

# MAGNETOSTRATIGRAPHIC TESTS OF SEQUENCE STRATIGRAPHIC CORRELATIONS FROM THE SOUTHERN CALIFORNIA PALEOGENE

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**ABSTRACT:** Several sequence stratigraphic analyses have been conducted on the Eocene–Oligocene rocks of the San Diego region and of the western Transverse Ranges in southern California. Recently developed magnetic stratigraphy and  $^{40}\text{Ar}/^{39}\text{Ar}$  dates, as well as previously neglected biostratigraphic data, provide a high-resolution chronostratigraphic framework to test correlation of these sequence stratigraphic interpretations to the global onlap–offlap chart (Haq et al. 1987, 1988; Hardenbol et al. 1998). In the San Diego area, previous stratigraphic analyses miscorrelated nearly all sequences and sequence boundaries to the global time scale; some correlations are off by as much as ten million years. In the western Transverse Ranges, three contradictory sequence stratigraphic analyses are evaluated. The revised dates of the sequence boundaries show poor correlation with the onlap–offlap chart of Haq et al. (1987, 1988) or Hardenbol et al. (1998), and some units are misdated by as much as six million years. In both regions, few sequences were correctly predicted by the onlap–offlap chart, suggesting that tectonic controls were more important than eustatic controls in this tectonically active region. The errors in so many sequence stratigraphic correlations when tested by high-resolution chronostratigraphic data should caution geologists about using sequence stratigraphic age assignments uncritically. Sequence stratigraphic correlations are only as good as the chronostratigraphy on which they are based.

## INTRODUCTION

Sequence stratigraphy has rapidly become one of the most popular and widely adopted methods in sedimentary geology and stratigraphy. Academic and industry geologists have applied sequence stratigraphic concepts to both outcrops and subsurface sections. Widespread acceptance of sequence stratigraphy suggests that it is valuable as a tool for understanding and interpreting strata, and for exploration.

However, some aspects of sequence stratigraphy have raised questions among geologists. One of the most controversial claims is that the Haq et al. (1987, 1988) onlap–offlap curve represents a globally synchronous record of eustatic sea level change that can be used for correlation. For example, Baum and Vail (1988, p. 322) asserted that “sequence stratigraphy offers a unifying concept to divide the rock record into chronostratigraphic units, avoids the weaknesses and incorporates the strengths of other methodologies, and provides a global framework for geochemical, geochronological, paleontological, and facies analysis.” A number of geologists have disputed the claim that the third-order cycles of the onlap–offlap curve are truly eustatic, but instead have a significant local tectonic component (see the extensive discussions in Hallam 1992; Prothero and Schwab 1996; Miall 1997). If the third-order cycles are not eustatic and globally synchronous, then they cannot be used to correlate between widely separated areas.

To determine whether a particular stratigraphic event can really be correlated to the Haq et al. (1987, 1988) curve, high-quality biostratigraphy is required. As Miller and Kent (1987) point out, the crux of the problem is stratigraphic resolution. With very low-resolution biostratigraphic data, most of the onlap–offlap cycles will apparently match any given sequence, because the biostratigraphy is incapable of discriminating closely spaced events. However, as higher resolution is approached, problems appear. The

first major problem is that the Haq et al. (1987, 1988) curve was based on some erroneous calibration points (also used by the time scale of Berggren et al. 1985), which have been replaced by a much improved time scale (Berggren et al. 1995). Thus, the numerical age estimates of stratigraphic boundaries on the Haq et al. (1987, 1988) curve have to be revised (reflected in the new sequence chart of Hardenbol et al. 1998). In the Eocene, for example, they have been adjusted by as much as 2–4 million years.

A second problem is the deceptively high but misleading precision of the curve of Haq et al. (1987, 1988), which often gives the numerical age of sequence boundaries to the nearest 100,000 years. A number of authors (e.g., Miall 1986, 1991, 1992, 1997; Dickinson 1993; Snyder and Spinosa 1993) have pointed out that most of the third-order cycles have durations on the order of 2 million years or less, yet most of the dating methods have error estimates in the order of  $\pm 2$ –3 million years or more, longer than most of the cycles. For example, Aubry (1991) studied deep-sea cores and sections throughout Eurasia, North Africa, and North America, and found at least two major regional unconformities that might correlate with the lower–middle Eocene boundary, or the 49.5 Ma “event” in the Haq et al. (1987, 1988) curve. The 49.5 Ma “event” appears to be a result of miscorrelation of biostratigraphic data and confusion about which closely spaced events are actually comparable.

A third problem is internal inconsistencies, even within the same paper. For example, Haq et al. (1988) give the age of the top of nannoplankton Zone NP16 as 44 Ma in their figure 11 but 41 Ma in their figure 14. Similarly, the top of Zone NP15 is quoted as 46 Ma in figure 11 and 43.1 Ma in figure 14 (Miall 1991). These boundaries are dated at 40.3 Ma (top of NP16) and 43.4 Ma (top of NP15) by Berggren et al. (1995), showing the huge discrepancy between numerical age estimates cited in the time scale of Haq et al. (1987, 1988) and current time scales.

If these problems are severe in passive-margin basins (which are dominated by changes of eustatic sea level), then they are further exacerbated in active-margin basins, where tectonic effects can be expected to dominate. The Paleogene basins of coastal southern California (Fig. 1) have relatively thick, complete Eocene and Oligocene sections which have been subjected to several rounds of sequence stratigraphic analysis. At the time most of these analyses were conducted, only limited biostratigraphic and chronostratigraphic data existed to test correlations to the curve of Haq et al. (1987, 1988). Since then, extensive magnetostratigraphic studies, combined with previously neglected biostratigraphic data and new  $^{40}\text{Ar}/^{39}\text{Ar}$  dates, have greatly improved the chronostratigraphic dating of these strata, often with resolution of less than 100,000 years. Such high-resolution chronostratigraphy now allows us to reexamine the sequence stratigraphy in two regions, the San Diego area and the western Transverse Ranges of Ventura and Santa Barbara counties, in order to determine whether sequence boundaries are truly correlative with the events on the Haq et al. (1987, 1988) curve, and the extent to which local tectonism controls sequence boundaries.

To avoid invalid comparisons, all data are standardized to the time scale of Berggren et al. (1995) and the sequence chart of Hardenbol et al. (1998). Even though the Eocene portions of the Haq et al. (1987, 1988) chart have changed greatly in the Hardenbol et al. (1998) chart (both in the numerical age estimates, and even in the number and correlation of the sequences), by matching up the old Haq et al. (1987, 1988) cycles with unchanged biostratigraphic reference points (such as the coccolith zonation, its primary calibration method), it is possible to interpret what a specific cycle in the

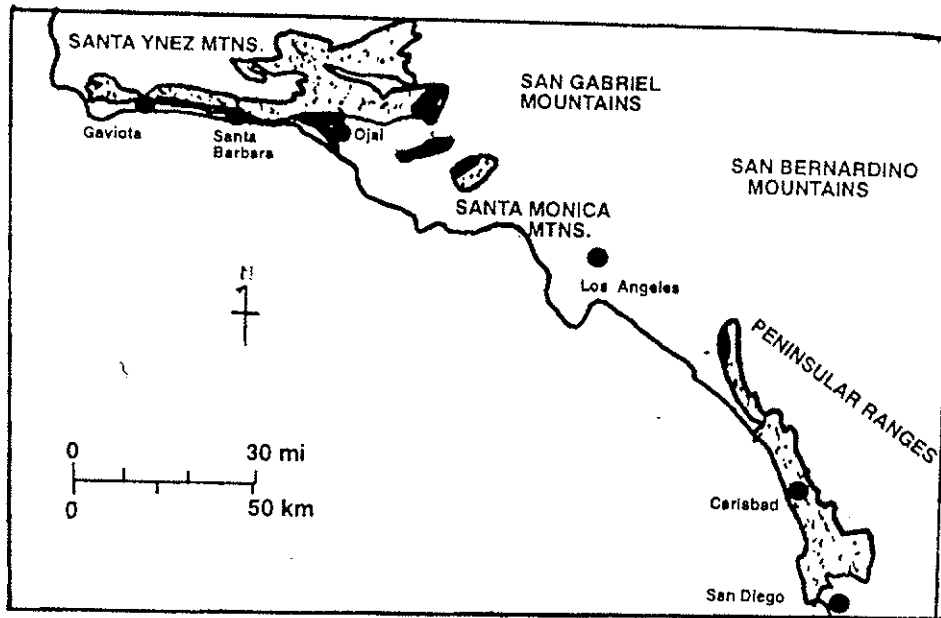


FIG. 1.—Index map showing the major outcrops of Eocene–Oligocene rocks in the western Transverse Ranges (Santa Ynez and San Gabriel Mountains), and San Diego area, showing localities mentioned in text. Stippled pattern indicates Eocene outcrops; dark gray pattern shows Oligocene outcrops; bold lines are major faults.

Haq et al. (1987, 1988) chart means in the current time scale and cycle chart. In both sequence-stratigraphic studies cited below, the authors tied their sequence boundaries to specific events on the Haq et al. (1987, 1988) chart. By recalibrating to the new cycle chart (Hardenbol et al. 1998), predictions about sea-level events can be tested against the new chronostratigraphic data.

#### SAN DIEGO AREA

##### *Lithostratigraphy*

Numerous fossiliferous exposures of Eocene age are known from the San Diego area and have been studied for over 75 years (Hanna 1926; Milow and Ennis 1961; Kennedy and Moore 1971; Kennedy 1975; Kennedy and Peterson 1975; Abbott 1979; Abbott and May 1981; Walsh et al. 1996). In recent years, detailed sedimentology has been described (e.g., Abbott 1979; Abbott and May 1981). Rapid facies change and interfingering of nonmarine, shallow-marine, and deep-marine facies provide rich biostratigraphic data, ranging from fossil mammals to molluscs to planktonic microfossils. In addition, several magnetostratigraphic studies have been conducted (Flynn 1986; Bottjer et al. 1991; Prothero 1991; Walsh et al. 1996), and a bentonite has yielded a  $^{40}\text{Ar}/^{39}\text{Ar}$  date (Berry 1991; Walsh et al. 1996). When these data are properly combined, the resulting high-resolution chronostratigraphy allows sequence stratigraphic correlations to be tested.

In general terms, the lower to middle Eocene stratigraphic succession in the San Diego area (Fig. 2) can be divided into two groups, the La Jolla and Poway groups. According to Kennedy and Moore (1971), the La Jolla Group begins with the lower Eocene Mount Soledad Formation, a nonmarine conglomeratic unit, which is laterally equivalent and interfingers to the west with the overlying lagoonal Delmar Formation and nearshore Torrey Sandstone. Overlying and interfingering with the Torrey Sandstone is the deeper-water middle Eocene Ardath Shale, the maximum transgressive phase in the area. The Ardath Shale has been interpreted as interfingering with the overlying shallow-marine Scripps Formation, which in turn interfingers with and is overlain by the nonmarine Friars Formation (Kennedy and Moore 1971). These units are unconformably overlain by the middle Eocene Poway Group, consisting of the nonmarine Stadium Conglomerate at the base, overlain and interfingering with the lagoonal and floodplain deposits of the Mission Valley Formation. At the top of the Poway Group

is the Pomerado Conglomerate, which overlies and interfingers with the Mission Valley Formation.

##### *Biostratigraphy*

Over the years, the biostratigraphic data base for the San Diego Eocene has improved considerably (Fig. 3). Originally, the succession was thought to extend from the upper lower Eocene to the upper Eocene (Kennedy and Moore 1971). Givens and Kennedy (1979) obtained Domengine stage molluscs from the upper part of the Mount Soledad Formation, and Steineck et al. (1972) reported planktonic foraminifers of Zones P10 or P11 from the upper Mount Soledad Formation. Both of these suggest that the upper Mount Soledad Formation is earliest middle Eocene, which is corroborated by interpretations of the pollen (Frederiksen 1991). Givens and Kennedy (1979) speculated that the lower, unfossiliferous part of the Mount Soledad Formation might be lower Eocene, but there are no biostratigraphic data to assess this suggestion.

Frederiksen (1991) reported pollen assemblages from the Delmar Formation that are consistent with calcareous nannoplankton Zone CP12b. Bridgerian mammals have also been reported from the Delmar Formation (Walsh 1996). The deeper-water Ardath Shale has yielded numerous diagnostic fossils, including planktonic foraminifers representing Zone P10 or P11 (Steineck et al. 1972), coccoliths of Zone CP12b (Bukry and Kennedy 1969; Okada and Bukry 1980) and possibly as young as CP13a to CP13c (May et al. 1991), and late Bridgerian or early Uintan mammals (Walsh 1996). The Scripps Formation yields molluscs of the Domengine stage at the base of the unit, and "Transition" stage molluscs in the upper part, which are associated with coccolith Zone CP13a (Squires 1988). The Friars Formation yields earliest Uintan mammals (Walsh 1996). The Stadium Conglomerate also yields early Uintan mammals and Tejon stage molluscs, but the highest part yields late Uintan mammals (Givens and Kennedy 1979; Walsh et al. 1996).

The Mission Valley Formation produces a diverse late Uintan mammal fauna (Walsh 1996; Walsh et al. 1996), as well as coccoliths of Zone CP14a. The upper part of the Mission Valley Formation contains a bentonite that gives an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $42.83 \pm 0.24$  Ma (Berry 1991; Walsh et al. 1996). Steineck et al. (1972) reported a foraminiferal sample from somewhere in the Stadium Conglomerate or Mission Valley Formation that correlated with Zone P13. Several studies have shown, however, that this

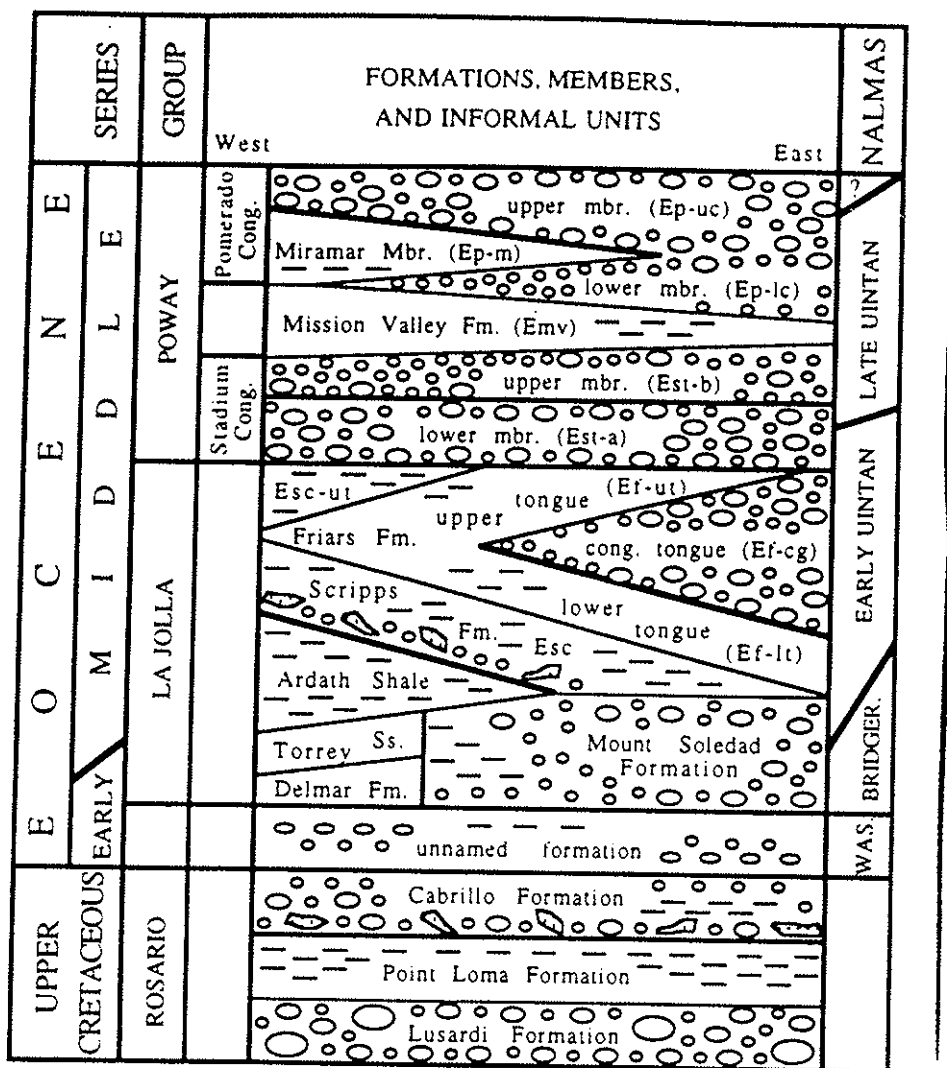


FIG. 2.—Schematic representation of the lithostratigraphy of the Cretaceous and Eocene rocks of the San Diego area from west to east (after Walsh et al. 1996). "NALMA" = North American land mammal "ages".

age assignment is based on two poorly preserved species and contradicts all other data, including the  $^{40}\text{Ar}/^{39}\text{Ar}$  date (McWilliams 1972; Philips 1972; Flynn 1986, p. 350; Prothero and Emry 1996; Walsh et al. 1996). Recent collections of fossil mammals (Walsh and Gutzler 1999) from the Pomerado Conglomerate suggest that it may be as young as Duchesnean or Chadronian, so it is much younger than the Mission Valley Formation.

#### Magnetostratigraphy

Magnetostratigraphic studies have further refined the chronostratigraphic correlation of these strata (Flynn 1986; Bottjer et al. 1991; Prothero 1991; Walsh et al. 1996). The Delmar Formation is entirely of reversed polarity, and correlates with Chron C21r (Bottjer et al. 1991). Most of the Ardath Shale is of normal polarity and, on the basis of the CP12b to CP13b coccoliths and P10 planktonic foraminifers, correlates with early Chron C21n (Flynn 1986; Bottjer et al. 1991). The Scripps Formation, and the lower Friars Formation, are also of normal polarity, and correlate with the latter part of Chron C21n, on the basis of the molluscs and early Uintan mammals (Flynn 1986; Bottjer et al. 1991; Walsh et al. 1996). The upper Friars Formation and the lower Stadium Conglomerate are of reversed polarity and correlate with Chron C20r, on the basis of the early Uintan mammals (Flynn 1986; Walsh et al. 1996). The Mission Valley Formation is mostly of normal polarity, and correlates with Chron C20n based on its late Uintan mammals and an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $42.83 \pm 0.24$  Ma in the middle of a

long normal-polarity magnetozone (Flynn 1986; Prothero 1991; Walsh et al. 1996). Bottjer et al. (1991) correlated the Mission Valley normal magnetozone with Chron C18n on the basis of the questionable identification of P13 planktonic foraminifers, but this is contradicted by all other evidence. The upper Mission Valley Formation may correlate with Chron C19r and younger intervals, although no biostratigraphic data constrain the upper age of this unit (Walsh et al. 1996).

#### Sequence Stratigraphy

Numerous sequence stratigraphic interpretations of the San Diego Eocene have been published (May et al. 1984; May et al. 1991; May 1985; May and Warme 1987, 1991; Lohmar and Morgan 1990; Lohmar et al. 1991; Campion et al. 1996). In the early interpretations, few precise age constraints were available. The first version (Figs. 3A, 4A) shows the San Diego units as spanning about 14 million years of the lower, middle, and upper Eocene, with most of the formations transgressing long intervals of time (May et al. 1984; May 1985; May and Warme 1987). May and Warme (1987, p. 36) suggested that the San Diego succession ranges from coccolith Zones CP11 to CP15b, although they cite no data that support this. As discussed above, only coccolith Zones CP12b through CP14a are actually documented from these rocks. May and Warme (1987) apparently were influenced by the traditional interpretation that the sequence spans the lower to upper Eocene, mostly on the basis of low-resolution molluscan

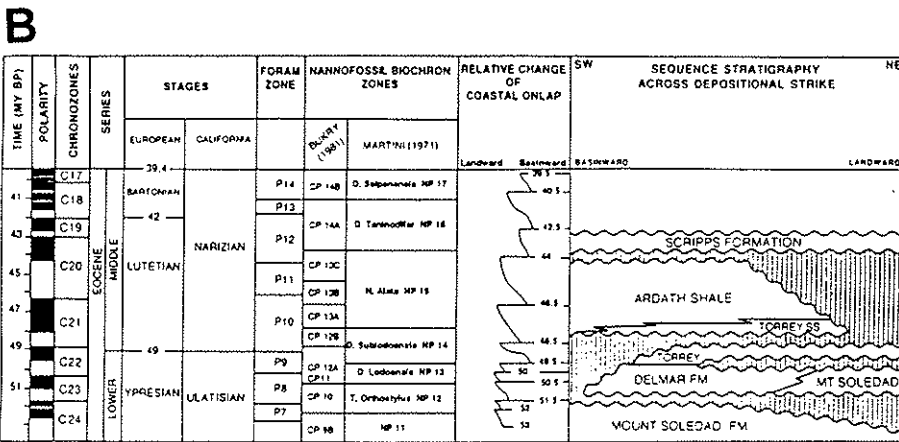
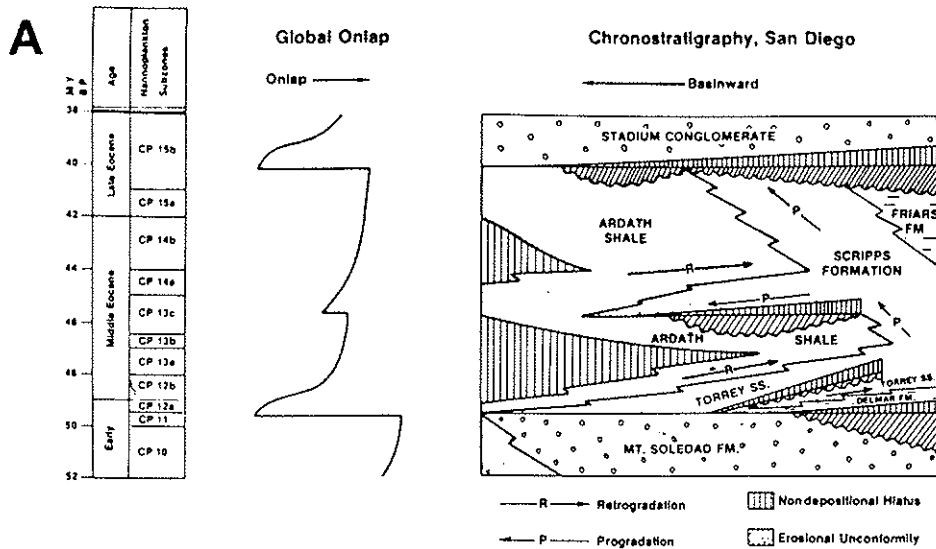


FIG. 3.—Sequence stratigraphic interpretations of the San Diego Eocene section by A. May and Warme (1987, figs. 2–7) and B. Campion et al. (1996, fig. 16). Compare with the chronostratigraphy in Figure 3.

biostratigraphy (Givens and Kennedy 1979) and the old time scales that placed coccolith Zone CP14 in the late Eocene. Recently, the middle–upper Eocene boundary has been shifted from the base to the top of the Bartonian Stage in Europe, so that many strata traditionally assigned to the “upper Eocene” are now middle Eocene (Berggren et al. 1985, 1995). These coccolith data and revised dating invalidate the interpretation (May et al. 1984; May 1985; May and Warme 1987) that the San Diego Eocene rocks can be correlated with the onlap–offlap cycles Ta4.1 to Ta3.1 of Haq et al. (1987, 1988). Instead, the strata apparently only span Ta3.1 to Ta3.4 (Fig. 3A, 4A).

Later sequence-stratigraphic interpretations (Figs. 3B, 4B) of these beds (Lohmar and Morgan 1990; Lohmar et al. 1991, fig. 1; Campion et al. 1996, fig. 16) compressed the time scale of these Eocene strata considerably over earlier versions (e.g., May et al. 1984; May 1985; May and Warme 1987). The Mount Soledad and Delmar formations were all shifted down into the lower Eocene, although no biostratigraphic data were cited to support this. This correlation is contradicted by the biostratigraphic data cited above. Campion et al. (1996, fig. 16) correlated the Ardath Shale with cycles Ta3.3, and Ta3.2, which also violates most of the data previously discussed (and available to these authors before 1996). The Scripps Formation was correlated with cycle Ta3.4, which would conflict with the mammals, magnetic stratigraphy, and the <sup>40</sup>Ar/<sup>39</sup>Ar date.

Although all previous sequence stratigraphic interpretations are contradicted by the current chronostratigraphy, it is interesting to see if the current dating of the transgressive–regressive cycles in San Diego is consistent with

the new cycle chart of Hardenbol et al. (1998) (Fig. 4). Given the poor age constraints on the Mount Soledad Formation, it is impossible to tell whether that unit matches the cycle chart. There is no correlation between the maximum onlap cycle of Ta3.2 and the transgressive strata of the Delmar–Torrey–Ardath Formations, because the Ardath transgressive peak occurs at the maximum offlap just younger than the Lu1 sequence boundary (Fig. 4). The peak regression (Stadium Conglomerate) does not correlate with an offlap event (such as the “46.5 Ma” event of Haq et al. 1987, 1988), but with the peak sea level highstand of the Ta3.3 cycle. The subsequent transgression represented by the Mission Valley Formation correlates not with a transgression in the cycle chart, but with the Lu4 regression of Hardenbol et al. (1998) or the “44 Ma” regression of Haq et al. (1987, 1988). There is apparently no correlation between the onlap–offlap charts of Haq et al. (1987, 1988) or Hardenbol et al. (1998) and any of the San Diego sea-level changes, so they are not eustatically controlled.

It is also interesting to note how changing stratigraphic conceptions have altered the way the San Diego strata are interpreted. Beginning with Kennedy and Moore (1971), and continuing with May et al. (1984; May 1985; May and Warme 1987), most of the units were shown as grossly diachronous parts of two or three major transgressive–regressive cycles. Later sequence stratigraphers have begun to represent these strata as nearly isochronous rock units, or units composed of several isochronous packages of strata (Campion et al. 1996, fig. 16). Such dramatic differences in interpretation lead one to wonder how much of the stratal geometry is based on objective outcrop evidence, and how much is influenced by preconcep-

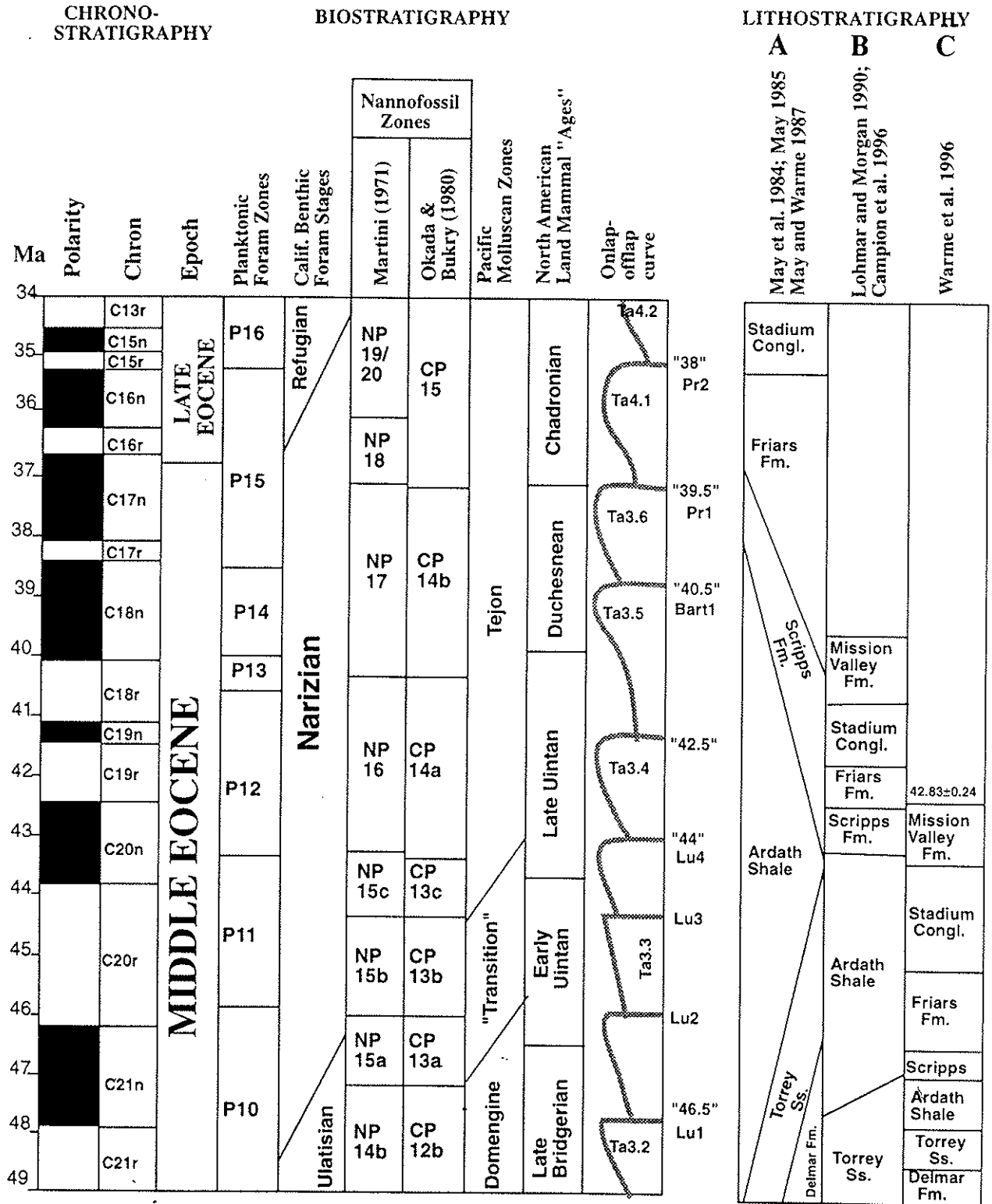


FIG. 4.—Chronostratigraphic correlation of the rocks in the San Diego area, showing the differing interpretations based on sequence stratigraphy (A, by May et al. 1984; B, by Lohmar and Morgan 1990) and the interpretation followed here (C, after Walsh et al. 1996). Time scale based on Berggren et al. (1995), with North American land mammal "ages" after Prothero (1995) and molluscan stages after Squires (1988). Exxon global cycles modified after Haq et al. (1987, 1988) and Hardenbol et al. (1998). The sequence boundaries identified by the numbers in quotations are from Haq et al. (1987, 1988); the others (e.g., Lu1, or Lutetian 1; Bart1 or Priabonian 1, etc.) are from Hardenbol et al. (1998).

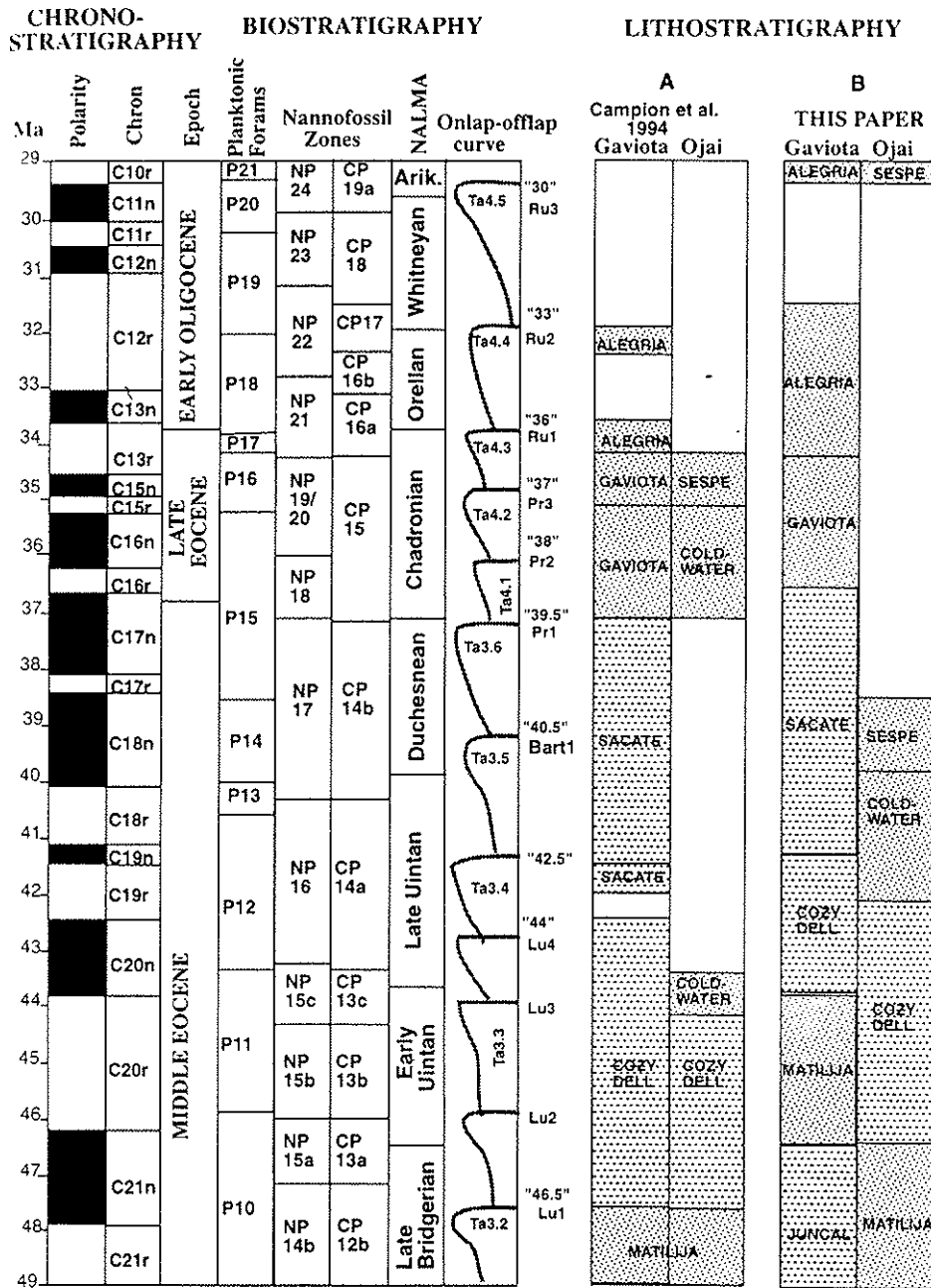


FIG. 5.—Chronostratigraphy of the Eocene-Oligocene section in the western Transverse Ranges, comparing the sequence stratigraphic interpretation of A, Campion et al. (1994) with B, the data discussed in this paper. Time scale and onlap-offlap curve as in Figure 4.

tions and models of stratigraphic pattern. In our experience, the outcrop evidence is so limited and difficult to interpret that either pattern could be supported by the available data (Walsh et al. 1996), as long as the pattern does not violate the biostratigraphic and magnetostratigraphic age constraints. Clearly, the biostratigraphic and magnetostratigraphic data (Fig. 4) do not allow the formations to be grossly time transgressive, although limited diachroneity is permitted within the durations of polarity zones and biostratigraphic zones.

WESTERN TRANSVERSE RANGES

*Lithostratigraphy*

Thick, fossiliferous marine and nonmarine Eocene and Oligocene strata are also known from the western Transverse Ranges of Ventura and Santa Barbara counties (Fig. 1). These were first studied over a century ago

(Watts 1897), and the excellent exposures, spectacular structural geology, and importance for many major oil fields have stimulated much study since (e.g., Kelley 1943; Dibblee 1950, 1966, 1982; Page et al. 1951; Jests 1963; Kleinpell and Weaver 1963; McCracken 1969, 1972; Vedder 1972; O'Brien 1972; Van de Kamp et al. 1974; Link 1975; Link and Welton 1982; Ingle 1980; Lander 1983, 1994; Howard 1987, 1989; Campion et al. 1994; Clark 1994; Jiao and Fritsche 1994; Prothero et al. 1996; Prothero and Vance 1996; Prothero and Thompson 2001; Prothero and Britt 1998).

In general (Fig. 5), the stratigraphic package in the western Transverse Ranges (Gaviota area) begins with the lower to middle Eocene deep-marine Juncal Shale, which is overlain by the deep-marine to shallow-marine Matilija Sandstone. To the east (Ojai area), the Matilija Sandstone grades upward into a thin nonmarine redbed sequence, then grades back into the deep-water Cozy Dell Shale. Overlying these strata is the shallow-marine Coldwater Sandstone, which grades laterally to the west (in the western

Santa Ynez Range) into the deep-marine Sacate Formation and shallow-marine Gaviota Formation. In the east, the Coldwater is capped by the nonmarine conglomerates and redbeds of the Sespe Formation, and these interfinger with the shallow-marine Alegria Formation as they pass to the west. Many of these units are well exposed along the south flank of the Santa Ynez Range and seem to be mappable and laterally traceable across long distances, so geologists have attempted detailed bed-by-bed lithostratigraphic correlation (e.g., Kleinpell and Weaver 1963, fig. 8; Campion et al. 1994).

### Biostratigraphy

These rocks are also important for biostratigraphic reasons. The apparently continuous Eocene–Oligocene exposures were critical for development of the California benthic foraminiferal and molluscan zonation (Kleinpell 1938; Weaver et al. 1944; Mallory 1959; Kleinpell and Weaver 1963; Hornaday 1965; Givens 1974; Gibson 1976; McDougall 1980; Kleinpell 1980; Tipton 1980; Warren and Newell 1980; Poore 1980; Almgren and Filewicz 1984; Almgren et al. 1988). The type section of the long-controversial late Eocene–earliest Oligocene Refugian benthic foraminiferal stage is located in Cañada de Santa Anita in the western Santa Ynez Range (Schenck and Kleinpell 1936). Several authors (e.g., Mallory 1959) have noted that the Santa Ynez Range has the best stratigraphically-superposed succession of the Ynezian–Bulitian–Penutian–Ulatisian–Narizian–Refugian–Zemorrian benthic foraminiferal stages in the Pacific Coast. The Sespe and Coldwater formations also contain important fossil mammal assemblages spanning the middle Eocene Uintan and Duchesnean through late Oligocene Arikareean land mammal “ages” (Stock 1930, 1948; Savage and Downs 1954; Lindsay 1968; Golz 1976; Golz and Lillegraven 1977; Krishtalka et al. 1987; Lander 1983, 1994; Mason and Swisher 1989; Kelly 1990, 1992; Kelly et al. 1991; Kelly and Whistler 1994). This is the only place in North America where these land mammal “ages” are superposed, and interfinger with marine strata to allow intercorrelation of marine and nonmarine zonations.

A wide spectrum of fossils are known from the Eocene rocks of the western Transverse Ranges, but the biostratigraphy has taken a long time to develop, and has long been plagued by miscorrelations. Although benthic Foraminifera are by far the most abundant index fossils, the California benthic foraminiferal stages are notoriously time-transgressive (Steineck and Gibson 1971; Schmidt 1975; McDougall 1980; Almgren et al. 1988; Prothero and Thompson 2001). Studies of planktonic foraminifers and calcareous nannofossils have considerably improved the correlation (Schmidt 1975; Warren and Newell 1980; Almgren and Filewicz 1984; Almgren et al. 1988), but planktonic microfossils are rare and found mostly in the deeper-water facies to the west.

Originally, the Lyellian epoch assignments of the mammalian fossils were poorly constrained, because there were few means of correlation between Eocene–Oligocene land mammal “ages” and the global time scale (Golz and Lillegraven 1977; Krishtalka et al. 1987). This situation has changed dramatically, however, with the advent of magnetic stratigraphy and  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of critical sequences all over western North America (Swisher and Prothero 1990; Prothero and Swisher 1992; Prothero 1995; many papers in Prothero and Emry 1996). These new data have resolved many problems. For example, Golz and Lillegraven (1977) were puzzled how “late Eocene Uintan” mammals could be associated with middle Eocene molluscs and foraminifers in the Hartman Ranch area. We now know that the Uintan is middle middle Eocene (Prothero and Swisher 1992; Prothero and Vance 1996). More importantly, the combination of the fine-scale mammalian planktonic microfossil zonations with magnetic stratigraphy offers much higher stratigraphic resolution and precision than was previously possible in this region.

The Juncal Shale is well known for its Ulatisian and Narizian benthic foraminifers, but these stages are notoriously long and low in resolution,

as well as being time-transgressive (Schmidt 1975; Almgren et al. 1988). Givens (1974) described late early Eocene and early middle Eocene (Capay and Domengine stage) molluscs from the Juncal Shale in the Pine Mountain area, as did Squires (1987) in the Whitaker Peak area. Filewicz (in Squires 1987, p. 12) identified early Eocene Zone CP9 and CP10 nannofossils from the lower Juncal Formation, and CP11 nannofossils from the upper Juncal Formation (Domengine stage) in the Whitaker Peak area. Filewicz (in Clark 1994, p. 22) discovered Zone CP12b nannofossils in the uppermost Juncal Formation in the Ojai area. Thompson (1988) reported nannofossils from Zones CP11 to CP13 in the type area of the Juncal Shale in the Agua Caliente anticline north of Santa Barbara.

In the type area north of Ojai (Figs. 1, 5), 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 (Blaisdell 1955; Jests 1963; Givens 1974), which correlate with nannofossil Zone CP13a (Givens and Kennedy 1979). These nannofossils indicate that the eastern part of the Matilija Sandstone spans the interval from about 45–49 Ma (Fig. 5). To the west, the Matilija Sandstone has yielded CP13 nannofossils (Almgren et al. 1988).

The Cozy Dell Formation in the type area north of Ojai yields Narizian benthic foraminifers (Kleinpell and Weaver 1963), Zone CP13–14 nannofossils (Gibson 1976; Poore 1976), and Zone P11–P12 planktonic foraminifers (Berman 1979; Link and Welton 1982). Berman (1979) tentatively suggested that the Cozy Dell also contained P13 planktonic foraminifers, but this is based on a few poorly preserved specimens of nondiagnostic taxa. To the west, the age of the much thinner Cozy Dell Shale in the western Transverse Ranges is CP14a, according to Almgren et al. (1988).

The Coldwater Sandstone in the Ojai area contains Tejon stage molluscs (which is not very diagnostic, because the Tejon stage is over 10 million years long, according to Squires 1988), Narizian benthic foraminifers (Kleinpell and Weaver 1963), and late Uintan and early Duchesnean fossil mammals (Lindsay 1968; Golz and Lillegraven 1977; Lander 1994; Prothero and Vance 1996). On the basis of the newly refined age constraints and correlations of the fossil mammals (Prothero et al. 1996; Prothero and Emry 1996), and the underlying constraint of the P12 planktonic foraminifers in the Cozy Dell Shale, the Coldwater Sandstone correlates with the interval between 42 and 39 Ma (Prothero and Vance 1996).

The nonmarine redbeds and conglomerates of the Sespe Formation were long thought to span most of the Oligocene (Stock 1948; Krishtalka et al. 1987). Detailed examination of the associated mammalian faunas, however, has correlated them with the late Uintan–early Duchesnean (late middle Eocene) faunas farther east in the Simi Valley area (Kelly 1990; Prothero et al. 1996). In the Ojai area, only early Duchesnean fossil mammals (such as *Amyndontopsis* and *Duchesneodus*) are known from the Sespe conglomerates (Lander 1994; Prothero and Vance 1996). An important insight about the Sespe Formation is that a major disconformity that removes most of the Chadronian, Orellan, and Whitneyan land mammal “ages” (30–37 Ma) is present throughout the formation (Howard 1989; Lander 1994; Prothero et al. 1996). Overlying this unconformable surface is a widespread upper Oligocene (earliest Arikareean, 28–29 Ma) pulse of Sespe deposition, which laps over Sespe or Coldwater rocks of widely different ages in Ventura County (Prothero et al. 1996).

As already noted, the Sacate Formation yields NP16 through NP19/20 nannofossils (Warren and Newell 1980) and Narizian benthic Foraminifera (Kleinpell and Weaver 1963; Tipton 1980). The Gaviota Formation, which was the original basis of the Refugian benthic foraminiferal stage, also contains NP19/20 nannofossils and P16 and P17 planktonic foraminifers (Warren and Newell 1980; Tipton 1980). The uppermost Gaviota yields CP16a calcareous nannofossils (Almgren and Filewicz 1984). The lower part of the overlying Alegria Formation also contains Refugian benthic Foraminifera and Tejon stage molluscs (Kleinpell and Weaver 1963). However, a late Oligocene oredont, *Scypia*, was found 7 m above the base of

member B (of Dibblee 1950) of the Alegria Formation in Gaviota Gorge (Lander 1983). This fossil shows that there is a major hiatus within the Alegria Formation that represents most of the early and middle Oligocene, as is already known in the Sespe Formation (Prothero et al. 1996; Prothero and Thompson 2000).

### Magnetostratigraphy

Magnetostratigraphic studies on these rocks have just begun, but already they have greatly refined the chronostratigraphy. In the Simi Valley–South Mountain area in eastern Ventura County (Prothero et al. 1996), the late Uintan–Duchesnean part of the Sespe Formation correlates with Chrons C19n–C16r (36.5–41.3 Ma). It is capped by an upper Oligocene (early Arikarean) package of Sespe Formation that correlates with Chrons C9r–C10r (28.0–29.5 Ma), as calibrated by an  $^{40}\text{Ar}/^{39}\text{Ar}$  date of  $28.2 \pm 0.2$  Ma (Mason and Swisher 1989). Between these two stratal packages is an unconformity that spans 7–8 million years.

In the Ojai–Sespe Creek area (Fig. 1) of western Ventura County (Prothero and Vance 1996), the uppermost Cozy Dell Formation and the lower Coldwater Sandstone correlate with Chron C19r, on the basis of the biostratigraphic constraints outlined above. The remaining parts of the Coldwater Formation (including redbeds in the Hartman Ranch area that are referred to the Sespe Formation by some authors; see Prothero et al. 1996, for discussion) correlate with Chrons C19n to lower C18n, as indicated by the latest Uintan mammals in the Hartman Ranch local fauna and early Duchesnean *Duchesneodus* and *Amynodontopsis* in the overlying strata. The succession is capped by Duchesnean Sespe conglomerates, which also correlate with Chron C18n (Prothero and Vance 1996). The magnetic stratigraphy of the type sections of the Cozy Dell and Matilija formations in the Matilija Hot Springs area correlates with Chron C19r–C21r (Prothero and Britt 1998).

In the western Santa Ynez Range–Gaviota Gorge area, Prothero and Thompson (2001) analyzed the magnetic stratigraphy of the Sacate–Gaviota–Alegria formations, including the type section of the Refugian benthic foraminiferal stage. The middle part of the Sacate Formation correlates with Chron C17n–C18n, on the basis of the presence of CP16 and CP17 calcareous nannoplankton (Warren and Newell 1980). The upper Sacate Formation and lowermost Gaviota Formation (and thus the Narizian–Refugian boundary in these sections) correlates with Chron C16r, on the basis of the occurrence of NP18 and NP19/20 nannofossils. The middle of the lower shale member of the Gaviota correlates with Chron C16n, according to the NP19/20 nannofossils. The upper part of the lower Gaviota shale, and the lower half of the middle Gaviota sandstone correlates with Chron C15r, on the basis of their P16 planktonic foraminifers and NP19/20 nannofossils. The upper part of the middle Gaviota Sandstone and lower part of the upper Gaviota shale correlate with Chron C15n. The remaining upper Gaviota shale and lower Alegria Sandstone correlate with Chron C13r, due to the presence of P16 and P16 planktonic Foraminifera and NP19/20 and NP21 (Warren and Newell 1980) and CP16a (Almgren and Filewicz 1984) nannofossils. This correlation also places the top of the type Refugian within Chron C13r. A short normal magnetozone in the lower Alegria may correlate with Chron C13n, but the remaining Alegria Formation appears to correlate with Chron C12r.

### Sequence Stratigraphy

Several different sequence stratigraphic interpretations of the Paleogene rocks of the western Transverse Ranges have been proposed. Thompson and Slatt (1990) published an abstract of their ideas. Clark (1994) gave a sequence stratigraphic interpretation of the Eocene strata in northern Ventura County. Campion et al. (1994, 1996) presented two different sequence stratigraphic interpretations of the same strata, and agreed with Clark (1994) on only one sequence boundary. Of these differing versions of the

sequence stratigraphy, only Clark (1994) did not attempt to tie his sequence boundaries to eustatic sea-level curves, since he was convinced that tectonics was the main factor in their development. Campion et al. (1994, fig. 10) explicitly tied each of the units to the cycles on the chart of Haq et al. (1987, 1988), so it is possible to test their predictions with the newly refined chronostratigraphy of these beds (Fig. 5), following the time scale of Berggren et al. (1995) and the sequence chart of Hardenbol et al. (1998).

Campion et al. (1994) considered the Matilija Sandstone to be composed of a series of isochronous units, deposited within cycles Ta2.8–2.9, Ta3.1, and Ta3.2 (between the “46.5,” “48.5,” “49.5” and “50.5” Ma unconformities). However, the available chronostratigraphic data refute this. In the Ojai area (Prothero and Britt 1998), the presence of Domengine and “Transition” stage molluscs (correlated with CP13a in several places; Givens and Kennedy 1979; Squires 1987, 1988) place the top of the Matilija late in Chron C21n (46.4 Ma) and the base well into Chron C21r (so the unit is no older than 49.0 Ma). By contrast, Campion et al. (1994) placed the Matilija–Cozy Dell contact at the “46.5” Ma (Lu1 of Hardenbol et al. 1998) unconformity (about a million years too old), and the base of the Matilija in cycle Ta2.8 (older than 51 Ma), which is about 2–3 million years too old. To the west, the Matilija contains CP13 nannofossils (Almgren et al. 1988), and the underlying Juncal Shale also contains CP13 nannofossils, so the Juncal–Matilija contact is three million years younger than it is at Ojai, and thus time transgressive.

Campion et al. (1994, fig. 10) correlated the Cozy Dell Shale in the Ojai area with the upper Ta3.2 and Ta3.3 cycles on the chart of Haq et al. (1987, 1988) (i.e., between the “44” and “46.5” Ma, and below the “46.5” Ma unconformities). However, the presence of P12 planktonic foraminifers (Berman 1979; Link and Welton 1982) and CP14 nannofossils (Gibson 1976; Poore 1976) in the upper Cozy Dell, as well as the reversed polarity of these strata (Prothero and Vance 1996), clearly contradicts this interpretation, and shows that the upper Cozy Dell is correlative with late Chron C19r (41.5–42.0 Ma) (Fig. 5). Few biostratigraphic or magnetostratigraphic data are available from the western Santa Ynez Range exposures of the Cozy Dell to test whether this unit is time transgressive.

The Sacate Formation was correlated by Campion et al. (1994) with two cycles, the Ta3.4 (below the “42.5” Ma unconformity) and the Ta3.6 and Ta3.5 cycles (between the “39.5” and “42.5” Ma unconformities). This interpretation is consistent with the NP16 nannofossils in the upper Sacate, but not with the NP18 nannofossils in the uppermost Sacate Formation (Warren and Newell 1980), nor with the magnetostratigraphic correlation of these sections with Chron C17n–C16r (Prothero and Thompson 2001).

Campion et al. (1994, fig. 10) interpreted the Coldwater Sandstone as spanning two widely separated sequences. In the Matilija Hot Springs area (north of Ojai), they correlated the lowest Coldwater with cycle Ta3.3 (between the “44” and “46.5” Ma unconformities). They correlated upper Coldwater with the lower Gaviota Formation and with cycle Ta4.1. Both of these correlations are contradicted by the magnetostratigraphic and biostratigraphic data (Prothero and Vance 1996). The lower Coldwater cannot be as old as upper Ta3.3 (about 44–45 Ma), because it is constrained by the P12 planktonic foraminifers and CP14 nannofossils in the underlying Cozy Dell, and its reversed polarity, to correlate with Chron C19r (41.5–42.0 Ma). Likewise, the upper Coldwater cannot be the lateral equivalent of the Gaviota Formation, or as young as Ta4.1 (35.5–37 Ma), because it is constrained by latest Uintan and Duchesnean mammals and magnetostratigraphic pattern to correlate with Chrons C18n–C19n (39–41.5 Ma) (Fig. 5). Thus, neither age assignment of the Coldwater Formation by Campion et al. (1994) is correct.

Part of the problem with the miscorrelation by Campion et al. (1994, 1996) lies in their misinterpretation of the biostratigraphic and magnetostratigraphic data. Campion et al. (1996, fig. 46) attempted to reinterpret the data presented in Prothero and Vance (1996). They pushed the upper Cozy Dell Shale down into Chron C20r, which is contradicted by the presence of P12 planktonic foraminifers and CP14 nannofossils in this unit. Their



diagram places an unconformity between the Cozy Dell and Coldwater formations, eliminating Chron C20n, but this is not supported by the biostratigraphic data. Their correlation of the lower Coldwater Sandstone with Chron C19r and the middle Coldwater redbeds with Chron C19n is consistent with the data presented by Prothero and Vance (1996). However, Campion et al. (1996) placed the upper Coldwater Sandstone at Hartman Ranch in Chron C18n, which is clearly contradicted by the presence of the late Uintan Hartman Ranch local fauna in this unit (Prothero and Vance 1996, fig. 7). In figure 46 of Campion et al. (1996), the location of this fauna is misplaced. If it is placed higher in the section where it actually occurs, then the interpretation of Chron C18n for these rocks is untenable. Campion et al. (1996, p. 171) claim that "it is unclear as to whether this fauna is from the red mudstone or the tan and white sandstone lithofacies of the Coldwater." However, the position of this fauna is clearly shown within the tan and white sandstone lithofacies by Prothero and Vance (1996, fig. 7). This figure was provided to Campion in 1995, and Prothero showed Campion the exact position of the Hartman Ranch local fauna on a field trip in 1994. The correlation by Campion et al. (1996) of the upper Coldwater-lower Sespe normal magnetozone (with its early Duchesnean mammals) with Chron C18n in the Beaver Camp and Meiners Oaks section is consistent with the data presented by Prothero and Vance (1996). However, most of the correlations in Campion et al. (1996, fig. 46) are inconsistent with their earlier correlations (Campion et al. 1994, fig. 10).

Campion et al. (1994, fig. 10) correlate the Gaviota Formation with onlap cycles Ta4.1 and Ta4.2 of Haq et al. (1987, 1988). These correlations are consistent with the presence of NP18 and NP19/20 nannofossils and P16 planktonic Foraminifera in these units (Warren and Newell 1980) and the magnetostratigraphic correlation with Chrons C16r to C13r (Prothero and Thompson 2001), although the Ta4.1 cycle begins well before the base of the Gaviota in Chron C16r. The correlation by Campion et al. (1994) of the lower Alegria with cycle Ta4.3 is also consistent with the presence of CP16a nannofossils and reversed rocks of Chron C13r in this unit. There is no evidence, however, to substantiate a second Alegria cycle in Ta4.4. Their correlation of the uppermost Alegria-Sespe clastic wedge with cycle Tb1.2 (between the "26.5" and "28.4" Ma unconformities) is too young for the biostratigraphic and magnetostratigraphic data, which place these strata between 28.0 and 29.5 Ma.

Inasmuch as most of the previous sequence stratigraphic correlations have been contradicted by the latest chronostratigraphic data, we might ask if the new data support *any* correlations with the cycle chart of Haq et al. (1987, 1988). Prothero and Vance (1996) showed that only one of the sequence boundaries delineated by Clark (1994) and Campion et al. (1994) within the Cozy Dell-Coldwater-Sespe strata in the Ojai area might match the global cycle chart. Their "48.5" Ma sequence boundary within the upper Matilija in the Ojai area might possibly correlate with the "46.5" Ma (Lu1) sequence boundary on the global cycle chart, although the resolution of the data is too coarse to test this at present. And this sequence boundary is clearly not a time plane, because the Matilija is younger to the west. The Alegria-Gaviota sequence boundaries between the "36", "37", "38", and "39.5" Ma unconformities are consistent with the current data, although those sequence boundaries are now redated at 33.7, 34.2, 35.3, and 37.1 Ma, respectively. (This age discrepancy is due to the fact that Haq et al. 1987 used invalid data for calibration of their time scale; see Berggren et al. 1995.) The prominent nonmarine sedimentation pulse of upper Oligocene Sespe-Alegria formations appears to correlate with the Tb1 cycle, after a major mid-Oligocene sea-level drop.

Given how great a thickness of strata are represented in this area, and how many sequence boundaries have been identified, this is a remarkably poor match with the cycle chart of Haq et al. (1987, 1988). As Miall (1991, 1992, 1997) pointed out, such a match could be due to random chance alone. There is little evidence that eustatic sea-level changes are responsible for most of the sequence boundaries in the Paleogene rocks of the western Transverse Ranges.

## CONCLUSIONS

Sequence stratigraphic methods are now routinely applied to the correlation of strata in a wide variety of depositional settings. In many cases, the sequence boundaries are correlated to the global cycle chart of Haq et al. (1987, 1988) without further testing by biostratigraphy or other chronostratigraphic techniques. Emery and Myers (1996, p. 89) noted that "sequence stratigraphy has now largely superceded [*sic*] biostratigraphy as the primary correlative tool in subsurface basin analysis." The last decade of layoffs of biostratigraphers from most major oil companies also seems to indicate that some geologists think they can get along fine without biostratigraphic data. Where the biostratigraphic data are very low in resolution, or highly facies-controlled, perhaps sequence stratigraphic correlations work better.

But if there is any lesson that two centuries of geological investigation since the days of William Smith have taught us, it is that *biostratigraphy is the ultimate arbiter of chronostratigraphic correlation*. The literature is full of lithostratigraphic correlation schemes that failed because of insufficient attention to biostratigraphy. For example, Adam Sedgwick's Cambrian was nearly swallowed up by Murchison's biostratigraphically defined Silurian System, and almost vanished from the time scale until a later generation of geologists found biostratigraphic criteria to recognize the Cambrian outside the type area. Many tectonic schemes that called upon global tectonic pulses and mountain-building events have come and gone after they were subjected to the scrutiny of careful biostratigraphic and chronostratigraphic analysis. Blindly correlating stratigraphic events to the outdated onlap-offlap curve of Haq et al. (1987, 1988), without determining whether biostratigraphic data support their correlations, continues the trend of poor science.

Nowhere is this problem better demonstrated than in the Eocene-Oligocene rocks in both the San Diego area and in the western Transverse Ranges. Only a few of the previously identified sequence boundaries appear to correlate with the revised dates of the global cycle chart, and these matches could have occurred by random accident. This, in turn, suggests that almost all the previously identified sequence boundaries (when two or more sequence stratigraphers can agree on them) have little or no eustatic control, but must be tectonically controlled. Such a discovery may not seem surprising for the tectonically active basins of southern California, but several sequence stratigraphers (e.g., Campion et al. 1994) have confidently asserted that eustasy is more important than tectonics in these basins. The biostratigraphic data clearly show that this is not true.

If there is a lesson to be learned here, it is this: *sequence stratigraphic correlations are only as good as the chronostratigraphic data on which they are based*. Sequence stratigraphy may be a very powerful tool for correlation of subsurface data, but for chronostratigraphic correlation to the global time scale, it has an abysmal track record. The failure of sequence stratigraphic correlations when high-resolution biostratigraphic data are available to test them should serve to warn those who would use sequence boundaries as correlation horizons in multiple areas of poor biostratigraphic control. Once good biostratigraphic data are obtained, sequence stratigraphic correlations from disparate areas may prove to be wrong.

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