MAGNETIC STRATIGRAPHY OF THE MIDDLE EOCENE SANTIAGO FORMATION, SAN DIEGO AND ORANGE COUNTIES, CALIFORNIA

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ABSTRACT

The Santiago Formation is a middle Eocene marine and non-marine siltstone and sandstone which occurs widely in Orange County and northwestern San Diego County, California. Magnetic sampling was undertaken in five key sections of the formation. The samples yielded a stable remanence held in both magnetite and hematite which passed a reversal test. The type Santiago Formation east of Irvine Park in the Santa Ana Mountains, Orange County, is earliest middle Eocene and correlates with Chron C21n (46.2-47.8 Ma). The referred "Santiago Formation" in northwestern San Diego County is younger, ranging from Chron C20r (45-46 Ma) to Chron C18r (40-41 Ma). This age discrepancy, along with the great differences in lithology and thickness, suggests that the San Diego County outcrops might not truly be referable to the Santiago Formation.

INTRODUCTION

Throughout northwestern San Diego County are isolated outcrops of a fossiliferous siltstone and sandstone known as the Santiago Formation. This unit is composed of complexly interfingering marine and non-marine facies and yields benthic foraminifera, marine molluscs and fossil mammals. In most cases, these isolated outcrops expose no more than a few meters to tens of meters of section, so no section spans the entire thickness of the formation. Due to much recent road building and the rapid spread of housing developments in northern San Diego County, extensive recent excavations have been made through this unit, yielding many new fossil localities and better sections (Walsh, 1991, 1996; Rasmussen et al., 1995). These excavations, combined with the biostratigraphy of their recently described fossils, and the refined chronostratigraphy of the Eocene strata of southern San Diego County (Walsh et al., 1996), allow us to obtain magnetic samples of the formation and correlate these short, isolated sections to the magnetic polarity time scale.

The Santiago Formation was first described by Dickerson (1914) as the "Tejon Formation" based on mollusc-bearing outcrops in the northern Santa Ana Mountains, Orange County (Fig. 1). Dickerson (1914) used the term "Tejon" in the biostratigraphic rather than lithostratigraphic sense, because the Orange County fossils were similar to those from the Tejon Formation in the San Emigdio Mountains, in the northern Transverse Ranges, 160 km to the northwest. Clearly, the Orange County rocks are not referable to the Tejon Formation, which was deposited in an entirely different depositional basin on the opposite side of the San Andreas fault, and has little or no lithologic similarity to the Orange County rocks. English (1926) also mapped several additional outcrops of the "Tejon Formation" between Santiago Creek and the Santa Ana River. Woodring and Popenoe (1945) ended the confusion between lithologic and faunal terms, and proposed the name "Santiago Formation" to replace the older term "Tejon." They designated a type section about 1 km northeast of Irvine Park in the Santa Ana Mountains. Schoellhamer et al. (1981) described the Santiago Formation in much greater detail.

In Orange County, the Santiago Formation is confined to three small areas: along the southeast side of the Santa Ana River; from the Santa Ana River southeast to Irvine Park; and type section from Santiago Creek to east of Irvine Park (Schoellhamer et al., 1981). Most of these outcrops are now inaccessible and/or poorly exposed, and yield few or no fossils, so they were unsuitable for paleomagnetic sampling. The base of the Santiago Formation consists of a conglomerate, overlain by gray-tan micaceous sandstones and feldspathic sandstones interbedded with a few siltstones. The unit has numerous calcite-cemented concretions, 5 cm to 1 m in diameter, which commonly contain either marine molluscs or plant remains. Silicified wood is common in the stratigraphically higher, non-marine part of the section. In Orange County, the Santiago Formation unconformably overlies the upper Paleocene Silverado Formation and is unconformably overlain by the upper Oligocene-lower

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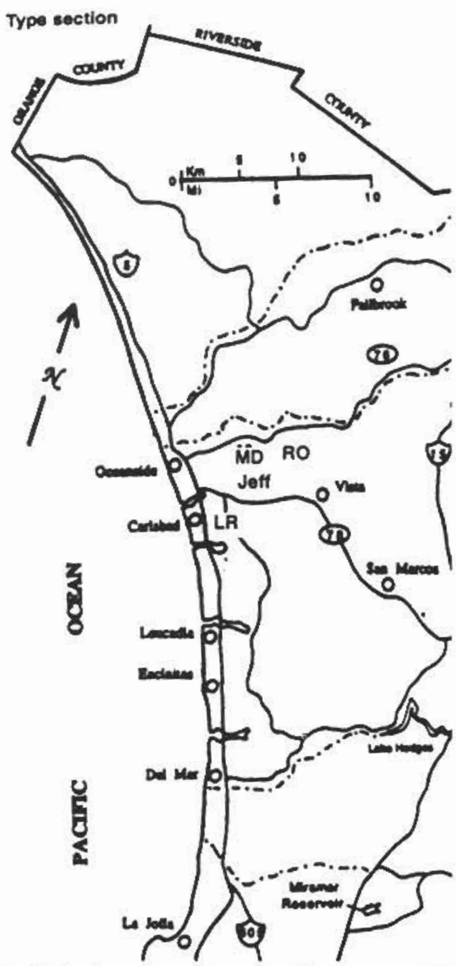

Figure 1. Index map showing location of localities mentioned in text (after Walsh, 1996). Jeff = Jeff's Discovery site; LR = Laguna Riviera; MD = Mesa Drive; RO = Rancho del Oro.

Miocene Sespe-Vaqueros formations (Schoellhamer et al., 1981; Prothero and Lopez, this volume; Prothero and Donohoo, this volume). Schoellhamer et al. (1981) reported a maximum thickness of 820 m of Santiago Formation, although most outcrops are much thinner. However, when sampling was conducted on the type section in 1998, we found that only a few meters of the basal sandstones of the type section are still continuously exposed.

In northern San Diego County, the outcrops referred to the Santiago Formation also contain both marine and non-marine fossils, although there are many lithologic differences with the type exposures in Orange County. The geology of these outcrops was described by Wilson (1972), who divided the formation into three members, informally labeled members A, B, and C. A maximum of only 30 m of member A and about 50 m of member B can be measured in any one place, although they may be much thicker. A disconformity separates members B and C, and the maximum measured thickness of member C is only 30 m. Even allowing for the possibility that the unit is thicker in the subsurface, it does appear that the rocks referred to the Santiago Formation in San Diego County are much thinner than the type Santiago Formation in Orange County.

In addition to the lithologic and thickness differences between the type Santiago Formation in Orange County and the referred outcrops in San Diego County, there are other differences that make it questionable whether all of these rocks should be referred to the same formation. The most obvious problem is that they do not appear to overlap in age. At one time, the Santiago Formation was correlated with the middle Eocene, and this low-resolution dating was sufficient. However, recent improvements of dating strata from the 12 million years (37-49 Ma) of the middle Eocene have shown that the age differences were much greater than first suspected. Schoellhamer et al. (1981, p. D31) reported that the lower part of the type Santiago Formation in Orange County yields a "Domengine" molluscan fauna, and a late Ulatisian benthic foraminiferal fauna, which is latest early Eocene to earliest middle Eocene in age (47-49 Ma) (Prothero, in press). By contrast, the mammalian faunas of the San Diego County "Santiago Formation" are much younger, from late early Uintan (about 45-46 Ma) to possibly early Duchesnean (about 40-41 Ma) (Walsh, 1991, 1996; Walsh et al., 1996). Of course, age is not a criterion for definition of a lithostratigraphic unit, but given the large lithologic differences as well, perhaps another name should be given to the San Diego County outcrops referred to the Santiago Formation.

METHODS

Sampling of the San Diego County exposures was conducted in 1989-1991 as ephemeral excavations due to housing developments and road cuts were made available. Most of these outcrops have now been destroyed or covered up. The type section of the Santiago Formation was sampled in 1998 as part of the sampling of the underlying type Silverado Formation (Prothero and Lopez, this volume). Sections were measured with a Jacob's staff (in the dipping strata of Orange County) or with a telescoping hand level (in the horizontal strata of San Diego County), and three oriented block samples were collected at every magnetic site.

Once samples were returned from the field, they were cut into cubes on a band saw with a tungsten-

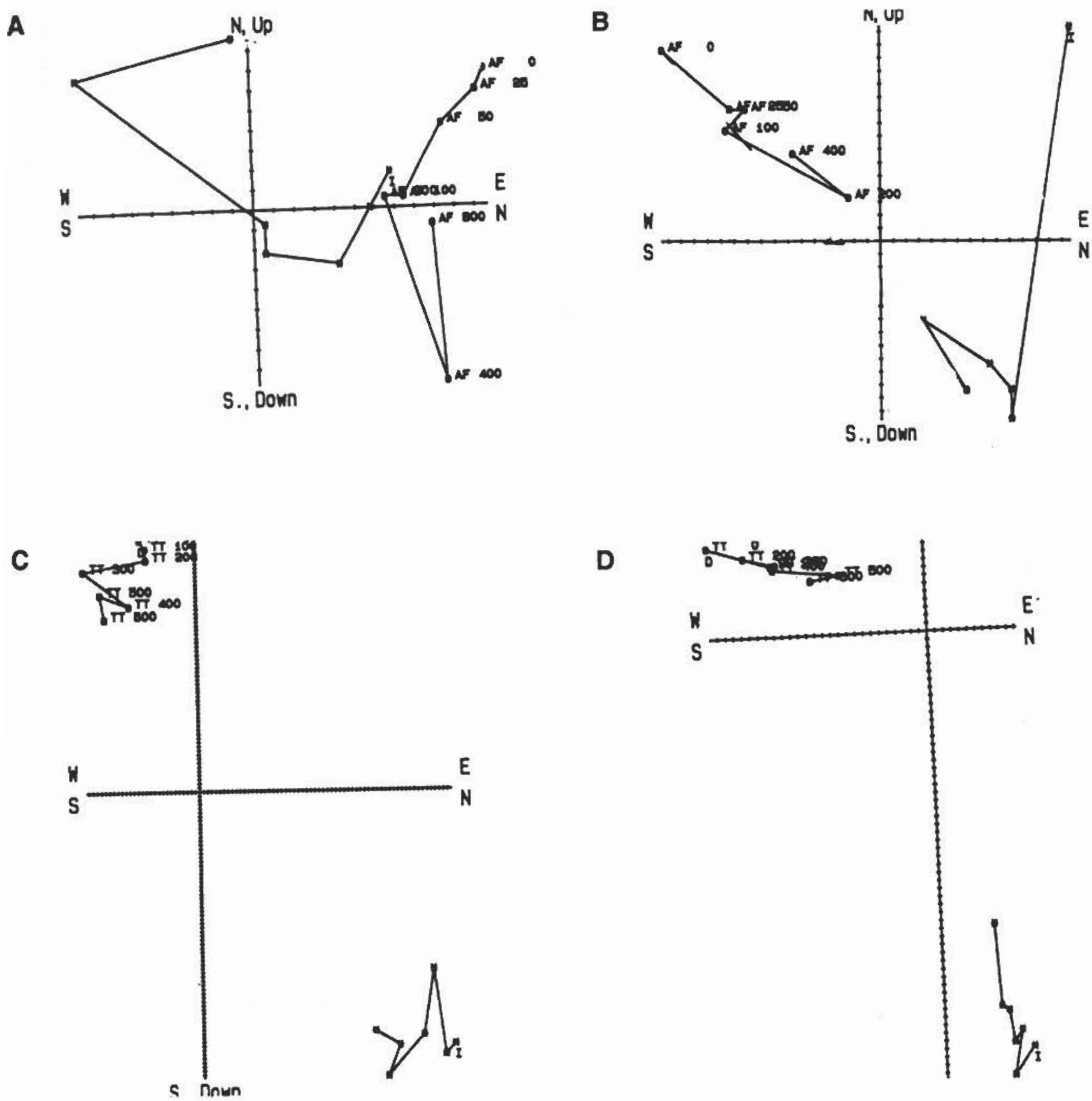

Figure 2. Orthogonal demagnetization ("Zijderveld") plots of representative samples. Squares indicate horizontal component; asterisks represent the vertical component. Demagnetization steps indicated by "AF" and demagnetization field (in Gauss) and "TT" and thermal step in degrees Centigrade. "I" = NRM direction of vertical component. Each division equals 10^{-7} emu.

carbide blade, and analyzed on the 2G cryogenic magnetometer at the California Institute of Technology. After measurement of natural remanent magnetization (NRM), pilot samples were demagnetized at alternating fields (AF) of 25, 50, 100, 400 and 800 Gauss to determine the coercivity behavior of the sample, and to remove any remanence held in multidomain grains. Other pilot samples were thermally demagnetized at 100, 200, 300, 400, 500 and 600°C to removed overprints held in iron hydroxides like goethite, and to determine how much magnetization remained above the Curie point of magnetite (580°C). Based on the behavior of these pilot samples, all remaining samples were measured at NRM, then thermally demagnetized at multiple steps of 300, 400 and 500°C to recover the remanence held

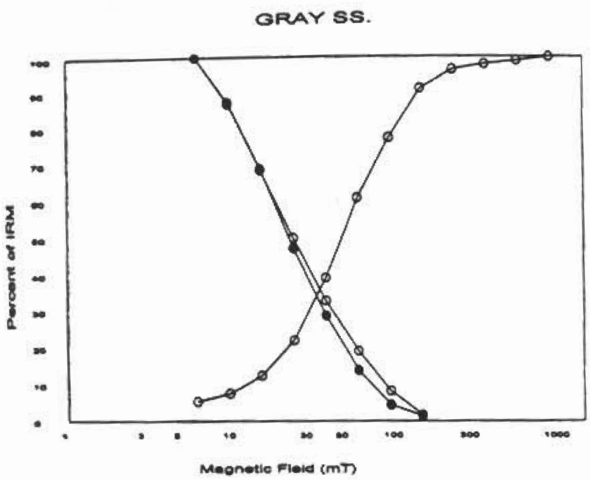

Figure 3. IRM acquisition (ascending curve on right) and modified Lowrie-Fuller test (two descending curves on left) for a representative powdered sample of the Santiago Formation. Solid boxes = ARM; open boxes = IRM.

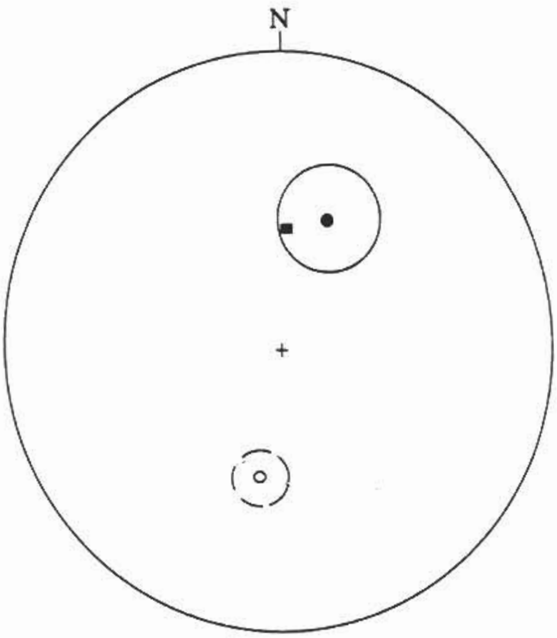

Figure 4. Stereoplot showing mean (solid circle) and circle of confidence (solid line) of normal sites (lower hemisphere projections), and of reversed sites (open circle, dashed lines, upper hemisphere projections). When this reversed direction is inverted through the center of the stereonet, the inverted mean (solid square) falls within the circle of confidence around the normal mean. Such a positive reversal test shows that the direction is primary.

in magnetite, while removing any possible overprints held in iron hydroxides like goethite (which dehydrates at 200°C). The samples from the type Santiago Formation were subjected to both AF demagnetization (at 25, 50, and 100 Gauss) followed by thermal demagnetization at 300, 400, 500, and 600°C. The resulting vectors were plotted on orthogonal demagnetization ("Zijderveld") plots, and their statistics calculated using the methods of Fisher (1953).

Several representative samples were also powdered and placed in epindorph tubes. These samples were subjected to increasing IRM (isothermal remanent magnetization) to determine their IRM acquisition behavior. They were also AF demagnetized twice, once after having acquired an IRM produced in a 100 millitesla (mT) peak field, and once after having acquired an ARM (anhysteretic remanent magnetization) in a 100 mT oscillating field. Such data are useful in conducting a modified Lowrie-Fuller test (Pluhar et al., 1991).

RESULTS

Magnetic behavior

Orthogonal demagnetization ("Zijderveld") plots of representative samples are shown in Figure 2. In many samples (Fig. 2A, B), there was considerable change in intensity during AF demagnetization, suggesting that the remanence is held in a low-coercivity mineral like magnetite. In these samples, a slight overprint was present, but by AF fields of 400 Gauss, normal overprints had been removed and reversed directions were revealed (Fig. 2A), or the sample stayed stably normal even at the highest AF step (Fig. 2B). However, thermal demagnetization (Fig. 2C, D) shows that considerable remanence was left even above the Curie point of magnetite (580°C) was exceeded, suggesting that there is also remanence held in hematite as well.

IRM acquisition analysis of selected powdered samples showed that the magnetic minerals reached IRM saturation at 300 mT (millitesla), further supporting the interpretation that the remanence is held in magnetite (Fig. 3). The IRM was more resistant to AF demagnetization than the ARM, suggesting that at least some of the remanence is held in multidomain grains (Fig. 3).

Fisher statistics for each of the localities described below are given in Table 1. On a stereonet, the mean for all normal sites (Table 2) is antipodal to the mean for all reversed sites (Fig. 4). This is a positive reversal test, suggesting that overprinting has been removed and the remanence is primary.

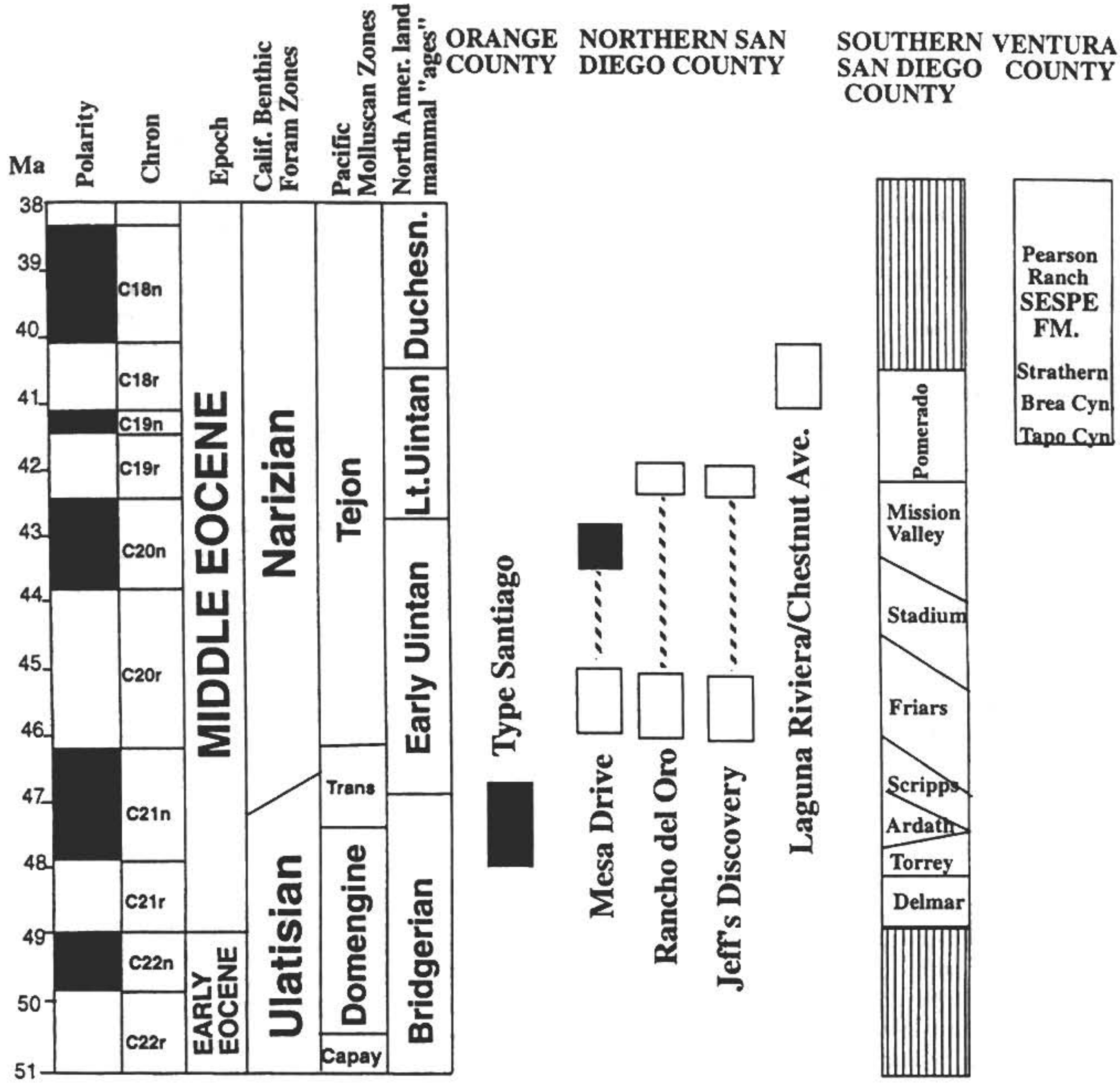

Figure 5. Correlation of the various Santiago sections with the magnetic stratigraphy of the southern San Diego County Eocene rocks (after Walsh et al., 1996) and Sespe Formation (after Prothero et al., 1996), and with the time scale of Berggren et al. (1995). Correlation of Pacific Coast molluscan and benthic foraminiferal zones after Prothero (in press).

Magnetic stratigraphy

Type Santiago Formation (Ulatisian/ Domengine), Orange County— As discussed above, only limited outcrops still remain of Woodring and Popenoe's (1945) type section of the Santiago Formation east of Irvine Lake and Irvine Park in the Santa Ana Mountains. Samples were taken of the sandstone just above the basal conglomerate, but not enough continuous vertical exposure of the section remained to justify more than one site in the type section. All three samples from the type section showed a stable normal polarity (Table 1). Based on the overlapping ranges of late Ulatisian benthic foraminifera and Domengine molluscs (Fig. 5), this normal magnetozone best correlates with Chron C21n (46.2-47.8 Ma, according to the time scale of Berggren et al., 1995). The Ulatisian benthic foraminiferal stage ranges from the early Eocene to the earliest middle Eocene, with its youngest fossils known from Chron C21n (Prothero, in press). The molluscan "Domengine Stage" ranges from Chron C22r to Chron C21n (Prothero, in press), so only in

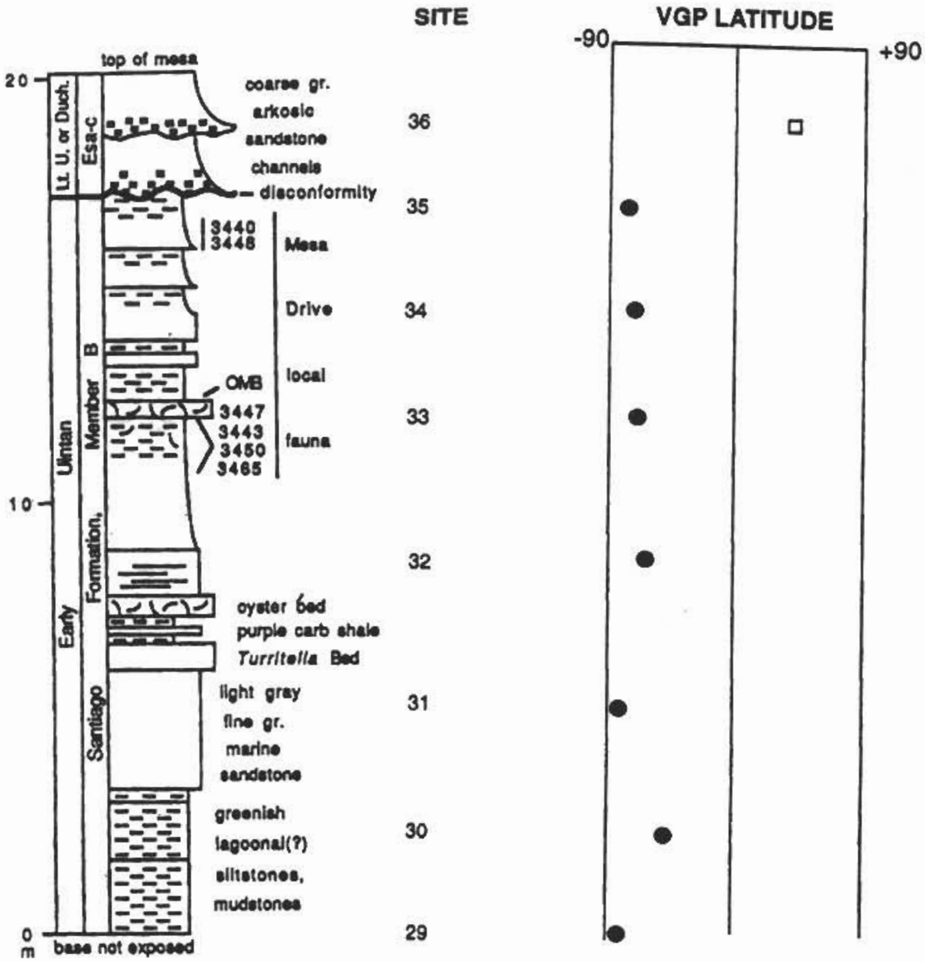

Figure 6. Magnetic stratigraphy of the "Santiago" Formation at Mesa Drive. Stratigraphy after Walsh (1996, Fig., 3). VGP = virtual geomagnetic pole. OMB = "Oyster Marker Bed." Solid circles are Class I sites of Opdyke et al. (1977), which are statistically distinguished from a random distribution at the 95% confidence level; open squares or circles with diagonal pattern are Class II sites, which had only two samples, so no statistics could be calculated; open circles are Class III sites, which had one sample divergent, but two vectors gave a clear indication of the polarity.

Chron C21n do both Domengine molluscs and Ulatisian benthic foraminifera occur together.

Mesa Drive section (early and late Uintan), San Diego County— Walsh (1991; 1996, fig. 3) described a section of about 18 m of Member B of the "Santiago Formation," which contains *Turritella uvasana, Miltha packi, Glyptoactis* sp., oysters, and other marine molluscs in the lower part of the section, and the early Uintan Mesa Drive local fauna in the upper part of the section. Overlying this section is a disconformity, in turn overlain by a few meters of coarse arkose of member C, which contains a late Uintan or early Duchesnean fauna in nearby outcrops. Six sites spanning the 18 m of member B (Fig. 6) were taken from a parallel section along Avenida de la Plata (formerly Barricade Road at the time of sampling) and analyzed; all were reversed in polarity (Table 1). A single site from the late Uintan or early Duchesnean arkose of member C was normal in polarity.

Walsh (1991, 1996) considered the early Uintan fossils of member B to be correlative with the early Uintan fossils of the Friars Formation in southwestern San Diego County. Walsh et al. (1996) concluded that the Friars Formation correlates mostly with early Chron C20r (43.8-46.2 Ma). Thus, the reversed strata of member B at Mesa Drive probably also correlate with early Chron C20r.

The late Uintan strata from member C at Mesa Drive were correlated with late Uintan faunas from the Mission Valley Formation by Walsh (1991, 1996). Walsh et al. (1996) suggested that the latter unit is probably correlative with Chron C20n (42.5-43.8 Ma) (Fig. 4). Thus, the normally magnetized late Uintan outcrops of member C at Mesa Drive probably also correlate with Chron C20n.

Jeff's Discovery section (early and late Uintan), San Diego County—Walsh (1991, 1996) described an important fossil locality in Oceanside which has produced a wealth of well preserved late Uintan mammals. The lower part of the section (Walsh, 1996, Fig. 5) consists of 16 m of unfossiliferous sandstones of member B, while the upper part of the section above the disconformity exposes 6 m of

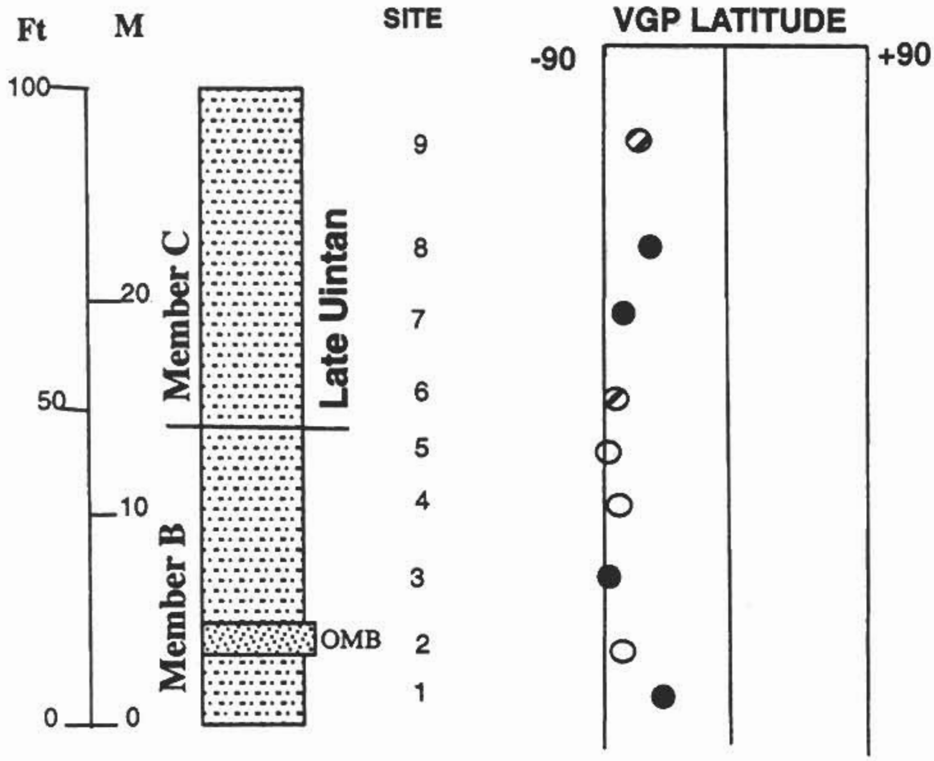

Figure 7. Magnetic stratigraphy of the "Santiago" Formation at Jeff's Discovery site. Stratigraphy after Walsh (1996, Fig. 5). All other conventions as in Figure 6.

member C, yielding all of the fossils from this site (Fig. 7). Eight sites were taken (Fig. 7, Table 1) and both members B and C at this locality are entirely of reversed polarity.

Although there are no fossils to constrain the age of the lower part of the section, it most likely correlates with Chron C20r, as did the other member B strata described above. The reversed strata of the upper part of the section probably correlate with Chron C19r (41.5-42.5 Ma), because correlative rocks with similar fossils from the upper Mission Valley Formation in southern San Diego County probably also correlate with this magnetic chron (Walsh et al., 1996). In this case, the disconformity between members B and C apparently represents the time of deposition of the intervening Chron C20n.

Rancho del Oro section (early and late Uintan), San Diego County— Walsh (1991, 1996; Rasmussen et al., 1995) described a series of late Uintan fossil localities from the lower part of member C in the Rancho del Oro II and III housing development in Oceanside. The stratigraphic section at this locality (Fig. 8) is very similar to that of the Mesa Drive area (Fig. 6), complete with the "Oyster Marker Bed." Samples were taken by T. Deméré and B.O. Riney in 1988, before the development was completed and the outcrops paved over.

As in the Mesa Drive and Jeff's Discovery sections, member B outcrops at Rancho del Oro are entirely reversed in polarity, and probably correlate with Chron C20r. As in the Jeff's Discovery section, member C outcrops (which yield the Rancho del Oro local fauna) are reversed in polarity, and probably also correlate with Chron C19r. Thus, the overall magnetostratigraphy is very similar to that of Jeff's Discovery site (Fig. 5).

Chestnut Avenue/Laguna Riviera (late Uintan-?Duchesnean), San Diego County— The Laguna Riviera local fauna (Golz, 1976; Golz and Lillegraven, 1977; Walsh, 1996) yields a crucial fauna that includes many important taxa, including the early camel *Poebrodon californicus*. The original outcrops of the Laguna Riviera and nearby Chestnut Avenue localities are now covered and inaccessible, but a section along El Camiño Real parallel to the original Chestnut Avenue section of Golz (1976) was sampled in 1991. This section spanned almost 35 m of strata of member C of the "Santiago" Formation, and all four sites were reversed in polarity (Fig. 9, Table 1).

Golz (1976) and Golz and Lillegraven (1977) originally thought that the Laguna Riviera and Chestnut Avenue local faunas were late Uintan in age. However, Walsh (1996, p. 92) suggested that the assemblage of mammals is more like the early Duchesnean Pearson Ranch local fauna of the Sespe Formation in Simi Valley, Ventura County, California. Prothero et al. (1996) showed that the

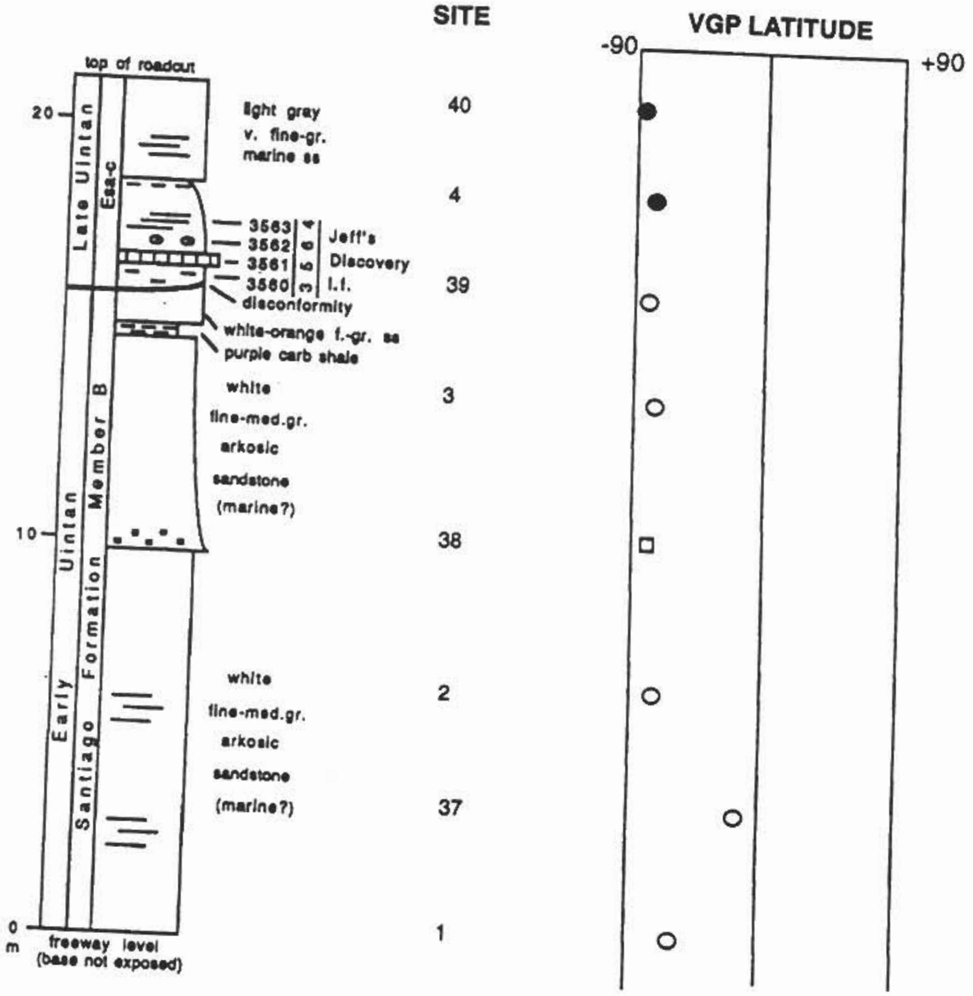

Figure 8. Magnetic stratigraphy of the "Santiago" Formation at Rancho del Oro. All conventions as in Figure 6.

Pearson Ranch local fauna is correlative with normal Chron C18n (38.5-40.2 Ma), which is inconsistent with the reversed polarity of the San Diego County rocks. However, in the Simi Valley section, strata representing reversed Chron C18r (40.2-41.0 Ma) yield the transitional late Uintan-early Duchesnean Strathern local fauna (Kelly, 1990; Prothero et al., 1996), which is very similar to the transitional Uintan-Duchesnean Laguna Riviera local fauna (Walsh, 1996). Thus, the most reasonable correlation of this section is with Chron C18r, since the next reversed magnetic chron (Chron C17r) correlates with middle-late Duchesnean faunas (Prothero and Emry, 1996).

DISCUSSION

Correlation of all the sections discussed in this paper is shown in Figure 5. As is apparent from this figure, the isolated outcrops referred to the Santiago Formation in two different counties apparently span most of the middle Eocene (from as young as 40.2 Ma to as old as 47.8 Ma). However, each section is very short and bounded by unconformities and poor exposure, so they are a very discontinuous and incomplete record of this 6 to 7 million year interval. In addition, there is no apparent age overlap between the youngest strata of the type Santiago Formation in Orange County, and the oldest sampled strata referred to the Santiago Formation in San Diego County. This, along with the lithologic, facies, and thickness differences between the two areas, raises the question (discussed above) whether the San Diego County outcrops should really be referred to the Santiago Formation, or given a new formational name. However, such a decision is beyond the scope of the present paper.

CONCLUSIONS

Based on biostratigraphy and magnetic stratigraphy, the rocks and fossils referred to the Santiago Formation in Orange and San Diego counties discontinuously span much of the middle Eocene. The type

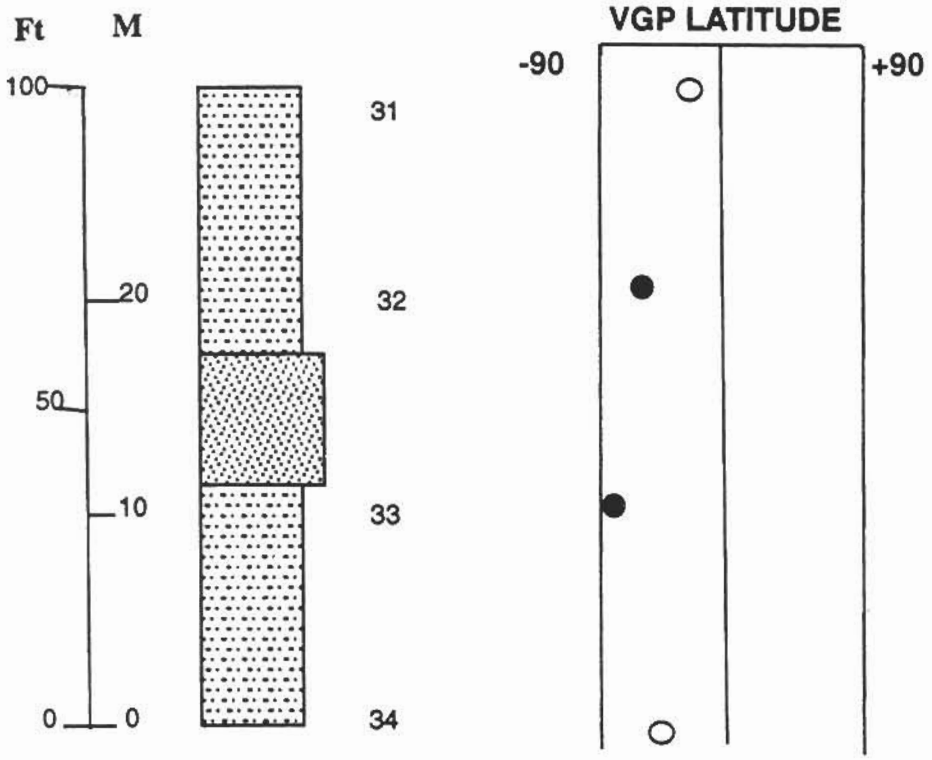

Figure 9. Magnetic stratigraphy of the "Santiago" Formation along El Camiño Real, near the Laguna Riviera and Chestnut Avenue localities. All conventions as in Figure 6.

section of the Santiago Formation in the Santa Ana Mountains in Orange County correlates with Chron C21n (46.2-47.8 Ma). The exposures of Member B of the referred "Santiago" Formation in northern San Diego County (at Mesa Drive, Rancho del Oro, and Jeff's Discovery Site) correlate with early Chron C20r (43.8-46.2 Ma). Late Uintan strata of Member C of the "Santiago" Formation at Mesa Drive are correlative with Chron C19n, while those from Jeff's Discovery site and Rancho del Oro are correlative with Chron C19r (41.5-42.5 Ma). Late Uintan-?Duchesnean rocks and fossils from the Laguna Riviera/Chestnut Avenue localities are probably correlative with Chron C18r (40.2-41.0 Ma). Thus, the rocks referred to the Santiago Formation in these two counties discontinuously spans the interval from 40.2-47.8 Ma, or most of the middle Eocene.

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TABLE 1—Fisher statistics of sites from the Santiago Formation. Stratigraphic position of sites shown in Figures 5-7. N: number of samples per site; D, I: declination, inclination; k, α_{95} precision parameters.

Site	N	D	I	k	α_{95}
Laguna Riviera/Chestnut Avenue					
31	3	247.8	-36.7	4.8	63.7
32	3	157.0	-17.1	136.3	10.6
33	3	154.8	-55.3	34.8	21.2
34	3	234.7	-49.8	2.0	139.1
Mesa Drive					
29	3	175.4	-47.5	5.5	58.9
30	2	238.6	-63.8	11.4	82.9
31	3	182.4	-37.1	21.2	27.5
32	3	212.6	-55.9	10.5	40.1
33	3	158.5	-40.8	427.7	6.0
34	3	169.2	-28.4	25.9	24.8
35	3	197.0	-37.2	24.0	25.7
36	2	38.6	45.9	37.9	41.7
Jeff's Discovery Site					
37	3	197.4	-47.2	3.5	79.2
38	2	173.4	-35.7	3.3	180.0
39	3	193.8	-50.7	2.1	124.3
40	3	173.1	-51.1	9.9	41.5
1	3	134.8	-46.1	3.8	74.9
2	3	192.8	-53.5	2.6	102.4
3	3	170.6	-73.2	2.7	99.3
4	3	160.8	-50.3	6.0	55.5
Type Santiago (Irvine Lake)					
11	3	13.2	30.3	36.0	20.9
Rancho del Oro					
1	3	223.8	-34.3	23.5	26.0
2	3	185.7	-65.4	1.7	180.0
3	3	168.7	-42.9	11.2	38.6
4	2	186.2	-50.1	53.4	34.9
5	3	182.5	-44.6	3.6	78.4
6	1	173.5	-51.0	-	-
7	3	196.9	-45.4	6.6	52.3
8	3	135.8	-36.8	6.6	52.5
9	2	150.9	-17.9	13.0	76.1

TABLE 2— Summary Fisher statistics of sites from the Santiago Formation. N: number of samples per site; D, I: declination, inclination; k, α_{95} precision parameters.

Locality	N	D	I	k	α_{95}
Laguna Riviera (rev.)	4	197.5	-48.8	4.3	50.7
Mesa Drive (rev.)	8	184.4	-46.9	17.1	13.8
Jeff's Discovery (rev.)	8	174.7	-52.7	23.3	11.7
Rancho del Oro (rev.)	9	183.9	-42.4	8.1	19.3
Formational normal mean	5	22.1	37.2	20.5	17.3
Formational reversed mean	29	183.8	-48.6	11.7	8.2