Chapter 3
Miocene Geology of eastern Santa Cruz Island, California

NICOLE LONGINOTTI [A*] AND ELEANOR S. BARTOLOMEO [B]
[A]DEPARTMENT OF GEOLOGY
[B]CIVIL & ENVIRONMENTAL ENGINEERING
UNIVERSITY OF CALIFORNIA, DAVIS, CA 95616
*NLONGINOTTI@UCDAVIS.EDU

Abstract
Eastern Santa Cruz Island is primarily composed of two Miocene geologic units: the Santa Cruz Island Volcanics and the younger Monterey Formation. The Santa Cruz Island Volcanics consist of andesitic flows and volcaniclastics, and the Monterey Formation is characterized by rhythmically bedded silicious marine mudstones. These geologic units provide a detailed record of the past tectonic settings, deposition, and environmental conditions of Santa Cruz Island, and indicate that the island has experienced a complex geologic history. Formation of the volcanics coincides with a period of transtension along the Pacific-North America plate boundary, which occurred as the boundary transitioned from a subduction zone to a transform margin. In the time since formation, the Santa Cruz Island Volcanics have also recorded significant rotation on Santa Cruz Island. The rocks are currently oriented 76.5° ± 14.5° from the geomagnetic field present at the time of rock formation. The Santa Cruz Island Volcanics indicate Santa Cruz Island experienced a combination of transtension and rotation. The younger Monterey Formation continued recording the history of Santa Cruz Island. The Monterey Formation accumulated in deep, sediment starved basins along the North America-Pacific plate boundary. The influx in the biogenic material that formed the Monterey Formation indicates a change in oceanic circulation and suggests increased upwelling occurred along the Pacific Ocean margin. Formation of the Monterey may have also led to global climate change by preferentially removing $\delta^{12}C$ from ocean circulation, which caused an increase in $\delta^{13}C$, more rapid drawing down of CO_2 from the atmosphere, and a cooler global climate.

Introduction
Santa Cruz Island is the largest of the four islands that make up the Northern Channel Islands. The island chain trends east-west and is the southernmost boundary of the western Transverse Ranges of south-central California. The region has undergone a complex tectonic history which has included subduction, transtension, rotation, and transpression (see Chapter 2). The eastern part of Santa Cruz Island, which is the focus of this study, is separated from the rest of the island by a neck as narrow as 3 km in width. The bedrock units that make up the eastern end of the

island are the Miocene Santa Cruz Island Volcanics and the Monterey Formation (Figure 3.1). In some coastal areas the Miocene units are overlain by Plio-Pleistocene terrace deposits.

This paper describes and interprets the geology of eastern Santa Cruz Island, with emphasis on the Miocene. Exploration of the Santa Cruz Island geology provides a better understanding of the complex tectonic and geologic history of the Channel Islands, and provides greater insight into how Santa Cruz Island connects to the broader geologic history of southern California.

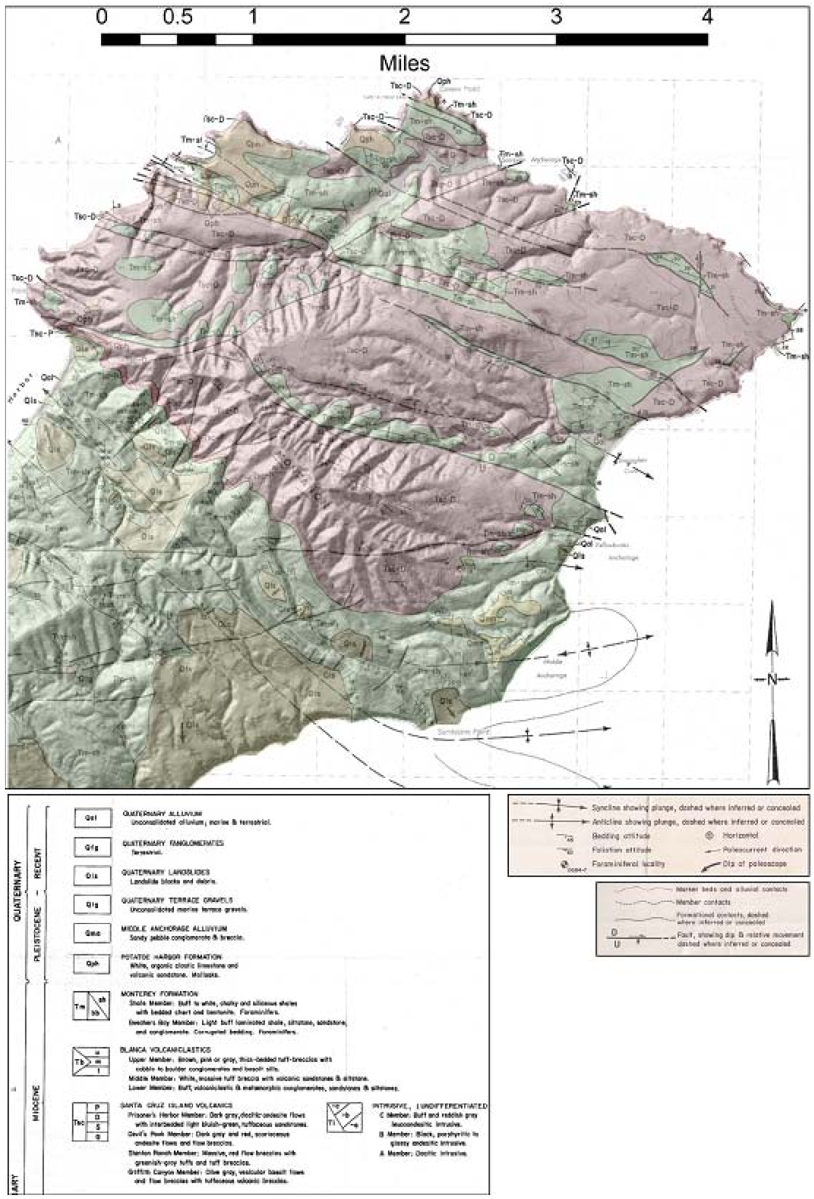

Figure 3.1. Geologic map of eastern Santa Cruz Island modified by Aaron King from Weaver et al., 1964. Transparent colors have been added to differentiate rock units. Red denotes members of the Santa Cruz Island Volcanics. The Monterey Formation appears in green, and Quaternary geology is various shades of yellow.

Background

The tectonic history of Santa Cruz Island has included a combination of subduction, transtension, rotation, and transpression. Santa Cruz Island is located near the western edge of the Transverse Ranges block. The island's geologic history is closely linked to the Transverse Range block, which was oriented north-south within the forearc region of a subduction zone until the early Cenozoic. At ~30 Ma the Pacific plate made contact with the North America plate, subduction ceased, and a transform boundary gradually formed. Extension and volcanism characterized the reconfiguration of the plate boundary (Atwater, 1998). During this time the Transverse Ranges block broke off the North America plate and experienced ~80-110° of clockwise rotation (Kamerling and Luyendyk, 1985). In the past ~5 Ma the Transverse Range block has experienced transpression as the block is being pushed into the "Big Bend" in the San Andreas fault (Atwater, 1998). The current strike-slip faulting, uplift, and folding occurring on Santa Cruz Island is in response to this convergence, which is discussed in detail in Chapter 4.

Santa Cruz Island is an exposed part of a regional anticlinorium that extends to the east into the Santa Monica Mountains and forms a 200 km long structure underlain by blind thrust faults (Pinter et al, 2003). The island is dissected by the left-lateral Santa Cruz Island fault, which is the dominant fault in the Northern Channel Islands. The fault divides Santa Cruz Island into two lithologically distinct regions (Figure 3.2). The geologic units exposed south of the fault are the pre-Jurassic Santa Cruz Island Schist, the Jurassic Willows Diorite, and the clastic and volcaniclastic rocks from the Tertiary. North of the fault are the Miocene Santa Cruz Island Volcanics and Monterey Formation and the Plio-Pleistocene Potato Harbor Formation.

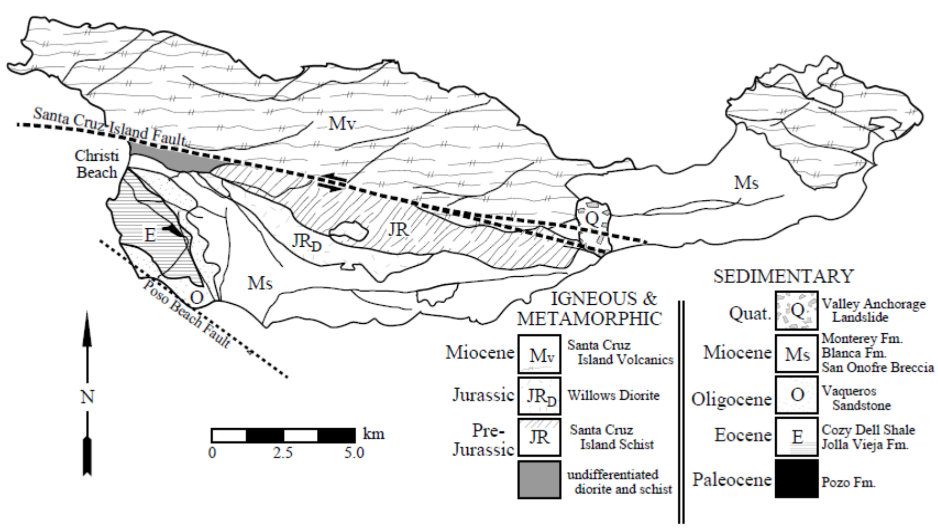

Figure 3.2. Geologic map of Santa Cruz Island (Pinter et al., 1998). The northwest-southeast trending Santa Cruz Island fault is shown with a dashed line. The fault divides the island in two distinct geologic sections. The Santa Cruz Island Volcanics, the Monterey Formation, and Quaternary deposits are found on the north side of the fault. Pre-Jurassic schist, Jurassic diorite, and Miocene volcanic and sedimentary rocks occur south of the fault.

Description

Santa Cruz Island Volcanics

The Santa Cruz Island Volcanics are mostly andesitic flows and volcaniclastics from the Miocene. They are exposed throughout eastern Santa Cruz Island as the resistant, cliff forming rocks (Figure 3.3). These volcanics appear dark brown to black in color, have a rough surface texture, and are often vesicular. The maximum cumulative thickness of these volcanics measured on Santa Cruz Island is 1676 meters. The base of the volcanics is not exposed on the island, however an additional 762 meters of thickness have been inferred using well data, which indicates a total thickness of the Santa Cruz Island Volcanics is around 2440 meters (Nolf and Nolf, 1969).

Figure 3.3. Field photograph of a near vertical cliff face composed of Santa Cruz Island Vocanics, with sea kayakers for scale. The rock exposure in this photo demonstrates the unit's high resistance to erosion. Photo by Robyn Suddeth.

There are four lithologically distinct members recognized within this unit (Nolf and Nolf, 1969), which are from oldest, the Griffith Canyon Member, Stanton Ranch Member, Devils Peak Member, and Prisoner Harbor Member (Figure 3.4). The average composition shifts from more mafic in the lower part of the section to more silicic in the upper section. At the base is the Griffith Canyon Member, which is poorly exposed and has a low resistance to erosion. This member consists primarily of basic lava flows (45-52% silica) and volcanic breccia. The Griffith Canyon Member is conformably overlain by the Stanton Ranch Member, which is composed of mainly andesite flows and flow breccia that are well exposed and resistant to weathering. The vast majority of the volcanics exposed on the eastern edge of Santa Cruz Island are classified as part of the Devils Peak Member, which forms local angular unconformities with the Stanton Ranch Member and is composed of scoracious flow breccia and lava flows. The fourth and youngest member, the Prisoners Harbor Member, is also exposed on the eastern part of Santa Cruz Island and unconformably overlies the Devils Peak Member. These well exposed, glassy andesite flows, dacite flows, flow breccia, and volcaniclastic sandstones crop out near Prisoners Harbor on the north side of the island. This local distribution distinguishes the Prisoners Harbor Member from the other three members, which appear nearly the full length of the island.

The only age data published for the Santa Cruz Island Volcanics are K/Ar dates from samples collected in the upper part of the Prisoners Harbor Member. These ages are 15.7 ± 0.9 my and 16.1 ± 0.8 my (Turner, 1970). Although there is no age data for the older part of the volcanic section, it is assumed the volcanics were emplaced relatively rapidly in the early Miocene or late Oligocene (Nolf and Nolf, 1969).

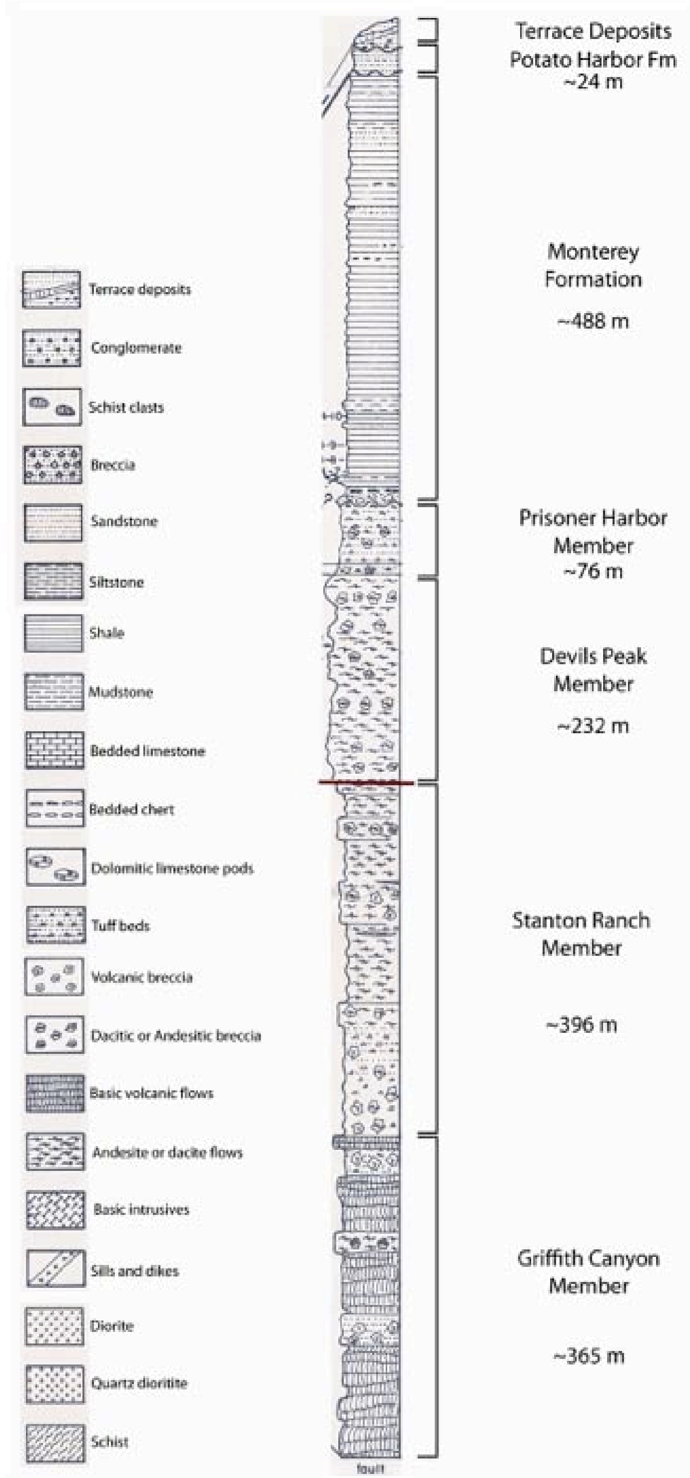

Figure 3.4. Stratigraphic column (modified from Weaver 1969) of the rock units north of the Santa Cruz Island fault. The stratigraphic column is a synthesis of two measured sections. The lower part of the column (below the red line) is located on the north-central part of Santa Cruz Island, west of Cañada del Puerto. The upper part of the stratigraphic column (above the red line) was measured at the east end of the island.

Monterey Formation

In stark contrast with the dark, resistant Santa Cruz Island Volcanics is the Monterey Formation with its creamy white color and high erodability (Figure 3.5). The Monterey Formation conformably overlies the Santa Cruz Island Volcanics and some exposures of the contact between these two units show the Monterey deposited above jagged, uneven, and sometimes brecciated volcanic surfaces (Figure 3.6). This rock unit is often chalky or powdery to the touch and characteristically demonstrates rhythmic or cyclic bedding (Figure 3.7). Also, this unit is susceptible to landslides and slumps, which contribute to the more rapid erosion and retreat of Monterey Formation structures. Notably, the narrow neck that separates eastern Santa Cruz Island from the rest of the island is composed entirely of Monterey Formation. Chapter 6 explores in depth the erodability of the Monterey Formation, and Chapter 9 investigates the effect of wave regimes on the Santa Cruz Island structure.

Figure 3.5. Field photograph of a hill exposure of the Monterey Formation. The rock unit is highly susceptible to erosion, which is demonstrated by the relatively gentle slope of the exposed rock. The slope of the Monterey exposure face can be compared to the much less erodable Santa Cruz Island Volcanics, which form near vertical cliff faces. Photo by Nicole Longinotti.

Unlike the Santa Cruz Island Volcanics, the Monterey Formation is not a local unit unique to the Channel Islands. Instead, outcrops of Monterey can be found along most of coastal California, and deposits similar to the Monterey are found all along the Pacific margin, stretching from the

Gulf of California to the Sea of Japan (Vincent and Berger, 1985). A general depositional trend has been described for the Monterey Formation and is subdivided into a lower, middle, and upper facies. The lower facies is usually calcareous, composed largely of foraminifer-coccolith mudstones. The middle facies is a transitional section composed of phosphatic shales and mudstones, with the phosphate occurring predominantly in nodules. The upper part of the unit is a thick section of diatomaceous sediment. Rhythmic bedding and cycles between a millimeter and a meter in scale are characteristic of this facies (Figure 3.7) (Isaacs et al., 1983).

Figure 3.6. Field photograph of an exposed contact between the Santa Cruz Island Volcanics and the Monterey Formation. The photo shows the Monterey conformably overlying the Santa Cruz Island Volcanics. The volcanics were formed prior to the deposition of the Monterey Formation. Photo by Jeffrey Mount.

Deposition of the Monterey Formation began at ~17.5 Ma and continued until ~6 Ma. The upper boundary of the Monterey, which is not seen in eastern Santa Cruz Island, is believed to be an unconformity (Barron, 1986). The most complete exposure of the Monterey Formation on Santa Cruz Island has a total thickness of 479 m. The top of the section has eroded away, so this measurement provides a minimum thickness (Weaver and Meyer, 1969). The Monterey Formation has been the focus of much interest and research because it is both a major source and reservoir for petroleum. The rock unit contains two unstable components, organic matter and biogenic silica. During burial these unstable components undergo diagenetic reactions, which results in the production of petroleum (Isaacs et al., 1983).

Potato Harbor Formation

The Miocene Santa Cruz Island Volcanics and the Monterey Formation are the two main rock units exposed on the eastern part of Santa Cruz Island, however each is discontinuously overlain by late Pliocene to early Pleistocene terrace deposits called the Potato Harbor Formation, which are fossiliferous limestones that are up to 26 meters thick (Weaver and Meyer, 1969). The origin of these marine terrace deposits is discussed in detail in Chapter 5.

Figure 3.7. Field photograph of small scale cyclic bedding in the Monterey Formation, with a red mechanical pencil for scale. Photo by Nicole Longinotti.

Depositional history and geologic significance

The Santa Cruz Island volcanics were a product of the changing tectonic margin. The rock unit appears to have erupted locally from multiple volcanic centers, some of which are exposed at present. The depositional environment was mainly subaerial, with possibly some marine exposure towards the top of the Prisoners Harbor Member (Nolf and Nolf, 1969). This volcanic activity coincides with a regional change in the tectonic setting, which shifted from subduction to transform faulting and extension along the North America-Pacific plate boundary (Atwater, 1998; see Chapter 2). A slab window formed when the East Pacific Rise intersected the North America subduction zone, resulting in volcanism, extension, and uplift (Atwater and Stock, 1998). Extension associated with the slab window thinned the overlying crust and decompressional melting and upwelling of mantle rocks generated Miocene volcanism along the North America-Pacific plate boundary (Dickinson, 1997). This period of volcanism coincides with the formation of the Santa Cruz Island Volcanics and suggests these volcanics resulted from extension along the plate boundary.

The Santa Cruz Island Volcanics have been useful in investigating the tectonic history of the Northern Channel Islands, the California Continental borderlands, and the Transverse Ranges. Volcanic rocks record the geomagnetic field at the time of rock formation and have been sampled for paleomagnetic studies of the region. Paleomagnetic results from the Santa Cruz Island Volcanics suggest Santa Cruz Island has undergone 76.5° ± 14.5° of clockwise tectonic rotation since the early Miocene (Kamerling and Luyendyk, 1985). Paleomagnetic data collected from a broader region that stretches from outcrops on both sides of the Santa Barbara Channel south to the Ventura region indicate 80° to 110° of clockwise rotation in the last 16 my (Atwater, 1998 and references therein).

In addition to its influence on the Santa Cruz Island Volcanics, the plate boundary shift to wrench fault tectonism appears linked to the deposition of the Monterey Formation. The transtensional tectonic environment associated with the plate boundary transition from a subduction zone to a transform boundary created basins aligned parallel to the California coast (Crouch, 1979). The basins subsided rapidly, faster than terrigenous sediment could be deposited. The rapid subsidence, combined with a rise in sea level in the early Miocene (Vail and Hardenbol, 1979), drowned local sediment sources and starved the basins of terrigeonous sediment (Isaacs et al., 1983). This provided suitable conditions for the accumulation of the biogenic material that formed the Monterey Formation. Deposition of the marine Monterey Formation above the subaerially formed Santa Cruz Island Volcanics indicates the island transitioned from a position above sea level to a position submerged below sea level.

The Monterey Formation is composed of an extensive amount of biogenic material that did not exist in the Pacific Ocean in such abundance prior to deposition of the Monterey. Increased upwelling in the Pacific Ocean, which pulls biogenic material up from the deep ocean and onto the continental margin, would provide the nutrients needed for higher biologic productivity. It has been proposed that in the late early Miocene production of the North Atlantic Deep Water increased (Keller and Barron, 1983). Young deep waters are corrosive to silica (Berger, 1970) and the increased production of deep water in the North Atlantic may have ended biosiliceous sediment deposition in the North Atlantic and Caribbean. This would increase the silica within the Circum Polar Deep Water, which flows into the Indian and Pacific Oceans (Keller and Barron, 1983). Deposition of the Monterey Formation was likely a combination of the formation of sediment starved basins and intensified upwelling.

Monterey Hypothesis

The deposition of the organic carbon-rich Monterey Formation in deep, tectonically active basins may have lead to global cooling, a theory known as the Monterey Hypothesis (Vincent and Berger, 1985). Monterey deposits closely coincide with the 14.5 to 14.1 Ma ice sheet growth in the Antarctic and deep water cooling (Flower and Kennett, 1993). The Monterey Hypothesis suggests that $\delta^{12}C$ was preferentially stored in organic matter that was deposited in deep tectonic basins along the northern Pacific Ocean. Preferential storage of $\delta^{12}C$ led to an increase in $\delta^{13}C$ in the ocean. The increase in $\delta^{13}C$ began at ~17.5 Ma, which correlates well with deposition of the Monterey Formation. The increase in carbon influenced the ocean-atmosphere reservoir, drawing out an enlarged amount of CO_2 from the atmosphere. A lowering of CO_2 in the atmosphere caused a decrease in global temperatures and resulted in a reverse greenhouse effect. The Monterey Hypothesis argues that the deposition of the Monterey Formation and Monterey-type deposits along the coast of the Pacific Ocean led to a cooler global climate (Vincent and Berger, 1985).

Conclusion

The geology of a region is useful in the interpretation of its depositional, tectonic, and environmental conditions. The geology of eastern Santa Cruz Island is largely composed of one volcanic and one sedimentary rock unit: the Miocene Santa Cruz Island Volcanics and Monterey Formation. Combined these two units reveal a complex history of tectonic reorganization, intense rotation, oceanic recirculation, and global climate change. The formation of the Santa Cruz Island Volcanics indicate the region underwent extension and crustal thinning, and published K/Ar data reveal the island experienced significant clockwise rotation. The transition from the subaerially formed Santa Cruz Island Volcanics to the deep marine Monterey Formation deposited above the volcanic unit suggests Santa Cruz Island became submerged beneath the Pacific Ocean for an extended period of time. The Monterey Formation was deposited in deep north-south trending basins along the coast of California. The influx in biogenic material that formed the Monterey implies a change in ocean circulation patterns. Upwelling of deep, nutrient-rich ocean water along the Pacific Ocean margin may have caused the increase in siliceous material. The Monterey Formation may have also affected global climate conditions. The preferential storage of $\delta^{12}C$ in deep basins may have led to global cooling.

References

Atwater, T., 1998, Plate Tectonic History of Southern California with emphasis on the Western Transverse Ranges and Santa Rosa Island, in Weigand, P. W., ed., Contributions to the geology of the Northern Channel Islands, Southern California: American Association of Petroleum Geologists, Pacific Section, MP 45, p. 1-8

Atwater, T. and Stock, J., 1998, Pacific-North America Plate Tectonics of the Neogene Southwestern United States: An Update: *International Geology Review*, v. 40, no. 5, p. 375-402

Barron, J.A., 1986, Paleoceanographic and tectonic controls on deposition of the Monterey Formation and related siliceous rocks in California; Palaeogeography, Palaeoclimatology, Palaeocology, v. 53, p. 27-45.

Berger, W.H., 1970, Biogenous deep-sea sediments: Fractionation by deep-sea circulation. *Geological Society of America Bulletin*, vol. 81, p. 1385-1402.

Crouch, J.K., 1979. Neogene tectonic evolution of the California Continental Borderland and western Transverse Ranges. *Geological Society of America Bulletin*., 90(1): 338-345.

Dickinson, W.R., 1997, Tectonic implications of Cenozoic volcanism in coastal California: *Geological Society of America Bulletin*, v. 109, p. 936-954.

Flower, B.P., and Kennett, J.P., 1993, Relations between Monterey Formation deposition and middle Miocene global cooling: Naples Beach section, California: *Geology*, v. 21, p. 877-880.

Isaacs, C.M., Pisciotto, K.A., Garrison, R.E., 1983. Facies and diagenesis of the Miocene Monterey Formation, California: A summary. Developments in Sedimentology*,* 36: 247-282

Kamerling, M.J. and Luyendyk, B.P., 1985, Paleomagnetism and Neogene Tectonics of the Northern Channel Islands, California: *Journal of Geophysical Research*, vol. 90, no. B14, p. 12485-12502

Keller, G., and Barron, J.A., 1983, Paleoceanographic implications of Miocene deep-sea hiatuses: *Geological Society of America Bulletin*, v. 94, p. 590-613.

Nolf, B., and Nolf, P., 1969, Santa Cruz Island Volcanics, in Weaver, D.W., and others, eds., Geology of the northern Channel Islands: American Association of Petroleum Geologists and Social Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication, p. 91-94.

Pinter N., Lueddecke, S.B., Keller, E.A., and Simmons, K.R., 1998, Late Quaternary slip on the Santa Cruz Island fault, California, *Geological Society of America Bulletin*, v. 110, no. 6, p. 711-722.

Pinter, N., Sorlien, C.C., and Scott, A.T., 2003, Fault-related fold growth and isostatic subsidence, California Channel Islands, American Journal of Science, vol. 303, p. 300-318.

Turner, D.L., 1970, Potassium-argon dating of Pacific coast Miocene foraminiferal stages, in Bandy, O.L., ed., Radiometric dating and paleontologic zonation: Geological Society of America Special Paper 124, p. 91-129.

Vail, P.R., Hardenbol, J., 1979. Sea-level changes during the Tertiary. Oceanus, vol. 22, p. 71-79.

Vincent, E., Berger, W.H., 1985. Carbon dioxide and polar cooling in the Miocene: The Monterey hypothesis. In: Sundquist, E.T., and Broecker, W.S., eds, The carbon cycle and atmospheric CO2: Natural variations Archean to present: Washington D.C., American Geophysical Union, p. 455-468.

Weaver, D.W., and Meyer, G.L., 1969, Stratigraphy of northeastern Santa Cruz Island in Weaver, D.W., and others, eds., Geology of the northern Channel Islands (California): American Association of Petroleum Geologists and Social Economic Paleontologists and Mineralogists, Pacific Section, Special Publication, p. 95-104.