age: 7.0–6.7 Ma, late Miocene
 Zone: Uppermost part of Subzone a of the *Nitzschia reinholdii* Zone
 Flora:
Thalassiosira antiqua –rare
Cavitatus jouseanus (linear form) –common to few
Rhaphoneis amphiceros var. *elongata* –common
 The silicoflagellate –*Distephanus speculum* –long spined form -common

Sample: 09C036
 Collector: RGS
 Latitude: 34.95876
 Longitude: -119.40887
 Map unit: Tbw
 Lithology: Dolomitic concretion
 Estimated age: 7.0–6.7 Ma, late Miocene
 Zone: Uppermost part of Subzone a of the *Nitzschia reinholdii* Zone
 Flora:
Thalassiosira antiqua –rare
Cavitatus jouseanus (linear form) –common to few
Rhaphoneis amphiceros var. *elongata* –common
Actinoptychus senarius f. *maxima* –rare
 The silicoflagellate –*Distephanus speculum* –long spined form -common

Sample: 09C037
 Collector: RGS
 Latitude: 34.95889
 Longitude: -119.40901
 Map unit: Tbw
 Lithology: Dolomitic concretion
 Estimated age: 7.0–6.7 Ma, late Miocene
 Zone: Uppermost part of Subzone a of the *Nitzschia reinholdii* Zone
 Flora:
Thalassiosira antiqua –rare
Cavitatus jouseanus (linear form) –common to few
Rhaphoneis amphiceros var. *elongata* –common
 The silicoflagellate –*Distephanus speculum* –long spined form -common

Sample: 10C053
 Collector: RGS
 Latitude: 34.96471

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Longitude: -119.41282

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 7.6–6.7 Ma, late Miocene

Zone: Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Thalassiosira antiqua

Actinoptychus undulatus f. *maxima*

Cavitatus jouseanus –abundant

Coscinodiscus marginatus

Hemiaulus polomorphus –common

Lithodesmium minusculum

Rhaphoneis amphiceros var. *elongata*

Silicoflagellates- *Distephanus speculum* w/ 2 long spines (typical of late Miocene)

Sample: 10C055

Collector: RGS

Latitude: 34.96839

Longitude: -119.41314

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, late Miocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone, likely the latter

Flora:

Poor preservation

Rhaphoneis amphiceros var. *elongata*

Cavitatus jouseanus

Coscinodiscus marginatus

Silicoflagellates- *Distephanus speculum* w/ 2 long spines (typical of late Miocene)

Sample: 10C056

Collector: RGS

Latitude: 34.97118

Longitude: -119.41136

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 7.6–6.7 Ma, late Miocene

Zone: Subzone a of the *Nitzschia reinholdii* Zone, likely uppermost part

Flora:

Thalassiosira antiqua

Cavitatus jouseanus

Coscinodiscus marginatus

Hemiaulus polymorphus

Rhaphoneis amphiceros var. *elongata*

Silicoflagellates- *Distephanus speculum* w/ 2 long spines (typical of late Miocene)

Dictyocha aspera clinata

Sample: 10C062

Collector: RGS

Latitude: 35.00539

Longitude: -119.45269

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, likely late Miocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Poor preservation

Coscinodiscus marginatus

Rhaphoneis amphiceros var. *elongata*

Sample: 10C064

Collector: RGS

Latitude: 35.00466

Longitude: -119.45322

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, late Miocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Poor preservation

Actinoptychus undulatus f. *maxima*

Cavitatus jouseanus

Coscinodiscus marginatus –common

Hemiaulus polymorphus

Lithodesmium minusculum

Rhaphoneis amphiceros var. *elongata*

Silicoflagellates- *Distephanus speculum* w/ 2 long spines (typical of late Miocene)

Sample: 10C214

Collector: RGS

Latitude: 35.11702

Longitude: -119.61906

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, late Miocene

Zone: None assigned

Flora:

Abundant, poorly preserved, highly fragmented specimens of *Coscinodiscus* and *Thalassiosira*

Actinocyclus ehrenbergii

Paralia sulcata

Coscinodiscus radiatus

Diploneis sp.

Thalassiosira antiqua

Cavitatus jouseanus

Cladogramma californicum

Sample: 10C215

Collector: RGS

Latitude: 35.11758

Longitude: -119.61727

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, late Miocene

Zone: Either Subzone b of the *Thalassiosira antiqua* Zone or Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Poor preservation

Coscinodiscus radiatus

Actinoptychus undulatus f. *maxima* –common

Thalassiosira antiqua

Cavitatus jouseanus

Grammaophora sp.

Paralia sulcata

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Thalassiothrix and *Thalassionema* fragments

Sample: 10C216

Collector: RGS

Latitude: 35.12228

Longitude: -119.61398

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, likely late Miocene

Zone: Either Subzone b of the *Thalassiosira antiqua* Zone or Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Diatoms abundant, but highly fragmented.

Abundant *Thalassiosira*, *Thalassionema* and *Coscinodiscus* fragments.

Azpeitia cf. *vetustissima*

Actinocyclus undulatus f. *maxima*

Thalassiosira antiqua

Actinocyclus ehrenbergii

Denticulopsis simonsenii –v. rare

Silicoflagellate *Distephanus speculum* with 2 long spines typical of the uppermost Monterey Formation

Sample: 10C246B

Collector: RGS

Latitude: 35.11937

Longitude: -119.60252

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: Younger than 8.6 Ma

Zone: None assigned

Flora:

Very poor preservation

Fragments of *Coscinodiscus* and *Thalassiosira* species.

Thalassiosira antiqua

Actinocyclus sp.

Sample: 10CB5733

Collector: EEB

Latitude: 34.99021

Longitude: -119.42956

Map unit: Tbw

Lithology: Siliceous mudstone

Estimated age: 8.6–6.7 Ma, late Miocene

Zone: likely Subzone a of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Poorly preserved, highly fragmented diatoms, did not break down in hydrochloric acid.

Coscinodiscus marginatus

Cavitatus jouseanus

Thalassionema nitzschioides

Sample: 10CB5733A

Collector: EEB

Latitude: 34.99021

Longitude: -119.42956

Map unit: Tbw

Lithology: Limestone

Estimated age: 8.6–6.7 Ma, late Miocene

Zone: Subzone a of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone

Flora:

Moderately to poorly preserved diatoms including

Coscinodiscus marginatus

Thalassiosira antiqua

Lithodesmium californicum

Cavitatus jouseanus

Silicoflagellate: *Distephanus speculum* with 2 long spines, typical of upper Monterey Formation

Sample: 10CB5742

Collector: EEB

Latitude: 34.99791

Longitude: -119.41866

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–6.7 Ma, late Miocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone. *Pyxilla* sp. reworked from the Eocene

Flora:

Moderately to poorly preserved diatoms including

Coscinodiscus marginatus

Cavitatus jouseanus

Rhaphoneis amphiceros var. *elongata*

Thalassiosira antiqua

Thalassionema nitzschioides

Pyxilla sp. –reworked from the Eocene

Sample: 10CB5742A

Collector: EEB

Latitude: 34.99791

Longitude: -119.41866

Map unit: Tbw

Lithology: Limestone

Estimated age: 8.0–5.0 Ma, late Miocene to early Pliocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to the *Thalassiosira oestrupii* Zone. *Pyxilla* sp. reworked from the Eocene

Flora:

Poorly preserved diatoms including

Coscinodiscus marginatus

Rhaphoneis amphiceros var. *elongata*

Thalassionema nitzschioides

Pyxilla sp. –reworked from the Eocene

Sample: 10CB5743

Collector: EEB

Latitude: 35.00131

Longitude: -119.41996

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: 8.0–5.0 Ma, late Miocene to early Pliocene

Zone: Subzone b of the *Thalassiosira antiqua* Zone to the *Thalassiosira oestrupii* Zone. *Pyxilla* sp. reworked from the Eocene

Flora:

Poorly preserved diatoms including

Coscinodiscus marginatus

Paralia sulcata

Rhaphoneis amphiceros var. *elongata*

Thalassionema nitzschioides

Pyxilla sp. –reworked from the Eocene

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Sample: 10CB5744
Collector: EEB
Latitude: 35.00361
Longitude: -119.41946
Map unit: Tbw
Lithology: Dolomitic concretion
Estimated age: 8.0–6.7 Ma, late Miocene
Zone: Subzone b of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone. *Pyxilla* sp. reworked from the Eocene
Flora:
Poorly preserved diatoms including
Coscinodiscus marginatus
Hemiaulus polymorphus
Paralia sulcata
Rhaphoneis amphiceros var. *elongata*
Thalassionema nitzschioides
Pyxilla sp. –reworked from the Eocene

Sample: 10CB5745
Collector: EEB
Latitude: 35.00441
Longitude: -119.41846
Map unit: Tbw
Lithology: Dolomitic concretion
Estimated age: 8.6–6.7 Ma, late Miocene
Zone: Likely Subzone a of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone (~8.6 to 6.7 Ma) based on the absence of *Actinocyclus ingens* and the presence of *Entopyla*.
Flora:
Poorly preserved diatoms including:
Actinoptychus spp.
Arachnoidiscus sp.
Coscinodiscus marginatus
Lithodesmium minusculum
Pyxilla sp. –reworked from the Eocene
Numerous benthic diatoms typical of the upper Monterey Formation, including *Cocconeis*, *Diploneis*, *Navicula*, *Entopyla*, *Grammatophora*.

Sample: 10CB5746
Collector: EEB
Latitude: 34.98531
Longitude: -119.39306
Map unit: Tbw
Lithology: Dolomitic concretion
Estimated age: 8.6–6.7 Ma, late Miocene
Zone: Likely Subzone a of the *Thalassiosira antiqua* Zone to Subzone a of the *Nitzschia reinholdii* Zone (~8.6 to 6.7 Ma) based on the absence of *Actinocyclus ingens* and the presence of *C. jouseanus*.
Flora:
Poorly preserved diatoms including
Coscinodiscus marginatus
Cavitatus jouseanus
Stictodiscus sp.
Paralia sulcata

Sample: 10CB5751A
Collector: EEB
Latitude: 34.96801

Longitude: -119.41306

Map unit: Tbw

Lithology: Dolomitic concretion

Estimated age: Younger than 6.2 Ma, latest Miocene to early Pliocene

Zone: Subzone b of the *Nitzschia reinholdii* Zone to the *Thalassiosira oestrupii* Zone. The silicoflagellate *D. frugalis* suggests an age younger than about 6.2 Ma

Flora:

Moderately to poorly preserved diatoms including

Coscinodiscus marginatus

Paralia sulcata

Rhaphoneis amphiceros var. *elongata*

Thalassiosira antiqua

Thalassionema nitzschioides

Silicoflagellate: *Distephanus frugalis*

Sample: 10C153A

Collector: RGS

Latitude: 35.01664

Longitude: -119.46691

Map unit: Tm

Lithology: Dolomitic concretion

Estimated age: 10.0–9.3 Ma, late Miocene

Zone: Subzone d of the *Denticulopsis lauta*-*D. hustedtii* Zone

Flora:

Poorly preserved diatoms

Denticulopsis dimorpha –few

Actinocyclus ingens

Cavitatus jouseanus –thin form

Hemiaulus polymorphus

Denticulopsis sp.

Mediaria splendida fragment

Silicoflagellate – *Distephanus crux* –middle Miocene form

Sample: 10C018

Collector: RGS

Latitude: 35.86745

Longitude: -120.45465

Map unit: Tpr

Lithology: Mudstone

Estimated age: 6.7–5.5 Ma, latest Miocene

Zone: Subzone b of the *Nitzschia reinholdii* Zone

Flora:

Diatoms include:

Thalassiosira antiqua

T. nativa of Schrader 1973

Delphineis sachalinensis

D. simbirskianus

Sample: 10C021

Collector: RGS

Latitude: 35.86565

Longitude: -120.45635

Map unit: Tpr

Lithology: Mudstone

Estimated age: 6.7–5.5 Ma, latest Miocene

Zone: Subzone b of the *Nitzschia reinholdii* Zone

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Flora:

Diatoms include:

Thalassiosira antiqua

T. sp. small of the Sisquoc Formation

Delphineis sachalinensis

D. simbirskianus

Rhaphoneis ampiceros var. *elongata*

Sample: 10C031

Collector: RGS

Latitude: 35.88336

Longitude: -120.47431

Map unit: Tpr

Lithology: Mudstone

Estimated age: 6.7–5.5 Ma, latest Miocene

Zone: Subzone b of the *Nitzschia reinholdii* Zone

Flora:

Diatoms include:

Thalassiosira antiqua

T. sp. small of the Sisquoc Formation

Azpeitia vetustissima

Actinoptychus undulatus f. *maxima*

Delphineis sachalinensis

D. simbirskianus

Sample: 10C162A

Collector: RGS

Latitude: 35.81137

Longitude: -120.39917

Map unit: Tpr

Lithology: Siltstone

Estimated age: 6.7–5.9 Ma, latest Miocene

Zone: Subzone b of the *N. reinholdii* Zone. Contains fragments of benthic diatoms and *Paralia sulcata*, suggesting a relatively shallow environment.

Flora:

Actinoptychus undulatus f. *maxima*

Nitzschia reinholdii -v. rare

N. cf. miocenica -v. rare

Thalassiosira antiqua

T. nativa of Schrader 1973

T. small sp. of Sisquoc Formation

Sample: 10C162B

Collector: RGS

Latitude: 35.81137

Longitude: -120.39917

Map unit: Tpr

Lithology: Siltstone

Estimated age: 6.7–5.9 Ma, latest Miocene

Zone: Subzone b of the *N. reinholdii* Zone. Contains fragments of benthic diatoms and *Paralia sulcata*, suggesting a relatively shallow environment.

Flora:

Thalassiosira antiqua

T. nativa of Schrader 1973

T. cf. miocenica

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