# 7. Magnetostratigraphy of the Upper Middle Eocene Coldwater Sandstone, Central Ventura County, California

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ABSTRACT

A magnetostratigraphic study was undertaken to improve the age control of the middle Eocene Coldwater Sandstone in southern California. The results show that, although magnetic overprinting is common in Coldwater rocks, most samples yield a stable characteristic remanence that passes reversal and fold tests and shows a clockwise rotation of about 100° ± 17° (consistent with other pre-Miocene units in the western Transverse Ranges). Magnetic stratigraphy and refined chronostratigraphy of the late Uintan and Duchesnean mammals found within redbeds of the Coldwater show that the upper Cozy Dell Shale-Coldwater Sandstone-Sespe Formation succession in central Ventura County spans Chrons C19r-C18n (approximately 39.5-42.5 Ma). These data do not corroborate the sequence stratigraphic interpretations of Campion et al. (1994) or Clark (1994). We suggest that local tectonic forces may have been more important than eustatic sea level fluctuations in causing sequence boundaries in the Coldwater and Sespe formations.

## INTRODUCTION

The Transverse Ranges of southern California (Fig. 1) contain an important succession of strata that records a complex history of transgressions and regressions during the Eocene. In the upper Sespe Creek area of central Ventura County, over 4,800 m of Eocene strata were deposited, and some of these formations are even thicker to the east or west. The Eocene succession starts with the lower Eocene deep-water Juncal Shale, overlain by the middle Eocene shallow- to deep-marine Matilija Sandstone, and then by the deep-water Cozy Dell Shale (Kerr and Schenk, 1928; Page et al., 1951; Vedder, 1972; Dibblee, 1966, 1982; Jestes, 1963; Ingle, 1980; Campion et al., 1994). After Cozy Dell deposition, a shallowing-upward trend is marked by the nearshore marine Coldwater Sandstone (Clark, 1994; Jiao and Fritsche, 1994) that is transitional with the overlying nonmarine Sespe Formation (McCracken, 1969, 1972; Howard, 1987, 1989; Prothero et al., this volume, Chapter 8).

Despite almost a century of study, however, the dating and correlation of these beds have never been very precise. For example, parts of the Matilija Sandstone, all of the Cozy Dell Shale and Coldwater Sandstone, and the lower part of the Sespe Formation are middle Eocene in age. Following current time scales (e.g., Berggren et al., 1995), the middle Eocene spans 12 million years (49-37 Ma), so a "middle Eocene" age assignment is not very helpful for high-resolution chronostratigraphy. Similarly, the local biostratigraphic units employed in coastal California are very long in duration, so they do not provide much resolution or precision. For example, the "Tejon" molluskan stage is about 10 million years in duration (about 34-44 Ma), and the "Narizian" benthic foraminiferan stage is about 8 million years in duration (39-48 Ma) (Fig. 2). In a few places, planktonic foraminifera allow more precise correlation, but they are rare, even in the deep-water units.

Several important fossil mammal localities are known from rocks assigned to the Coldwater Sandstone by some authors (or the Sespe Formation by others). With the newly refined dating of the Sespe Formation in Simi Valley to the east (Prothero et al., this volume, Chapter 8), these fossils turn out to be more age-diagnostic than any other kind. The mammalian biostratigraphic framework established in Simi Valley, tied to the global magnetic time scale, allows us to extend our magnetostratigraphic correlation down into the underlying Coldwater Sandstone in Ventura County and greatly improve the age constraints of the rock unit.

Why is such fine-scale dating important? Of course, there is the obvious value of improving the chronostratigraphy of the California Eocene. In recent years, however, the Eocene strata in the Transverse Ranges have been studied in the context of sequence stratigraphy (Thompson and Slatt, 1990; Campion et al., 1994; Clark, 1994). Many of the Eocene sequence boundaries have very imprecise age constraints, so some sequence stratigraphers (e.g., Campion et al., 1994) have chosen to assume that they matched the Exxon global onlap-offlap chart (Haq et al., 1987, 1988). These assumptions and correlations can be tested with biostratigraphically controlled magnetic stratigraphy to see if sequence boundaries are really eustatically controlled, or whether they might be due to local tectonism.

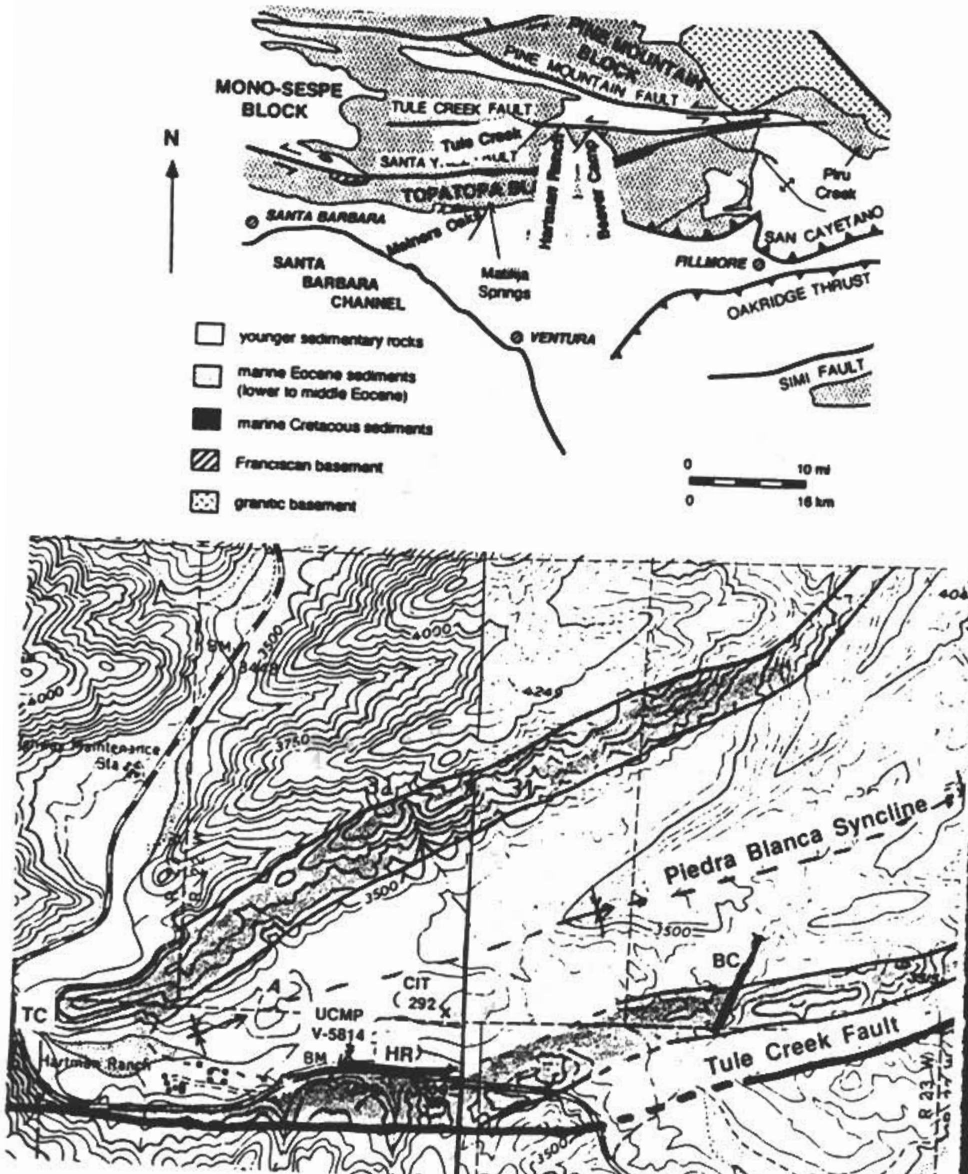


Figure 1. (*Top*) Index map showing location of four sections sampled in this study (after Clark, 1994). (*Bottom*) Details of localities in the Hartman Ranch area. Shaded area shows the outcrop of the marine Coldwater Sandstone plunging northeasterly along the nose of the Piedra Blanca syncline. The area inside the syncline includes the Coldwater redbeds and conglomerates mapped as Sespe Formation by Dibblee (1985, 1987). Location of stratigraphic sections and main fossil localties are shown as follows: A, *Amynodontopsis* tooth fragments; BC, Beaver Camp; HR, Hartman Ranch; TC, Tule Creek. Geology modified from Dibblee (1985, 1987).



## THE COLDWATER SANDSTONE

The Coldwater Sandstone was first described by Watts (1897, 1900) and Taliaferro (1924) and named by Kew (1924). Taliaferro (1924) designated the type section as Coldwater Creek in the Topatopa Mountains north of Fillmore (Vedder, 1972; Clark, 1994). The name "Coldwater" has been widely used in the region (e.g., Page et al., 1951; Dibblee, 1966), so that even though the name has been used at least twice elsewhere in North America, Vedder (1972) argued that it should be retained because it had become so well established.

The Coldwater Sandstone (Fig. 1) crops out almost continuously from its type area north of Fillmore to west of Santa Barbara, a distance of more than 80 km (Merrill, 1954; Dibblee, 1966; Kleinpell and Weaver, 1963). As the formation is traced west of Santa Barbara, it interfingers with the mudstones and siltstones of the upper part of the deeper-water Sacate Formation (Weaver, 1965, fig. 1; Dibblee, 1966; O'Brien, 1972). The Sacate Formation extends all the way to Point Conception, another 40 km to the west. At its type area, the Coldwater is about 150 m thick, but it thickens to 750 m in our study area in upper Sespe Creek. It reaches about 1000 m in thickness north of Santa Barbara, and then thins rapidly to the west as it interfingers with the Sacate Formation. Outcrops of the Coldwater Sandstone also occur in the Pine Mountain area and in the Santa Maria Basin.

At the type locality, the Coldwater gradationally overlies the Cozy Dell Shale. Elsewhere, the contact is gradational or represented by a small disconformity (Vedder, 1972). In some places, the Coldwater/Cozy Dell contact has been confused because a similar-looking shallow marine sandstone body also occurs in the upper part of the Cozy Dell. Some authors (e.g., Dibblee, 1985, 1987a; Clark, 1994) have extended the Coldwater downward to include this sandstone, and called the rocks in between the "Coldwater Shale." Others (e.g., Jestes, 1963; Fritsche, 1994; Squires, 1994) refer to this sandstone as the "Circle B sandstone member" of the Cozy Dell Formation. In this chapter, we will follow the latter usage, since it has been clearly delineated in the sections we measured (Fritsche, 1994; Jiao and Fritsche, 1994).

The upper contact of the Coldwater with the Sespe Formation is even more confusing. Traditionally, most terrestrial redbeds in the region have been mapped as Sespe Formation. However, in several sections in the study area, shallow marine Coldwater sandstones interfinger with these redbeds. Thus, some authors draw the Coldwater/Sespe contact at the base of the first redbed (e.g., Dibblee, 1985; Howard, 1989; Clark, 1994), whereas others place it at the top of the last marine sandstone (e.g., Dibblee, 1987a), or at the base of the first conglomerate in the Sespe (e.g., Campion et al., 1994). The contact is so confusing that in the Meiners Oaks section in the Matilija Quadrangle, Dibblee (1987a) mapped the redbeds as "red siltstone" layers within the Coldwater, but at Hartman Ranch in the Wheeler Springs Quadrangle (the next quadrangle to the north), Dibblee (1985) mapped the same redbeds as Sespe Formation. As we shall show below, these controversial redbeds are equivalent in age to the Sespe redbeds in the Simi Valley area. As long as one is aware of the complications of the Coldwater/Sespe contact, it really makes no difference whether one includes the redbeds in the Coldwater or the Sespe. Such a complex situation should be expected of transitional, interfingering contacts.

To add to the confusion, the internal stratigraphy of the Sespe Formation is also very complex. Howard (1989) suggested that it is composed of two discrete depositional cycles, a middle Eocene pulse, and a late Oligocene pulse (Prothero et al., this volume, Chapter 8). In some areas, conglomerates in the upper part of the Sespe Formation (which are upper Oligocene) are deeply incised into the lower units, so they cut out much of the section. Prothero et al. (this volume, Chapter 8) showed that an erosional event removed about 8 million years of upper Eocene and lower Oligocene strata in Simi Valley. In the Sandstone Camp (= Pine Mountain Inn) area along Highway 33 near upper Sespe Creek, conglomerates of the upper part of the Sespe cut out the lower part of the Sespe completely, and are incised into the Coldwater (or ?Sespe) redbeds (Howard, 1989).

The depositional interpretation of the Coldwater Sandstone in the study area was most recently summarized by Jiao and Fritsche (1994). As part of his thesis, in early 1994 the junior author of this chapter (EHV) undertook his own independent analysis of the depositional environments of the Coldwater, unaware of the earlier, unpublished work of Jiao (1989). Most of his conclusions corroborated those of Jiao and Fritsche (1994), which were published after his work was completed. We concur with Jiao and Fritsche (1994) that the Coldwater Sandstone represents wave-dominated and storm-dominated nearshore facies, with minor tidal influences. After correction for 90° of Miocene clockwise tectonic rotation, provenance studies and paleocurrents indicate that sediments were eroded from highlands in the Pine Mountain area and transported southeasterly. The Coldwater also progrades to the southeast (after correction for tectonic rotation).

Dating of the Coldwater Sandstone has long been very imprecise (Fig. 2). The only marine fossils found in it are mollusks assigned to the "Tejon Stage" (Squires, 1994), which has about a 10-million-year duration. Link and Welton (1982) reported planktonic microfossils from the upper Cozy Dell Shale that placed it in planktonic foraminiferal Zones P11 and P12. Just south of our study area, Berman (1979, p. 34) reported planktonic foraminiferans which last occur in Zone P12, constraining the age of the upper Cozy Dell to

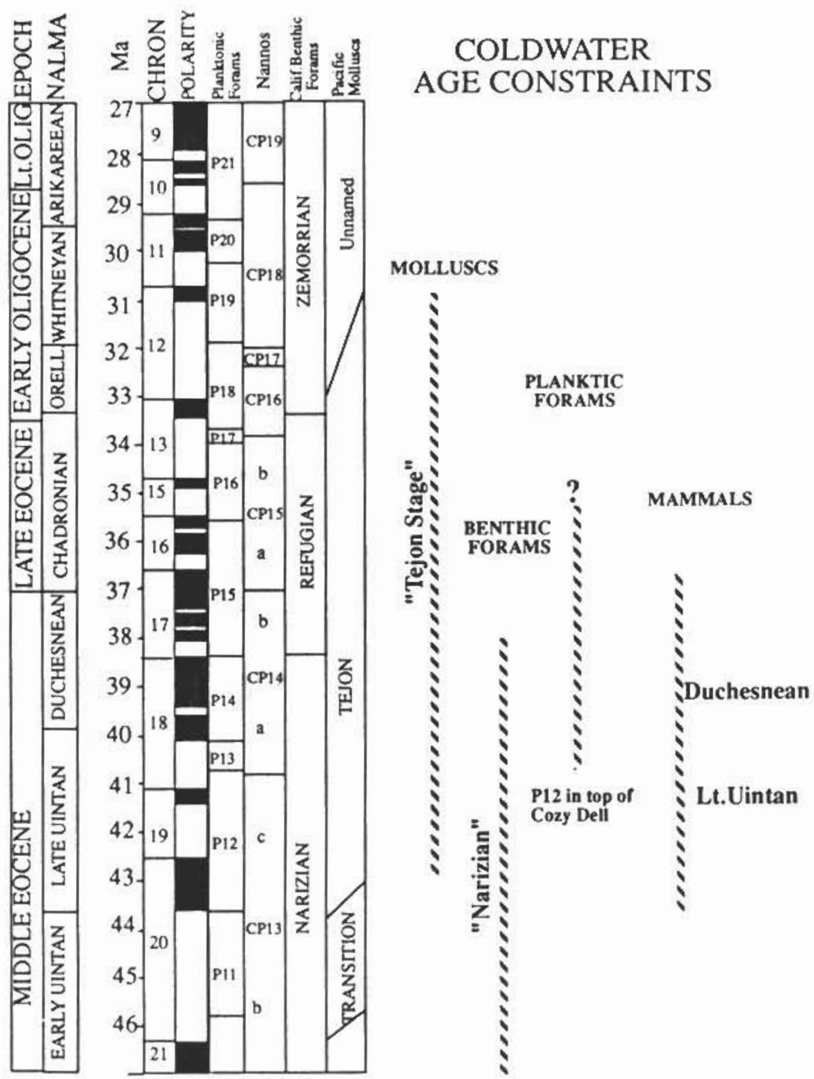


Figure 2. Biostratigraphic age constraints on the Coldwater Sandstone before this study. Time scale after Berggren et al. (1995). California benthic foraminiferal stages after Almgren et al. (1988) and Clark (1994); molluskan stages after Squires (1994).



between 40.5-44.0 Ma, or magnetic Chrons C18r-C20n (Berggren et al., 1995). Benthic foraminiferans from the upper Cozy Dell are assigned to the A-1/A-2 transition (Kelley, 1943; Almgren et al., 1988), which is less age-diagnostic than the planktonic foraminiferans. Fossil mammals from the redbeds between the marine sandstones at Hartman Ranch (Lindsay, 1968; Kelly, 1990; Lander, 1994) are assigned to the late Uintan, but the exact chronostratigraphic position of the late Uintan did not become clear until recent work on the type Uintan in the Uinta Basin of Utah (Prothero, this volume, Chapter 1), and the Uintan faunas of the Sespe Formation in Simi Valley (Prothero et al., this volume, Chapter 8). The redbeds above the marine sandstones have produced Duchesnean mammals in several places. Together with the magnetic stratigraphy, these new biostratigraphic constraints greatly improve the precision of correlation.

## MAGNETIC ANALYSIS

Only a few stratigraphic sections of the Coldwater Sandstone produce age-diagnostic mammals that make magnetic sampling worthwhile. Four sections were sampled in this study (Fig. 1). Sections were measured using a Brunton compass and Jacob's staff. Each section was sampled with a coring drill or hand tools, producing 40 sites spaced at about 10-30 meter intervals, depending upon exposure. Three samples were taken per site so that site statistics could be calculated (Fisher, 1953). The hand samples were trimmed into 2.5-cm cubes on a band saw with a tungsten-carbide blade, and then analyzed at the paleomagnetics laboratory at the California Institute of Technology.

Previous work on rocks of the Transverse Ranges (e.g., Hornafius, 1985; Prothero et al., this volume, Chapter 8) has shown that they often contain complex overprinted components that make the primary component hard to recognize and extract. For this reason, each sample was measured at NRM (natural remanent magnetization), and then demagnetized at alternating fields (AF) of 25, 50, and 100 Gauss to remove multidomain components, followed by thermal demagnetization at 200, 300, 400, 500, and 600°C, for a total of nine demagnetization steps. Typical results are shown in Figures 3 and 4. Most normally magnetized samples (i.e., those with downward inclinations) were pointed almost due east, and the component of magnetization between 300 and 500°C showed a stable normal direction with about 100° clockwise rotation (Fig. 3). Likewise, reversed samples (i.e., those with upward inclinations) showed stable directions that were pointed about 280° in declination, which is consistent with about 100° clockwise rotation (Fig. 4). A few samples had intractable normal overprints due to the present-day earth's magnetic field that could not be removed at any demagnetization step. A number of samples yielded highly scattered, random results that could not be interpreted at all. These were omitted from the analysis.

The vector demagnetization ("Zijderveld") plots also show that a complex magnetic mineralogy is responsible for the remanence. In some samples (e.g., Fig. 4), the magnetization declined rapidly in intensity under AF demagnetization, showing that magnetite is the primary carrier of the remanence; the intensity of these samples was very weak above the Curie point of magnetite (i.e., the 600°C step). In others, the AF demagnetization had no effect on the intensity, showing that a high-coercivity phase, such as goethite or hematite, was the primary carrier; these samples also retained significant intensity above 600°C, which is also consistent with hematite.

To test these conclusions, several IRM (isothermal remanent magnetization) acquisition tests were conducted on different lithologies (Fig. 5). Some samples (Fig. 5B) showed saturation at 500 mT (millitesla), consistent with magnetite, but others (Figs. 5A, C) did not saturate even at 1300 mT, which indicates that they contained significant hematite. Along with the IRM acquisition analyses, the same samples were subjected to a modified Lowrie-Fuller test (Johnson et al., 1975; Pluhar et al., 1991), which compares the resistance to AF demagnetization of both the IRM produced in a 100 mT peak field, and the ARM (anhysteretic remanent magnetization) gained in a 100-mT oscillating field. As can be seen in Figure 5, the ARM (solid squares) demagnetizes at higher fields than the IRM (open squares) in most samples, so much of the remanence appears to be carried by single-domain or pseudo-single domain grains.

If a stable component was apparent, its vector was averaged for those of the other two samples at that site using the methods of Fisher (1953; see Butler, 1992). These yielded site statistics, which were classified following the system of Opdyke et al. (1977). Class I sites are significantly separated from random at the 95% confidence level, and are shown by the solid circles in Figure 6. Class II sites (circles with diagonal pattern) had one sample missing, so site statistics could not be calculated, but a clear polarity was apparent from the remaining samples. Class III sites (open circles) had one sample divergent, so they did not cluster at the 95% confidence level, but their polarity was clear from the two remaining sites.

The means for the normal and reversed sites were averaged using the methods of Fisher (1953). The mean for all Class I normal sites ($N = 17$) was $D = 99.0°$, $I = 57.0°$, $k = 5.2$, $\alpha_{95} = 17.3$; the mean for all Class I reversed sites ($N = 10$) was $D = 293.8$, $I = -57.3$, $k = 13.1$, $\alpha_{95} = 13.9$. These directions are almost exactly antipodal, so the magnetic vectors pass the reversal test and are probably due to primary magnetization, and not overprints. The mean declinations clearly show that this block has been rotated clockwise by about 100° since the Eocene, which is consistent (within the $\alpha_{95}$

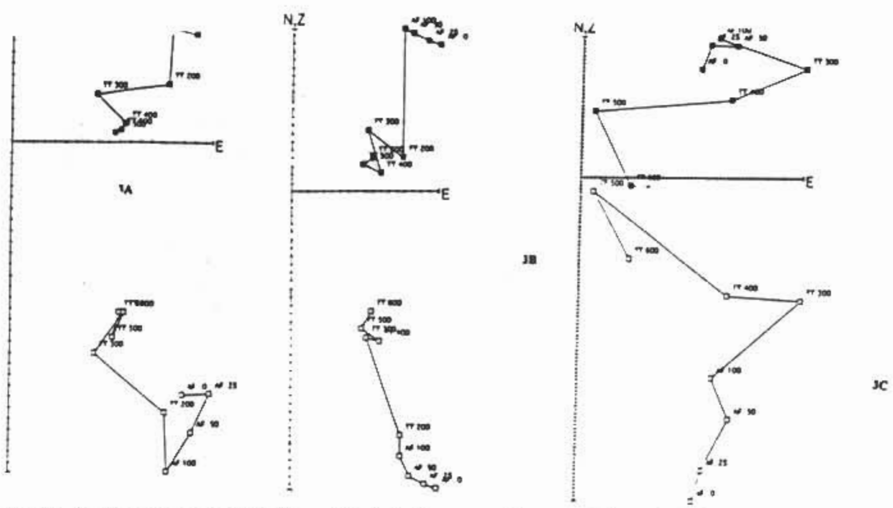


Figure 3. Vector demagnetization ("Zijderveld") plots of representative normal (east and down) samples. Solid squares indicate declination; open squares indicate inclination. AF and thermal ("TT") demagnetization steps are labeled. Each increment is $10^{-6}$ emu. Note that in most samples, an overprint was removed at 200-300°C, leaving a stable component pointed east and down that decayed to the origin. In samples 3A and 3B, the lack of response to AF demagnetization and the high intensity remaining at 600°C shows that significant hematite was present; in 3C, the sample responded to AF demagnetization and was nearly demagnetized by 500°C, showing that magnetite is the main carrier of the remanence.

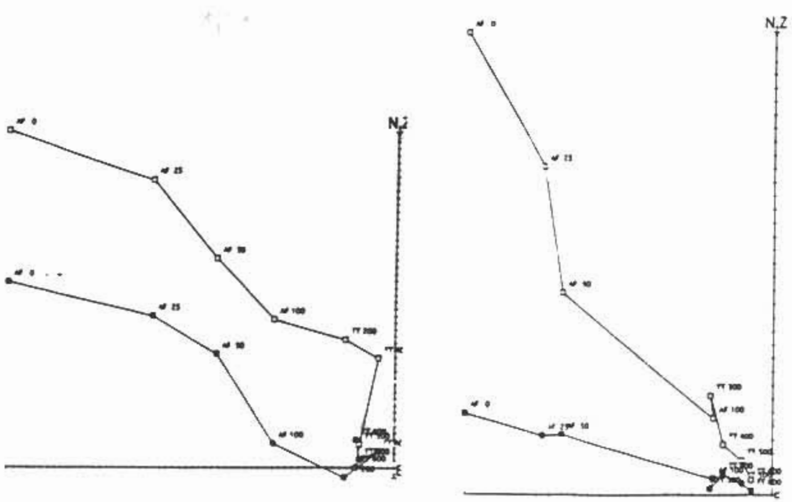


Figure 4. Vector demagnetization plots of typical reversed (west and up) samples. All conventions as in Fig. 3. Note that nearly all samples responded to AF demagnetization and were nearly demagnetized by 500°C, suggesting that magnetite is the main carrier of the remanence.



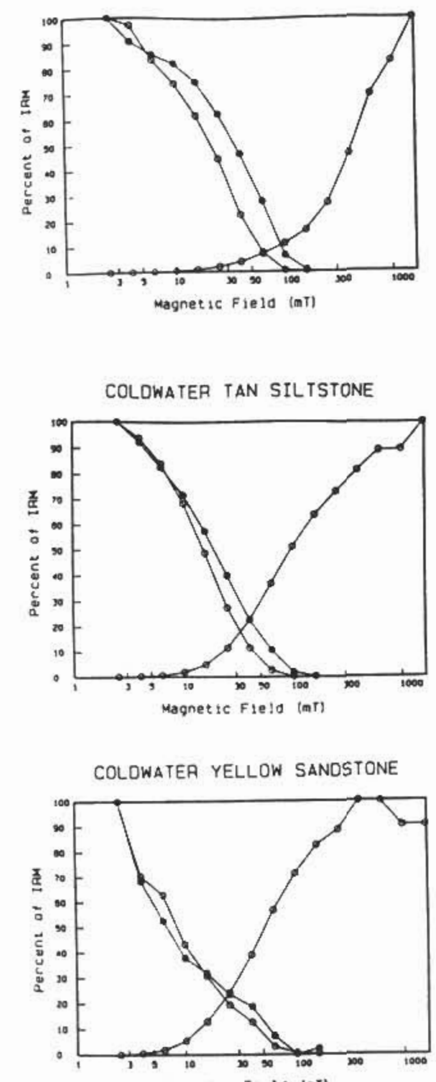


Figure 5. IRM (isothermal remanent magnetization) and Lowrie-Fuller tests for typical lithologies. IRM = open circles, ARM = solid circles. Note that in most samples (except the yellow sandstone), the IRM fails to saturate, indicating the presence of hematite. In most samples, the ARM is more resistant to AF demagnetization than the IRM, indicating that the remanence is carried by single-domain or pseudo-single domain grains (see Pluhar et al., 1991, for further details of the experimental methods).

error estimates) with the approximately 90° clockwise rotation reported for this tectonic block by Luyendyk et al. (1980, 1985).

The mean inclinations would produce an Eocene paleolatitude of 38° ± 17.3° (present latitude = 34.0°), which is actually north of its present position, and further north than would be expected from the shallow paleolatitudes of most Eocene rocks in the region (Lund et al., 1991). However, the error estimates are large enough to accommodate this possibility.

A fold test was also conducted to determine the stability of the magnetic directions. The scatter of the uncorrected normal mean ($\alpha_{95}$ = 32.5) and reversed mean ($\alpha_{95}$ = 25.6) was significantly greater than the means of the sites after dip correction. This shows that the magnetization must have been acquired before folding took place.

## MAGNETIC STRATIGRAPHY

### Meiners Oaks

One of the thickest sections of the Coldwater Sandstone in the region is exposed in west-facing roadcuts along Highway 33 just north of the town of Meiners Oaks (center NE Sec. 33, T5N, R23W, Matilija 7.5' quadrangle). These exposures lie stratigraphically above the type Cozy Dell Shale at Cozy Dell Creek, and span almost 500 m of section. The basal 100 m of section above the Cozy Dell contains lithologies typical of the Coldwater Sandstone, with wave-ripple cross-beds, herringbone cross-beds, glauconitic layers, flaser beds, storm-battered shell lags, and other shoreface-intertidal features. The upper part of the section consists of 400 m of redbeds and fluvial sandstones. However, Dibblee (1987a) mapped the redbeds as "red siltstone" tongues within the Coldwater Sandstone, not as Sespe Formation, as he did in other exposures. Undisputed Sespe Formation occurs to the south of the roadcut (above the top of the section) in the backyards of north Meiners Oaks, but no good sections were available for sampling. This section was also discussed by Campion et al. (1994, p. 20, and figs. 31, 35, and 36).

The basal 100 m of marine Coldwater is entirely of reversed polarity (Fig. 6). The next 100 m of redbeds are of normal polarity. From about 200 m in the section until the covered interval begins at 330 m, the section is again of reversed polarity. An edentulous rodent jaw (University of California, Berkeley, Museum of Paleontology, or UCMP locality V-81116) occurs at about the 330-meter level, but it is not diagnostic of age. The only other exposures (between 380 and 460 m) are of normal polarity. Just above where the exposures disappear in slumped material and vegetation, a *Duchesneodus* (brontothere) jaw was collected (UCMP V-82372). This specimen would indicate that the upper part of the section transitional between Coldwater and Sespe is Duchesnean in age.

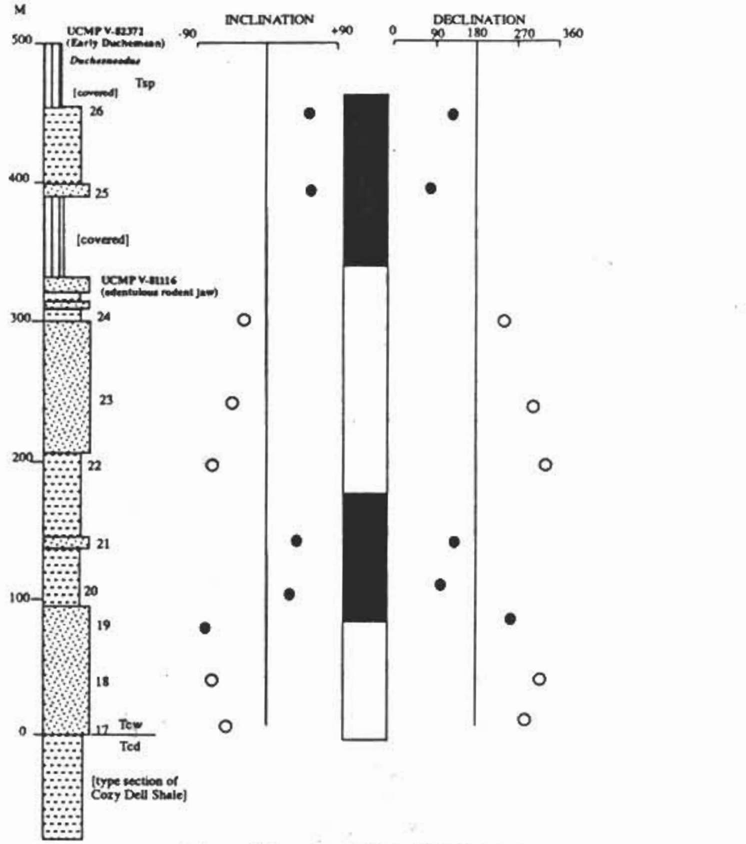


Figure 6. Magnetostratigraphic plots of the Meiners Oaks section. Details of sections described in text. Tcw = Coldwater Sandstone; Tcd = Cozy Dell Shale; Tsp = Sespe Formation. UCMP V = University of California (Berkeley) Museum of Paleontology vertebrate fossil locality. Site numbers shown in small numbers to right of lithostratigraphy. R = redbeds. Solid circles = Class I sites of Opdyke et al. (1977), which are significantly separated from a random distribution at the 95% confidence level; circles with diagonal slash = Class II sites (one sample missing, so no statistics could be performed); open circles = Class III sites (two samples show a polarity preference, but one sample was divergent). Note that most normal sites have a positive inclination and declinations around 90°; reversed sites have a negative inclination and declinations around 270°.

## Hartman Ranch

The most important exposures in the area occur in north-facing roadcuts along Highway 33 (N 1/2 NE Sec. 2, T5N, R23W, Wheeler Springs 7.5' quadrangle). Campion et al. (1994, p. 18, fig. 31) gave a brief description of this section, and it was described as the "lower Sespe" by Howard (1989, fig. 4). It begins with about 80 m of Coldwater Sandstone characterized by wave-ripple cross-beds, *Ophiomorpha* burrows, abraded shell beds and other wave- and storm-dominated shoreline features. This unit is entirely of reversed polarity (Fig. 7). Between 80 and 140 m, there are poorly exposed redbeds (called Coldwater by Campion et al., 1994, but mapped as Sespe Formation by Dibblee, 1985, and considered to be Sespe Formation by Howard, 1989). Near the top of this unit in a green sandstone on a north-facing roadcut just east of milepost 28.77, is the Hartman Ranch locality (UCMP V-5814, shown by Squires, 1994, fig. 3), that produces a late Uintan fauna correlative with the Tapo Canyon and Brea Canyon local faunas in the middle member of the Sespe Formation in Simi Valley (Lindsay, 1968; Kelly, 1990; Lander, 1994). The remaining 40 m of section are intertidal marine sandstone (with flaser beds, larger rip-up clasts, and interference ripples) typical of the Coldwater (yet mapped as Sespe by Dibblee, 1985). The entire upper 100 m of this section is of normal polarity.



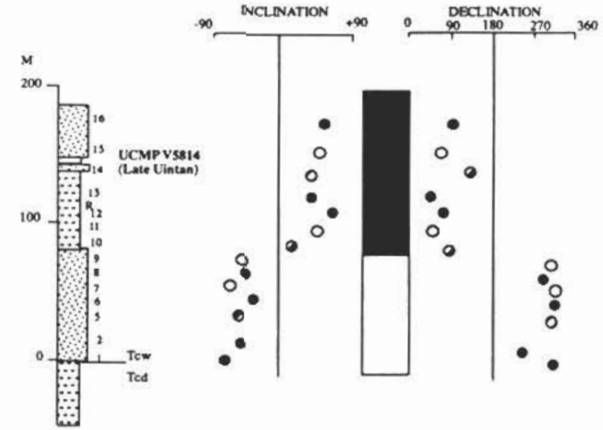


Figure 7. Magnetostratigraphy of the Hartman Ranch section. Conventions as in Fig. 6.

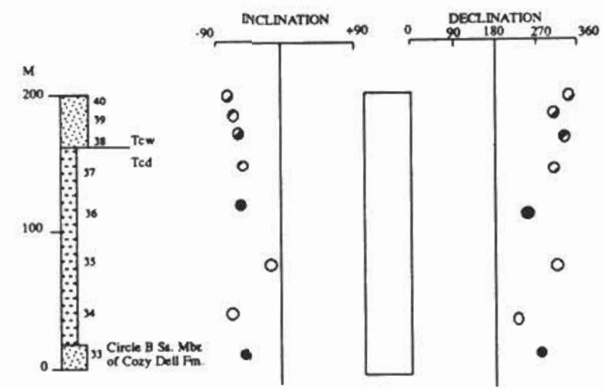


Figure 8. Magnetostratigraphy of the Tule Creek section. Conventions as in Fig. 6.

## Tule Creek

To supplement the Hartman Ranch section, another section was taken on the same side of Highway 33 in the east-facing roadcuts where the highway crosses Tule Creek (NE NE NE Sec. 3, T5N, R23W, Wheeler Springs 7.5' quadrangle). Jiao and Fritsche (1994, fig. 3, "Highway 33 roadcut") previously measured and described the upper part of this section. We began the section with exposures of the Circle B sandstone member of the Cozy Dell north of the creek, and sampled some 120 m of Cozy Dell Shale, before concluding at the base of typical Coldwater Sandstone on the south side of the creek. The entire section (Fig. 8) was of reversed polarity, from the lowest exposures of the Circle B sandstone to the typically reversed lower Coldwater Sandstone.

## Beaver Camp

The Eocene beds in the Hartman Ranch area are folded into the Piedra Blanca syncline, which plunges west (Dibblee, 1985, 1987b). Just north of Beaver Campground (SE SW SW Sec. 32, T6N, R22W, Lion Canyon 7.5' quadrangle), a small southeast-flowing tributary of Sespe Creek cuts through the cuestas on the south limb of the syncline, exposing a section of upper Coldwater Sandstone, plus several tens of meters of redbeds, capped by typical lower Sespe Formation conglomerate (Fig. 9). This section is near the one labeled "West of Circle B Ranch" as described and measured by Jiao and Fritsche (1994, fig. 3).

The lower 120 m consist of typical marine Coldwater Sandstone with low-angle shoreface cross-beds marked by heavy mineral lags, convolute bedding, tabular and trough cross-bedding, wave-ripple cross-beds, flaser

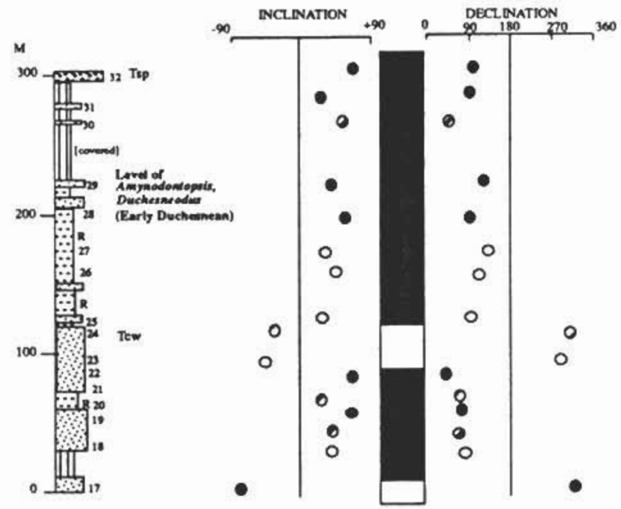


Figure 9. Magnetostratigraphy of the Beaver Camp section. Conventions as in Fig. 6.

bedding, and *Ophiomorpha* burrows. The remaining 180 m of section consists of poorly exposed redbeds, capped by Sespe conglomerate with sandstone clasts characteristic of the middle Eocene phase of Sespe deposition (Howard, 1989, fig. 4). Except for the stratigraphically lowest Coldwater site (which is an unknown height above the base of the Coldwater), and two sites between 100 and 120 m in the section, the entire section was of normal polarity.

Although no fossil mammal localities are known from the Beaver Camp section, a number of important localities occur in nearby areas of the syncline. Kelly (1990, p. 34) reported that *Amynodontopsis* (rhino) teeth were recovered from the correlative redbeds on the north limb of the syncline just northeast of the main (former) Hartman Ranch buildings. This collection was deposited in the Los Angeles County Museum of Natural History (LACM), but never accessioned or catalogued. Apparently, these specimens have been misplaced, because recent attempts by Kelly to locate them have failed (Kelly, personal communication). Kelly (1990, p. 34) also located the exact spot of locality LACM (CIT) 292, from which a *Duchesneodus* palate was collected by Chester Stock and field parties (Stock, 1938). Although it is also on the north limb of the syncline, it was collected from the basal Sespe sandstones and conglomerates correlative with our highest Beaver Camp magnetic sites. Together, these two localities were called the "Sespe Creek local fauna" by Kelly (1990) and Lander (1994), and are correlative with the early Duchesnean Pearson Ranch local fauna in Simi Valley (Kelly, 1990; Lander, 1994). These correlations, in turn, suggest that the upper part of the Beaver Camp section is also early Duchesnean.

## Summary of correlations

Correlation of all the Coldwater sections discussed above is shown in Figure 10. The uppermost Cozy Dell Shale (starting with the Circle B sandstone member) and the lower 100 m of typical marine Coldwater Sandstone are of reversed polarity. Above this is a zone of normal polarity in the lowest redbed interval (whether it is called Coldwater or Sespe); this zone also yields the late Uintan Hartman Ranch local fauna. In the Meiners Oaks and Beaver Camp sections, the upper redbeds and fluvial-intertidal Coldwater sandstones are of reversed polarity. Finally, the remaining redbed sequence, up to and including the Sespe sandstones and conglomerates, is entirely of normal polarity; this zone produces early Duchesnean mammals in two sections.

By comparison to the magnetically calibrated Sespe sections in eastern Ventura County (Prothero et al., this volume, Chapter 8), it is possible to correlate this Coldwater sequence to the magnetic polarity time scale. The late Uintan Hartman Ranch local fauna is most similar to the Tapo Canyon and Brea Canyon local faunas in Simi Valley, which occur early in Chron C18r (about 41 Ma); this suggests that the normal zone at the top of the Hartman Ranch section and elsewhere is probably Chron C19n. The presence of P12 planktonic foraminiferans in the upper Cozy Dell means that the reversed zone in the upper Cozy Dell and lower Coldwater must be Chron C19r, and cannot be an older reversed Chron (Fig. 2). The early Duchesnean specimens at Meiners Oaks and Beaver Camp occur in a long zone of normal polarity. This correlates with the early Duchesnean Pearson Ranch local fauna in Simi Valley, which occurs in the early part of Chron C18n (about



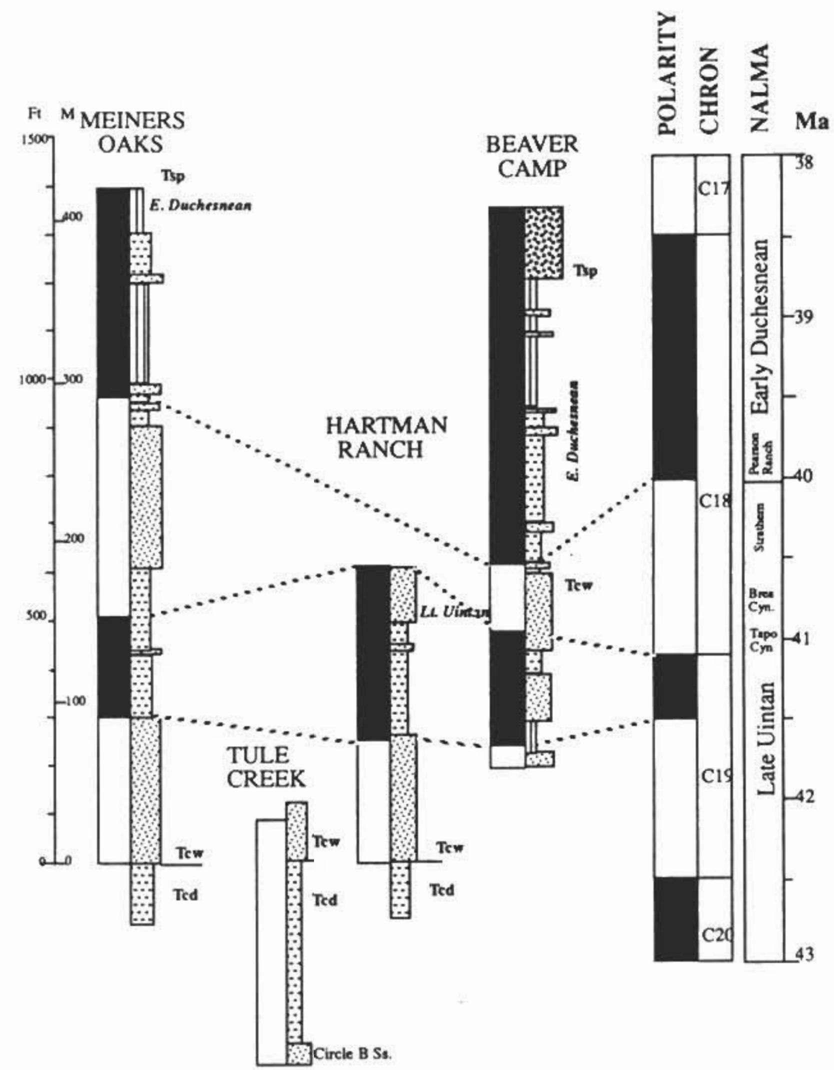


Figure 10. Correlation of Coldwater sections to the magnetic polarity time scale (after Berggren et al., 1995). NALMA = North American land mammal "ages." Chronostratigraphic position of key Sespe local faunas from Simi Valley are also shown (after Prothero, Howard, and Dozier, this volume, Chapter 8).

39.5 Ma). Thus, the entire upper Cozy Dell-Coldwater-Sespe sequence in central Ventura County appears to span C19r (base of the Circle B sandstone), which begins about 42.5 Ma, to somewhere in C18n (lower Sespe), or about 39.0 Ma.

These correlations and calibrations also clear up an apparent contradiction discussed by Golz and Lillegraven (1977). They found it perplexing that "late Eocene" brontotheres such as those from the Sespe Formation at locality LACM (CIT) 292 occurred immediately above middle Eocene mollusks in the Coldwater Sandstone. This anomaly is now resolved by the fact that the Uintan and Duchesnean are both middle Eocene, not late Eocene, as was thought in 1977 (Prothero and Swisher, 1992).

## IMPLICATIONS FOR SEQUENCE STRATIGRAPHY

In recent years, sequence stratigraphy (Vail et al., 1977; Posamentier et al., 1988; Van Wagoner et al., 1988, 1990) has become one of the dominant tools of sedimentary geology. Sequence stratigraphic concepts have been applied to a wide variety of sedimentary settings, although its assumptions are not without critics (e.g., Miall, 1991, 1992; Christie-Blick, 1991; Hallam, 1992). The thick, well exposed transgressive-regressive Eocene rocks of the western Transverse Ranges are ideally suited for sequence stratigraphic analysis, and recently two detailed interpretations have appeared (Campion et al., 1994; Clark, 1994; Thompson and Slatt, 1990, is an abstract).

One of the central tenets of sequence stratigraphy is that unconformable surfaces (sequence boundaries) represent time-synchronous surfaces. Many sequence stratigraphers believe these surfaces can be correlated to the Exxon-Vail onlap-offlap curve (Haq et al., 1987, 1988). The predictions of sequence stratigraphy have been successfully tested in passive margin settings by the biostratigraphy of key sections with good exposures and abundant microfossils (e.g., Poag and Schlee, 1984; Olsson, 1988). However, other critics (Aubry, 1991; Miall, 1992) have pointed out that the Exxon-Vail curve has so many events, and the biostratigraphic control is so poor in many cases, that *any* sequence of rocks could be fit to the curve. Moreover, applications of sequence stratigraphy in active tectonic settings provide a much more dynamic context, with the attendant potential for miscorrelation and misidentification of sequence boundaries. Clearly, fine-scale biostratigraphy, magnetostratigraphy, or chronostratigraphy are critical in testing sequence stratigraphic correlations.

In the western Transverse Range Eocene succession, however, time control has been notoriously poor and the dating based on benthic foraminiferans has long been controversial (McDougall, 1980; Almgren et al., 1988). This poor time control has forced sequence stratigraphers to make a leap of faith and *assume* that their sequence boundaries matched the global eustatic curve of Haq et al. (1987, 1988). Now that much finer chronostratigraphic resolution is possible for the Coldwater and Sespe formations, it is possible to test these sequence stratigraphic predictions (Fig. 11).

### The Campion, Lohmar, and Sullivan (1994) interpretation

Campion et al. (1994) based their sequence stratigraphic interpretations on the Haq et al. (1987, 1988) curve, which was based on the old Berggren et al. (1985) time scale. Unfortunately, the numerical age assignments in the Haq et al. (1987, 1988) curve must be considerably revised since the Eocene time scale has changed so radically in the last few years (Berggren et al., 1995). Although this makes all the numerical dates in Campion et al. (1994) off by several million years, it is still possible to test their predictions by matching their sequence boundary assignments to the original Haq et al. (1987, 1988) curves, and finding out what magnetic chron these events fall in. The correlation between the planktonic microfossil zonation, the Exxon-Vail curve, and the magnetic polarity time scale has not changed over the last decade, even though the numerical age assignments have.

Campion et al. (1994) placed a sequence boundary at the contact between the lower marine sandstone and the first redbeds in the Coldwater (which they label the "39.5 Ma unconformity" or the "Ta3.6/Ta4.1" boundary of Haq et al., 1988). This was based on the assumption that the Coldwater can be traced westward in the Santa Ynez Range as a correlative of the Sacate and lower Gaviota formations, which are late Eocene (planktonic foraminiferal Zones P15 and P16, according to Tipton, 1980). Haq et al. (1987, 1988) place the Ta3.6/Ta4.1 boundary in Chron C17n. However, the presence of P12 planktonic foraminifera in the underlying Cozy Dell Shale, and late Uintan mammals just above this sandstone, plus the magnetic pattern, shows that this boundary occurs in the transition between C19r and C19n (about 41.5 Ma), which corresponds to no sequence boundary on the Haq et al. (1987, 1988) chart.

Campion et al. (1994) recognized a second sequence boundary (their "38 Ma unconformity," or the "Ta4.1/Ta4.2" boundary of Haq et al., 1987, 1988) at the top of the redbed sequence at Hartman Ranch. According to Haq et al. (1987, 1988), this sequence boundary should fall within Chron C15r. However, the occurrence of late Uintan mammals below this level, and early Duchesnean mammals above it, plus the magnetic pattern, show that the top of the redbeds occurs within early Chron C18n (about 40 Ma), which is in the middle of the Ta3.5 cycle and thus is not associated with any sequence boundary on the Haq et al. (1987, 1988) curve.

Campion et al. (1994) placed a third sequence boundary at the base of the Sespe conglomerates, which they interpret as the "36 Ma unconformity" or the "Ta4.3/Ta4.4" boundary of Haq et al. (1987, 1988). In the original global cycle chart, this boundary falls late in Chron C12n, close to the Eocene/Oligocene and Chadronian/Orellan boundaries. However, the presence of Duchesnean mammals in the Sespe conglomerate, such as the *Duchesneodus* in LACM (CIT) 292, and the early Duchesnean *Amynodontopsis* just below it (which first occur in Simi Valley in Chron C18n, about 39.5 Ma) clearly falsifies this correlation. The unconformity below the Sespe conglomerate may correspond to the Ta3.5/Ta3.6 boundary, which does occur late in Chron C18n, although Chron C18n is so long in duration that it is hard to say with confidence that they match.

In summary, the age assignments of Campion et al. (1994) are off by at least four or five cycles on the Haq et al. (1987, 1988) chart, and only one of the three sequence boundaries they recognize (the unconformity below the Sespe) might match the predictions of the Exxon chart. Clearly, this does not confirm the interpretations of eustatic control assumed by Campion et al. (1994).

### The Clark (1994) interpretation

Six months later, Clark (1994) published another sequence stratigraphic interpretation of the same rocks. Unlike Campion et al. (1994), he had access to the new Berggren et al. (1995) time scale, and to some of the information in this chapter, and thus could adjust his interpretations accordingly. Clark (1994, fig. 7) placed a sequence boundary (his "Na2/Na3" boundary) at the Cozy Dell/Coldwater contact, which he correlated with



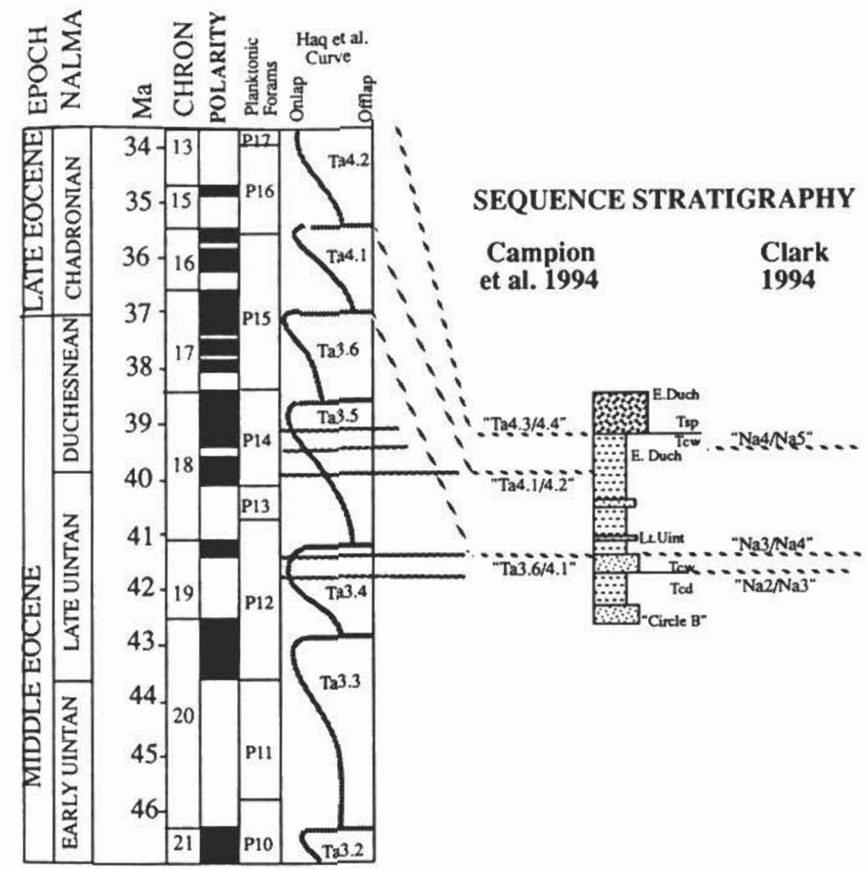


Figure 11. Comparison of chronostratigraphy of Cozy Dell-Coldwater-Sespe section in central Ventura County with sequence stratigraphic correlations of Campion et al. (1994) and Clark (1994), showing the lack of correspondence to the eustatic curve of Haq et al. (1987, 1988). Time scale after Berggren et al. (1995).

the base of Chron C18n (Clark, 1994, fig. 12). As he pointed out (p. 25), this age assignment does not match any sequence boundary on the Haq et al. (1987, 1988) curve. We concur that the Cozy Dell/Coldwater contact does not match any of the Exxon regressions. However, our data show that this boundary is in the middle of Chron C19r (not C18n), and corresponds to no sequence boundary on the Exxon chart, because it would be in the middle of cycle Ta3.4.

Clark (1994) placed a second sequence boundary ("Na3/Na4" boundary) at the contact between the marine sandstones and the redbeds in the Meiners Oaks section (as did Campion et al., 1994, who labeled it the "39.5 Ma" unconformity). As discussed above, this unconformity does not match any on the Haq et al. (1987, 1988) curve, unless one assumes that this curve is not precise to within a polarity zone and a million years.

Clark's (1994) third sequence boundary ("Na4/Na5" boundary) is more difficult to interpret, because his "Matilija Springs" section (which corresponds in part to our Meiners Oaks section) shows a thick sequence of coarse sandstone (Clark, 1994, fig. 7, unit O) where we found only redbeds with a few sandstone beds (Fig. 6). However, he (p. 25) suggested that this boundary correlates with the "39.5 Ma" unconformity of Campion et al. (1994), which is not consistent with our interpretation of the section. If our reading of Clark's (1994, fig. 7) section is correct, the Na4/Na5 boundary falls somewhere in Chron C18n, so it is impossible to tell if this corresponds to any of the unconformities of the Haq et al. (1987, 1988) chart. Clearly, however, it is not the "39.5" unconformity, which falls within Chron C17n.

In summary, none of Clark's (1994) sequence boundaries appear to match the Exxon cycle chart. To his credit, Clark (1994) does not automatically assume eustatic control of every unconformity, but attributes some to local tectonic forces.

## CONCLUSIONS

The Coldwater Sandstone in central Ventura County has been rotated clockwise by about 100°, consistent with other results in the same tectonic block. It is magnetically and biostratigraphically correlated to Chrons C19r-C18n (39.5-42.5 Ma), or late Uintan to early Duchesnean. Detailed examination of the sequence stratigraphic correlations of Campion et al. (1994) and Clark (1994) show that few if any sequence boundaries clearly correlate to the global cycle chart of Haq et al. (1987, 1988), suggesting that local tectonism was more important than eustasy in causing unconformities in the Cozy Dell-Coldwater-Sespe sections in this region.

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