MAGNETIC STRATIGRAPHY OF THE LOWER MIOCENE (EARLY HEMINGFORDIAN) SESPE-VAQUEROS FORMATIONS, ORANGE COUNTY, CALIFORNIA

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ABSTRACT

The nonmarine redbeds of the Sespe Formation and the overlying gray marine sandstones of the Vaqueros Formation are widespread in southern California, and in many places yield middle Eocene and late Oligocene mammals and molluscs. However, in the northern Santa Ana Mountains of Orange County, California, these same formations yield early Miocene (early Hemingfordian) mammals. Many of these same taxa are also known from early Hemingfordian faunas of the High Plains, such as the Marsland fauna of Nebraska, the Flint Hill fauna of South Dakota, and the Martin Canyon 'A' fauna of Colorado. A 1100-meter-thick section was taken along recent excavations of the Eastern Transportation Corridor south of Jamboree Road, and another 200-meter-thick section was taken near the classic locality at Bolero Lookout. The normal and reversed magnetic directions, held mainly in hematite, passed a reversal test. The pattern of magnetic polarity zones best correlates with Chron C5Cr to C5Er (17.0-19.0 Ma), consistent with the magnetic stratigraphy and fission-track date of 19.2 ± 0.5 Ma on the late Arikareean-early Hemingfordian rocks of Nebraska. This correlation implies that the upper Sespe and lower Vaqueros formations in Orange County are about ten million years younger than they are in Ventura and Santa Barbara counties, only 160 km to the north.

INTRODUCTION

The Sespe Formation was first defined by Watts (1897), based on exposures in lower Sespe Creek near Fillmore in Ventura County, California. Characterized by red floodplain muds, channel sandstones, and conglomerates, the Sespe Formation is widespread through the western Transverse Ranges, and reaches thicknesses of over a thousand meters in places. The gray shallow-marine sandstones of the Vaqueros Formation overlie the Sespe Formation through most of the Transverse Ranges and Coast Ranges. Originally based on exposures in the Santa Lucia Range near King City, as described by Hamlin (1904), the Vaqueros Formation contains a distinctive assemblage of molluscs, including *Turritella inezana* and *Rapana vaquerosensis*, which are the basis for the Vaqueros Molluscan Stage in California (Loel and Corey, 1932; Addicott, 1972). In most places, these formations are mapped as separate units, largely based on color differences, although their contact is often gradational and difficult to locate.

In the Santa Ana Mountains of Orange County, California (Fig. 1), a similar sequence of mammal-bearing terrestrial redbeds overlain by gray marine sandstones with a Vaquerosian molluscan fauna occurs. These beds have been extensively mapped and described (Vedder et al., 1957; Schoellhamer et al., 1981; Belyea, 1984; Belyea and Minch, 1989). Ranging in thickness from 300 to 900 m, in most respects they are indistinguishable from the Sespe and Vaqueros outcrops to the north, even though the northern outcrops are over 160 km away from the Santa Ana Mountains and were formed in different depositional basins. Because the contact between these formations is gradational in Orange County, Schoellhamer et al. (1981) mapped the units as "Sespe-Vaqueros undifferentiated" and this practice has been followed by subsequent workers (Lander, 1994; Lucas et al., 1997).

Fossil mammals were first reported from the nonmarine redbeds of the Sespe Formation in Ventura County, California, by Stock (1930, 1948), and soon became critical to our understanding of the evolution of mammals on the Pacific Coast. The Sespe sequence in Ventura and Santa Barbara counties was particularly important, because it was the only place in North America in which middle

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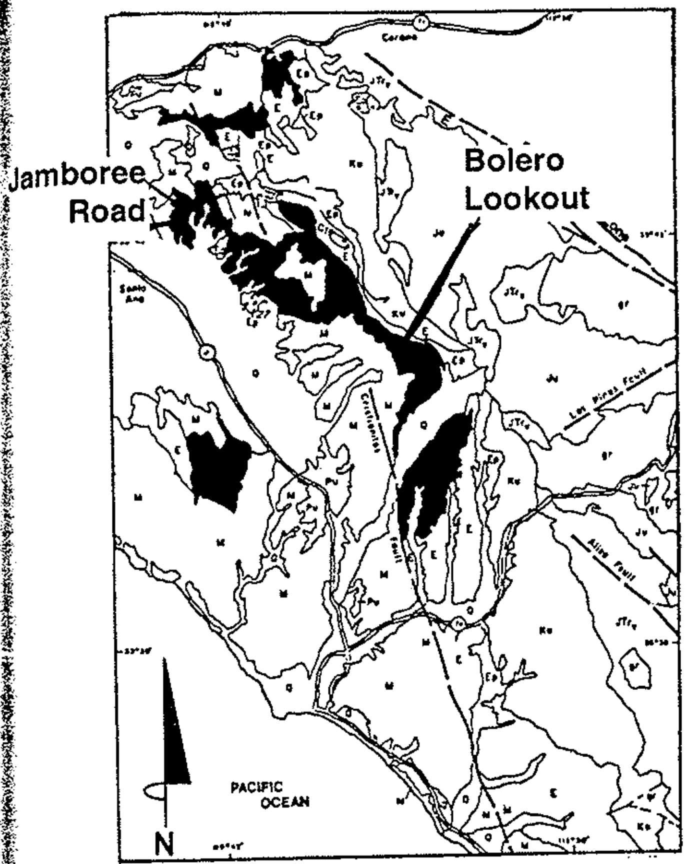

Figure 1. Index map showing location of study area within the western Transverse Ranges (after Belyea and Minch, 1989).

Eocene (Uintan-Duchesnean) mammalian faunas were found stratigraphically beneath Oligocene (Arikareean) faunas (Krishtalka et al., 1987). However, no late Eocene (Chadronian) or early Oligocene (Orellan-Whitneyan) faunas were reported from the Sespe, and recent analysis (Prothero et al., 1996) has shown that a 7-million-year unconformity eliminates all late Eocene and early Oligocene strata from the Sespe Formation.

In 1947, Chester Stock and associates collected mammalian fossils from redbeds referred to the Sespe Formation in Orange County, California, at a locality known as Bolero Lookout. This collection was originally given the Caltech locality number CIT 449, but since has been acquired by the Natural History Museum of Los Angeles County, so its current number is LACM(CIT) 449. Schoellhamer et al. (1981) mentioned that these fossils had been examined by G. Edward Lewis of the U.S. Geological Survey. Lewis (in Schoellhamer et al., 1981, p. D36) compared the camelid material from Bolero Lookout to *Paratylopus primaevus*, and suggested an "upper Oligocene, but possibly lower Miocene" age for the assemblage. However, the systematics and stratigraphic distribution of Oligocene-early Miocene camelids was so poorly known at that time that this identification was tentative, and not very indicative of the age of the fauna. Material correctly referred to *Paratylopus primaevus* has since been restricted to the late early Oligocene Whitneyan land mammal "age" (Prothero, 1996). Unfortunately the original Bolero Lookout camelid material cannot be located (Lucas et al., 1997), so its true identity cannot be determined. More recently collected specimens from Bolero Lookout were compared to the early Miocene camelid, cf. *Michenia* sp., by Lucas et al. (1997).

Savage (1972) and Raschke (1984) briefly mentioned the Bolero Lookout l.f., and suggested that it might be late Arikareean, comparable in age to the Pyramid Hill l.f. of the southern San Joaquin Valley. According to Lander (1994), their age identification was based largely on poorly preserved equid specimens they referred to *Miohippus*, and these are actually from UCMP V-6100, not from Bolero Lookout. Belyea and Minch (1989) revised the age estimate of the Bolero Lookout l.f., following Hugh Wagner's 1983 collections, which suggested a early to middle Hemingfordian age for the fauna. In the most recent review of Wagner's Bolero Lookout collections, Lucas et al. (1997), identified the horse *Parahippus pawniensis*, the entelodont *Daeodon hollandi*, and the camelid cf. *Michenia* sp., and numerous marine vertebrates. This assemblage is best compared with early Hemingfordian faunas of the Great Plains, such as the Flint Hill l.f. of South Dakota, and the Martin Canyon "A" beds of Colorado (Lucas et al., 1997).

Extensive excavations due to development of highways, housing projects, and landfills in Orange County have greatly increased the known fauna from the Sespe Formation in this region. Raschke (1984) reported Hemingfordian mammals (insectivores, rabbits, rodents, camels and oreodonts) from the Sespe Formation at Upper Oso Dam. In his report for the Bee Canyon Landfill access road, Raschke (1988) suggested a late Whitneyan (based on Lander's identification of the oreodont *Sespia nitida*) to earliest Hemingfordian (based on Lander's identification of the oredont *Merychyus arenarum*) age for the Sespe Formation. In collections from excavations of the Santiago Canyon Landfill, Lander (1994) and Whistler (1994) reported a much larger and more diagnostic early Hemingfordian assemblage, including the dog *Tomarctus canavus*, the lagomorph

Cuyamalagus dawsoni, twelve species of rodents including *Mookomys* sp., *Proheteromys* sp., *Schizodontomys* sp., *Leidymys* n. sp., *Pseudotheridomys cuyamensis*, *Cupidinimus lindsayi* and *Paciculus montanus*, the camelids *Michenia agatensis* and *Tanymykter brachydontus*, the oreodont *Merychyus arenarum*, the ruminants *Machaeromeryx tragulus* and *Blastomeryx advena*, the rhinoceros *Menoceras barbouri*, and the horses *Parahippus pawniensis* and *Anchitherium clarencei*. Many of these taxa, especially *Merychyus arenarum*, *Parahippus pawniensis*, *Menoceras barbouri*, and some of the rodents, are restricted to the early Hemingfordian. They were compared to faunas such as those from the earliest Hemingfordian of the Caliente and Vaqueros Formations of the Transverse Ranges (Repenning and Vedder, 1961), and more distantly, the Marsland-Runningwater Formations of Nebraska, the Flint Hill l.f. of South Dakota, and the Martin Canyon "A" beds of Colorado (Lander, 1994; Tedford et al., 1987). Large collections have also been made from the excavations for toll roads of the Eastern Transportation Corridor; these are currently under study by Bruce Lander, Mark Roeder and David Whistler (pers. commun., 1998).

All of these identifications suggest that the upper Sespe Formation and the Vaqueros Formation in Orange County are considerably younger than they are to the north in Ventura and Santa Barbara counties, but the precise age difference has never been determined. Magnetostratigraphic analysis of the Sespe Formation in Ventura and Santa Barbara counties (Prothero et al., 1996) has greatly refined the age estimates of those units. In this paper, we will try to establish similarly precise age estimates for the Sespe-Vaqueros formations in Orange County, using magnetic stratigraphy.

Institutional Abbreviations—LACM(CIT), California Institute of Technology collection, now housed at the Natural History Museum of Los Angeles County; UCMP, Museum of Paleontology, University of California, Berkeley.

METHODS

A 1100-meter-thick section of the Sespe-Vaqueros formations was measured by Mark Roeder, and sampled in 1998 along the temporary roadcuts of the Eastern Transportation Corridor just south of Jamboree Road. These outcrops have since been covered as the highway was finished (Fig. 1). A 200-meter-thick section of the uppermost Sespe-Vaqueros formations was sampled along the dirt road to the east of Bolero Lookout, following the measured section (labeled "Aliso Divide") described by Belyea (1984). In both sections, three oriented block samples were taken at each site, using simple hand tools. After removal from the field, samples were hardened with dilute sodium silicate, and were trimmed into 2-cm diameter cylinders. Especially friable samples were placed in quartz glass jars and sealed up with Zircar aluminum ceramic plugs. The samples were then measured in the 2G cryogenic magnometer at the California Institute of Technology paleomagnetics lab, using an automatic sample changer.

After measurement of natural remanent magnetization (NRM), each sample was demagnetized in alternating fields (AF) of 25, 50, and 100 Gauss. After AF demagnetization, each sample was then thermally demagnetized at 300, 400, 500, and 600°C. The resultant directions were then analyzed using orthogonal demagnetization plots, and summarized with Fisher (1953) statistics.

Powdered samples of representative lithologies (about 0.1 g each) were placed in epindorph tubes and subjected rock magnetic analysis. Each sample was AF demagnetized twice, once after having acquired an isothermal remanent magnetization (IRM) produced in a 100 mT (millitesla) peak field, and once after having acquired an ARM (anhysteretic remanent magnetization) in a 100 mT peak oscillating field. These data were used to conduct a modified Lowrie-Fuller test (Pluhar et al., 1991). These same powdered samples were also subjected to IRM acquisition experiments up to 1300 mT.

RESULTS

Magnetic Analysis

Orthogonal demagnetization ("Zijderveld") plots of representative samples (Fig. 2) showed very little response to AF demagnetization, and considerable remanence above 600°C. This demonstrates that some high-coercivity, high-blocking-temperature mineral, such as hematite, is the primary carrier of the remanence in most samples. After AF demagnetization, most samples showed a clear stable remanence between 300 and 500°C, which exhibited either normal or reversed polarity. This component was summarized using the least squared method of Kirschvink (1980), and then averaged using Fisher (1953) statistics.

IRM acquisition analysis (Fig. 3) showed that the samples were not saturated at 300 mT, but con-

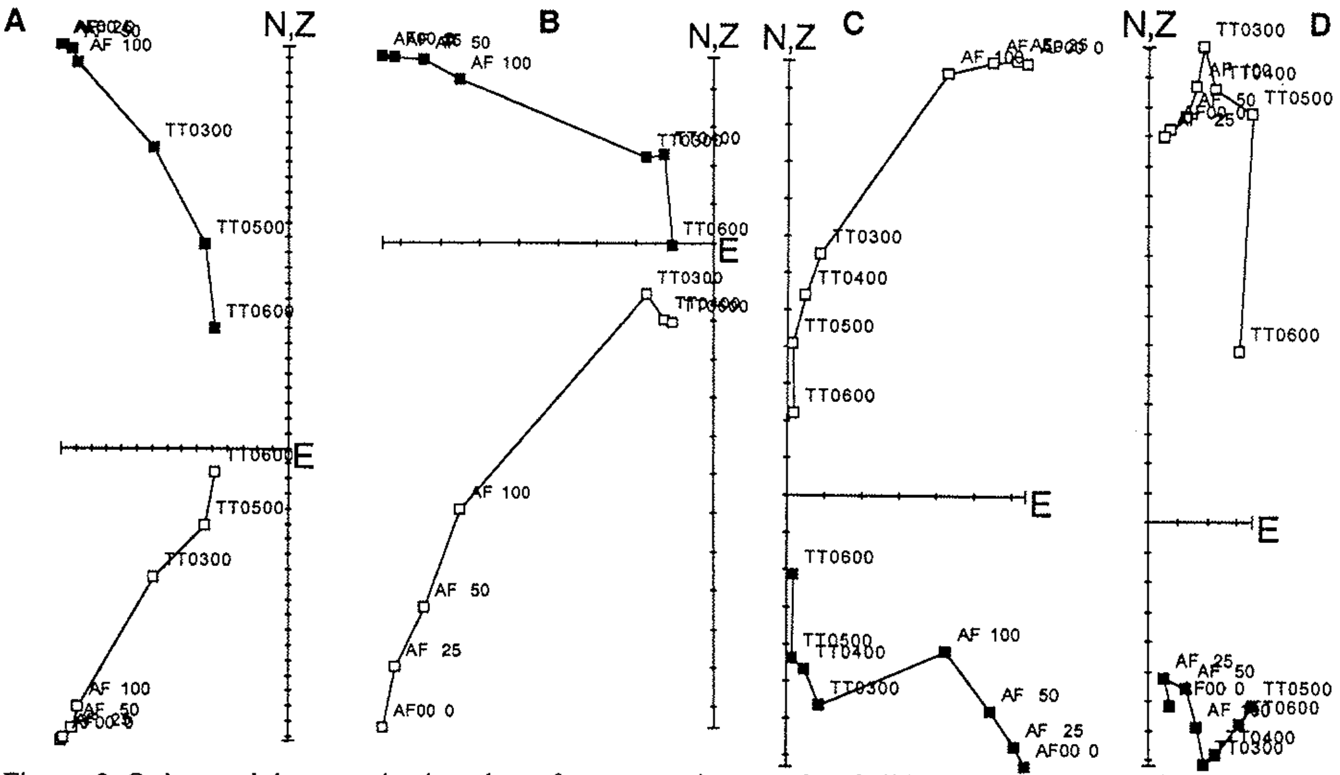

Figure 2. Orthogonal demagnetization plots of representative samples. Solid squares indicate horizontal component; open squares indicate vertical component. AF demagnetization steps ("AF") in Gauss; thermal demagnetization steps ("TT") in degrees Centigrade. Each division = 10^{-6} emu. (A) Bolero sample 10a; (B) Jamboree sample 14c. Both of these samples show typical behavior due to normal polarity (declination north, inclination down). (C) Bolero sample 15b; (D) Jamboree sample 21b. Both of these samples shown a stable reversed polarity (declination south, inclination up) at NRM, which persisted until 600°C.

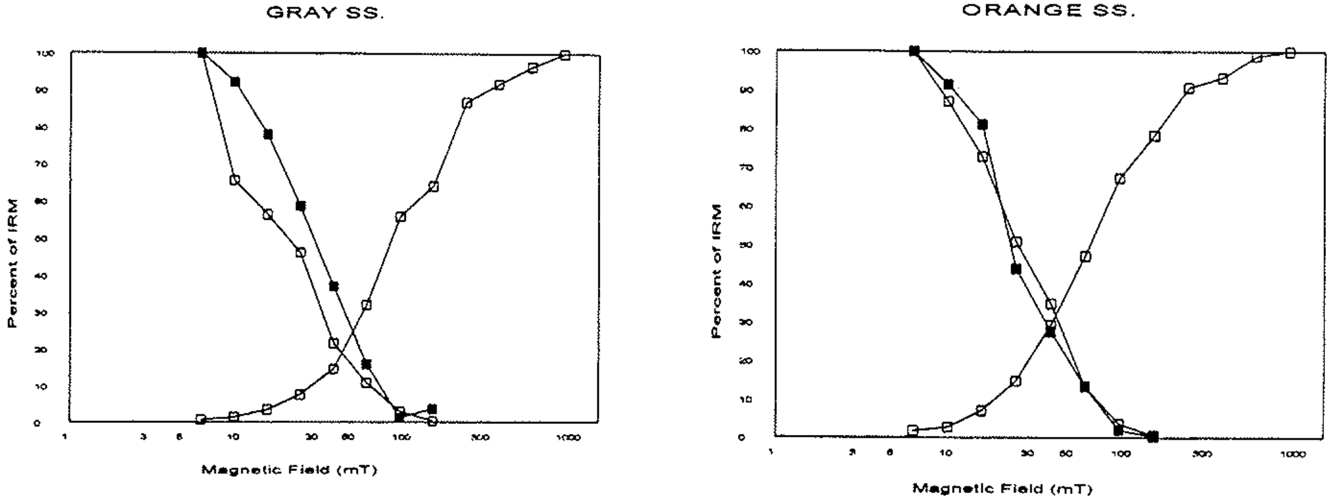

Figure 3. IRM acquisition analysis and modified Lowrie-Fuller test (see Pluhar et al., 1991, for details) of representative powdered samples. Open squares = IRM; solid squares = ARM. In all three cases, the IRM (ascending curve on right) does not saturate at 300 mT, indicating that remanence is held in hematite. In addition, the ARM is more resistant to AF demagnetization than the IRM (descending curves to left), suggesting single domain or pseudo-single domain grains.

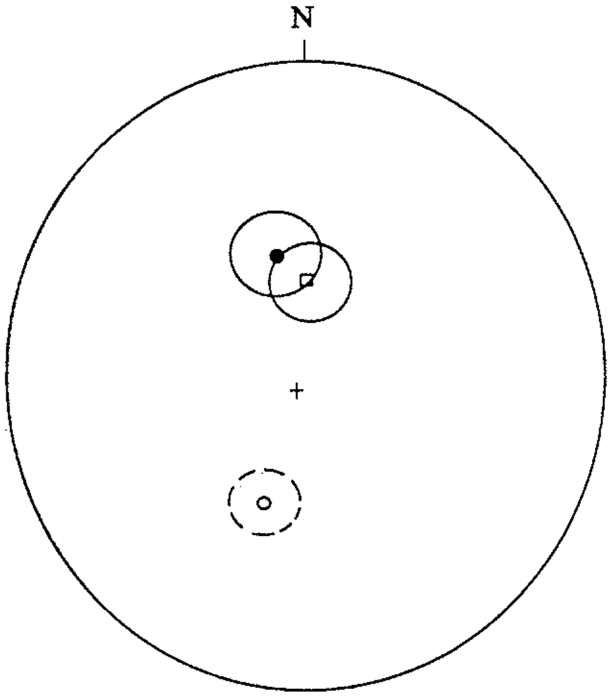

Figure 4. Stereoplots of mean poles and circles of confidence for the data discussed in this study. Solid circles indicate lower hemisphere projections; dashed lines and open circles indicate upper hemisphere projections. Open square indicates mean of reversed samples projected through the origin to the lower hemisphere.

tinued to acquire magnetization up to 1300 mT. Again, this suggests that hematite is the primary carrier of the remanence. In representative lithologies (Fig. 3), the ARM (solid squares) was more resistant to AF demagnetization than the IRM (open squares), suggesting that the remanence is held in single-domain or pseudo-single-domain grains. Many samples had an obvious red stain, and under reflected light microscopy, tiny (0.01 mm in diameter) grains of specular hematite were clearly visible. These results are consistent with the rock magnetic analyses of the Sespe Formation in Ventura and Santa Barbara counties (Prothero et al., 1996).

Results of statistical averaging of the normal and reversed sites for each locality are shown in Table 1. In both Bolero Lookout and Jamboree Road, the normal and reversed directions are antipodal within error estimates (Fig. 4). This positive reversal test shows that the directions are primary, and that overprinting has been largely removed. The dips of the rocks were not variable enough, however, to conduct a fold test.

Magnetic Stratigraphy

At each site, the 3 resultant vectors were averaged and then classified according to the system of Opdyke et al. (1977). In Class I sites (n = 21), the three vectors were statistically distinguishable from a random scatter at the 95% confidence interval. In Class II sites (n = 5), one sample crumbled and only two remained, so site statistics could not be calculated. In Class III sites (n = 18), two vectors showed a clear polarity preference, but one vector was divergent.

In the Eastern Transportation Corridor section near Jamboree Road (Fig. 5), the lower 400 m of section was of reversed polarity. The next 200 meters was characterized by normal polarity, but a reversed magnetozone occurred between 600 and 800 m on the measured section. The rest of the section was normal in polarity (including the Sespe-Vaqueros contact), except for the highest Vaqueros site at 1000 m on the measured section.

In the much thinner Bolero Lookout section (Fig. 6), the lower 110 m was of reversed polarity, while the remaining 90 m was of normal polarity. This section concluded just below the microwave tower at the top of Bolero Lookout itself, but did not sample the overlying Vaqueros exposures.

Correlation of these sections is shown in Figure 7. Both sections yield early Hemingfordian mammals through most of the exposure. MacFadden and Hunt (1998) showed that early Hemingfordian mammals of the Marsland-Runningwater formations occurred in Chron C5En and C5Er (18.2-19.0). This correlation is calibrated by a fission track date of 19.2 ± 0.5 Ma on the Agate Ash, which is located high in the late Arikareean Chron C6n. Thus, the most parsimonious interpretation of the Jamboree Road section is that it correlates with Chrons C5Cr to C5Er (17.0-19.0 Ma). The much shorter Bolero Lookout section represents the uppermost member of the Sespe, according to Belyea (1984) and Belyea and Minch (1989), and is directly overlain by the Vaqueros. Thus, it probably correlates with the upper half of the Jamboree Road section, or Chron C5Dn and C5Dr (17.3-18.0 Ma).

DISCUSSION

The implications of these correlations are shown in Figure 8. Prothero et al. (1996) showed that the Sespe Formation in Ventura and Santa Barbara counties spanned the middle Eocene (Uintan and Duchesnean, 37-41 Ma), and the late Oligocene

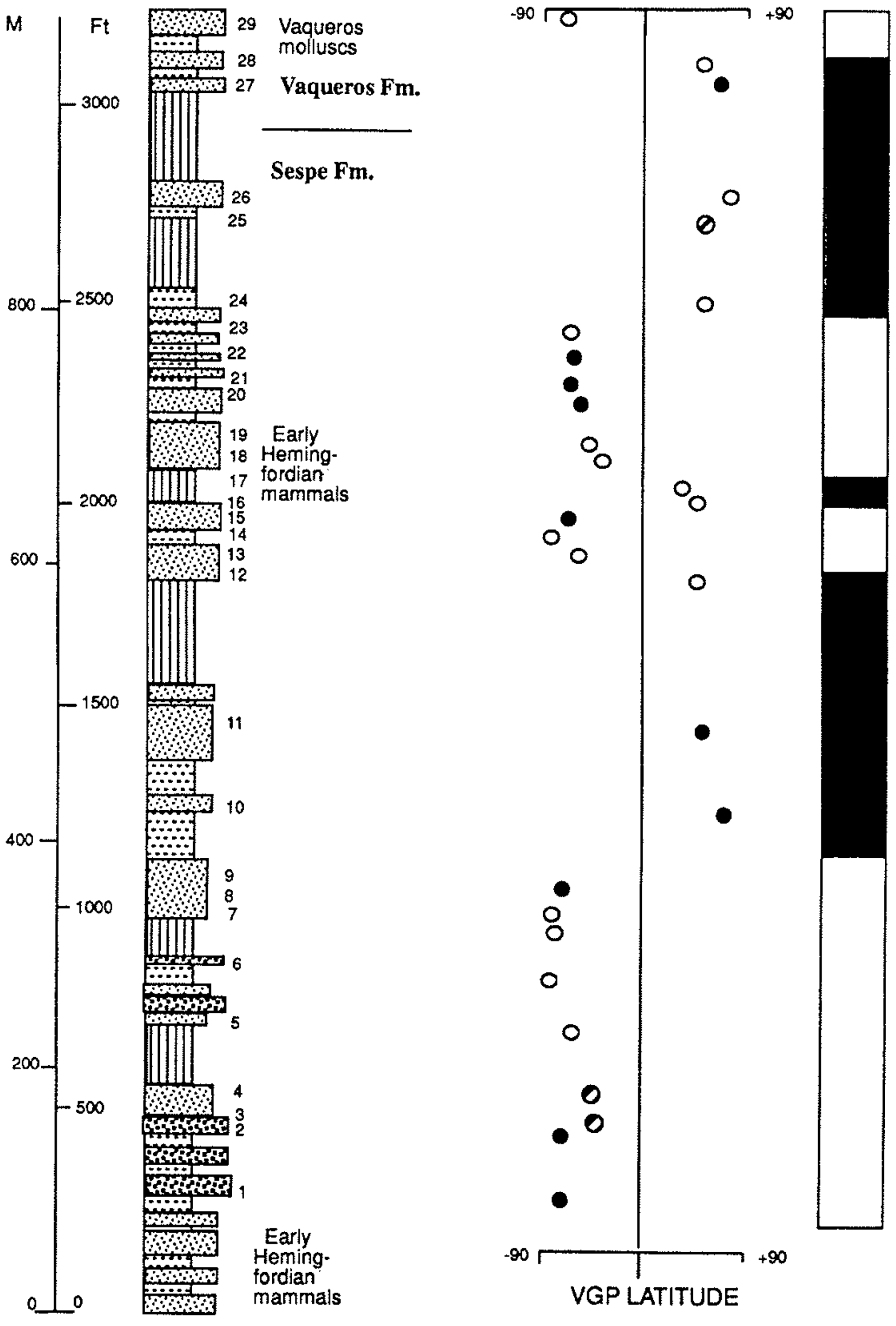

Figure 5. Lithostratigraphy and magnetic data for the Jamboree Road (Eastern Transportation Corridor) section shown in Figure 1. Lithostratigraphy after Roeder (pers. commun.). Solid circles indicate Class I sites of Opdyke et al. (1977); circles with diagonal pattern are Class II sites; open circles are Class III sites. VGP = virtual geomagnetic pole. Vertical pattern indicates covered intervals; all other lithostratigraphic symbols are standard.

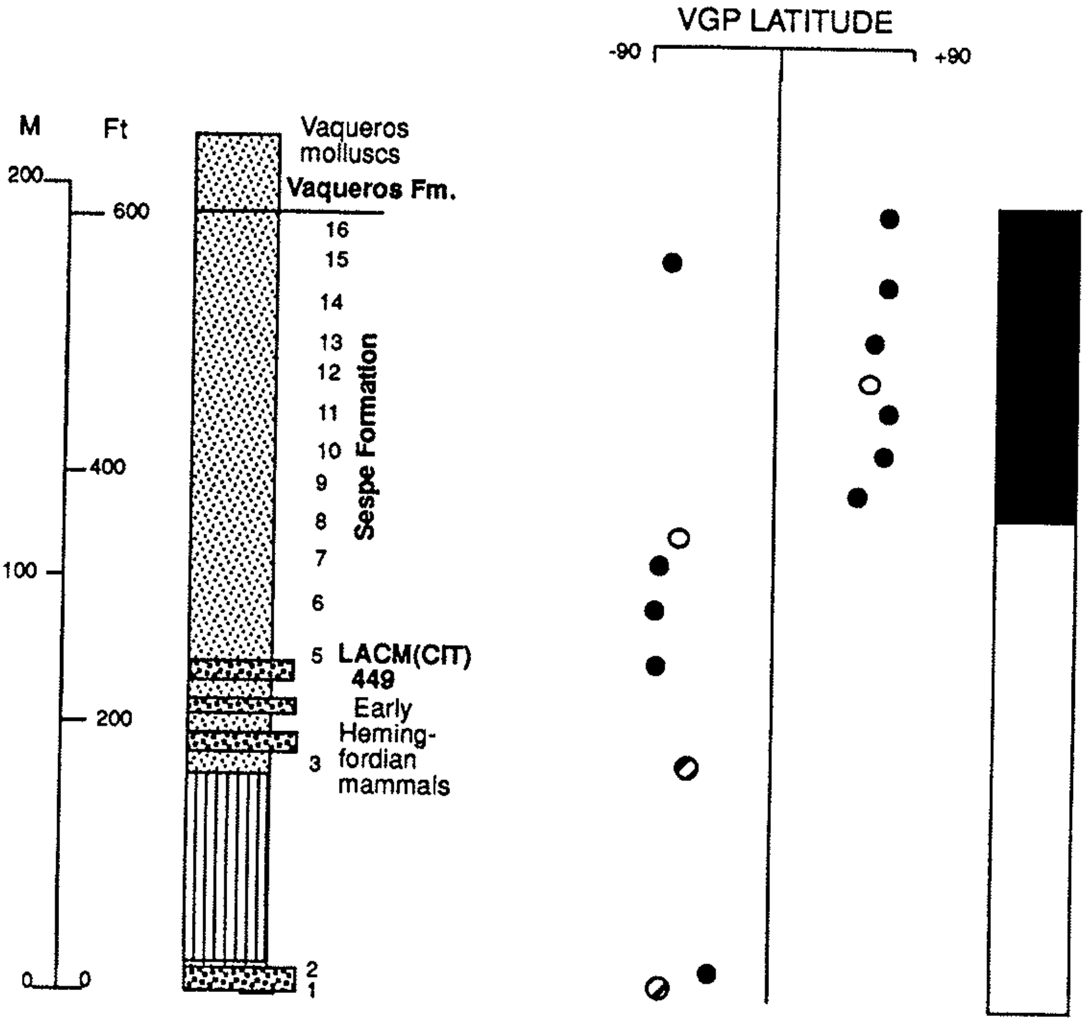

Figure 6. Lithostratigraphy and magnetic data for the Bolero Lookout section ("Aliso Divide" section of Belyea, 1984, and Belyea and Minch, 1989). All conventions as in Figure 5.

(early Arikareean, 28-30 Ma), with a 7-million-year unconformity between these two sedimentary packages that eliminates the Chadronian, Orellan, and Whitneyan. The conformably overlying Vaqueros Formation and its faunas apparently are as old as 28 Ma. However, our studies have shown that the Orange County Sespe-Vaqueros formations are as much as 9 million years younger (17.0-19.0 Ma). This age difference is much bigger than previously anticipated. In the past, the fact that there was some late Oligocene (Arikareean) represented in the northern Sespe exposures made the discrepancy with the early Hemingfordian mammals seem less extreme. However, our recent work has precisely calibrated just how much of the Oligocene and Miocene is represented by these sections, and it turns out that there are major gaps (7 million years missing between the lower and upper Sespe in Ventura and Santa Barbara counties; 9 million years between the youngest Sespe in Ventura County and the oldest Sespe in Orange County).

In addition, these studies help calibrate the timespan of the Vaqueros Molluscan Stage. Long thought to be early Miocene and possibly latest Oligocene, it now appears that the Vaqueros molluscan fauna was very stable and long-lived, spanning the interval from 28-17 Ma—by far the longest molluscan stage in California. Unfortunately, this means that a biostratigraphic assignment of "Vaqueros stage" is no longer very diagnostic; it could represent any time in the 11 million years between 28 and 17 Ma. Studies are now underway to calibrate other "Vaqueros stage" strata in California, but it appears that this study gives the maximum age span of this stage. It is interesting to note that a similar stability marks the late Oligocene-early Miocene Arikareean land mammal "age", which spans the 10 million year interval from 19-29 Ma (Fig. 8)—by far the longest

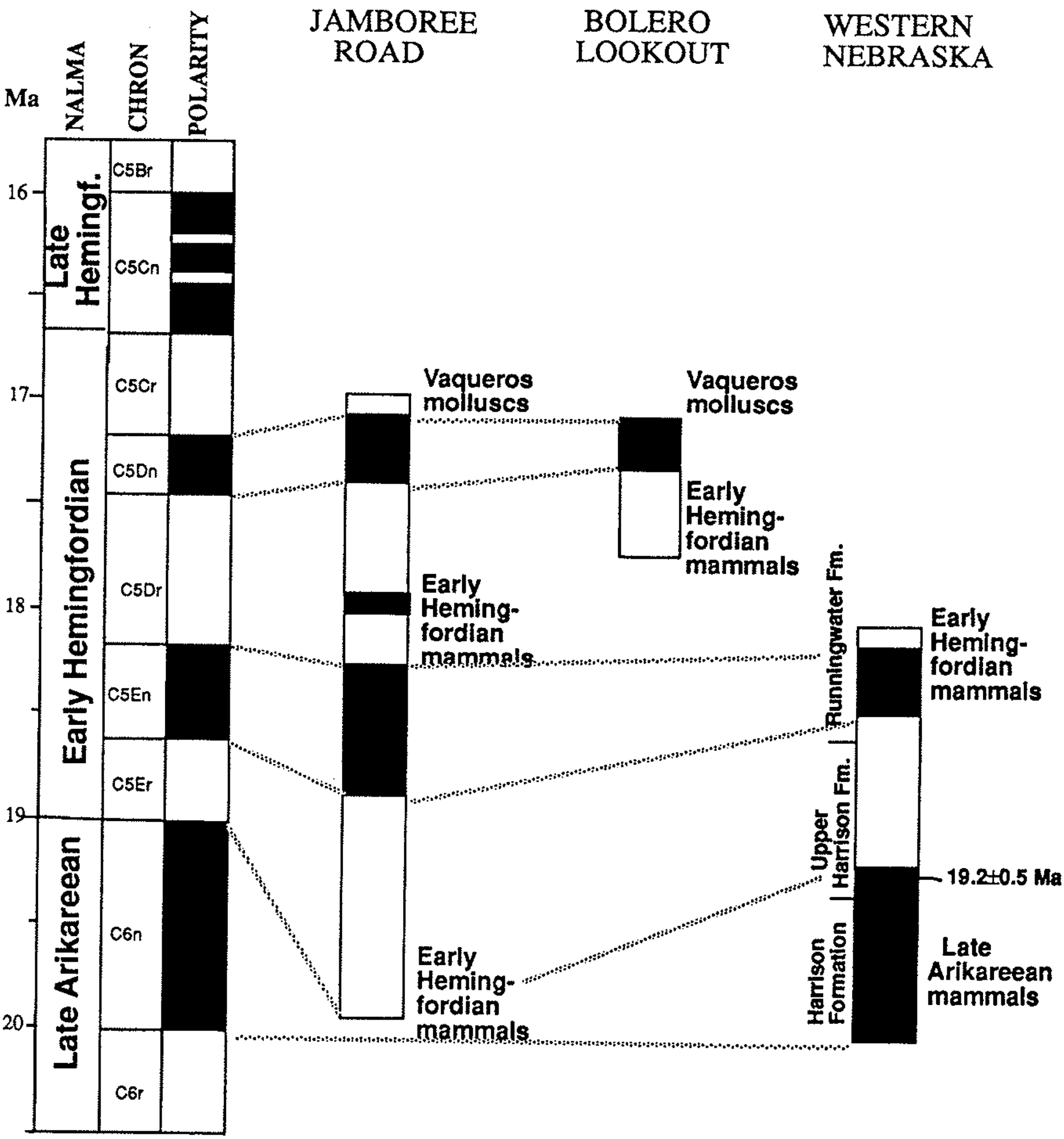

Figure 7. Correlation of the Sespe-Vaqueros sections at Jamboree Road and Bolero Lookout with the magnetostratigraphy of the sections in western Nebraska (after MacFadden and Hunt, 1998).

land mammal "age" of the Cenozoic.

Such a huge age discrepancy between the two major regions of Sespe outcrops raises a larger question: should the Orange County outcrops be referred to the Sespe in the first place? After all, they differ in age by 9 million years, with no strata which cover this time gap, and were formed in different depositional basins, probably by different drainages than formed the northern Sespe outcrops. However, age should not be a criterion for defining lithostratigraphic units (North American Stratigraphic Commission, 1983). Vedder et al. (1957), Schoellhamer et al. (1981) and other mappers are justified in calling the Orange County rocks "Sespe Formation," since they are lithologically indistinguishable from those found in the Ventura and Santa Barbara coun-

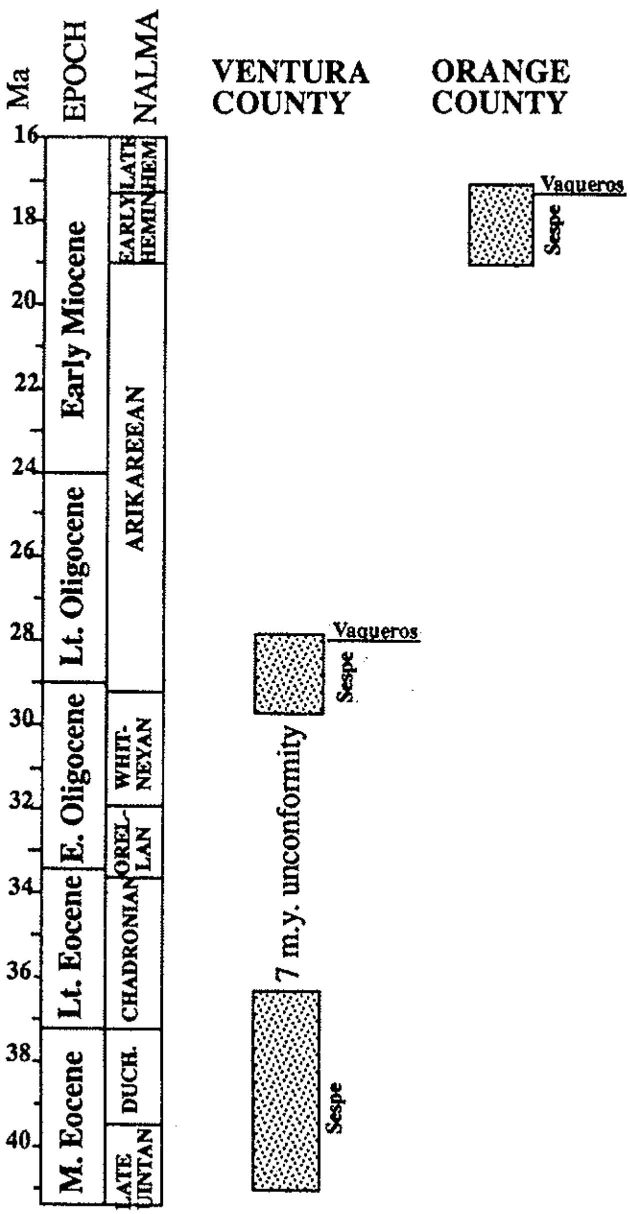

Figure 8. Comparison of the age of the Sespe-Vaqueros formations in Ventura County with that in Orange County. Time scale after Prothero et al. (1996).

ties. This dilemma further underscores the fact that lithostratigraphic units are independent of time. They can be time-transgressive, or composed of separate packages which are grossly different in age, as long as they are distinctive and consistently mappable. In fact, the same problem applies to the overlying Vaqueros Formation rocks—even though they have both the same lithology and the same fossils, the "Vaqueros stage" is so long that Vaqueros rocks can differ in age by 10 million years from one region to another.

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REFERENCES CITED

Addicott, W.O., 1972, Provincial middle and late Tertiary molluscan stages, Temblor Range, California, *in* Stinemeyer, E.H., ed., The Proceedings of the Pacific Coast Miocene Biostratigraphic Symposium: Pacific Section SEPM, pp. 1-22.

Belyea, R.R., 1984, Stratigraphy and depositional environments of the Sespe Formation, northern Peninsular Ranges, California [M.A. thesis]: San Diego, San Diego State University, 206 pp.

Belyea, R.R., and Minch, J.A., 1989, Stratigraphy and depositional environments of the Sespe Formation, northern Santa Ana Mountains, California: Pacific Section SEPM 62:281-300.

Fisher, R. A., 1953, Dispersion on a sphere: Proceedings of the Royal Society, v. A217, p. 295-305.

Hamlin, H., 1904, Water resources of the Salinas Valley, California. U.S. Geological Survey Water-Supply Paper 89:1-91.

Kirschvink, J. L., 1980, The least-squares line and plane and the analysis of paleomagnetic data: examples from Siberia and Morocco: Geophysical Journal of the Royal Astronomical Society, v. 62, p. 699-718.

Krishtalka, L., Stucky, R.K., West, R.M., McKenna, M.C., Black, C.C., Bown, T.M., Dawson, M.R., Golz, D.J., Lillegraven, J.A. and Turnbull, W.D., 1987, Eocene (Wasatchian through Duchesnean) chronology of North America, *in* Woodburne, M.O., ed., Cenozoic

Mammals of North America: Geochronology and Biostratigraphy: Berkeley, University of California Press, pp. 77-117.

Lander, E.B., 1994, Palentologic resource impact mitigation program final report: Santiago Canyon Landfill, southeast and southwest borrows, Orange County, California: Prepared for County of Orange Integrated Waste Management Department, 55 pp.

Loel, W., and Corey, W.H., 1932, The Vaqueros Formation, lower Miocene of California: University of California Publications in Geological Sciences, v. 22, p. 31-410.

Lucas, S.G., Whistler, D.P., and Wagner, H.M., 1997, Giant entelodont (Mammalia, Artiodactyla) from the early Miocene of southern California: Contributions in Science, Natural History Museum of Los Angeles County, v. 466, p. 1-9.

MacFadden, B.J., and Hunt, R.M., 1998, Magnetic polarity stratigraphy and correlation of the Arikaree Group, Arikareean (late Oligocene-early Miocene) of northwestern Nebraska: Geological Society of America Special Paper, v. 325, p. 143-165.

North American Stratigraphic Commission, 1983, North American Code of Stratigraphic Nomenclature: American Association of Petroleum Geologists Bulletin, v. 67, p. 841-875.

Opdyke, N. D., Lindsay, E. H., Johnson, N. M., and Downs, T., 1977, The paleomagnetism and magnetic polarity stratigraphy of the mammal-bearing section of Anza-Borrego State Park, California: Quaternary Research, v. 7, p. 316-329.

Pluhar, C., Kirschvink, J. L., and Adams, R. W., 1991, Magnetostratigraphy and clockwise rotation of the Plio-Pleistocene Mojave River Formation, central Mojave Desert, California: San Bernardino County Museum Association Quarterly, v. 38, n. 2, p. 31-42.

Prothero, D.R., 1996, Camelidae, *in* D.R. Prothero and R.J. Emry, eds., The Terrestrial Eocene-Oligocene Transition in North America: Cambridge, Cambridge Univ. Press, pp. 591-633.

Prothero, D.R., Howard, J., and Dozier, T.H.H., 1996, Stratigraphy and paleomagnetism of the upper middle Eocene to lower Miocene (Uintan-Arikareean) Sespe Formation, Ventura County, California, *in* Prothero, D.R., and Emry, R.J., eds., The Terrestrial Eocene-Oligocene Transition in North America: Cambridge, Cambridge Univ. Press, pp. 156-173.

Raschke, R.E., 1984, Early and middle Miocene vertebrates from the Santa Ana Mountains, California: Memoirs of the Natural History Foundation of Orange County 1:61-67.

Raschke, R.E., 1988, Final report on paleontological monitoring for the Bee Canyon access road, Irvine, California: RMW Paleo Associates. Prepared for the Orange County Integrated Waste Management Department.

Repenning, C.A., and Vedder, J.G., 1961, Continental vertebrates and their stratigraphic correlation with marine mollusks, eastern Caliente Range, California: U.S. Geological Survey Professional Paper, v. 424C, p. 235-239.

Savage, D.E., 1972, Nonmarine vertebrates and marine-nonmarine tie-ins, pp. 125-136, *in* Stinemeyer, E.H., ed., The Proceedings of the Pacific Coast Miocene Biostratigraphic Symposium: Pacific Section SEPM.

Schoellhamer, J.E., Vedder, J.G., Yerkes, R.F., and Kinney, D.M., 1981, Geology of the northern Santa Ana Mountains, California: U.S. Geological Survey Professional Paper, v. 420-D.

Stock, C., 1930, Oreodonts from the Sespe deposits of South Mountain, Ventura County, California: Carnegie Institute of Washington Publication 404:27-42.

Stock, C., 1948, Pushing back the history of land mammals in western North America: Geological Society of America Bulletin 59:327-332.

Tedford, R.H., Galusha, T., Skinner, M.F., Taylor, B.E., Fields, R.W., Macdonald, J.R., Rensberger, J.M., Webb, S.D., and Whistler, D.P., 1987, Faunal succession and biochronology of the Arikareean through Hemphillian interval (late Oligocene through earliest Pliocene Epochs) in North America, *in* Woodburne, M.O., ed., Cenozoic Mammals of North America, Geochronology and Biostratigraphy: Berkeley, University of California Press, pp. 153-210.

Vedder, J.G., Yerkes, R.F., and Schoellhamer, J.E., 1957, Geologic map of the San Joaquin Hills-

San Juan Capistrano area, Orange County, California: U.S. Geological Survey Oil and Gas Investigations Map OM-193.

Watts, W.L., 1897, Oil and gas yielding formations of Los Angeles, Ventura, and Santa Barbara Counties: California State Mining Bureau Bulletin 11:1-94.

Whistler, D. P., 1994, Appendix C, *in* Lander, E.B., Palentologic resource impact mitigation program final report: Santiago Canyon Landfill, southeast and southwest borrows, Orange County, California: Prepared for County of Orange Integrated Waste Management Department.

TABLE 1—Fisher statistics for normal and reversed directions in the Sespe-Vaqueros formations of Orange County.

Sample	D	I	k	α_{95}	n
Jamboree normal	351.9	49.2	11.4	13.4	12
Jamboree reversed	195.2	-55.3	13.9	9.9	17
Bolero normal	10.4	48.2	5.8	27.3	7
Bolero reversed	195.7	-45.0	18.7	13.1	8
Formational mean	358.5	49.2	8.6	12.1	44

TABLE 2—Site statistics

Sample	D	I	k	α_{95}	n
Bolero Lookout					
1	179.7	-44.7	4.4	180.0	2
2	230.4	-29.7	5.9	55.9	3
3	208.7	-41.3	—	—	1
4	174.9	-59.7	5.6	58.1	3
6	184.2	-35.5	5.6	150.5	3
7	203.2	-54.8	15.2	32.8	3
8	209.8	-45.0	4.6	-65.3	3
9	19.6	38.6	13.5	35.0	3
10	330.9	25.0	32.4	22.0	3
11	4.0	38.4	6.0	55.3	3
12	117.8	44.5	1.3	180.0	3
13	24.5	51.6	264.0	7.6	3
14	354.5	62.3	5.2	60.9	3
15	168.8	-34.8	14.8	33.2	3
16	360.0	24.4	7.5	48.6	3

TABLE 2. Site statistics (cont.)

Sample	D	I	k	α_{95}	n
Jamboree Road					
1	179.4	-37.7	9.4	42.7	3
2	189.9	-36.6	5.5	58.4	3
3	246.4	-62.8	5.7	145.8	2
4	354.3	12.4	1.0	180.0	3
5	223.3	-43.9	4.9	63.2	3
6	182.0	-38.6	4.4	67.8	3
7	188.2	-68.4	1.7	180.0	3
8	201.2	-54.9	4.7	64.9	3
9	218.8	-64.2	7.3	49.3	3
10	353.4	54.4	7.6	48.4	3
11	337.3	40.8	5.5	58.7	3
12	341.4	82.5	3.3	83.2	3
13	189.4	-69.5	2.0	139.4	3
14	182.6	-50.5	3.5	79.7	3
15	169.0	-29.0	5.5	58.5	3
16	322.6	53.2	4.6	65.7	3
17	335.9	39.4	2.1	126.7	3
18	255.6	-44.2	3.1	87.8	3
19	12.2	67.1	2.1	125.8	3
20	200.0	-78.1	16.6	31.3	3
21	162.9	-33.2	6.8	51.5	3
22	208.0	-60.1	6.2	54.4	3
23	161.8	-71.7	2.4	111.3	3
24	34.3	40.6	3.2	84.7	3
25	324.0	44.5	4.1	180.0	2
26	13.3	50.6	2.8	94.1	3
27	28.2	41.2	9.8	41.7	3
28	328.8	3.3	2.4	109.8	3
29	196.9	-46.2	4.2	69.6	3