MAGNETOSTRATIGRAPHY: A POWERFUL TOOL FOR HIGH-RESOLUTION AGE-DATING AND CORRELATION IN THE MIOCENE MONTEREY FORMATION OF CALIFORNIA: RESULTS FROM SHELL BEACH SECTION, PISMO BASIN

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ABSTRACT: Magnetic polarity stratigraphy (magnetostatigraphy) offers a powerful stratigraphic tool of great promise for high-resolution age-dating and correlation in the middle Miocene Monterey Formation of California in which precise age-dating and long-range correlation have not been possible due mainly to the absence or inadequate preservation of age-diagnostic siliceous microfossils (diatoms). For this reason, we have conducted a detailed magnetostatigraphic study of a 290-m thick Monterey section at Shell Beach in Pismo basin, central California. The results of this study, which is the first that provides high-resolution numerical age data for an entire section of the Monterey, clearly illustrate the potential that magnetostatigraphy holds for establishing a much-needed temporal framework for the Monterey. The lack of precise chronologic control in the Monterey has posed a serious obstacle to understanding the true origin of this economically and scientifically important unit of California.

Detailed stepwise demagnetization analysis of some 1,021 closely spaced oriented samples of the Monterey rocks from the Shell Beach section, the age of which is constrained by limited diatom and calcareous nanofossil biocenotologic control, shows that the Monterey lithologies, especially its dolomite, have faithfully preserved the geomagnetic reversal record that these rocks acquired at or near the time of deposition during the middle Miocene. Our data, which pass both the fold and reversal tests at greater than 95 percent confidence level, result in the recognition of 17 well-defined, lithologically independent and stratigraphically controlled magnetozones. Nine of these zones are of normal polarity (N1-N9) and eight are of reversed polarity (R1-R8). We correlate these magnetozones with the interval from the lower part of the magnetic polarity Chron 5B to the lower part of Chron 5r of the standard geomagnetic polarity time scale of Harland and others (1982). From the ages of polarity zone boundaries and extrapolation of sedimentation rates to the base and top of the section, we conclude that the Shell Beach section of the Monterey was deposited between approximately 15.15 Ma and 11.0 Ma at an average post-compaction sediment-accumulation rate of 94 meters per million years. Our data indicate that the facies boundary between the lower calcareous-phosphatic facies and upper siliceous facies is marked by a hiatus/disconformity that lasted about one million years, from approximately 14.3 Ma to 13.25 Ma. We speculate that this hiatus may have been caused by an eustatic fall in sea level that began around 14.3 Ma due to global climatic cooling. The onset of predominantly siliceous sedimentation may signal the intensification of coastal upwelling caused by the increased pole-to-equator temperature gradients accompanying this same climatic cooling, an event clearly recorded by the Monterey rocks at around 13.25 Ma.

Sandstone of the overlying Pismo Formation truncates the Monterey section at Shell Beach. We suggest that this erosional contact may have been caused by a latest middle Miocene sea-level fall at around 11.0 Ma. We note that a large eustatic fall in sea level is proposed by Haq and others (1987) at around 10.8 to 11.0 Ma.

INTRODUCTION

Monterey Formation of California

Large deposits of distinctive, organic-rich biosiliceous sedimentary rocks of Miocene age (≈17 to 5.0 Ma) are present around much of the Pacific margin at least as far southwest as the Philippines and, proceeding clockwise around the Pacific rim, at a great many intervening localities north to the Bering Sea shelf, east to the Gulf of Alaska, and south to Chile (Garrison and others, 1981; Ingle, 1981; Dunbar and others, 1990). Their deposition is thought to have been caused mainly by the interplay of climatic, oceanographic, and tectonic factors, and thus to hold valuable information about regional and global change of the ocean-atmospheric system. These rocks are also of great economic importance: They are the source of most of the petroleum produced around the Pacific Rim (e.g., California, Japan, Peru, and Ecuador). The Monterey Formation of California is typical of these deposits. An example of an organic-rich pelagic-hemipelagic unit, the rhythmically bedded Monterey Formation extends for over 800 km along the California coast, where Plio–Pleistocene uplifts led to striking exposures on land and beaches, along sea cliffs, and in intertidal zones. The Monterey rocks comprise a complex patchwork of lithologies that defy simple classification. The Monterey is predominantly a biosiliceous unit, originally a diatomaceous ooze frequently altered to opal-CT porcelanite, quartz porcelanite, or chert by wholesale diageneis during burial (Isaacs, 1980, 1981; Pisciotto and Garrison, 1981). It also contains distinctive kinds of organic-rich mudstones, calcareous shales, well-laminated phosphatic marlstones, authigenic dolomites/dolostones and limestones, and minor amounts of turbidite sandstones and siltstones. The Monterey is thus also an important repository of silica, phosphorous, and carbon.

The sedimentary realm of the Monterey Formation was the western margin of the Miocene Pacific coast of North America. Complete sequences as much as 2000 m thick were deposited on the slopes and bottom of a series of rapidly subsiding, sediment-starved, nutrient-rich, and organically productive extensional basins separated by structural highs in a borderland-type of topographic setting similar to the present-day southern California and Gulf of California (Ingle, 1981; Pisciotto and Garrison, 1981). These basins developed after the disruptive passage of the Pacific-Farallon spreading center beneath the western margin of the North American Plate at around 28 Ma (Blake and others, 1978).

The Monterey Formation is widely regarded as the principal source and significant reservoir rock of hydrocarbons in many of the Neogene basins in coastal California, an area in which over 20 billion barrels of oil have been pro-
duced from the earliest oil production in the 1870s through the 1980s (California Division of Oil and Gas, 1990). With recent discoveries in southern California of large offshore oil fields in the Santa Barbara and Santa Maria basins, interest in the Monterey has intensified. One of these, the Point Arguello field, is the largest discovery of petroleum in North America in more than 30 years (Williams, 1985). Not only was the Monterey Formation the source of petroleum, its brittle and highly fractured siliceous rocks provided the reservoir in which oil accumulated (Crain and others, 1985). The Monterey Formation is, therefore, important both scientifically and economically.

Among all the exposed sedimentary units of Neogene age, the Monterey Formation is probably one of the most intensively studied rock units because of its unusual and complex lithologic anatomy and problems relating to its origin, the abundance of authigenic carbonates and phosphates, and its tremendous hydrocarbon potential. Since the first classic study of the Monterey by Bramlette (1946), geologic research on various aspects of the Monterey has mushroomed, especially in the past two decades (see, e.g., Isaacs, 1980; Garrison and others, 1981, 1984; William and Graham, 1982). However, after nearly 50 years of intensive geologic scrutiny, many questions still remain pertaining to its complex lithologies and its origin.

An inherent problem in the investigation of the Monterey Formation is the determination of its precise age. Indeed, difficulties in determining high-resolution numerical ages of the Monterey rocks have long been a major obstacle to studies designed to understand the origin of this complex sedimentary unit of California. A high-resolution temporal framework for the Monterey is needed to determine sediment-accumulation rates in different basins, to date facies boundaries, to study cyclical sedimentation so common in the Monterey and, finally, to interpret the Monterey lithofacies and fundamental cause(s) for their evolution.

The lack of a high-resolution chronologic framework for the Monterey stems largely from the widespread absence or inadequate preservation of age-diagnostic siliceous microfossils (diatoms). These microfossils were dissolved by the wholesale diageneis experienced by more than 90 percent of the Monterey during burial, making precise high-resolution age-dating and correlation difficult. Biostratigraphic dating based on benthic foraminifera (Kleinpell, 1938; Blake, 1981; Poore and others, 1981; Finger and others, 1990) has been useful for general purposes, but lacks the necessary resolution and accuracy to address many of the current problems. Radiometric dating methods such as those based on fission-track techniques are difficult to apply to the common lithologies of the Monterey, and the few such dates that exist (e.g., Obradovich and Naeser, 1981) are too low in resolution to be useful for comprehensive time-stratigraphic correlations. The strontium isotope method is a potentially valuable age-dating and stratigraphic correlation tool for the Monterey (DePaolo and Finger, 1991), but its application is limited to only those sections of the Monterey in which pristine carbonate material, required to reliably trace the strontium isotopic evolution of sea water, is available. Because the majority of the Monterey sections have experienced diageneis during relatively deep (>300 m) burial, which may have caused significant modification of the ratio of $^{87}Sr$ to $^{86}Sr$, unaltered carbonate material in its sections is a rarity, thereby limiting wide application of this method in the Monterey. Further, the use of the strontium isotope method for correlation purposes depends entirely on the rate of change of $^{87}Sr$/$^{86}Sr$ of sea water. The reference sea-water curve for the Neogene (DePaolo and Finger, 1991) shows near zero variation of $^{87}Sr$/$^{86}Sr$ with time between approximately 16.0 and 11.5 Ma, the time interval in which a fairly substantial portion of the Monterey was deposited. This further limits wide application of this method in the Monterey. A multiple-fossil biochronologic scheme for the northeastern Pacific, which has been developed by Barron (1986a) and which uses diatoms, allows high-resolution ($\pm300$ ky) dating, but its application has been limited to only those portions of the Monterey in which diageneis has not caused dissolution of diatoms during burial. Such diagenetically unaltered sections make up less than 10 percent of the Monterey. Occasionally, well-preserved diatoms are present in the Monterey dolomites from diagenetically altered sections; however, dolomites are not stratigraphically continuous. They are also less abundant in the siliceous facies, which constitute the upper three-fourths of the Monterey. Thus, at no single locality has it yet been possible to biostratigraphically age-date an entire Monterey section that has experienced diagenetic alteration. Consequently, despite numerous studies, the ages of the Monterey lithofacies have been perceived only in general terms.

**Magnetostratigraphy and Its Potential as a Correlation and Age-Dating Tool in the Monterey Formation of California**

There is currently much interest in the development of a comprehensive chronostratigraphic framework for the Monterey. Magnetic polarity stratigraphy (magnetostratigraphy) provides one of the best means for obtaining much-needed high-resolution chronologic framework for the Monterey. What makes magnetostratigraphy so attractive for the Monterey is that it holds potential for furnishing highly resolved numerical ages, is independent of lithology, and supplies synchronous time markers as a framework for other kinds of stratigraphic studies.

Magnetostratigraphy has proved to be a development of major importance for age-dating sedimentary deposits (Kennett, 1980; King and Channell, 1991). It continues to play a pivotal role as a standard age-dating and correlation tool in Ocean Drilling Program studies, aimed at stratigraphic, paleotectonic, paleoclimatic, and paleoceanographic investigations. It has been used in dating Mesozoic and Tertiary sediments and sedimentary rocks both on land and in the oceans (Channell and others, 1984; Ogg and Lowrie, 1986; Heller and others, 1988; McNeill and others, 1988; Aissaoui and others, 1990, Kent and others, 1991), especially those that have been diagenetically altered to varying degrees (Shive and others, 1984). Other applications have included dating diagenetic events in sedimentary rocks (Channell and others, 1982); refinement and re-evaluation of geologic period and stage boundaries (Lowrie and
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Channell, 1983; Alvarez and Lowrie, 1978; Hilgen and Langereis, 1988; Opdyke, 1990; Langereis and Hilgen, 1991); correlation of stratigraphic sections with no common fossils and with different fossil groups (Opdyke and Foster, 1970; Butler and Opdyke, 1979); dating faunal evolution (Tauxe, 1979; Johnson and others, 1981; Lindsay and others, 1990); dating faunal transitions and appearance or extinction of microfossils, especially from different water masses (Hays, 1971); development of climatostratigraphy for the deep-sea Pleistocene (Ninkovich and others, 1966; Hays and others, 1969; Shackleton and Opdyke, 1973); and dating biostratigraphic, paleoceanographic, and paleoclimatic events (Liddicoat and others, 1980; Braiser and others, 1989; Verosub and others, 1989; Aissaoui and others, 1990; Backman and others, 1990; Channell and others, 1990; Miller and others, 1990; Rio and others, 1990; Omarzai and others, 1991).

Magnetostratigraphy is based on the facts that the Earth's magnetic field occasionally reverses polarity and that some sedimentary rocks contain a magnetic imprint of the field at the time they were deposited. From the beginning of the Miocene to the present time, the field has reversed more than 50 times. Because the length of time for the geomagnetic field to flip from one polarity state to another is only about 5 ky (Fuller and others, 1979), the boundaries between magnetozones (stratigraphic zones of one polarity) in sections of magnetized rocks are extremely sharp. Moreover, because the entire field of the Earth reverses within this geologically short time, magnetozones are essentially synchronous all over the globe. Once identified, magnetozones can be used for precise correlation in the same way as nontransgressive marker beds such as ash layers, with the additional advantage that each boundary occurs over the entire globe.

Finally, because the time between successive reversals is a random variable (following nearly a Poisson distribution), the pattern of thicknesses of several magnetozones in each part of a steadily deposited section is a distinctive fingerprint that can be correlated between distant sections and matched with the well-established global geomagnetic polarity time scale (GPTS) and thus dated with unusual accuracy. The GPTS, which was established first by radiometric dating of subaerial lava flows (Cox and others, 1964) and greatly extended by interpreting marine magnetic anomalies (Vine, 1966; Heirtzler and others, 1968), has been cross-checked and refined by magnetostatigraphic studies of classic paleontological sections (Alvarez and others, 1977; Lowrie and Alvarez, 1981). The GPTS provides age estimates for reversals that occurred during the last 150 million years (Harland and others, 1982; Berggren and others, 1985; Cande and Kent, 1992).

Thus, the various methods available, magnetostatigraphy offers the best tool for high-resolution numerical age-dating and precise intra- and interbasin correlation within the Monterey Formation and similar units in California and around the Pacific Rim. It has not been widely applied to the Monterey mainly because its rocks usually carry a relatively weak remanent magnetization. However, with the advent of sensitive squid cryogenic magnetometers, the remanence of the Monterey rocks can now be easily measured. Earlier paleomagnetic studies of the Monterey have clearly demonstrated that magnetostatigraphy can furnish high-resolution numerical ages for the Monterey rocks (Hornafius and others, 1981; Coe and others, 1984; Hornafius, 1985; Luyendyk and others, 1985). Hornafius (1984) also showed that the primary remanence in the Monterey dolomite is predominantly carried by detrital magnetite. Subsequently we have shown that besides dolomites, other lithologies, especially unweathered dolomitic shales and clayey siliceous mudstones, also carry stable natural remanent magnetization that records polarity reversals, thereby making magnetostatigraphy most appropriate for age-dating in the Monterey, especially in the sections containing fresh and unweathered rock surfaces and fairly frequently occurring dolomites (Omarzai and Coe, 1987; Omarzai and others, 1988).

The present study at Shell Beach, Pismo Basin, central California, which is part of an ongoing project aimed at establishing a high-resolution temporal framework for the Monterey, is the first study that provides precise and highly detailed ages for an entire section of the Monterey. We report here the results of our investigation in the hope that future studies such as this one, magnetostatigraphy will eventually become a practical dating method of sedimentary sections, not only in the Monterey, but also in other similar Neogene biosiliceous units that are commonplace around the Pacific Rim and in which precise age-dating has not been possible due to a lack of well-preserved age-diagnostic microfossils.

Geologic Setting of the Shell Beach Section

The Shell Beach section of the Monterey Formation is approximately 15 km south of the city of San Luis Obispo (Fig. 1) in central coastal California (Lat. = 35.17°N, Long. = 120.75°W). It is 290 m thick, easily accessible, and well-exposed perpendicular to strike along the beach near the town of Pismo Beach. Extremely fresh rocks are exposed along the sea cliffs and during low tides in the intertidal zones. The section contains 110 dolomite horizons spread throughout the section, and numerous dolomitic-siliceous shale, dolomitic-calcareous shale, and siliceous mudstone layers (Fig. 2).

This section lies within the Pismo basin, one of the many small Neogene extensional basins that developed in the California borderland during Late Oligocene-Early Miocene (Blake and others, 1978) and served as a depocenter during most of Miocene and Pliocene time (Hall, 1973; Surdam and Stanley, 1981). The basin was uplifted and gently folded into a simple synclinal feature, which is usually referred to as the Pismo syncline, during the Plio-Pleistocene. The section lies in the southwestern limb of the Pismo syncline, the majority of its beds striking in a westerly direction (240°–300°) and dipping (30°–50°) to the north-northeast. Several small, open folds occasionally repeat the stratigraphic section (Fig. 2). Among these, the folds that have amplitude less than approximately 0.5 m are usually related to soft-sediment deformation, whereas larger folds are thought to be of tectonic origin.
marked by an abrupt up-section increase in resistance to erosion and thinly bedded interbeds of porcelanites and siliceous shales/mudstones of the upper siliceous facies. This resistance to erosion is attributed to a high biogenic silica content of this upper facies (Isaacs, 1980).

The upper 215-m thick siliceous facies is more homogeneous in appearance, mainly because of its distinctive thinly bedded and interbedded siliceous rocks. This facies contains 1- to 5-cm thick interbeds of porcelanite, porcelaneous shales, and siliceous mudstones; 0.3- to 0.9-m thick dolomite layers; and minor amounts of 1.0- to 2.5-cm thick chert layers and small dark chert nodules observed locally in the uppermost 25 m of this facies. Both the thickness and induration of dolomites increase up-section in this facies. Except for a 25-cm thick silty diatomite bed exposed just below the Monterey-Pismo contact, the Shell Beach section contains no diagenetically unaltered diatomaceous rocks, implying that complete diagenetic alteration of siliceous oozes occurred during burial of these Monterey strata.

**Field and Laboratory Methods**

We collected a total of 1,052 closely-spaced oriented minicores (diameter = 2.5 cm and average length ≈10 cm) from the 290-m thick Shell Beach section of the Monterey. These minicores were separated into 89 groups for the convenience of data collection and reduction, discussion of results, and data presentation. A few beds, usually representing a stratigraphic thickness of 1 to 3 m, were drilled and combined into a single group. We have called them groups instead of sites because, strictly speaking, in paleomagnetic convention, one site is one horizon, not several. From 10 to 25 (generally 10–13) independently oriented minicores were included in each group. The presence of frequent reversals during middle Miocene time demanded that our sampling density be high, so that short geomagnetic polarity events are not missed.

About 80 percent of the minicores were drilled from 110 dolomite horizons, dolomitic shales (both calcareous and siliceous), and interlayers of siliceous mudstones in the intertidal zone. These three lithologies provided the highest-quality data. The remaining 20 percent of the cores were obtained from siliceous-porcelanous shales, chert, cherty porcelaneous shales, calcareous-phosphatic shales, and occasional turbiditic siltstones and sandstones. We collected almost all of the cores from fresh rock surfaces exposed during low tide in the intertidal zone. Of 1,052 minicores obtained, we drilled 959 (91 percent) with a portable diamond coring drill. These cores were drilled over as large an outcrop area as possible. The remainder of the cores (93) were drilled in the laboratory from 36 oriented block samples. Magnetic orientations in the field were determined by a Brunton compass and orienting device. Periodically sun sights were used to check for local magnetic anomalies, but no significant difference was found between magnetic and solar azimuths. We measured the strike and dip of each bed sampled and corrected all directions of remanent magnetizations for bedding tilt by rotating the bed to horizontal about the strike. In the lab, each minicore was cut into at least two or more standard 2.4-cm long segments (= sam-
Explanation:

- Dolomite/Dolostone (concretions and lenticular layers)
- Calcareous - Phosphatic Shale (often laminated)
- Siliceous mudstone/shale/cherty porcelanite
- Pismo Formation (upper Miocene-Pliocene shallow marine)

Fig. 2.—Detailed lithostratigraphy of the Monterey Formation section at Shell Beach showing lithologies and lithofacies.

(ples). The natural remanent magnetization (NRM) of generally the lowermost sample from each core was measured using a 2G-Enterprises three-axis superconducting squid magnetometer, housed in a field-free room (<300 gammas) in the paleomagnetic laboratory of the University of California, Santa Cruz.

During the initial stages of our study, we progressively demagnetized samples in alternating fields, up to 100 mil-
litesla (mT) peak value or thermally demagnetized them in temperatures up to 580°C. Although alternating field demagnetization reveals the correct paleomagnetic polarity, especially in well-indurated dolomite and siliceous mudstones of the upper siliceous facies, the stable component that predates the Pli-Pleistocene regional folding is isolated most accurately by thermal demagnetization above about 250°C. We, therefore, used, for nearly 90 percent of the samples, progressive thermal demagnetization in a Schonstedt TSD-1 shielded furnace with a nulled magnetic field (<10 gammas), at intervals of 25 to 100°C from 100 to 580°C. We adjusted the number of demagnetization steps, which varied from 5 to 16, to fit the unblocking temperature spectra of the samples and the complexity of their NRM. Results were plotted on orthogonal vector plots (Zijderveld, 1967) to determine the orientation of the stable characteristic remanent magnetization (ChRM) of the samples by principal component analysis (Kirschvink, 1980), and used Fisher statistics (Fisher, 1953) to compute the sample, group, and locality mean directions and confidence limits. We used each group mean direction to calculate the relative longitude and latitude of virtual geomagnetic pole (VGP). We calculated the locality mean (section mean) direction and pole by giving unit weight to each group mean direction and pole. These data are listed in Table 1 along with corresponding Fisher statistics.

**PALEOMAGNETIC RESULTS**

Of 1,021 samples analyzed, 751 (73.6 percent) possessed an identifiable stable ChRM. For reasons that will become apparent below, we interpret this as the primary component acquired at or very soon after the time of deposition of the Monterey strata. We divided the samples possessing stable ChRM into two classes. Class I samples (number of samples, n = 460) possessed stable characteristic component of magnetization that was represented by a reasonably well-defined linear demagnetization path on orthogonal vector plots and contained excellent polarity information (Figs. 3 A–D). About 85 percent of Class I samples are from fresh dolomite surfaces. The remainder are from dolomitic shales and siliceous mudstones. A minimum of at least three and maximum of thirteen Class I samples were observed in 80 of the 89 groups. The remainder of the groups (9) did not yield any Class I samples. These 80 groups provided sufficient data for high-resolution magnetostratigraphic interpretation and statistical tests (tilt and reversal tests), even when the Class II samples were not used. However, we have used the Class II samples to tightly constrain our magnetostratigraphy of the section. Class II samples (n = 291) exhibited clear-cut polarity information and a high-temperature characteristic stable component that decayed toward the origin of its orthogonal vector plot but did not quite make it to zero, becoming swamped either by an unstable component created during heating between approximately 325° and 525°C (e.g., Fig. 3E), or erratic behavior when their intensities became close to the instrument noise level. These samples include dolomite, dolomitic-phosphatic and dolomitic-siliceous mudstone and siliceous mudstone. The majority of the hard and well-indurated cherty porcellaneous shale and highly phosphatic marlstone samples were found to be either too weakly magnetized, unstable, or completely overprinted with stable secondary components of both normal and reversed polarity.

We used samples from both Classes I and II for magnetic polarity zonation of the section; however, only Class I samples, which were grouped into 80 groups, were used for section-wide tilt and reversal tests. The 270 samples that we discarded neither Class I nor II) were (1) either unstable or very weakly magnetized (NRM intensities $\leq 4 \times 10^{-5}$ amperes per meter (A/m); n = 84 samples) or (2) magnetized with a stable secondary magnetic remanence acquired in the Pleistocene to Recent. Unlike primary directions, the remanent directions of these latter samples were generally close to the dipole field direction (both normal and reversed) for the region (inclination (I) = 54.7°C, declination (D) = 0°; and I = -54.7°, D = 180°) prior to structural corrections (n = 186 samples).

The remanent magnetization of the Monterey rocks at Shell Beach is in general fairly simple. Their NRMs range from $\approx 6 \times 10^{-4}$ to $8 \times 10^{-4}$ A/m and average $\approx 4 \times 10^{-4}$ A/m (1 A/m = 10^{-5} emu/cc). While relatively weak, these intensities are well above the noise level of our magnetometer ($1 \times 10^{-5}$ A/m) and were, therefore, readily measurable. Dolomites on the average had stronger NRMs. Many of the Class I and II samples used for the data presented here contain two components of magnetization. One of these is thermally distributed and is generally unblocked at demagnetization temperatures of $\approx 250–300°C$ (Fig. 3). Of variable orientation, this component is probably a combination of viscous remanent magnetization acquired during the present normal Brunhes Chron and during storage in the laboratory. The second component of magnetization is isolated in the majority of the samples over a spectrum of unblocking temperatures usually ranging from about 300°C up to 500°C, but occasionally persisting to temperatures up to 550°C (Fig. 3A). This is the stable characteristic component (ChRM) described above.

The following lines of evidence suggest strongly that the high-temperature, characteristic component of magnetization isolated during demagnetization was acquired in the direction of the ancient geomagnetic field very close to the time the Monterey rocks were deposited.

**Fold Test**

A fold test (Graham, 1949; McElhinny, 1964) is a necessary (but not sufficient) requirement for the ChRM to be
Fig. 3.—Orthogonal vector demagnetization diagrams (Zijderveld, 1967) showing representative behavior of the Monterey Formation rocks from Shell Beach during progressive thermal demagnetization. All directions are plotted in tilt-corrected coordinates. In each diagram solid triangles and solid circles are projections of remanent magnetic vector on the horizontal (declination) and vertical (inclination) planes, respectively. Sample names (e.g., 88K0505A), temperature range in degree Celsius (°C), lithology and magnetization intensity scales are provided in each diagram. The NRM intensity, $I_{NRM}$, is given in A/m. The stratigraphic height of the samples, reported in each diagram (H in meters), identifies their position in the stratigraphic columns of Figures 2 and 6. In all cases thermal demagnetization treatment yields well-defined stable characteristic remanent directions at temperatures between ≈300°C and 550°C. 

(A–D) are the examples of some of the best Class I samples with reversed polarity; (E) is an example of Class I sample having a normal polarity stable direction. (B–D) are from the same site. At the same stratigraphic height in the section (B) and (C) are from a dolomite layer and ≈17 m apart laterally. Note the close directional similarity between (B), (C), and (D), which indicates internal consistency of the data.
primary. The classical fold test of Graham (1949) uses the folding to establish the stability of magnetization. If the ChRM directions of samples collected from different limbs of a fold show a poor grouping with the beds in their present attitude, but cluster after unfolding the beds and rotating the directions of magnetization along with them, then the ChRM of the beds was acquired prior to folding and has remained since that time. If the ChRM was acquired after folding of the beds, sample mean ChRM directions should cluster before unfolding the beds and scatter upon correcting the directions for structural tilting, constituting a negative fold test. Strictly speaking, the classic “fold test” may be applied only to a single structure, such as a fold. When the test is applied over a wide area, which is the case in the majority of paleomagnetic studies, where samples are collected from beds with a number of different bedding tilts, it may be termed a “tilt test.” In this work, we have applied both a fold and tilt test to establish the stability of the ChRM.

A small syncline, which has an amplitude of about 4 m and a plunge of approximately 4°, is present in the section at about 150 m above the base of the section. It contains an excellently exposed and continuously washed folded bed of dolomite, which we sampled for a fold test. The sample directions of the high-temperature ChRM of these dolomite samples collected from both limbs and hinge of the syncline are plotted in Figure 4, which clearly demonstrates the improvement in grouping upon unfolding the bed. We calculated the best estimate (k) of the Fisher (1953) precision parameter (k) and \( \alpha_{95} \) values for both in situ and tilt (dip) corrected (after unfolding) directions. The values of k(\( \alpha_{95} \)) before and after the unfolding are 3.2 (27.5°) and 65 (5°), respectively, for \( N = 16 \) class I samples. The difference in grouping before and after unfolding can be proven significant by the statistical analysis of McFadden and Jones (1981) and by the method of McElhinny (1964), at the 99 percent confidence level. The folding at this locality appears to be the result of synsedimentary slumping of soft sediments. The positive result of the fold test shows that the high-temperature characteristic remanent component of magnetization was locked in very close to the time of deposition of the Monterey.

**Tilt Test**

Variation in structural attitudes within the Shell Beach section are sufficient to allow a tilt test. Results of the tilt test are illustrated in Figure 5. When the group mean directions for the ChRM (Class I samples) are rotated about the local strike of observed bedding to the paleohorizontal, the scatter of the mean directions is reduced significantly, thereby constituting a positive tilt test. The value of k before (after) tilt correction is 10 (15.9) for the overall mean of the 39 normal group mean directions and 8.7 (19.8) for the overall mean of the 41 reversed group mean directions (Table 1). The value of k for the entire population (when reversed group mean directions are inverted to normal

![Fig. 4. - Plot of high-temperature characteristic sample mean directions for Shell Beach dolomite samples drilled from both limbs and hinge of a fold before (A) and after (B) unfolding. Projections are equal area stereographic. Open circles (crosses) denote upper (lower) hemisphere projections. As seen in (B), the characteristic sample mean directions cluster more after unfolding (stratigraphic coordinates) than in in situ (geographic coordinates).](image-url)
through the origin) before (after) tilt correction is 9.2 (17.9). Although the improvement in clustering of group mean directions following bedding-tilt correction is not visually dramatic (Fig. 5), the increase in the best estimate (k) of the overall precision parameter (k) for the population is significant at the 99 percent confidence level. The positive tilt test thus also indicates that the high-temperature ChRM predates the Pliocene-Pleistocene folding and likely date to the time of deposition of the Monterey strata.

Reversal Test

We observe both normal and reversed polarities in the Shell Beach section, which adds to our confidence that the ChRM is a primary recording of the reversing geomagnetic field. The tilt-corrected overall mean computed from the group mean directions is \( D/I = 35.6^\circ/40.1^\circ \), \( \alpha_{95} = 6^\circ \), for 39 normal groups (Fig. 5 and Table 1) and 220.4°/−41.3°, \( \alpha_{95} = 5.1^\circ \), for 41 reversed groups mean directions. The F-ratio test (Watson, 1956) indicates that the two tilt-corrected mean directions of the characteristic component are not significantly different if one polarity is inverted to the other. This constitutes a positive reversal test for stability, meaning that the reversals recorded by the ChRM are insignificantly contaminated by unremoved secondary components and thus record accurately the polarity changes of the ancient geomagnetic field.

Consistency of Rock Types

A comparison of thermally cleaned ChRM for different rock types within a given group or a family of groups yielding the same polarity shows that the mean direction of ChRM isolated in samples from different rock types is essentially the same within statistical limits (Figs. 3 B–D). The magnetization directions for samples from different parts of several tens of meter long beds, especially of dolomite with fresh and continuously washed surfaces, are also significantly different from each other (Figs. 3 B–C). Thus, it seems unlikely that the ChRM of these samples has been significantly affected since its acquisition.

In light of the above lines of evidence, and because there is no doubt about the paleohorizontal for these well-stratified rocks, we confidently conclude that the ChRM isolated during demagnetization is "primary," that is, was "frozen in" at or near the time of deposition of these rocks during middle Miocene, and is reliable for magnetostratigraphic and tectonic interpretation.

Magnetic Polarity Stratigraphy

We have computed paleomagnetic declinations, inclinations, and virtual geomagnetic poles, using the tilt-corrected characteristic group mean directions, for both Class I and II samples. The north-seeking groups (with northerly
declinations and positive inclinations) were assigned "normal" magnetic polarities, whereas the south-seeking groups (with southerly declinations and negative inclinations) were assigned "reversed" magnetic polarity. ChRM from all of the samples with northerly (southerly) declinations had clear-cut positive (negative) inclinations with a wide range of values ranging from 15 to 70° (average value around 40°).

The group mean declinations for both Class I and II samples are plotted against the stratigraphic thickness of the section in Figure 6, showing a well-defined magnetic polarity sequence for the entire section of the Monterey at Shell Beach, with 16 reversals of the ancient geomagnetic field. These reversals delineate 17 long and short magnetozones of normal (N1–N9) and reversed (R1–R8) polarity. Each of these magnetozones is defined within approximately ±0.55 m or better, and by more than one group and at least thirteen samples. Shown by solid lines in Figure 6 are the correlations between these magnetozones and the 10.5–15.5 Ma portion of the standard global geomagnetic polarity time scale (GPTS) of Harland and others (1982).

We have based these correlations on the limited diatom and nannofossil age control and visual matches of polarity patterns. No age-diagnostic benthic or planktonic foraminifera were observed in any of the Shell Beach samples analyzed (M. Cotton-Thorton, pers. commun., 1989). Well-preserved age-diagnostic diatoms were recovered from a diatomaceous bed present near the top of the section and from three dolomite horizons within the uppermost 20 m of the section. The biostratigraphically significant species recovered from this portion of the section are characterized by Denticulopsis (D.) praedimorpha, D. hustedtii, Rhizosolenia (R.) barboi, R. praebarboi, Mediarea splendida, Thalassiosira sp., and Actinocyclus ingens. These diatoms fall within the basal part of the subzone "c" of the D. hustedtii-D. lauta diatom zone of Barron (1986a), to which he assigned an age of ≈11.4–11.0 Ma. This assemblage has been observed also in the Toro Road section of the Monterey (Type Monterey section) by Barron (1976), where it is associated with a tuff layer with a fission track age of 11.3 ± 0.9 Ma (Obradovich and Naeser, 1981). The diatom data, therefore, age-bracket the uppermost 20 m of the section between approximately 11.4 and 11.0 Ma. From this constraint and from the match of the pattern of our magnetozones for the upper 215 m of the section and the GPTS discussed below, we conclude that the reversal boundary between N9 and R8, corresponding to the 263.5 m level in the section, corresponds to the geomagnetic polarity reversal boundary between Chron 5A and 5r (boundary between oceanic anomaly 5 and 5A), the age of which has been estimated at 11.47 Ma (Harland and others, 1982).

Between the stratigraphic interval from 150 m to 220.4 m above the base, the section has a relatively long reversed interval (R4–R6) punctured by two brief normal events (N6 and N7) that matches the next lower chron of the GPTS extremely well. There is no evidence of a hiatus within this stratigraphic interval that might cause some polarity intervals to be missed. Given the high density of our sampling and the distinctive pattern of these magnetozones, the only reasonable interpretation of this relatively long sequence of predominantly reversely magnetized rocks is that it is Chron 5Ar with assigned age of 12.76–12.03 Ma (Harland and others, 1982).

Continuing the one-to-one correlation downward of magnetozones to chron 6 results in acceptable matches between ages of polarity boundaries and age ranges for diatoms identified near the bottom of N5 and also in the upper part of the next lower normal zone (Barron's 1986a) D. hustedtii-D. lauta subzones "b-c" and "a," respectively. Below this level, however, the correlation breaks down. An age-diagnostic diatom assemblage recovered from a phosphaetic marlstone bed about 4 m lower in the same normal zone (73.5 m level in Fig. 6) places it in the interval from the uppermost portion of subzone "a" to the middle portion of subzone "b" of the D. lauta zone, which suggests an age between 15.2 and 14.6 Ma (Barron, 1986a). This is over a million years older than the expected age from the GPTS if this entire, unusually long, normal magnetozone corresponds to Chron 5AB. The diatom age call is supported by age-diagnostic nannofossils extracted from the same marlstone sequence that can be confidently placed in the nannofossil zone CN4, to which Bukry (1975) and Okada and Bukry (1980) have assigned an age of 16.1–14.3 Ma. Moreover, if we proceed further with the one-to-one correlation, assuming R2 = 5ABr, N2 = 5AC, R1 = 5ACr, and N1 = the top of 5AD, the GPTS age for the bottom of the section would be about 14.5 Ma, about a million years younger than the K-Ar age of 15.4 ± 0.5 Ma for the conformably underlying Obispo tuff (Turner, 1970).

These discrepancies gave us a strong hint that the rocks between 77 and 73.5 m stratigraphic level might either record a dramatic decrease in sedimentation rate or contain a major hiatus. We subsequently revisited the section and found physical evidence for this in the form of a condensed interval composed of two closely spaced and approximately 8-cm thick layers of phosphaetic lag-deposit, otherwise known as phosphaetic "hardgrounds." They are exposed in the section about 75 m above the base and mark the calcareous-phosphatic/siliceous facies boundary. We densely resampled 5 m of the section above and below this condensed interval and, once again, our detailed demagnetization analysis yielded ChRM of only normal polarity. Thus, we divide the long normal zone between the 50 and 90 m levels in Figure 6 into two normal magnetozones, one above (N4) and the other below (N3) the condensed interval. N4 we correlate with the top of Chron 5AB, whereas N3 we correlate with the bottom of Chron 5AD.

This correlation brings the biostratigraphic age constraints for N3 into conformity with the GPTS. Furthermore, one-to-one correlation of magnetozones to chron 5A down to the bottom of the section yields a GPTS age estimate of 15.15 Ma for the basal Monterey at Shell Beach. This is consistent with the age of the uppermost Obispo tuff, which conformably underlies the Monterey Formation, the top portion of which has been K-Ar dated at 15.4 ± 0.5 Ma by Turner (1970) at its type section along San Luis Creek, some 2.8 km north of Shell Beach. This date is corrected for the new decay constant for $^{40}$K (Dalrymple, 1979). The excellent agreement between these two independently estimated ages for the lowermost Monterey and uppermost Obispo demonstrates that our correlations are in-
Fig. 6.—Generalized lithostratigraphy and magnetostratigraphy derived from the polarity of high-temperature characteristic remanence of Shell Beach sites. Progressive thermal demagnetization of samples results in the recognition of nine normal (N1-N9) and eight reversed (R1-R8) polarity zones. The saw-toothed line at ≈75 m level indicates a hiatus/disconformity representing about a one-million-year gap in the section (see text and Fig. 7). Using the limited diatom and nannofossil data as an approximate guide, an excellent fit, shown by solid lines, to the standard geomagnetic polarity time scale (GPTS) is obtained. The GPTS is from Harland and others (1982). Diatom zones and ages are from Barron (1986a). Nannofossil ages are from Bukry (1975) and Okada and Bukry (1980).
deed reliable in the lower portion (0 to 70 m) of the section, where no age-diagnostic fossils are observed.

The post-compaction sedimentation rate, even when averaged over intervals approximately 75 m in thickness that comprise several magnetozones, is quite variable (Fig. 7), ranging from 77 to 154 m/My. These variable rates may be attributed to the hemipelagic nature of the Monterey Formation, as evidenced by the presence of locally observed slump deposits in the section and to fluctuating rates of production and preservation of biogenic material, which can be caused by short-term changes in paleoclimatic, paleoceanographic, and tectonic conditions. Linear extrapolation of the rates in Figure 7 allows estimation of the duration of the hiatus, which appears to have lasted for about 1.05 Myr from approximately 14.30 to 13.25 Ma. Moreover, such extrapolation also yields an age of 11.0 Ma for the top of the section, in excellent agreement with the estimate of 11.0 to 11.4 Ma based on diatoms. The overall average sedimentation rate for the entire section is 94 m/My, similar to the rates observed by us and others (e.g., Barron, 1986a) elsewhere in the Monterey Formation sections in coastal California. As can be seen from Figure 5, the study area has rotated clockwise relative to North America since the Middle Miocene. We are preparing a separate manuscript on detailed tectonic implications of our paleomagnetic data.

In summary, the magnetostratigraphy that we propose matches a very distinctive fingerprint of the middle Miocene GPTS (Chron 5Ar) and agrees with the available biostratigraphic and radiometric dates within their uncertainties. Our presumption of a one million year break in the sedimentary record based on the magnetic polarity and diatom data was confirmed by our discovery of a condensed interval in exactly the predicted stratigraphic interval of the section. The magnetostratigraphy provides average post-compaction sediment-accumulation rates for the different parts of the section, which in turn yield ages of 15.15 and 11.0 Ma, respectively, for the base and top of the Monterey Formation at Shell Beach.

**ORIGIN OF THE MONTEREY LITHOFACIES AND PALEOCEANOGRAPHIC-PALEOClimATIC IMPLICATIONS**

Studies on the paleoceanographic and paleoclimatic aspects of the Monterey Formation have not yet matured to the point of strong scientific consensus. This stems mainly, again, from a lack of precise chronologic control. Although a number of workers (e.g., Ingle, 1981; Barron, 1986b; Garrison and others, 1987) have suggested links between lithologic changes within the Monterey and global paleoclimatic and paleoceanographic events, it has not been possible to show precise correlation between such events (for example, eustatic sea level changes) and the Monterey lithofacies and their boundaries.

Our Shell Beach data provide some interesting insights in these regards. As described above, we identified a hiatus at ~75 m above the base of the section coinciding with two closely spaced phosphatic lag-deposits (condensed interval) that corresponds to the interval between ~14.3 Ma and 13.25 Ma (Fig. 7). A partially correlative condensed interval having a basal age of ~14.3 Ma (we have adjusted Hornafius’ (1985) age to Harland and others (1982) time scale) is present at the Naples Beach section, some 70 km to the south of Shell Beach (Fig. 1). These condensed intervals may represent lag deposits related to a middle Miocene eustatic sea-level fall. We note that Haq and others (1987) propose a sea-level fall at ~14.2 Ma (Fig. 8). It is, therefore, quite possible that the hiatus seen in the Shell Beach section to which we assign a basal age of 14.3 Ma was caused by, or at least linked in some way, to a fall in sea level. Further data from other sections of the Monterey will provide an opportunity to confirm or reject the inferences drawn here.

Above the hardgrounds there is an abrupt transition up-section from a calcareous-phosphatic facies to a predominantly siliceous facies (Fig. 2). We assign an age of approximately 13.25 Ma to this transition and suggest that this onset of diatomaceous sedimentation in the Shell Beach section may have been caused by a combination of tectonically driven rapid subsidence of the basin, creating favorable conditions for the preservation of diatomaceous ooze and a global climate change from a relatively warmer climate of early middle Miocene (pre-14 Ma) to a cooler climate, which began around 13–14 Ma and continued throughout the middle Miocene. This global climatic change has been widely reported in stable oxygen isotope studies of deep-sea sediments of Neogene age from the equatorial Pacific, Atlantic, and Southern oceans (Shackleton and Kennett, 1975; Kennett, 1977, 1986, 1991). According to Woodruff and Savin (1991) and Woodruff and others (1981), a large increase in benthic foraminifera δ18O values around 13–14 Ma (Fig. 8) represents a rapid major growth and permanent accumulation of the East Antarctic ice cap and

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**Fig. 7.—**The plot of time (age) versus stratigraphic height above the base of the Monterey section at Shell Beach provides average post-compaction sediment-accumulation rates for different parts of the section. These rates vary from 77 m/My to 154 m/My. Extrapolation of sedimentary rates to the base and top of the section provide the ages for the base and top of the section at 15.15 Ma and 11.0 Ma, respectively, and duration of the “hiatus” (14.3–13.25 Ma). The age estimate of 15.15 Ma for the base of the section is in agreement with the K-Ar age of 15.4 ± 0.5 Ma for the uppermost Obispo tuff, which conformably underlies the Monterey. Ages for the plot are obtained from the ages of magnetozone boundaries as shown in Figure 6.
Fig. 8.—Tentative correlation between the Monterey lithofacies at Shell Beach and major middle Miocene oceanographic-climatic events. As shown in the figure, the observed hiatus/disconformity between 14.3 Ma and 13.25 Ma may have been caused by a global eustatic fall in sea level that probably began at ~14.3 Ma. The onset of siliceous sedimentation at 13.25 Ma appears to be closely linked to global climatic cooling as seen in a positive shift of oxygen isotope curve around 14–13 Ma, which may have given rise to intense coastal upwelling in coastal California during middle Miocene time. The Monterey-Pismo unconformity also seems to be related to a large eustatic fall in sea level at around 11.0 Ma. Coastal onlap and eustatic sea level curves are after Haq et al. (1987). Oxygen isotope data and climatic interpretation are from Kennett (1986).

Associated decrease in surface and bottom water temperatures of the Antarctic Ocean, which has been the major source of cold water for the Pacific, related to enhanced polar glaciation. Oxygen isotope ratios of benthic and planktonic foraminifera suggest that these events were accompanied by a marked increase in the equator-to-pole thermal gradients leading to intensified circulation in both the atmosphere and the oceans, which may have led in turn to intensified upwelling of nutrient-rich and highly fertile water along coastal regions around much of the Pacific, where Monterey equivalent siliceous sediments of Miocene age are commonplace. Again, our high-resolution numerical age of 13.25 Ma for the onset of predominantly siliceous sedimentation in the Shell Beach section appears to provide a firm and quantitative link between the Monterey lithofacies boundary and major middle Miocene climatic and oceanographic events, which, in concert with local tectonic subsidence of the basin, may have markedly influenced the lithologic make-up of the Monterey at Shell Beach.

Sandstones of the overlying Pismo Formation truncate the Monterey at the top of the Shell Beach section. As shown in Figures 6 and 7, we date the uppermost Monterey sediments at about 11.0 Ma. We suggest that the angular unconformity/erosional contact between the Monterey and shallow marine Pismo Formation may have been caused by a latest middle Miocene sea-level fall to which we assign an approximate age of 11.0 Ma. This event appears to be the same global event (eustatic fall in sea level) proposed by Haq and others (1987) at approximately 10.8 to 11.0 Ma. The Monterey-Pismo erosional contact may also have been caused by local tectonic uplift of the basin margin around 11.0 Ma (Garrison and Ramirez, 1989) or by a complex convergence of eustasy and local tectonism.

The above observations lead us to make the following speculation on the origin of the Monterey lithofacies at Shell Beach: The Monterey rocks appear to record the interplay of complex tectonic, climatic, and oceanographic events, which shaped their deposition during middle Miocene time. These rocks were deposited in the tectonically controlled Pismo basin, which developed when the western border of Miocene California was fragmented by the San Andreas fault system. Like other fault-bounded and rapidly subsiding small extensional basins, the Pismo basin became the receptacle for organic-rich pelagic and hemipelagic sediments of the Monterey. The vertical succession of Monterey lithofacies appears to have been shaped predominantly by paleoceanographic-climatic changes. The lower calcareous-phosphatic facies was originally a coccolith-foraminiferal-diag-
tom ooze deposited in relatively warm marine waters of early middle Miocene (≤14 Ma; Fig. 8). Very intense and more or less continuous coastal upwelling, resulting from marked expansion of the East Antarctic ice cap and global climatic deterioration that probably began around 14.0 Ma, led to proliferation of diatoms and the onset of upper siliceous facies at around 13.25 Ma. Tectonically controlled rapid subsidence of the basin, in concert with climatically initiated eustatic fall in sea level, around 14–13 Ma, may also have played a significant role in setting the stage for deposition and preservation of diatomaceous oozes, the forerunner of the upper siliceous facies at Shell Beach. During latest middle Miocene a large eustatic sea-level fall around 11.0 Ma in concert with probable local tectonic uplift (Garrison and Ramirez, 1989) may have caused shallowing of the basin, leading to increased detrital sedimentation and deposition of the shallow-marine and clastic rich Pismo Formation at Shell Beach.

Such ideas have been presented by various workers (Ingle, 1981; Pisciotto and Garrison, 1981; Barron and Keller, 1983; Barron, 1986b; Garrison and others, 1987) on the basis of the presence of biogenic siliceous deposits in the circum-Pacific and the analogy of modern siliceous deposition in areas of intense coastal upwelling system (e.g., Gulf of California and Pacific margin of Peru). However, our data provide the first quantitative evidence for the link between major middle Miocene oceanographic-climatic events and the lithologic anatomy of the Monterey at Shell Beach. Further data from other sections of the Monterey are needed to confirm or reject the inferences presented here.

CONCLUSIONS

Our detailed paleomagnetic study of the Monterey Formation at Shell Beach has resulted in a reversal sequence with a fingerprint of long and short magnetic polarity zones that provides a satisfying match to part of the standard geomagnetic polarity time scale of Harland and others (1982) for the middle Miocene and that is consistent with the limited diatom and nannofossil data. Short extrapolations from the closest polarity boundaries near the top and bottom show that the 290-m thick Monterey section was deposited between ∼15.15 Ma and 11.0 Ma. These data also demonstrate that the sedimentary hiatus separating the two lithofacies in the section spans about 1 m.y from approximately 14.3 Ma to 13.25 Ma. Subtracting it from the interval spanned by the section, we find an average post-compaction sediment-accumulation rate of 94 m/my. We speculate that this hiatus may have been caused by a global eustatic fall in sea level that began at ∼14.3 Ma, probably as a result of expansion and permanent accumulation of the East Antarctic ice cap. The onset of predominantly siliceous sedimentation at ∼13.25 Ma may also have been caused by a confluence of local rapid tectonic subsidence of the basin around 13–14 Ma, global climatic cooling, and intense coastal upwelling, which began at around 13–14 Ma associated with the middle Miocene southern hemisphere glaciation. We suggest that the unconformity between the Monterey and Pismo Formations at the top of the section probably also represents a long hiatus and may be linked to a latest middle Miocene eustatic sea-level fall. Relative to the expected Miocene direction, the section mean declination is significantly deflected in a clockwise sense. We interpret the deflected mean declination to record local tectonic block rotation about a vertical axis most likely associated with dextral strike-slip movement along the Horsgri-San Andreas Fault system that bounds the study area on the west and east.

The results of our study illustrate that magnetostratigraphy holds the potential for precise and high-resolution numerical age-dating and correlation within the Monterey Formation and similar units in which age-dating is hampered by scarcity of age-diagnostic fossils. It also illustrates the critical role that paleomagnetism and magnetostratigraphy can play in gaining much-needed insights into the origin of the Monterey Formation of California and in identifying possible sea-level changes in tectonically active regions such as coastal California.

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