Reprinted from

EARTH AND PLANETARY SCIENCE LETTERS

Earth and Planetary Science Letters 163 (1998) 261–273

Magnetic stratigraphy and tectonic rotation of the Middle Eocene Matilija Sandstone and Cozy Dell Shale, Ventura County, California: implications for sequence stratigraphic correlations

Donald R. Prothero *, Justin R. Britt

Department of Geology, Occidental College, Los Angeles, CA 90041, USA

Received 12 May 1998; revised version received 27 August 1998; accepted 27 August 1998

ELSEVIER

EARTH AND PLANETARY SCIENCE LETTERS

PUBLICATION INFORMATION

Earth and Planetary Science Letters (ISSN 0012-821X). For 1998 volumes 154–163 are scheduled for publication. Subscription prices are available upon request from the publisher. Subscriptions are accepted on a prepaid basis only and are entered on a calendar year basis. Issues are sent by surface mail except to the following countries where air delivery via SAL is ensured: Argentina, Australia, Brazil, Canada, Hong Kong, India, Israel, Japan, Malaysia, Mexico, New Zealand, Pakistan, PR China, Singapore, South Africa, South Korea, Taiwan, Thailand, USA. For all other countries airmail rates are available upon request. Claims for missing issues must be made within six months of our publication (mailing) date.

Orders, claims, product enquiries: please contact the Customer Support Department at the Regional Sales Office nearest to you:

New York: Elsevier Science, PO Box 945, New York, NY 10159-0945, USA; phone: (+1) (212) 633 3730, [toll free number for North American customers: 1-8884ES-INFO (437-4636)]; fax: (+1) (212) 633 3680; e-mail: usinfo-f@elsevier.com
Amsterdam: Elsevier Science, PO Box 211, 1000 AE Amsterdam, The Netherlands; phone: (+31) 20 4853757; fax: (+31) 20 4853432; e-mail: nlinfo-f@elsevier.nl
Tokyo: Elsevier Science K.K., 9-15 Higashi-Azabu 1-chome, Minato-ku, Tokyo 106, Japan; phone: (+81) (3) 5561 5032; fax: (+81) (3) 5561 5045; e-mail: info@elsevier.co.jp
Singapore: Elsevier Science, No. 1 Temasek Avenue, #17-01 Millenia Tower, Singapore 039192; phone: (+65) 434 3727; fax: (+65) 337 2230; e-mail: asiainfo@elsevier.com.sg
Rio de Janeiro: Elsevier Science, Rua Sete de Setembro 111/16 Andar, 20050-002 Centro, Rio de Janeiro - RJ, Brazil; phone: (+55) (21) 509 5340; fax: (+55) (21) 509 1991; e-mail: elsevier@campus.com.br [Note (Latin America): for orders, claims and help desk information, please contact the Regional Sales Office in New York as listed above]

ELSEVIER

Earth and Planetary Science Letters 163 (1998) 261–273

EPSL

Magnetic stratigraphy and tectonic rotation of the Middle Eocene Matilija Sandstone and Cozy Dell Shale, Ventura County, California: implications for sequence stratigraphic correlations

Donald R. Prothero *, Justin R. Britt

Department of Geology, Occidental College, Los Angeles, CA 90041, USA

Received 12 May 1998; revised version received 27 August 1998; accepted 27 August 1998

Abstract

The Matilija Sandstone and Cozy Dell Shale in the western Transverse Ranges of California record a long history of Eocene regression from deep marine turbidites to non-marine red shales and then transgression to deep marine shales in a rapidly subsiding tectonic basin. In its type area along the Ventura River north of Ojai, the Matilija Sandstone consists of over 800 m of deep marine to non-marine sandstones, and the Cozy Dell Shale contains over 760 m of deep marine shales and turbidite sandstones. Paleomagnetic sampling of these rocks yielded a stable magnetic remanence which passed both a fold test and a reversal test; some samples were reversed at NRM after dip correction. Based on calibration from planktonic microfossils, the Matilija Sandstone spans the interval from Chron C21r to early Chron C20r (46.0–48.5 Ma), and the Cozy Dell from late Chron C20r to C19r (46.0–42.0 Ma). The samples show a tectonic rotation of approximately 85 ± 18° clockwise, consistent with previous results reported for this tectonic block. Previous sequence stratigraphic correlations of these rocks are inconsistent with this chronostratigraphy. None of the sequence boundaries predicted from these sections matches the global sequence chart.

Keywords: Eocene; magnetostratigraphy; tectonics; Transverse Ranges; sequence stratigraphy

1. Introduction and tectonic setting

The western Transverse Ranges in southern California contain a sequence of up to 7000 m of well exposed, relatively continuous sedimentary rocks ranging in age from the Cretaceous to the Pliocene [1–11]. Except for the non-marine Sespe Formation, these rocks are largely marine, and they record a long history of events in the rapidly subsiding Santa Ynez–Ventura basin. They are located in a region of very active tectonics, just south of the San Andreas transform, and in a tectonic block which shows about 90° of clockwise rotation since the Middle Miocene [12,13]. These rocks were originally deposited in a forearc basin that preceded the development of the transform margin. This basin was once located much further south than it is at present, and oriented north–south (rather than east–west as it is now after the 90° clockwise rotation), with sediments derived largely from the Mojave Desert region [5,7,11,14,15].

In addition to the tectonic importance of this basin, it has great stratigraphic and economic importance as well. The sedimentary rocks of the western

* Corresponding author. Tel.: +1 (213) 259-2557; Fax: +1 (213) 259-2704; E-mail: prothero@oxy.edu

0012-821X/98/$ – see front matter
PII: S0012-821X(98)00192-7

Transverse Range were the basis for much of Pacific Coast Cenozoic biostratigraphy [16]. The type areas of several California benthic foraminiferal stages are in the western Transverse Ranges, including the Ynezian, Bulitian, and Refugian stages of the Eocene [17]. The excellent exposures along the entire south face of the Santa Ynez Range have invited much stratigraphic study and detailed mapping, especially since these same beds plunge down into the rich oil-producing parts of the Ventura–Santa Ynez basins [18]. In recent years, several sequence stratigraphic studies have been conducted on these rocks [10,11,19,20].

Paleomagnetic studies in the area have focused mainly on determining rotations from volcanic rocks [13], although sedimentary units such as the Coldwater Formation [21], the Sespe Formation [22,23], the Monterey Formation [24], and the 'Santa Margarita' Formation [25] have yielded both magnetic stratigraphy and data which indicate a 90° clockwise rotation. Since the Matilija and Cozy Dell formations are among the thickest and best exposed Middle Eocene stratigraphic units on the entire Pacific Coast of California, their magnetic stratigraphy is important to our calibration of other Middle Eocene units in the San Diego region and further north in California, Oregon, and Washington.

1.1. Lithostratigraphy

The Matilija Sandstone was named by Kerr and Schenck [26,27] based on exposures near Matilija Hot Springs (Fig. 1). The Matilija Sandstone crops out almost continuously from as far east as Fillmore to the central Santa Ynez Range, a distance of almost 100 km, and also is mapped in structural blocks north of the Santa Ynez fault. In the type area, the Matilija Sandstone is 811 m thick; it thickens to almost 900 m in the east near Piru Gorge, and thins rapidly to the west, pinching out north of Santa Barbara. According to several authors [5,7,28,29], the rocks mapped as 'Matilija Sandstone' west of San Marcos Pass by Dibblee [1,2] and many other authors, e.g., [30] are miscorrelated; they should be mapped as the Camino Cielo Member of the Juncal Formation. The lithostratigraphy, petrology, and depositional environments of the Matilija Sandstone were discussed by several authors [4,7–9,31,32]. They interpret most of the Matilija Sandstone as a thick sequence of turbidites. In the Ojai area, the turbidites grade upward into regressive shallow marine sandstones and non-marine redbeds, followed by a transgressive sequence of shallow marine sandstones and turbidites that grade into the overlying Cozy Dell Shale.

The Cozy Dell Shale was also named by Kerr and Schenck [26,27] based on exposures in Cozy Dell Canyon, just to the east of the type Matilija (Fig. 1). In its type area, it is over 1000 m thick, but it thins rapidly to the east and west [11]. It extends to the east of the type area as far as Fillmore [33,34] and as far west as Point Conception [30], for a total east–west extent of over 120 km. Although the Cozy Dell is predominantly composed of dark gray, micaceous deep marine shale, at its base it grades into turbidites of the uppermost Matilija Sandstone, and in several places there are as many as four sandstone lenses within the Cozy Dell Shale. These include a 'mid-Cozy Dell sandstone' over 76 m thick in the type area [11], as well as the 'Circle B sandstone member' in the Sespe Creek area [31, 35,36]. The Cozy Dell Shale grades upward into the shallow marine Coldwater Sandstone in some places, although in others it is sharply truncated by Coldwater Sandstone in apparent disconformity.

1.2. Biostratigraphy

In the type area north of Ojai, the lower and middle parts of the Matilija Sandstone contain Ulatisian and Narizian benthic foraminifers, and molluscs of the Domengine stage, while the upper sandstone member contains 'Transition' stage molluscs [4,31,37], which correlate with nannofossil Zone CP13a [38]. To the west, the Matilija Sandstone has yielded Zone CP13 nannofossils [39].

The Cozy Dell Formation in the type area north of Ojai yields Narizian benthic foraminifers [30], Zone CP13–14 nannofossils [40,41], and Zone P11–P12 planktonic foraminifers [9,42]. Berman [42] tentatively suggested that the Cozy Dell also contained P13 planktonic foraminifers, but this is based on a few poorly preserved specimens of non-diagnostic taxa. To the west, the much thinner Cozy Dell Shale in the western Transverse Ranges is correlated with nannofossil Zone CP14a [39].

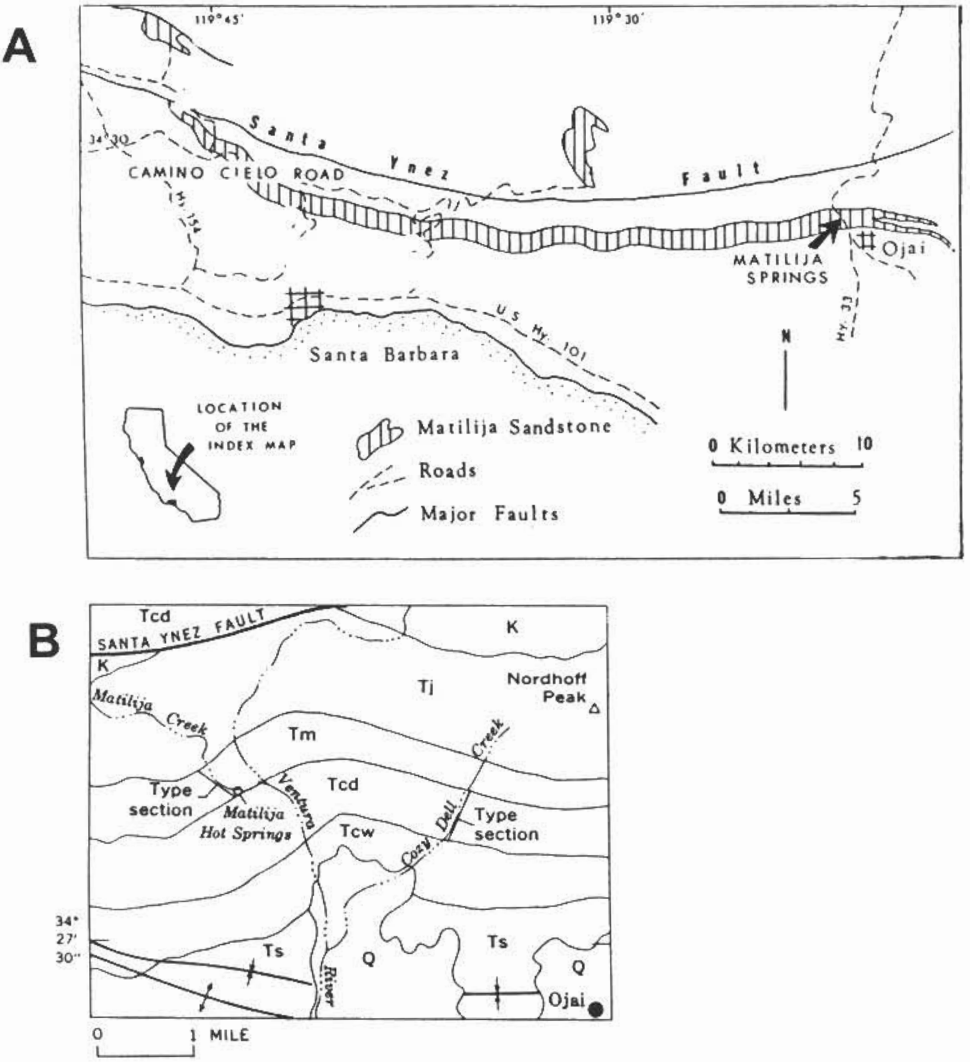

Fig. 1. (A) Index map showing location of study area within the western Transverse Ranges (after [11]). (B) Location of study section (modified from [27]).

2. Methods

The type section of the Cozy Dell Shale is poorly exposed, and on inaccessible private land. The type section of the Matilija Sandstone is presently inaccessible due to restrictions by private landowners. However, the exposures along Highway 33 are easily accessible, continuous, and located only a 1–2 km along strike from the type sections, so these were substituted. The Highway 33 section was measured using a Jacob's staff, following the stratigraphic sections of Link and Welton [9] and Clark [11] and the map of Dibblee [43]. Where resistant outcrops were available, samples were taken with a portable gasoline-powered coring drill. If the outcrops were composed of brittle shales that could not be drilled, oriented hand samples were taken with simple hand tools, and cored in the lab using a drill press. Sampling sites were spaced approximately 10–30 m stratigraphically, depending upon availability of exposures. A minimum of 3 samples were taken at each of 44 sites, which spanned approximately 1500 m of the Matilija and Cozy Dell formations.

The samples were measured at NRM (natural remanent magnetization) in a 2G cryogenic magnetometer at the California Institute of Technology. Each sample was then demagnetized in alternating field (AF) steps of 25, 50, and 100 Gauss to determine the coercivity behavior of the sample, and to demagnetize any multi-domain components before thermal demagnetization locked in a secondary remanence. All samples were then thermally demagnetized at 300°, 400°, 500°, and 600°C in a magnetically shielded oven, and then measured in the magnetometer. This not only helps determine the blocking temperature of the magnetic minerals, but also removes any secondary chemical remanent overprint that might be carried by goethite or other iron hydroxides.

Approximately 0.1 g of several samples were powdered and placed in an epindorph tube for further rock magnetic analysis. These samples were AF demagnetized and then subjected to increasing IRM (isothermal remanent magnetization) intensities to determine if IRM saturation (indicative of magnetite) could be obtained. The same samples were subjected to a modified Lowrie–Fuller test [44] to determine whether they contained single-domain or multi-domain grains. Several representative lithologies were made into polished thin sections and examined under reflected light to determine their opaque mineralogy.

3. Results

The resulting magnetic data were plotted on orthogonal demagnetization ('Zijderveld') diagrams, which show both the changes and direction and intensity in a single two-dimensional plot. Many samples were reversed at NRM; after removal of a slight overprint, they stabilized at directions that pointed up and west (a reversed polarity direction rotated 90° clockwise) at 400–500°C (Fig. 2A). Most of these samples showed a large intensity change under AF demagnetization and almost no remanence at 600°C, indicating that a low-coercivity, lower blocking-temperature mineral such as magnetite is the major carrier of the remanence. A few samples had a normal overprint that was removed by the first thermal demagnetization step (Fig. 2B), leaving a stable reversed component pointed west and up. These samples showed little response to AF demagnetization, suggesting that hematite is the primary carrier of their remanence.

Other samples (Fig. 2C,D) showed a stable, single-component magnetization that was pointed east and down (a normal direction rotated 90° clockwise). Some of these samples tended to show less of a response to AF demagnetization, and were not completely demagnetized at 600°C, suggesting that the remanence is held by a mixture of both magnetite and hematite. A few samples yielded directions that were unstable or uninterpretable, or showed north and down directions before dip correction (the beds are vertical or overturned in this area) that were clearly modern normal overprints.

The IRM acquisition analysis of the powdered samples (Fig. 3) showed saturation at 300 mT (millitesla), indicating that magnetite is present in these samples; there was little evidence of hematite from these tests. The modified Lowrie–Fuller test [44] consistently showed that the ARM was more resistant to AF demagnetization than the IRM, suggesting that the remanence is mainly held in single-domain or pseudo-single domain grains (Fig. 3). Polished thin sections revealed detrital grains of magnetite about 0.01 mm in diameter, with rims of hematite and iron hydroxides on some of the diagenetically altered minerals; these are consistent with the demagnetization results which suggested that both magnetite and hematite were present.

3.1. Stability tests

The characteristic vectors of stable, interpretable samples were determined using the least squared method [45], and then averaged [46]. The mean for all stable normal vectors was $D = 105.1°$, $I = 31.3°$, $k = 7.7$, $\alpha_{95} = 18.6°$, $n = 30$; the mean for stable reversed directions was $D = 262.3°$, $I = -41.8°$, $k = 4.1$, $\alpha_{95} = 14.3°$, $n = 65$. These means are antipodal within the confidence limits, and pass a 'Class A' reversal test ($\gamma_c = 2.32°$) [47], and suggesting that the direction is a primary or characteristic remanence. The rocks vary greatly in dip from overturned and vertical to as shallow as 30°, so it

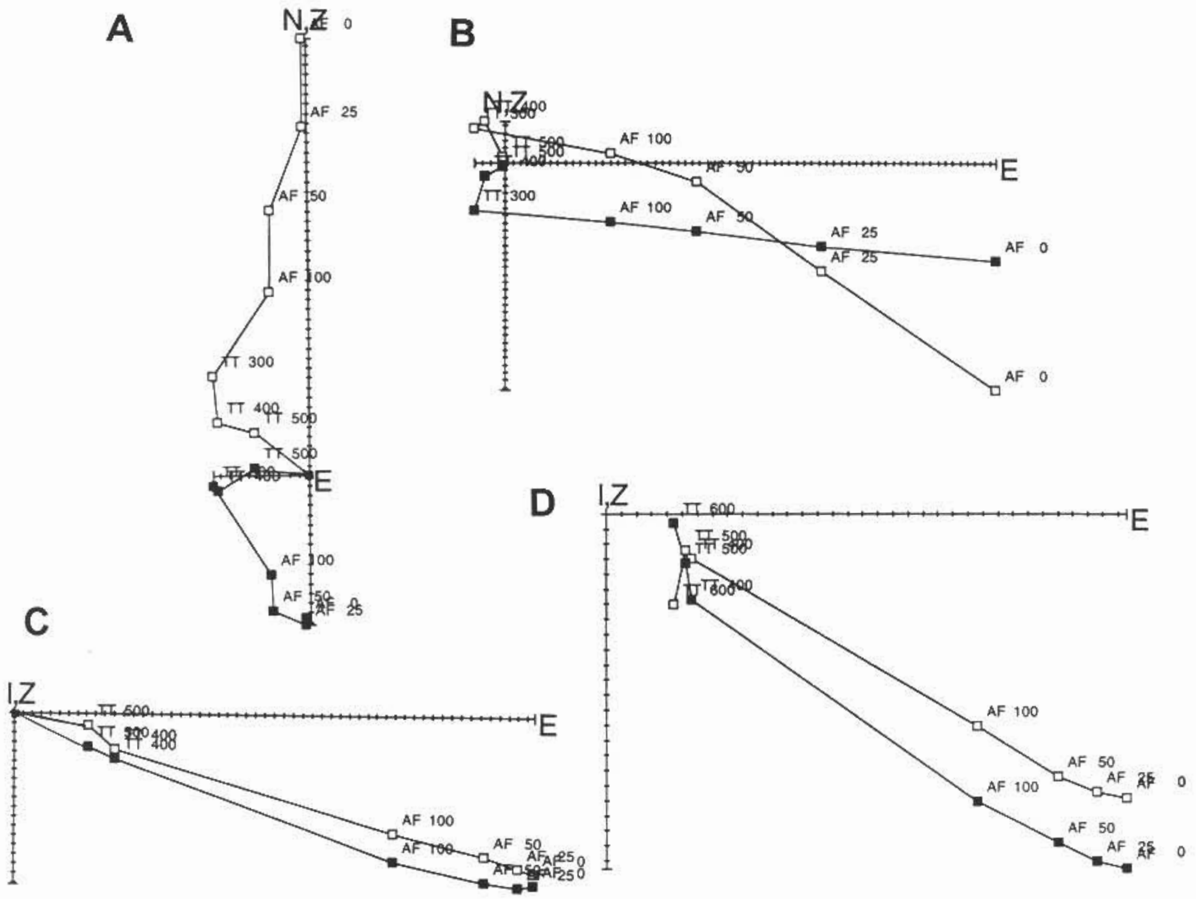

Fig. 2. Orthogonal demagnetization plots of representative samples. Solid squares indicate horizontal component; open squares indicate vertical component. AF demagnetization steps (*AF*) in Gauss; thermal demagnetization steps (*TT*) in °C. Each division = 10^{-7} emu. (A) Matilija sample 35a. (B) Matilija sample 38a. (C) Cozy Dell sample 8a. (D) Cozy Dell sample 11b.

was also possible to conduct a modified fold test as well. The k and α_{95} of uncorrected normal directions was 3.6 and 42.6°; the k and α_{95} of the uncorrected reversed directions was 2.5 and 34.8°. Because the scatter of vectors decreases after dip correction, this suggests that the remanence was acquired before tilting.

3.2. Tectonic rotation and translation

Both the normal and reversed directions showed about 85° of clockwise rotation by comparison with the North American Eocene cratonic reference pole [48]. This is consistent with previous results on rocks in the western Transverse Range block, including Miocene volcanics and sedimentary rocks [12,13,49], the Middle Eocene–Oligocene Sacate–Gaviota–Alegria formations [50], the Middle Eocene Coldwater Formation [21], the Middle Eocene–Late Oligocene Sespe Formation [22,23], the Middle Miocene Monterey Formation [24], and the Late Miocene 'Santa Margarita' Formation [25].

The expected inclination for these rocks (present latitude = 34.5°N) is 54°, so the inclination of the Matilija–Cozy Dell samples is about 13–23° shallower than predicted (measured inclination = 31.3 ± 18.6° for normal sites; 41.8 ± 14.3° for reversed sites). With such large error estimates, only the normal sites are significantly shallower than expected. However, Lund et al. [51] report paleolatitude values as great as 20° south of present latitude for Eocene rocks in this terrane. Prothero et al. [22]

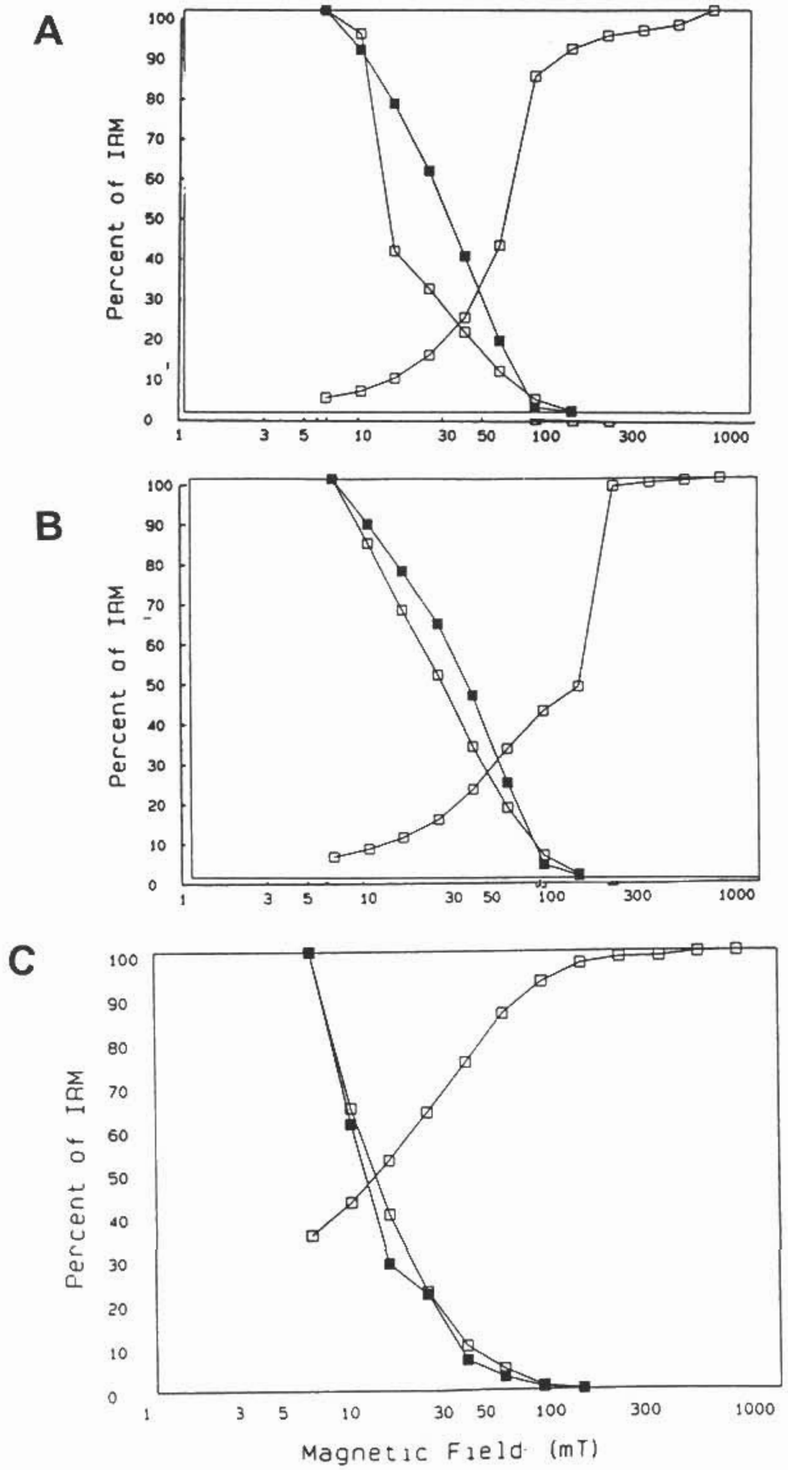

Fig. 3. IRM acquisition analysis and modified Lowrie–Fuller test [44] of representative powdered samples. Open squares = IRM; solid squares = ARM. In all three cases, the IRM (ascending curve on right) saturates at around 300 mT, and the ARM is more resistant to AF demagnetization than the IRM (descending curves to left).

reported a mean inclination of 30.1 ± 7.5° for Middle Eocene rocks of the overlying Sespe Formation in our study area, and Liddicoat [23] reported similarly shallow values for the Sespe Formation near Santa Barbara. But Kodama and Davi [52] showed that as much as 10° of inclination flattening can be attributed to post-depositional compaction in turbidites and shales. Thus, the Matilija–Cozy Dell formations have inclinations which are consistent with about 13–23° of post-Eocene northward translation, although their error estimates are so large that this evidence is not conclusive.

3.3. Magnetic stratigraphy

The polarity interpretations of the Highway 33 Matilija–Cozy Dell section is shown in Fig. 4. The available vectors for each site were averaged and classified according to the scheme of Johnson et al. [53]. Class I sites ($n = 14$) had at least three vectors which were statistically separated from a random distribution at the 95% confidence level. Class II sites ($n = 26$) were not statistically significant, usually because most were brittle, fissile shales that shattered, so only two samples survived and site statistics could not be calculated. A few Class II sites had two magnetic directions which were parallel and showed a clear polarity preference, but a third vector which was divergent. Samples which yielded unstable or uninterpretable data are not shown in Fig. 4.

As shown in Fig. 4, the entire lower and middle Matilija Sandstone was of reversed polarity, but the upper part of that formation (the transgressive beds above the non-marine red shale) was of normal polarity. The highest Matilija site, and the lower and upper Cozy Dell Shale was of reversed polarity, but a 250-m-thick normal magnetozone surrounds the 'mid-Cozy Dell sandstone'. As reported by Prothero and Vance [21], the lower part of the overlying Coldwater Sandstone is also of reversed polarity.

3.4. Magnetic correlation

Correlation of the Matilija and Cozy Dell formations with the time scale of Berggren et al. [54] is shown in Fig. 5. The reversed magnetozone in the lower and middle Matilija Sandstone probably correlates with Chron C21r (47.9–49.0 Ma), based on the presence of 'Domengine' stage molluscs, which correlate with nannofossil Zone CP12b [38]. The upper Matilija normal magnetozone correlates with Chron C21n (46.3–47.9 Ma) based on the 'Transition' stage molluscs, which are correlative with nannofossil Zone CP13a [38]. The reversed–normal–reversed sequence in the Cozy Dell Shale correlates with Chrons C20r–C20n–C19r (42.0–46.3 Ma), based on the presence of both P11 and P12 planktonic foraminifera, and CP13 and CP14a nannofossils. The 'mid-Cozy Dell sandstone' is in the middle of the normal magnetozone that we correlate with Chron C20n. These correlations are also consistent with the interpretation that the base of the overlying Coldwater Sandstone is also within Chron C19r, based on additional biostratigraphic constraints [21].

This correlation tends to shorten the apparent duration of Chron C20r compared to its actual duration on the magnetic polarity time scale (Fig. 5). However, the lower Cozy Dell Shale is unusually thin in this region; in other areas, the interval between the Matilija Sandstone and the 'mid-Cozy Dell sandstone' is much thicker [11].

4. Implications for sequence stratigraphic correlations

Campion et al. [10,20] presented a sequence stratigraphic interpretation of these strata (Fig. 6). They placed numerous sequence boundaries through the section studied in this paper, and attempted to correlate them to the Haq et al. [55,56] onlap–offlap chart. Although they used some of the available biostratigraphic data, their correlation was largely based on the assumption that each sequence boundary in the Middle Eocene of California was eustatically controlled, and could be matched up to sequence boundaries on the Haq et al. [55,56] curve.

The improved magnetobiostratigraphic dating of these same rocks presented here allows us to test the chronostratigraphic correlations of Campion et al. [10,20]. Fig. 6 compares the correlations of Campion et al. [10,20] calibrated to the time scale of Berggren et al. [54], and the revised sequence chart of Hardenbol et al. [57]. The Hardenbol et al. [57] chart has made numerous changes from the Haq et al. [55,56]

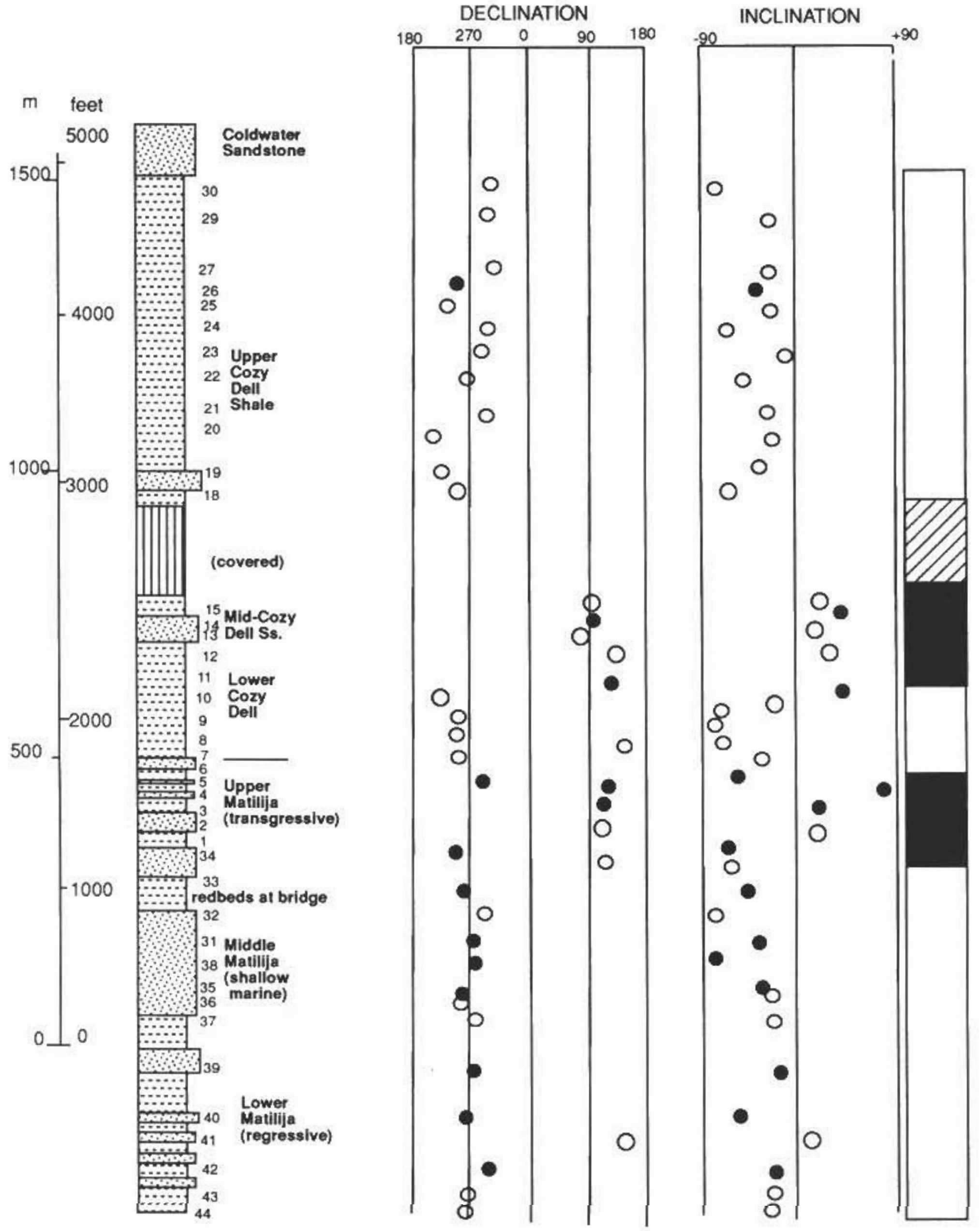

Fig. 4. Lithostratigraphy and magnetic data for the Matilija–Cozy Dell section shown in Fig. 1. Lithostratigraphy after Link and Welton [9] and Clark [11]. Solid circles indicate Class I sites [53]; open circles are Class II sites.

correlation chart, but these have been corrected for in Fig. 6, so the correlations of Campion et al. [10,20] can be consistently compared.

Fig. 6 shows that almost none of the correlations of Campion et al. [10,20] are consistent with the new chronostratigraphic data. For example, they interpreted the Matilija Sandstone as occurring in three discrete unconformity-bounded packages ranging between 47.5 and 51.0 Ma. Our data show that the Matilija Sandstone ranges between 46.0 and 48.5

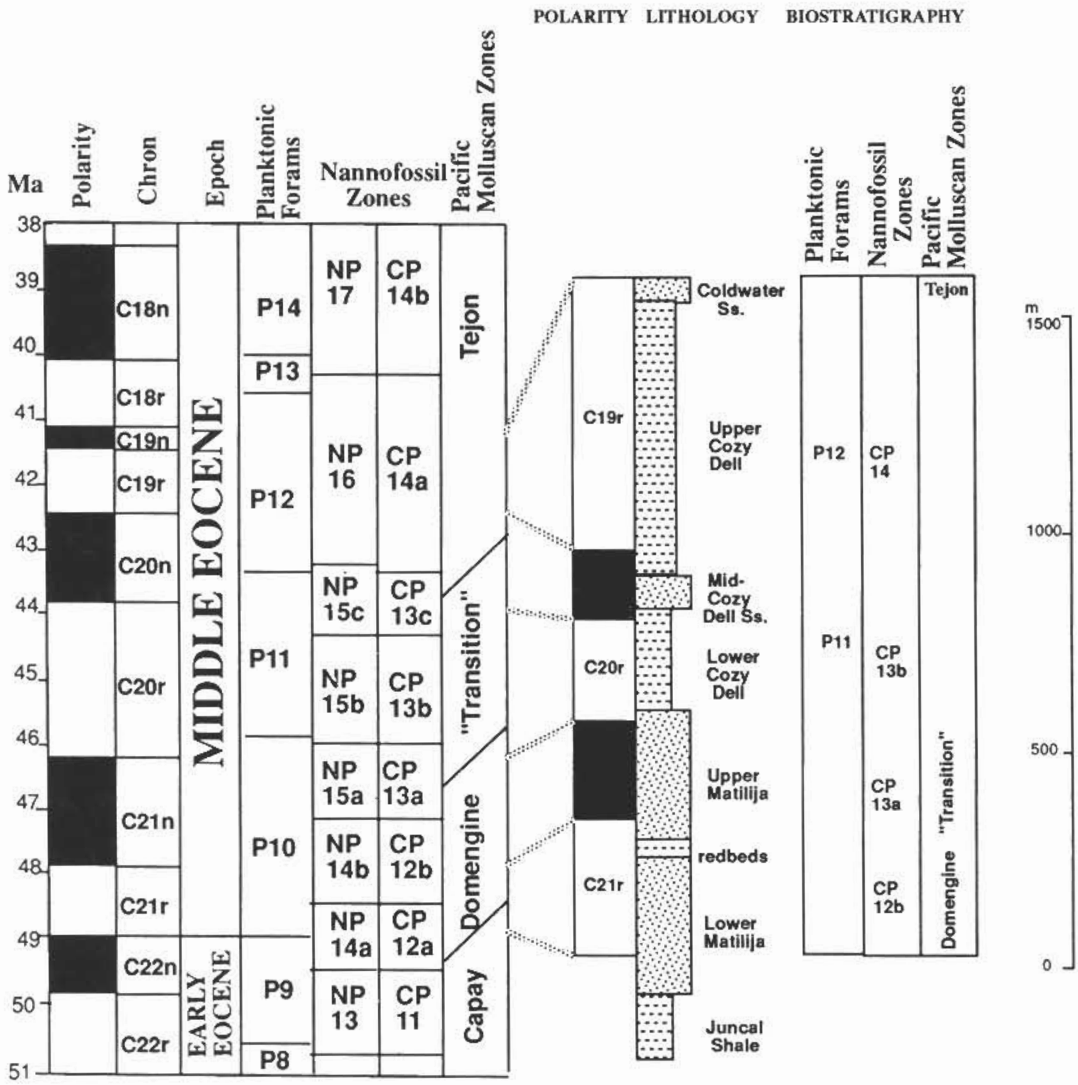

Fig. 5. Correlation of the Matilija and Cozy Dell formations with the time scale of Berggren et al. [54].

Ma. This miscorrelation of about 1–2 m.y. is further established by the presence of Zone CP12a nannofossils in the upper Juncal Shale [11], so clearly their placement of the Juncal–Matilija contact is at least 3 million years too old. Campion et al. [10,20] place the 'mid-Cozy Dell sandstone' at the base of cycle Ta3.3, between 45.5 and 46.5 Ma, but our data show that it actually is 43.0–43.5 Ma in age, a miscorrelation of 2–3 m.y. They place the Cozy Dell–Coldwater contact at about 44 Ma, but our data show that it is about 42 Ma in age – another miscorrelation by about 2 m.y. Their miscorrelations of the Coldwater and Sespe formations are discussed further by Prothero and Vance [21] and Prothero [58].

In nearly every instance their correlations are in error by 1–3 million years. With the new chronostratigraphic data, their sequence boundaries no longer match the cycle chart of Hardenbol et al. [57]. There are several reasons for these miscorrelations. The most obvious problem is that they did not use much of the available biostratigraphic data, such as the CP12a nannofossils in the upper Juncal Shale

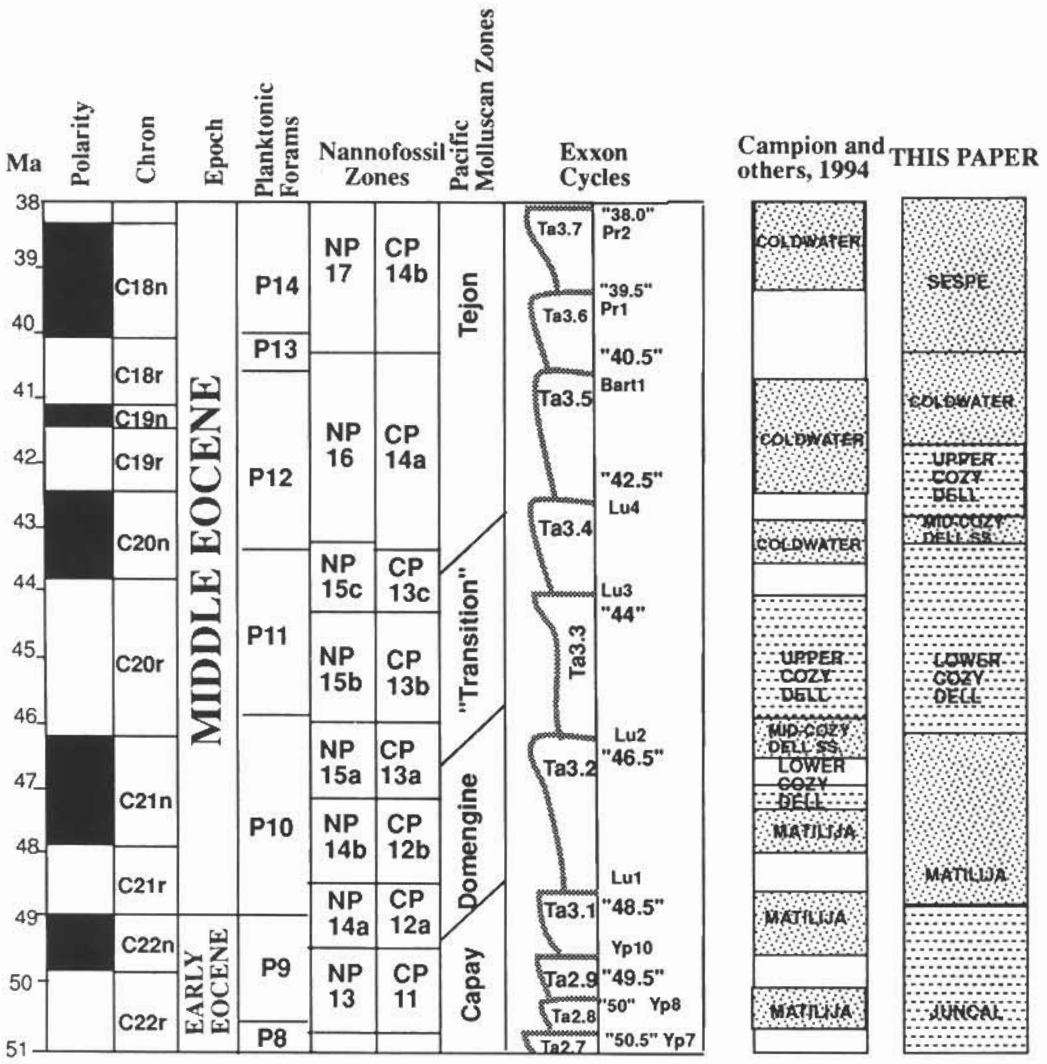

Fig. 6. Comparison of our magnetostratigraphic correlations with the sequence stratigraphic correlations of Campion et al. [10,20]. Magnetostratigraphy of Coldwater and Sespe formations after [21,22]. Time scale after Berggren et al. [54] and Hardenbol et al. [57].

that would have prevented their miscorrelation of the lower Matilija Sandstone. More importantly, the lack of correspondence to the revised cycle chart of Haq et al. [55,56] or to the new cycle chart of Hardenbol et al. [57] suggests that most of the sequence boundaries in these strata are not eustatically controlled, but instead must have tectonic causes. This should be no surprise in such a tectonically active region like southern California.

Clark [11] presented an entirely different sequence stratigraphic interpretation of these same strata. He recognized a sequence boundary at the Juncal–Matilija contact (the '50.5' sequence boundary of Campion et al. [10,20]), and another above the upper Matilija redbeds (the '48.5' sequence boundary of Campion et al. [10,20]), but no sequence boundary within the lower or middle Matilija Sandstone (Campion et al. [10,20] recognized a '49.5' sequence boundary). Clark placed the upper Matilija Sandstone and the entire Cozy Dell Shale within a single sequence; he did not recognize the sequence boundary at the base of the 'middle Cozy Dell sandstone' suggested by Campion et al. [10,20]. None of the sequence boundaries recognized by Clark correspond to global sequence boundaries on the Hardenbol et al. [57] chart. However, Clark thought that these sequence boundaries were controlled by tectonic rather than eustatic forces, and did not attempt to correlate them to the Haq et al. [55,56] chart.

As discussed and further documented by Prothero [58] and Miall [59], these conflicts show that sequence stratigraphic correlations to the global cycle chart must be interpreted cautiously, especially in tectonically active regions like southern California. Sequence stratigraphic correlations are only as good as the biostratigraphy and chronostratigraphy on which they are based.

5. Summary and conclusions

Magnetic data from the Middle Eocene Matilija and Cozy Dell formations near their type sections showed that these rocks are rotated about 85° clockwise, translated about 20° north from their original site of deposition, and span Chrons C21r–C19r (42.0–48.5 Ma). Detailed comparison of the new magnetobiostratigraphy of these sections with sequence stratigraphic correlations of Campion et al. [10,20] and Clark [11] showed that almost none of the sequence boundaries match the global cycle chart of Haq et al. [55,56] or Hardenbol et al. [57]. Sequence stratigraphic correlations are only as good as the biostratigraphy on which they are based, and should be used with caution in tectonically active basins.

Acknowledgements

This research was supported by NSF grant EAR94-05942 to Prothero. We thank Joseph Kirschvink for access to the California Institute of Technology paleomagnetics laboratory. We thank Mr. Cole Epstein for access to private land along Highway 33. We thank Scott Bogue, William Dickinson, Joseph Kirschvink, and Richard Squires for their helpful comments on various drafts of the manuscript. ***[RV]***

References

[1] T.W. Dibblee Jr., Geology of southwestern Santa Barbara County, California, Calif. Dep. Nat. Resources, Div. Mines Bull. 150 (1950) 1–95.

[2] T.W. Dibblee Jr., Geology of the central Santa Ynez Mountains, Santa Barbara County, California, Calif. Div. Mines Bull. 186 (1966) 1–99.

[3] B.M. Page, J.G. Marks, G.W. Walker, Stratigraphy and structure of mountains northeast of Santa Barbara County, California, Am. Assoc. Pet. Geol. Bull. 35 (1951) 1727–1780.

[4] R.C. Blaisdell, The stratigraphy and Foraminifers of the Matilija, Cozy Dell, and 'Coldwater' Formations near Ojai, California, M.S. thesis, Univ. Calif., Berkeley, 1955.

[5] P.C. Van de Kamp, J.D. Harper, J.J. Conniff, D.A. Morris, Facies relations in the Eocene–Oligocene in the Santa Ynez Mountains, California, J. Geol. Soc. London 13 (1974) 545–565.

[6] W.R. Dickinson, Geologic problems in the mountains between Ventura and Cuyama, in: W.R. Dickinson (Ed.), Upper Sespe Creek, Pac. Sect. SEPM Field Trip Guidebook, 1969, pp. 1–23.

[7] W.R. Dickinson, Paleogene depositional systems of the western Transverse Ranges and adjacent southernmost Coast Ranges, California, Pac. Sect. SEPM 75 (1995) 53–83.

[8] M.H. Link, Matilija Sandstone: a transition from deep-water turbidite to shallow-marine deposition in the Eocene of California, J. Sediment. Petrol. 45 (1975) 63–78.

[9] M.H. Link, J.E. Welton, Sedimentology and reservoir potential of Matilija Sandstone: an Eocene sand-rich deep-sea fan and shallow-marine complex, California, Am. Assoc. Pet. Geol. Bull. 66 (1982) 1514–1534.

[10] K.M. Campion, J.M. Lohmar, M.D. Sullivan, Paleogene sequence stratigraphy, western Transverse Ranges, California, Pac. Sect. AAPG–SEPM 1994 Ann. Mtg. Field Trip Guidebook, pp. 1–29.

[11] M.S. Clark, Sedimentation response to earthquake-related events, middle Eocene Ventura Basin, California, Pac. Sect. SEPM 74 (1994) 9–38.

[12] B.P. Luyendyk, A model for Neogene crustal rotations, transtension and transpression in southern California, Geol. Soc. Am. Bull. 103 (1991) 1528–1536.

[13] B.P. Luyendyk, M.J. Kamerling, R. Terres, Geometric model for Neogene crustal rotations in southern California, Geol. Soc. Am. Bull. 91 (1980) 211–217.

[14] T.H. Nilsen, E.H. McKee, Paleogene paleogeography of the western United States, in: J.M. Armentrout, M.R. Cole, M. Terbest (Eds.), Cenozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium 3, Pac. Sect. SEPM, 1979, pp. 257–276.

[15] K. Grove, Latest Cretaceous basin formation within the Salinian terrane of west-central California, Geol. Soc. Am. Bull. 105 (1993) 447–463.

[16] C.E. Weaver et al., Correlation of the marine Cenozoic

formations of western North America, Geol. Soc. Am. Bull. 55 (1944) 569–598.
[17] V.S. Mallory, Lower Tertiary Stratigraphy of the California Coast Ranges, American Association of Petroleum Geologists, Tulsa, OK, 1959.
[18] J.C. Taylor, Geologic appraisal of the petroleum potential of offshore southern California: the borderland compared to onshore coastal basins, U.S. Geol. Surv. Circ. 73 (1976) 1–43.
[19] P.R. Thompson, R.M. Slatt, Depositional sequence stratigraphy of middle to upper Eocene units, Santa Ynez Mountains (abstract), Am. Assoc. Pet. Geol. Bull. 74 (1990) 778.
[20] K.M. Campion, M.D. Sullivan, J.A. May, J.E. Warme, Sequence stratigraphy along a tectonically active margin, Paleogene of southern California, Pac. Sect. SEPM 80 (1996) 125–188.
[21] D.R. Prothero, E.H. Vance, Jr., Magnetostratigraphy of the upper middle Eocene Coldwater Sandstone, central Ventura County, California, in: D.R. Prothero, R.J. Emry (Eds.), The Terrestrial Eocene–Oligocene Transition in North America, Cambridge Univ. Press, Cambridge, 1996, pp. 155–170.
[22] D.R. Prothero, J.L. Howard, T.H.H. Dozier, Stratigraphy and paleomagnetism of the upper middle Eocene to lower Miocene (Uintan to Arikareean) Sespe Formation, Ventura County, California, in: D.R. Prothero, R.J. Emry (Eds.), The Terrestrial Eocene–Oligocene Transition in North America, Cambridge Univ. Press, Cambridge, 1996, pp. 171–188.
[23] J.C. Liddicoat, Tectonic rotation of the Santa Ynez Range, California, recorded in the Sespe Formation, Geophys. J. Int. 102 (1990) 739–745.
[24] J.S. Hornafius, Neogene tectonic rotation of the Santa Ynez Range, western Transverse Ranges, suggested by paleomagnetic investigations of the Monterey Formation, J. Geophys. Res. 90 (B14) (1985) 12503–12522.
[25] E.L. Wilson, D.R. Prothero oMa, Magnetic stratigraphy and tectonic rotation of the middle–upper Miocene 'Santa Margarita' and Chanac Formations, north-central Transverse Ranges, California, Pac. Sect. SEPM 82 (1997) 35–48.
[26] P.F. Kerr, H.G. Schenck, Significance of the Matilija overturn, Santa Ynez Mountains, California, Geol. Soc. Am. Bull. 39 (1928) 1087–1182.
[27] J.G. Vedder, Revision of stratigraphic names for some Eocene formations in Santa Barbara and Ventura counties, California, U.S. Geol. Surv. Bull. 1354-D (1972) 1–12.
[28] T.L. Bailey, Geology of southwestern Santa Barbara County, California, by T.W. Dibblee, Jr. [review], Am. Assoc. Pet. Geol. Bull. 36 (1952) 176–182.
[29] P.H. Stauffer, Sedimentologic evidence on Eocene correlations, Santa Ynez Mountains, California, Am. Assoc. Pet. Geol. Bull. 51 (1967) 607–611.
[30] R.M. Kleinpell, D.W. Weaver, Oligocene biostratigraphy of the Santa Barbara embayment, Univ. Calif. Publ. Geol. Sci. 43 (1963) 1–77.
[31] E.C. Jestes, A Stratigraphic Study of some Eocene Sandstones, Northeastern Ventura Basin, California, Ph.D. dissertation, Univ. Calif., Santa Barbara, 1963.
[32] P.L. Heller, W.R. Dickinson, Submarine ramp facies model for delta-fed, sand-rich turbidite systems, Am. Assoc. Pet. Geol. Bull. 69 (1985) 960–976.
[33] W.R. Merrill, Geology of the Sespe Creek–Pine Mountain area, Ventura County, Calif. Div. Mines Bull. 170 (1954), map sheet 3.
[34] T.W. Dibblee, Jr., Geologic map of the Fillmore quadrangle, Ventura County, California, Thomas W. Dibblee, Jr. Foundation, Santa Barbara, CA, 1990.
[35] A.E. Fritsche, Field guide to Eocene rocks of the upper Sespe Creek area, Ventura County, California, Pac. Sect. SEPM 74 (1994) 89–106.
[36] A.E. Fritsche, R.O. Schmitka, Introduction to a field trip along upper Sespe Creek, Ventura County, California, with comments on the Tertiary stratigraphy of the area, Pac. Sect. SEPM Field Guide 3 (1978) 1–5.
[37] C.R. Givens, Eocene molluscan biostratigraphy of the Pine Mountain area, Ventura County, California, Univ. Calif. Publ. Geol. Sci. 109 (1974) 1–107.
[38] C.R. Givens, M.P. Kennedy, Eocene molluscan stages and their correlation, San Diego area, California, in: P.L. Abbott (Ed.), Eocene Depositional Systems, San Diego, California, Pac. Sect. SEPM, 1979, pp. 81–95.
[39] A.A. Almgren, M.V. Filewicz, H.L. Heitman, Lower Tertiary foraminiferal and calcareous nannofossil zonation of California: an overview, Pac. Sect. SEPM 58 (1988) 83–105.
[40] J.M. Gibson, Distribution of planktonic foraminifera and calcareous nannoplankton, late Cretaceous and early Paleogene, Santa Ynez Mountains, California, J. Foram. Res. 6 (1976) 87–106.
[41] R.Z. Poore, Microfossil correlation of the California lower Tertiary sections: a comparison, U.S. Geol. Surv. Prof. Pap. 743-F (1976) F1–F8.
[42] B.H. Berman, Biostratigraphy of the Cozy Dell Formation in Ventura and Santa Barbara Counties, M.S. Thesis, Calif. State Univ., Long Beach, 1979.
[43] T.W. Dibblee, Jr., Geologic map of the Matilija Quadrangle, Ventura County, California, Thomas W. Dibblee, Jr. Foundation, Santa Barbara, CA, 1987.
[44] C. Pluhar, J.L. Kirschvink, R.W. Adams, Magnetostratigraphy and clockwise rotation of the Plio-Pleistocene Mojave River Formation, central Mojave Desert, California, San Bernardino Co., Mus. Q. 38 (2) (1991) 31–42.
[45] J.L. Kirschvink, The least-squares line and plane and the analysis of paleomagnetic data: examples from Siberia and Morocco, Geophys. J. R. Astron. Soc. 62 (1980) 699–718.
[46] R.A. Fisher, Dispersion on a sphere, Proc. R. Soc. A 217 (1953) 295–305.
[47] P.L. McFadden, M.W. McElhinny, Classification of the reversal test in palaeomagnetism, Geophys. J. Int. 103 (1990) 725–729.
[48] J.F. Diehl, M.E. Beck Jr., S. Beske-Diehl, D. Jacobson, B.C. Hearn Jr., Paleomagnetism of the Late Cretaceous–

early Tertiary north-central Montana alkalic province, J. Geophys. Res. 88 (1983) 10593–10609.

[49] K.J. Whidden, S.P. Lund, D.J. Bottjer, Extension of the western Transverse Range zone of Cenozoic block rotations north of the Santa Ynez fault, California, Pac. Sect. SEPM 75 (1995) 181–192.

[50] D.R. Prothero, M. Thompson, Magnetic stratigraphy of the type Refugian stage (Eocene–Oligocene), western Santa Barbara County, California, Pac. Sect. SEPM (in press).

[51] S.P. Lund, D.J. Bottjer, K.J. Whidden, J.E. Powers, M.C. Steele, Paleomagnetic evidence for Paleogene terrane displacements and accretion in southern California, Pac. Sect. SEPM 68 (1991) 99–106.

[52] K.P. Kodama, J.M. Davi, A compaction correction for the paleomagnetism of the Cretaceous Pigeon Point Formation of California, Tectonics 14 (1995) 1153–1164.

[53] N.M. Johnson, N.D. Opdyke, G.D. Johnson, E.H. Lindsay, R.A.K. Tahirkheli, Magnetic polarity stratigraphy and ages of Siwalik Group rocks of the Potwar Plateau, Pakistan, Palaeogeogr., Palaeoclimatol., Palaeoecol. (1982) 17–42.

[54] W.A. Berggren, D.V. Kent, C.C. Swisher III, M.-P. Aubry, A revised Cenozoic geochronology and chronostratigraphy, SEPM Spec. Publ. 54 (1995) 129–212.

[55] B.U. Haq, J. Hardenbol, P. Vail, Chronology of fluctuating sea levels since the Triassic, Science 235 (1987) 1156–1167.

[56] B.U. Haq, J. Hardenbol, P. Vail, Mesozoic and Cenozoic chronostratigraphy and cycles of sea level change, SEPM Spec. Publ. 42 (1988) 71–108.

[57] J. Hardenbol, J. Thierry, M.B. Farley, T. Jacquin, P.-C. de Graciansky, P.R. Vail, Mesozoic–Cenozoic chronostratigraphic framework, SEPM Spec. Publ. 59, 1998.

[58] D.R. Prothero, Magnetostratigraphic tests of sequence stratigraphic correlations from the southern California Paleogene, SEPM Spec. Publ. (in press).

[59] A.D. Miall, The Geology of Stratigraphic Sequences, Springer, Berlin, 1997, 433 pp.