Lucas et al., eds., 2008, Neogene Mammals. New Mexico Museum of Natural History and Science Bulletin 44.

MAGNETOSTRATIGRAPHY, BIOSTRATIGRAPHY, AND TECTONIC ROTATION OF THE MIOCENE CALIENTE FORMATION, VENTURA COUNTY, CALIFORNIA

DONALD R. PROTHERO[1,2], THOMAS S. KELLY[2], KRISTEN J. MCCARDEL[3] AND ERIN L. WILSON[4]

[1] Department of Geology, Occidental College, Los Angeles, CA 90041; [2] Research Associate, Vertebrate Paleontology Section,
Natural History Museum of Los Angeles County, 900 Exposition Blvd., Los Angeles, CA 90007;
[3] 1911B Casa Grande Dr., Austin, TX 78733; [4] 4331 Sierra Dr., Honolulu, HI 96816

Abstract—The Caliente Formation in the Cuyama Badlands of northern Ventura County, California, contains a sequence of nonmarine strata that span the late Hemingfordian, Barstovian, Clarendonian, and early Hemphillian land-mammal "ages" (18-8 Ma), and also K-Ar dated volcanics. Paleomagnetic analysis of over 3000 samples from three sections (Dry Canyon, Apache Canyon, Sequence Canyon) showed that the remanence is held largely in hematite with minor magnetite, and passes a reversal test for stability. These strata rest on a block within Transverse Range-San Andreas region that has been tectonically rotated since the early Miocene. The older strata (18 to 11 Ma) are rotated from 37° ± 19° (18 Ma) to 37° ± 13° (11 Ma) clockwise, but show no progressive rotational trends during this 7-million-year span. About 7° of rotation apparently took place between 8 and 11 Ma (an interval missing from the Caliente Formation due to an unconformity), because beds dated between 8-9 Ma are rotated 30 ± 20°. An additional rotation of 7° occurred between 8 and 4 Ma, because strata dated between 3-4 Ma are rotated about 23° ± 7° clockwise. Rotation to present orientation took place since 1.7 Ma. These patterns indicate that most of the rotation took place between 11 Ma and the present, with almost no rotation during the interval from 11-18 Ma.

The polarity patterns of the late Hemingfordian to Clarendonian section in Dry Canyon is correlated with Chrons C5Dr to C5r (18-11 Ma). Apache Canyon contains a thick early-late Clarendonian sequence correlated with Chrons C5An to C5r (12.5-11 Ma), and Sequence Canyon contains a late Clarendonian-early Hemphillian sequence correlated with Chrons C4r (8.1-8.4 Ma).

INTRODUCTION

The Transverse Ranges of southern California have been an area of great geological interest for many years. Originally they were studied in the context of their stratigraphic and paleontological resources, but as the structural implications for the evolution of the modern plate boundary configuration became evident, many geologists have studied their tectonics. Their east-west orientation is very different from other mountain ranges along the west coast, particularly the Peninsular and Coast Ranges of California, Washington, and Oregon.

One of the key stratigraphic units in the Transverse Ranges is the middle-upper Miocene Caliente Formation (Fig. 1). In the Cuyama Badlands, this formation yields a unique sequence of four superposed Miocene land mammal "ages" (late Hemingfordian through late Hemphillian) in thick, well-exposed sections of fine-grained rocks with several dated volcanic units. As pointed out by Repenning and Vedder (1961), "this record of superposed mammalian assemblages is equaled at few places in the world. By tracing fossiliferous beds, faunas representing three of these ages can be correlated with the assemblages of abundant marine mollusks in the same area." In some places, such as Dry Canyon, it is possible to walk through a sequence over 700 m in thickness spanning the late Hemingfordian, early and late Barstovian, early and late Clarendonian, and Hemphillian—a span of 11 million years (from 18 to 7 Ma). In this same section is a tuff K-Ar dated at 15.6 Ma (Evernden et al., 1964, corrected for new constants). This tuff was redated by ^{40}Ar/^{39}Ar methods at 13.4 ± 0.14 Ma (Swisher, 1992; Tedford et al., 2004). The Caliente Formation offers an unparalleled opportunity to provide a detailed magnetostratigraphy for nearly the entire Miocene, and fill in the gaps of other studies that cover only one or two land-mammal "ages."

A second interesting aspect of the region is the activity of tectonic blocks adjacent to the San Andreas transform fault. In the last 30 years numerous studies have shown that most of the tectonic blocks in the California Transverse Ranges have been rotated by as much as 90° clockwise since the early Miocene (Kamerling and Luyendyk, 1979, 1985; Luyendyk et al., 1980, 1985; Hornafius, 1985; Terres and Luyendyk, 1985; Hornafius et al., 1986; Luyendyk and Hornafius, 1987; Luyendyk, 1991). These rotations are apparently caused by the shearing of the fault blocks in the Transverse Ranges as the whole region has undergone right-lateral strike-slip. Most of the Miocene paleomagnetic data that suggested this rotation come from isolated basalts (Luyendyk et al., 1980, 1985), or from limited dolomite horizons within the Monterey Formation (Hornafius, 1985). Consequently, they present a rather discontinuous record of the rotation, scattered among many different fault blocks.

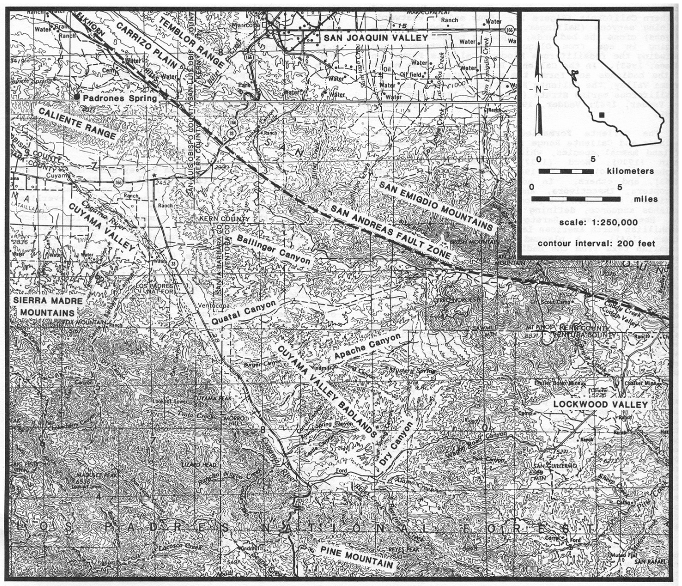

FIGURE 1. Index map showing location of the Caliente Formation in the Cuyama Badlands, and other significant geographic and geologic features (after Kelly and Lander, 1988).

The Cuyama Badlands are located on a triangular, fault-bounded block just southwest of the Big Bend in the San Andreas fault (Fig. 1). This region has been tectonically active since the middle Miocene, and it encompasses the transition from strike-slip to transpressional forces associated with the bend. The area is bounded by the San Andreas fault to the north, the Big Pine fault to the southeast, and several minor faults to the south and west, including the Ozena and Nacimiento faults. Thus we hypothesize that this basin has undergone rotation due to the right-lateral strike-slip motion of the San Andreas and associated faults, as described by Luyendyk et al. (1980). They propose that rotation of crustal blocks associated with Pacific-North American relative motion began around 18 Ma, when subduction of the Farallon plate beneath the North American plate ceased. Atwater (1989) and Crowell (1987) suggested that crustal extension and basin formation preceded rotation and strike-slip faulting by a few million years. As the zone of extension increased, fault-bounded blocks rotated, and sedimentation began in triangular basins forming between the rotating and nonrotating crust. Rotation of these crustal blocks began in the west and migrated east, as indicated by the progression of amounts of rotation as one moves westward across California from approximately 95° on more westerly blocks to about 35° in the Mojave desert region (Hornafius et al., 1986; Luyendyk, 1991). The model was revised by Luyendyk (1991) to allow for two episodes of rotation rather than a constant rotation rate. These two episodes are associated with: 1) transtension caused by Farallon plate subduction (before 20 Ma) and 2) transtension and transpression in the boundary zone between the Pacific and North American plates (after 18 Ma). In this paper, we are concerned with the second mode of rotation, in which there may have been multiple pulses of rotation, as evident from the compilation of magnetic directions of igneous rocks on nearby blocks for three intervals in the Miocene by Hornafius et al. (1986).

THE CALIENTE FORMATION

The Caliente Formation was discussed informally by numerous authors (English, 1916; Reed and Hollister, 1936; Eaton, 1939; Eaton et al., 1941), but it was formally described by Hill et al. (1959) and Carman (1964). James (1963) described the geology in greater detail, and summarized the smaller mammalian fossils recovered from the beds. More recent summaries of the mammalian biostratigraphy can be found in Woodburne (1975), Tedford et al. (1987, 2004), and Kelly and Lander (1988, 1992).

The Caliente Formation extends 60 km from the Caliente Range to Lockwood Valley. Maximum thickness of the unit increases to the west, from approximately 700 m in the badlands district at the east to about 1700 m on the northeastern flank of the Caliente Range at the far western end of the outcrop (Fig. 1). This thick sequence and lateral thickening are the results of deposition in a rapidly subsiding, fault-bounded graben during the middle Miocene. The Caliente Formation rests unconformably over Oligocene and early Miocene marine deposits of the Simmler Formation and the Soda Lake Shale and Painted Rock members of the Vaqueros Formation in the west, and upon granitic rocks of the Pattiway Ridge and nonmarine conglomerates and sandstones of the Oligocene Plush Ranch Formation in the southeast. It unconformably underlies the Plio-Pleistocene Quatal and Morales formations. Laterally, the nonmarine Caliente Formation interfingers westward with marine sandstones and shales in the adjacent Caliente Range containing abundant marine fossil assemblages (Repenning and Vedder, 1961; James, 1963; Woodburne, 1975; Tedford and Hunter, 1984).

According to James (1963), the Caliente Formation can be divided into three informal units: the lower, middle, and upper members. The lower member of the Caliente Formation is late Hemingfordian in age and consists of about 130 m of coarse sandstones and conglomerates, indicative of a braided river system. These calcite-cemented, argillaceous sandstones are massive or thickly bedded. The layers are easily distinguished by color, which varies from red and brown to gray, often grading from one color in the west to another in the east within beds of the same character.

The middle member of the Caliente Formation consists of about 330 m of thick-bedded sandstones and siltstones that are poorly sorted and calcareously cemented. They contain fossil mammals of the Barstovian to Clarendonian mammal "ages." Color grades from reddish-brown in the west (Ballinger and Quatal Canyons) to gray in the east (Dry Canyon). This section grades upward from coarse-to-medium sandstone into fine-grained sandstone and mudstone. It is interbedded with pinnacle-forming channel sands and gravel beds in Quatal, Apache, and Ballinger Canyons, indicating an increasingly lacustrine environment. Volcaniclastic layers and basalt flows are evident throughout the sequence, and several have been radiometrically dated. The upper member consists of about 70 m of mudstones and bentonitic claystones, and contains Hemphillian mammals. The entire sequence is overlain by the Lockwood Clay, which was deposited as a single lake bed and marks the boundary between the Caliente Formation and the overlying Quatal Formation (James, 1963; Woodburne, 1975).

The area also contains several volcanic units, including tuffs and bentonitic clays that are very helpful in both tephrostratigraphy and by yielding specific radiometric dates. A biotite tuff in the section has been K-Ar dated at 15.2 Ma (Evernden et al., 1964) and later corrected to 15.6 Ma due to recalibration of the K-Ar decay constants (Dalrymple, 1979). Swisher (1992) redated this tuff by $^{40}Ar/^{39}Ar$ methods at 13.4 ± 0.14 Ma. Basalts to the north have yielded corrected K-Ar dates of 14.6 and 16.5 Ma. These volcanic units erupted from a local source in the eastern Caliente Range.

METHODS

Three sections were chosen to sample the maximum thickness of the Caliente Formation, and to incorporate as many fossil localities into the section as possible (Figs. 1-2). These sections were taken in Dry Canyon (late Hemingfordian-Clarendonian), Apache Canyon (Clarendonian), and Sequence Canyon (Hemphillian). Pilot samples were collected in Dry Canyon during the summer field season of 1992, and more complete sampling was undertaken in Apache Canyon, Dry Canyon and Sequence Canyon in 1995 and 1996. Section was measured using a Jacob's staff, following published maps and aerial photographs of James (1963) and unpublished maps and sections by Kelly. Oriented samples were taken with simple hand tools, and hardened in the field with dilute sodium silicate solution if they were too friable. Ninety sites, spanning late Hemingfordian to early Hemphillian, were taken altogether. Although as many as 7 samples were collected at some sites, most consisted of 3-4 samples per site to allow statistical analysis. In the laboratory, the samples were cut into 2.5-cm cubes on a band saw with a tungsten-carbide band saw blade.

Sample magnetism was measured using a 2G cryogenic magnetometer at the California Institute of Technology. Samples were measured at NRM, then subjected to three alternating-field (AF) demagnetization steps (2.5, 5.0, and 10.0 mT) in order to remove any multi-domain components. Following the AF demagnetization, the samples were thermally demagnetized in multiple steps from 300°C to 600°C. This removes any remanence held in iron hydroxides such as goethite, and also allows determination of blocking temperature of the magnetic minerals. Any remanence above the Curie point of magnetite (580°C) must be held in hematite.

About 0.1 g of powdered samples of a number of representative lithologies were placed in epindorph tubes and subjected to increased isothermal remanent magnetization (IRM) to determine their IRM saturation behavior. These same samples were also AF demagnetized twice, once after having acquired an IRM produced in a 100 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 (Johnson et al., 1975; Pluhar et al., 1991).

Ellis et al. (1993) studied the uppermost (late Hemphillian) por-

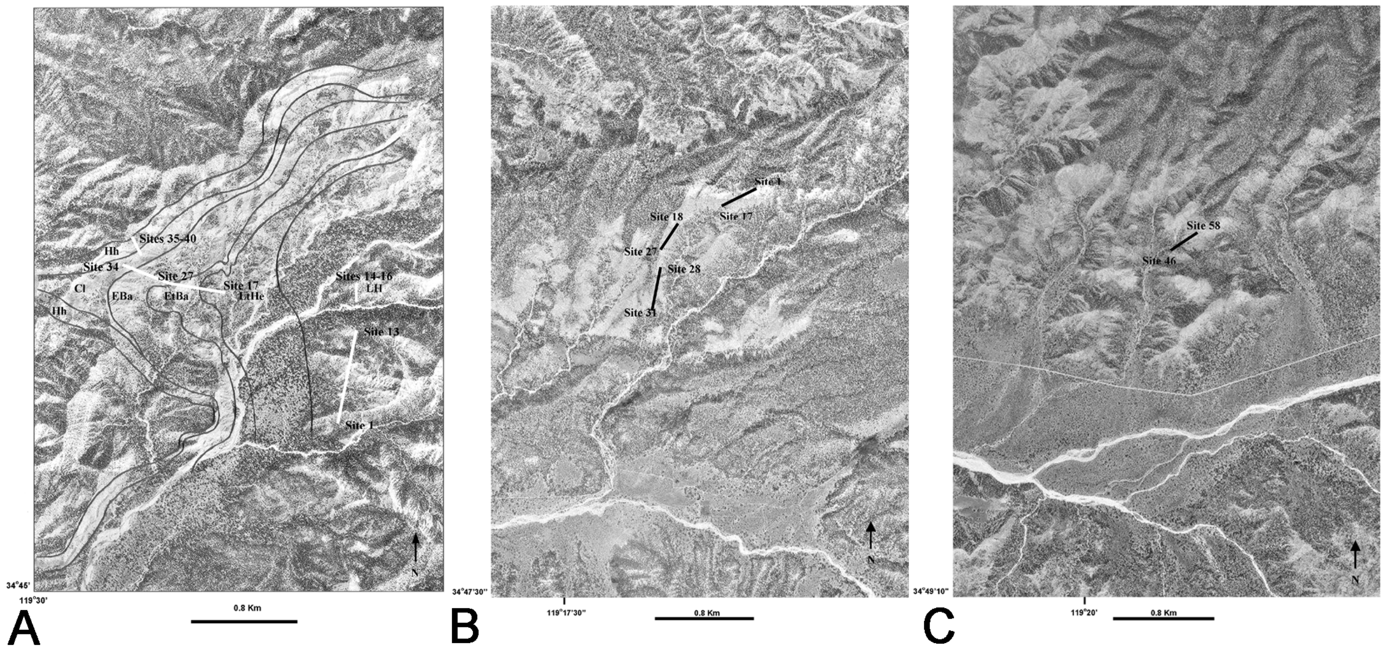

FIGURE 2. **A**, Aerial photograph of Dry Canyon area showing measured sections and geographic positions of biostratigraphic units based on locality data, lateral tracing of marker beds, and on correlated magnetostratigraphic polarity units (base map U.S.G.S. 1:24,000). Abbreviations are as follows (chronology based on North American Land Mammal Ages): LHe, late Hemingfordian strata yielding the Hidden Treasure Spring l.f.; LtHe, latest Hemingfordian strata yielding the West Dry Canyon l.f.; EtBa, earliest Barstovian strata yielding the lower Dome Spring l.f.; EBa, early Barstovian strata yielding the Upper Dome Spring l.f.; Cl, Clarendonian strata containing early and late Clarendonian localities; and He, Hemphillian strata. Bold white lines show traverse of magnetostratigraphic section, with location of key site numbers shown. **B**, Aerial photograph of Nettle Spring Canyon and Apache Canyon, showing measured section (base map U.S.G.S. 1:24,000). Conventions as in Figure 2A. **C**, Aerial photograph of Sequence Canyon area showing measured section (base map U.S.G.S. 1:24,000). Line of paleomagnetic section shown, with lowest and highest site numbers.

tion of the Caliente Formation and overlying Plio-Pleistocene deposits in Quatal and Ballinger Canyons. Their study showed an average rotation of 23°± 7° clockwise and stable normal directions for their three upper Caliente Formation sites. Because this previous study indicates that overlying sediments in the Cuyama Basin are rotated a minimum of 16° (based upon the mean minus the error limit), we must assume that the older Caliente sediments are also rotated. When examining the paleomagnetic data for evidence of rotation, we rejected any site which did not deviate at least 16° from north before tilt correction as overprinted with the modern normal field, and only the sites with rotations greater than 16° (78% of the sites) were used in the reversal test. In addition, sites which did not show a stable polarity for at least 3 consecutive demagnetization steps were eliminated from the analysis.

After the characteristic component of magnetization was isolated, the mean directions for each sample were summarized using the least-squares method of Kirschvink (1980), and then analyzed using Fisher (1953) statistics. Sites were ranked according to the scheme of Opdyke et al. (1977).

Reflected light mineralogy was also determined using a petrographic microscope with oil immersion lens and polished thin sections in order to determine magnetic mineralogy.

RESULTS

Magnetic Analysis

Magnetic results for this study are given in Table 1. Representative orthogonal demagnetization plots are shown in Figure 3. Normal overprints were usually removed by the 200°C step, probably due to dehydration of iron hydroxides such as goethite and destruction of multi-domain components by AF demagnetization, although a few samples never lost their overprints and were rejected from the analysis. Stable components were most often visible between thermal steps of 300°-500°C, but at 600°C, the sample direction often became wildly unstable. At this temperature, all of the remanence held in magnetite, and some of the remanence held in hematite, has been removed, and the samples were very weakly magnetized and easily affected by viscous magnetic components (despite our best efforts to keep the samples in magnetically shielded spaces while cooling).

The IRM acquisition experiments (Fig. 4) indicated that the samples contained significant amounts of hematite, as they continued to acquire IRM rather than saturating at 300 mT. The Lowrie-Fuller tests indicated that the grains in the sample were single-domain or pseudo-single-domain, since the ARM was more resistant to AF demagnetization than the IRM.

Thin-section analysis showed that the magnetism is held in a variety of minerals and grain forms. Iron oxides were found in the form of large, rounded detrital grains, as rims on other grains, and as the microcrystalline result of the alteration of iron-rich micas. Study of a number of grains in each thin section confirmed that the majority of magnetic grains were either hematite or ilmenite, or mixtures of the two, although a few grains were tentatively identified as magnetite. The abundance of microcrystalline hematite and iron oxide rims explains the common normal overprinting in these samples, as these are the results of breakdown of minerals after deposition and groundwater processes. The reversal test for stability (Table 2, Fig. 5) showed that the mean direction of cleaned directions of reversed sites was antipodal to the mean of normal sites, indicating that both were primary directions.

Magnetic Stratigraphy

The magnetic stratigraphy of the sections at Dry Canyon, Apache Canyon, and Sequence Canyon is shown in Figures 6-8. According to the scheme of Opdyke et al. (1977), 46 sites were Class I (significantly distinguished from random at the 95% confidence level), 12 were considered Class II (only two samples available), and 30 were in Class III (two or more vectors gave a clear indication of polarity, but one direction was divergent). In the 1000 m of strata at Dry Canyon (Fig. 6), the basal two

TABLE 1. Paleomagnetic data from the Caliente Formation. N = number of vectors (samples); DEC = declination (in degrees); INC = inclination (in degrees); K = precision parameter; α_{95} = 95% ellipse of confidence around the mean. Site numbers as in Figures 6-8, except that the 1993 pilot samples are labeled "93-xx".

SITE	N	DEC	INC	K	α_{95}
<u>Dry Canyon</u>					
1	3	20.3	17.2	111.7	11.7
2	2	258.6	-31.3	4.3	180.0
3	3	98.7	57.4	1.1	180.0
4	3	74.9	48.4	1.3	180.0
5	2	323.5	-6.6	7.0	116.8
6	3	240.6	-47.7	9.0	43.8
7	1	182.0	-18.3	—	—
8	2	173.6	-7.7	3.2	180.0
10	3	219.4	28.6	2.2	119.3
11	3	17.3	37.8	2.1	131.8
12	3	357.1	42.0	5.8	56.9
13	3	345.7	-17.3	8.7	44.5
14	3	356.4	32.4	4.0	72.8
15	3	22.4	-19.1	5.2	60.5
16	3	19.6	46.9	14.2	34.0
17	3	15.7	53.2	5.4	59.5
18	3	22.3	13.2	32.6	21.9
19	3	237.1	55.7	1.8	169.3
20	3	354.8	59.4	64.2	15.5
21	3	231.0	-46.1	26.6	24.4
22	2	239.4	-12.0	36.4	42.7
23	3	239.9	0.5	1.7	180.0
24	3	218.5	-26.8	5.9	55.9
25	3	250.6	-30.4	2.2	121.5
26	3	269.3	-31.2	5.4	59.1
27	3	249.9	-15.7	1.9	147.1
28	3	189.3	-45.0	4.4	67.9
30	3	197.7	-44.7	131.7	10.8
31	3	342.6	30.4	127.1	11.0
32	3	345.1	-14.8	2.6	100.6
33	3	317.1	41.8	2.5	106.8
34	3	348.9	50.2	65.1	15.4
37	3	340.5	61.6	6.7	51.9
39	3	342.8	47.8	12.3	36.8
41	3	165.9	-35.1	44.4	18.7
43	3	171.4	-39.8	248.8	7.8
44	2	46.5	39.6	19.9	59.3
45	2	25.8	61.9	4.2	180.0
93-1	6	39.6	37.6	7.0	37.3
93-2	4	266.1	-27.8	4.8	63.8
93-3	7	182.7	-14.3	50.2	8.6
93-4	7	206.1	-33.9	16.7	15.2
93-5	3	240.9	-41.6	9.4	42.6

TABLE 1 continued

93-6	8	218.4	-37.7	38.5	9.0
93-7	7	63.4	55.9	55.9	16.6
93-9	5	34.4	2.8	1.5	180.0
93-10	6	34.9	49.4	9.0	43.8
Normal mean	15	33.0	27.3	8.6	13.4
Reversed mean	21	220.3	-35.1	10.4	10.4
Apache Canyon					
1	3	238.1	-61.7	24.0	25.8
3	3	26.8	43.4	5.4	59.3
4	3	8.1	16.7	86.6	13.3
5	2	139.1	-3.1	4.7	180.0
6	3	198.2	-13.2	1.3	180.0
7	3	220.8	0.2	1.1	180.0
8	3	14.8	15.5	575.9	5.1
11	3	356.8	32.2	9..0	43.7
12	3	257.1	-42.7	2.0	140.7
13	3	202.4	-21.8	1.9	148.5
14	3	186.2	-36.7	63.3	15.6
15	3	170.9	18.9	4.7	64.9
16	3	174.3	-43.3	13.6	34.9
17	3	235.0	-4.9	19.6	28.6
18	3	228.7	30.9	1.2	180.0
19	3	345.2	43.1	9.3	43.0
20	2	353.7	44.8	9.5	93.0
21	3	143.8	-0.7	1.8	164.9
22	3	192.8	12.5	2.2	123.5
23	3	202.5	50.7	1.6	180.0
24	3	177.5	-42.7	42.7	19.1
25	3	249.2	-6.3	1.3	180.0
26	3	188.8	-42..9	106.5	12.0
27	3	200.5	19.5	1.5	180.0
28	3	172.5	-20.4	4.4	67.6
29	3	190.6	-5.5	8.4	45.5
30	3	212.5	-51.7	4.3	69.0
31	3	230.1	-36.4	2.7	97.0
32	3	181.1	64.3	183.8	9.1
Normal mean	6	4.7	33.4	19.9	15.4
Reversed mean	23	198.7	-13.0	3.7	18.4
Sequence Canyon					
46	3	20.9	-57.4	1.0	180.0
47	3	253.1	26.5	3.4	80.6
48	3	218.4	33.8	5.9	56.1

TABLE 1 continued

49	3	209.0	-23.6	2.3	114.9
50	3	223.6	-2.0	1.4	180.0
51	3	233.9	58.0	7.0	50.5
52	3	141.4	-63.0	2.0	136.6
54	2	238.5	66.3	195.7	17.9
55	2	175.8	0.7	3.6	180.0
56	3	169.9	-6.9	2.5	105.1
57	3	123.8	-66.7	10.2	40.8
58	3	255.6	78.8	96.1	12.6
Reversed mean	12	205.5	5.6	1.7	49.8

sites (latest Hemingfordian, University of California Museum of Paleontology [UCMP} locality V-5674) were of normal polarity, but the next 180 m of section was of reversed polarity. This was followed by a 400 m of normal polarity, which ends with more late Hemingfordian mammal fossils. Above this is a 170-m-thick reversed magnetozone with early Barstovian mammals (including UCMP localities V-6414, 5667, and 5668), followed by a 160-m-thick normal magnetozone containing late Barstovian and early Clarendonian mammals. No fossil mammals are known above this level in Dry Canyon. The upper part of the Dry Canyon section includes a 70-m-thick reversed magnetozone, then the remaining strata below the Lockwood Clay (as well as those above it) are of normal polarity. The Lockwood Clay itself could not be sampled, because it was too crumbly for analysis.

The 350 m of Caliente Formation at Apache Canyon (Fig. 7) showed a much simpler magnetic pattern. The basal site was reversed, followed by a 30-m-thick normal magnetozone, and a 50-m-thick reversed magnetozone containing early Clarendonian mammals (UCMP V-5907). The next 60 m were of normal polarity, but the remaining 200 m of the section (containing both early and late Clarendonian mammals in apparently conformable succession) was of reversed polarity.

The 200 m of late Clarendonian to Hemphillian strata in Sequence Canyon (Fig. 8) was entirely of reversed polarity.

DISCUSSION

Biostratigraphy

Eight local faunas (l.f.) that span four North American land-mammal "ages" (Hemingfordian, Barstovian, Clarendonian, and Hemphillian), are currently recognized from the Caliente Formation of the Cuyama Badlands (James, 1963; Kelly and Lander, 1988; Kelly, 1992). These are the Hidden Treasure Spring, West Dry Canyon, Lower Dome Spring, Upper Dome Spring, Doe Spring, Mathews Ranch, Nettle Spring, and Sequence Canyon local faunas. Revised taxa lists of these faunas are presented in Appendix 1.

Only a small number of taxa comprise the Hidden Treasure Spring l.f., most of which are not useful for biostratigraphic correlation (Appendix 1). The horse *Parapliohippus carrizoensis* has been recorded in a number of late Hemingfordian faunas from California and Nevada (Kelly, 1995). Because of its presence in the Hidden Treasure Spring l.f., most investigators have regarded the fauna as late Hemingfordian in age (James, 1963; Tedford et al., 1987, 2004; Kelly and Lander, 1988, 1992; Kelly, 1995).

The biostratigraphy, magnetostratigraphy, and radiometric dating of the late Hemingfordian to late Barstovian Barstow Formation of the Mojave Desert have been extensively investigated to characterize the Barstovian land mammal "age" and define the Barstovian-Hemingfordian boundary (MacFadden et al., 1990; Woodbume et al., 1990; Woodbume and Swisher, 1995; Woodbume, 1996). Based on magnetostratigraphy, the stratigraphic interval containing the Hidden Treasure Spring l.f. correlates with the lower part of the Owl Conglomerate Member of the Barstow Formation, which has not yielded a fauna. However, the upper part of the Owl Conglomerate has yielded the Red Division Fauna, dated at about 16.5 Ma, which also contains *Parapliohippus carrizoensis*. Tedford et al. (1987, 2004) regard the Red Division Fauna as equivalent to the late Hemingfordian Sheep Creek Fauna of northern Great Plains. A late Hemingfordian age for the Hidden Treasure Spring l.f. is also supported by the presence of *Acritohippus* cf. *tertius*, a taxon that is very similar in dental morphology to *Acritohippus tertius* of the Sheep Creek Fauna. Based on all these considerations, we correlate the paleomagnetic data from the lower part of Dry Canyon containing the Hidden Treasure Spring l.f. with magnetic Chrons C5Dn and C5Cr, or about 17.2 Ma (Figs. 9, 10).

The latest Hemingfordian West Dry Canyon l.f. is characterized by the first local appearances of *Acritohippus quinni*, *Brachycrus buwaldi, Miolabis fricki*, and *Bouromeryx* cf. *B. americanus* and the last local occurrence of *Parapliohippus carrizonensis*. The association of *P. carrizonensis* and *B. buwaldi* occurs elsewhere only in the late Hemingfordian portion of Punchbowl Formation of Cajon Valley, California, about 155 m above the base of Unit 3 (Lander, 1985; Kelly and Lander, 1988). Following the magnetostratigraphic correlations discussed above, the West Dry Canyon l.f. occurs within the upper part of Chron C5Cn, dated at about 16.3 Ma. This would make the West Dry Canyon l.f. equivalent to the latest Hemingfordian Rak Division Fauna of the Barstow Formation, which also occurs within Chron C5Cn and is dated from about 15.9 to 16.3 Ma (MacFadden et al., 1990; Woodbume et al., 1990; Woodbume, 1996).

The earliest Barstovian Lower Dome Spring l.f. is characterized by the first local appearance of "*Cynorca" occidentale*, the last local occurrence of *Brachycrus buwaldi* and the restricted local occurrences of *Cuyamacamelus jamesi* and *Rakomeryx sinclairi*. The Lower Dome Spring l.f. appears to be a correlative of the Green Hills Fauna of the Barstow Formation based on the shared occurrences of *"Cynorca" occidentale* and *Brachycrus buwaldi*, and the restricted occurrence of *Rakomeryx sinclairi*. Based on correlations with the magnetostratigraphy of the Barstow Formation, the Lower Dome Spring l.f. occurs within the lower part of Chron C5Br, whereas the Green Hills Fauna occurs within all of Chron C5Br and the lower part of Chron C5Bn, dated from about 15.9 to 15.2 Ma (MacFadden et al., 1990; Woodbume et al., 1990; Woodbume, 1996).

The early Barstovian Upper Dome Spring l.f. is characterized by the first local appearances of *Petauristodon uphami, Perognathus furlongi*, and *Lanthanotherium sawini*, the last local occurrences of "*Cynorca"*

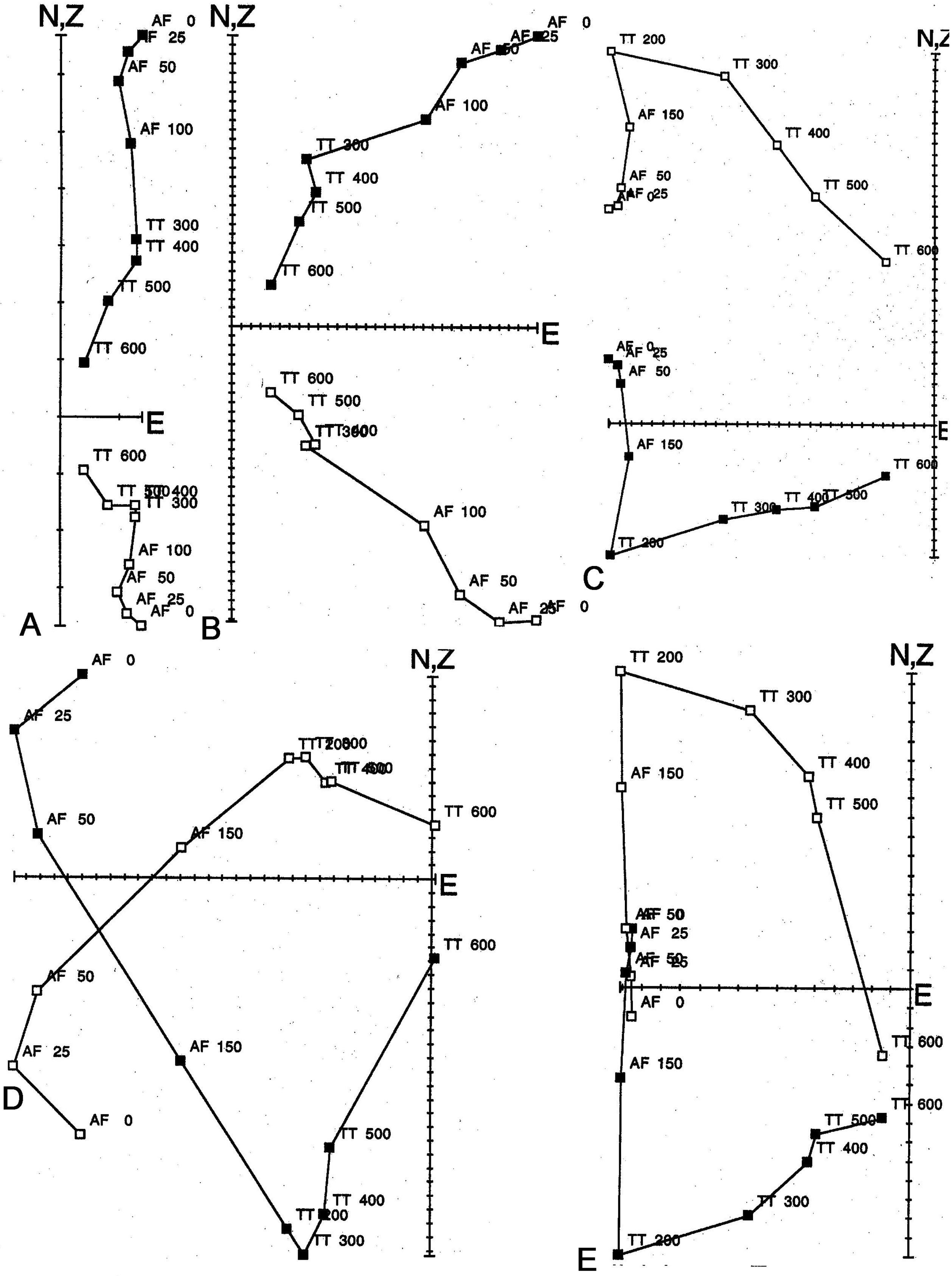

FIGURE 3. Orthogonal demagnetization ("Zijderveld") plots of representative samples. Solid squares indicate declination (horizontal component); open squares indicate inclination (vertical component). First step is NRM, followed by AF steps of 25, 50, and 100 Gauss, then thermal steps from 300° to 600°C. Each division equals 10^{-5} emu. Plots A and B show typical normal samples with clockwise rotation. Plots C-E show reversed samples (also with a clockwise rotation) with normal overprints that were removed by 300°C.

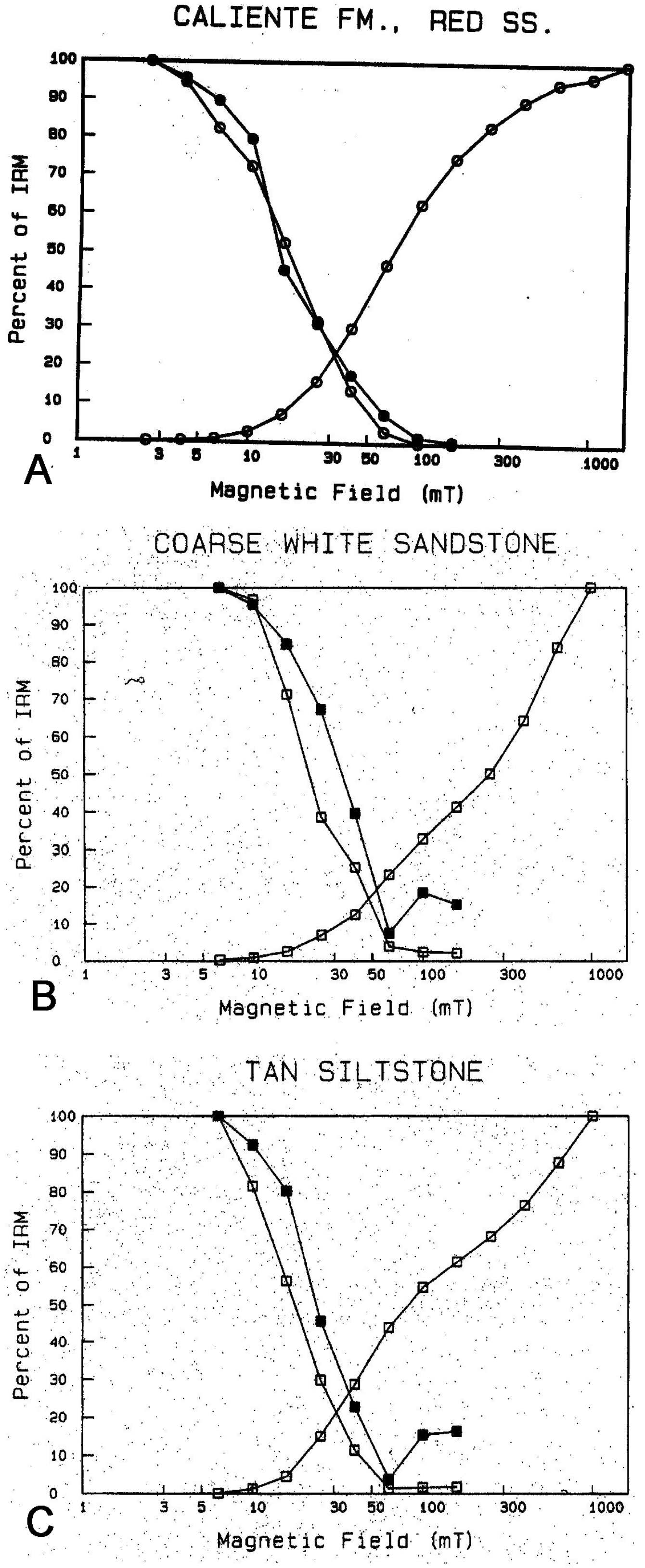

FIGURE 4. IRM acquisition (ascending curve on right) and Lowrie-Fuller test (two descending curves on left) of a representative powdered sample from the Caliente Formation. Open squares = IRM; solid squares = ARM. In all samples, the IRM fails to saturate, indicating that hematite is a primary carrier of the remanence. The ARM is more resistant to AF demagnetization than the IRM, showing that the remanence is held largely in single-domain or pseudo-single-domain grains.

TABLE 2. Means of sites in the same magnetic chron. Abbreviations as in Table 1.

CHRON	N	DEC	INC	K	α_{95}
C4Ar (4-5 Ma)	8	210.0	-54.0	8.6	20.0
C5r (11-12 Ma)	10	37.8	44.8	13.7	14.5
C5An (12-13 Ma)	10	38.3	43.2	12.8	13.2
C5Br (15.3-16.3 Ma)	31	218.7	-35.5	13.5	7.3
C5Cn (16.3-17.0 Ma)	8	34.7	32.5	31.9	10.0
C5Cr (17.0-17.6 Ma)	10	206.6	-31.6	5.3	23.1
C5Dn (17.7 Ma)	7	38.1	32.6	7.8	23.1

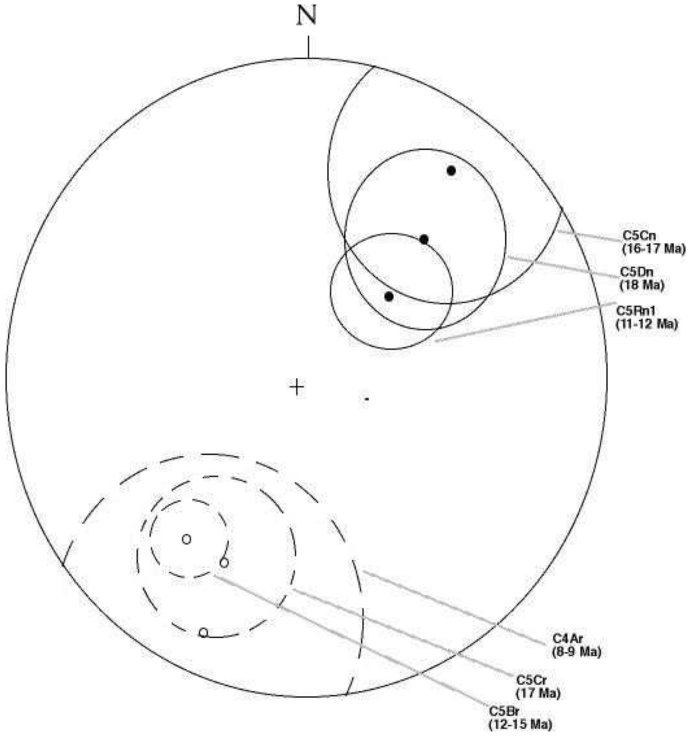

FIGURE 5. Stereonet of means of normal and reversed sites. Solid circles and lines indicate means and circles of confidence of normal sites (lower hemisphere projections) for each of the magnetic chrons in all three sections (see Table 2). Open circles and dashed lines indicate mean of reversed samples (upper hemisphere projection) for the reversed magnetic chrons. The directions are antipodal, showing that the overprinting has been largely removed and the directions are primary. They also show a clockwise tectonic rotation of about 35-40°.

occidentale, Miolabis fricki and *Bouromeryx* cf. *B. americanus* and the restricted local occurrences of *Proheteromys maximus, Tomarctus hippophaga*, *Archaeohippus mourningi, "Merychippus" brevidontus, Hesperocamelus* cf. *alexandrae*, and *Paramiolabis taylori*. The Upper Dome Spring l.f. appears to correlate with the Second Division Fauna of the Barstow Formation based on the shared restricted occurrence of *A. mourningi* and the notable absence of *Brachycrus* and *Rakomeryx* in both faunas. *Archaeohippus mourningi* is restricted in the Barstow Formation from the Skyline Tuff to 10 m above the Skyline Tuff, an interval that Woodburne (1996) correlates with the upper part of Chron C5Bn. In the Caliente Formation, it appears that *A. mourningi* is restricted in Dry Canyon from the upper part of Chron C5Br through Chron C5Bn. Woodbume's (1996) interpretation of the composite magnetic polarity zonation at Barstow places the Second Division Fauna within most of Chron C5Bn. Based on magnetostratigraphy, the Upper Dome Spring l.f. correlates only with part with the Second Divison Fauna.

The late Barstovian Doe Spring l.f. is characterized by the first local appearances of *Gomphotherium* and *Paracosoryx* cf. *furlongi* (=

Merycodus cf. *cerroensis* of James, 1963) and the last local occurrences of *Petauristodon uphami* and *Acritohippus quinni*. The Doe Spring l.f. appears to be a correlative of the Barstow Fauna of the Barstow Formation because both faunas record the first local appearances of *Gomphotherium*. The section in Quatal Canyon that contains the Doe Spring l.f. was not paleomagnetically sampled because of difficulties arising from complex local faulting and slumping in this part of the section.

Savage (1955) defined two formal biostratigraphic units for the Clarendonian of California: 1) the Cerrotejonian Stage, based on the fauna and strata of the South Tejon Hills of the southern San Joaquin Valley; and 2) the Montediablan Stage, based on the fauna and strata at Black Hawk Ranch near Mount Diablo. Savage (1955) and most subsequent investigators have equated the "Cerrotejonian" with the early Clarendonian and the "Montediablan" with the late Clarendonian. Tedford et al. (1987) and Woodburne and Swisher (1995) defined the beginning of the Clarendonian by the first appearance of *Barbourofelis* in North America at about 11.5 Ma. On the other hand, Whistler and Burbank (1992) redefined the Barstovian-Clarendonian boundary in California based on their extensive study of the biostratigraphy, magnetostratigraphy, and radiometric dating of the Dove Spring Formation at Redrock Canyon in the Mojave Desert. They regard their *Cupidinimus avawatzensis/ Paracosoryx furlongi* Assemblage Zone of the Dove Spring Formation as early Clarendonian, which would place the Barstovian-Clarendonian boundary at about 12.5 Ma. Recently, Tedford et al. (2004) have revised their concept of the Barstovian-Clarendonian boundary to coincide the first appearance of *Pseudoceras* at 12.5 Ma.

The Clarendonian of the Cuyama Badlands is represented by the Mathews Ranch and Nettle Spring local faunas, which have generally been assigned to the early Clarendonian ("Cerrotejonian Stage") and late Clarendonian ("Montediablan Stage"), respectively (James, 1963; Tedford et al., 1987, 2004; Kelly and Lander, 1992). Although at least 13 species are common to both faunas, the Mathews Ranch l.f. contains eight species not recorded in the Nettle Spring l.f., while the Nettle Spring l.f. contains six species not recorded in the Mathews Ranch l.f. (Appendix 1). The Mathews Ranch l.f. contains *Borophagus littoralis, Hipparion tehonense*, and "*Pliohippus*" *tehonensis*, three of Savage's (1955) original index fossils for the "Cerrotejonian." The Nettle Spring l.f. contains *Cormohipparion occidentale* s.l. (= *Hipparion* cf. *H. mohavense*), one of Savage's (1955) original index fossils of the "Montediablan," but notably lacks certain other "Montediablan" index taxa such as *Hipparion forcei* and "*Dinohippus*" *leardi*. James (1963) and Kelly and Lander (1992) regarded the Mathews Ranch l.f. as early Clarendonian and the Nettle Spring l.f. as late Clarendonian primarily because *C. occidentale* s.l. was recorded in the Nettle Spring l.f. but lacking in the Mathews Ranch l.f., and *H. tehonense* and "*P.*" *tehonensis* were also lacking in the Nettle Spring l.f. However, recent biostratigraphic and magnetostratigraphic data from Redrock Canyon, Tejon Hills, and Black Hawk Ranch, along with the data presented here, provides the following conclusions regarding the geochronologic ranges of these index fossils (Whistler and Burbank, 1992; Wilson and Prothero, 1997; Prothero and Tedford, 2000): (1) *Borophagus littoralis* (= "*Osteoborus" diabloensis*) is known from Chron C5An through about the middle of Chron C4Ar, or about 12.3 to 9.3 Ma.; (2) *H. tehonense* and "*P.*" *tehonensis* are known from about the middle of Chron C5An through Chron C5r4 or about 12.3 to 10.5 Ma.; (3) *C. occidentale* s.l. is known from Chron C5An to about the middle of Chron C5Ar, or about 12.5 to 9.3 Ma; (4) *H. forcei* is known from Chron C5n to about the middle of Chron C5Ar, or about 10.9 to 9.3 Ma; and (5) "*D.*" *leardi* is known from about the middle of Chron C5r through the middle of Chron C5Ar, or about 11.5 to 9.3 Ma. The revised stratigraphic ranges of these taxa suggest that only *H. forcei* and "*D.*" *leardi* remain valid index fossils of the "Montediablan," which would then begin at about the middle of Chron C5r or about 11.5 Ma.

Barbourofelis, a taxon whose immigration to North America has been used to define the beginning of the Clarendonian (Tedford et al., 1987; Woodbume and Swisher, 1995), is now known to first appear in California in Chron C5n at about 10.7 Ma, whereas east of the Rocky Mountains it is reported to first appear at about 11.5 Ma. If the first appearance of *Barbourofelis* in North America is used to define the beginning of the Clarendonian, then the Clarendonian in California would begin at about the middle of Chron C5r at about 11.5 Ma, and would include only the Nettle Spring l.f. of the Cuyama Badlands. The Mathews Ranch l.f. and South Tejon Hills l.f. would then be reassigned to the latest Barstovian or Ba3 of Woodburne and Swisher (1995). However, Whistler and Burbank (1992) have provided convincing biostratigraphic evidence that the Clarendonian of California should be extended down through Chron C5An, which places the Barstovian-Clarendonian boundary at about 12.5 Ma. (This conclusion is now followed by Tedford et al., 2004). Following Whistler and Burbank (1992), the Mathews Ranch l.f., which occurs from Chron C5An through the lower half of Chron C5r, and the Nettle Spring l.f., which occurs within the upper half of Chron C5r, are Clarendonian in age. Whistler and Burbank (1992) placed the beginning of the late Clarendonian or "Montediablan" at the beginning of Chron C5n or at about 10.9 Ma. Whistler and Burbank (1992) noted that a portion of Chron C5r is missing from the section at Redrock Canyon, apparently due to an unconformity that may represent as much as 0.7 m.y., which resulted in a lack of biostratigraphic data within this interval. However, Chron C5r appears to be well represented in the sections from the Cuyama Badlands and Tejon Hills. If the Nettle Spring l.f. is regarded as late Clarendonian, then the beginning of the late Clarendonian in California would be extended slightly downward to about the middle of Chron C5r or about 11.5 Ma.

Based on the biostratigraphic data from Redrock Canyon, Tejon Hills, and Black Hawk Ranch (Whistler and Burbank, 1992; Wilson and Prothero, 1997; Prothero and Tedford, 2000), along with that for the Cuyama Badlands presented here, a revised characterization for the Clarendonian of California can be made. The early Clarendonian or "Cerrotejonian" of California occurs from Chron C5An up to the middle of Chron C5r (about 12.5 to 11.5 Ma) and is characterized by the first local appearances of *Scapanus schultzi, Alluvisorex chasse, Petauristodon mathewsi, Ammospermophilus fossilis, Protospermophilus quatalensis, Cupidinimus avawatzensis, Borophagus littoralis, Martinogale, Ustatochoerus californicus, Cormohipparion occidentale* s.l., *Hipparion tehonense*, "*Pliohippus*" *tehonensis*, and *Heteropliohippus hulberti*. The late Clarendonian or "Montediablan" of California occurs from the middle of Chron C5r through Chron C4Ar (about 11.5 to 9.0 Ma) and is characterized by the first local appearances of *Lanthanotherium dehmi, Cupidinimus cuyamensis, Pliosaccomys wilsoni, Hypolagus tedfordi, Barbourofelis, Actiocyon leardi, Epicyon haydeni* (= "*Epicyon aphobus*" of Whistler and Burbank 1992), *Hipparion forcei*, and "*Dinohippus*" *leardi*. The Clarendonian of California is also characterized by the last occurrences of the following taxa that are known as well from late Barstovian or older assemblages: *Limnoecus tricuspis, Lanthanotherium sawini, Perognathus minutus, Perognathus furlongi, Cupidinimus tertius, Copemys russelli, Copemys dentalis, Pliohippus tantalus, Megahippus matthewsi*, and *Paracosoryx furlongi*.

The Hemphillian Sequence Canyon l.f. is represented by two specimens (UCMP 50057 and 156068) consisting of horse upper cheek teeth. James (1963) and Kelly and Lander (1992) referred these specimens to "*Dinohippus*" cf. *D. interpolatus*, a species that first appears in North America during the Hemphillian at about 7.5 Ma (Kelly, 1998). Reexamination of these teeth indicates that they differ from those of "*D.*" *interpolatus* by having fossettes that are relatively wider transversely and hypoconal grooves that do not extend as far down the crown. They differ from those of "*D.*" *leardi* by lacking notable tapering of the crowns and hypoconal grooves that extend further down the crown. In size, crown height, and occlusal morphology, the Sequence Canyon horse teeth are indistinguishable from those of "*D.*" *spectans*. Thus, these specimens are referred here to "*Dinohippus*" *spectans*.

"*Dinohippus*" *spectans* has been previously recorded in the fol-

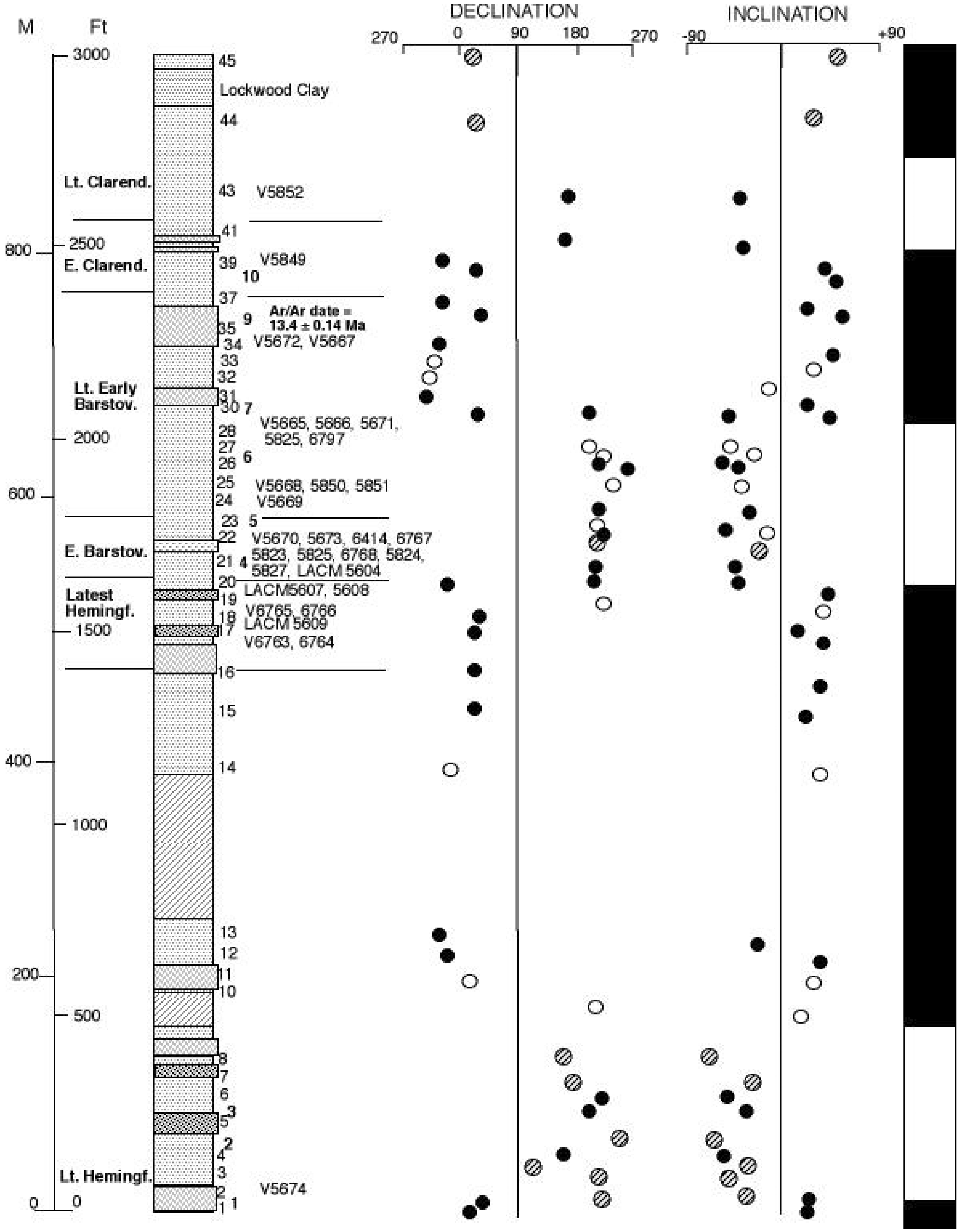

FIGURE 6. Lithostratigraphy, biostratigraphy, and magnetic stratigraphy of the Caliente Formation at Dry Canyon. Declination and inclination of magnetic sites are shown. Site numbers are indicated to the right of the lithostratigraphic column. Site numbers in bold face are from the 1993 pilot study (labeled "93-xx" in Table 1). Solid circles are sites that are statistically removed from a random distribution at the 95% confidence level (Class I sites of Opdyke et al., 1977); hachured circle represents a site with only two samples, so site statistics could not be calculated (Class II site of Opdyke et al., 1977); open circles represent sites with one vector divergent (Class III sites of Opdyke et al., 1977). Stratigraphic location of important UCMP ("V" numbers) and LACM fossil localities is shown.

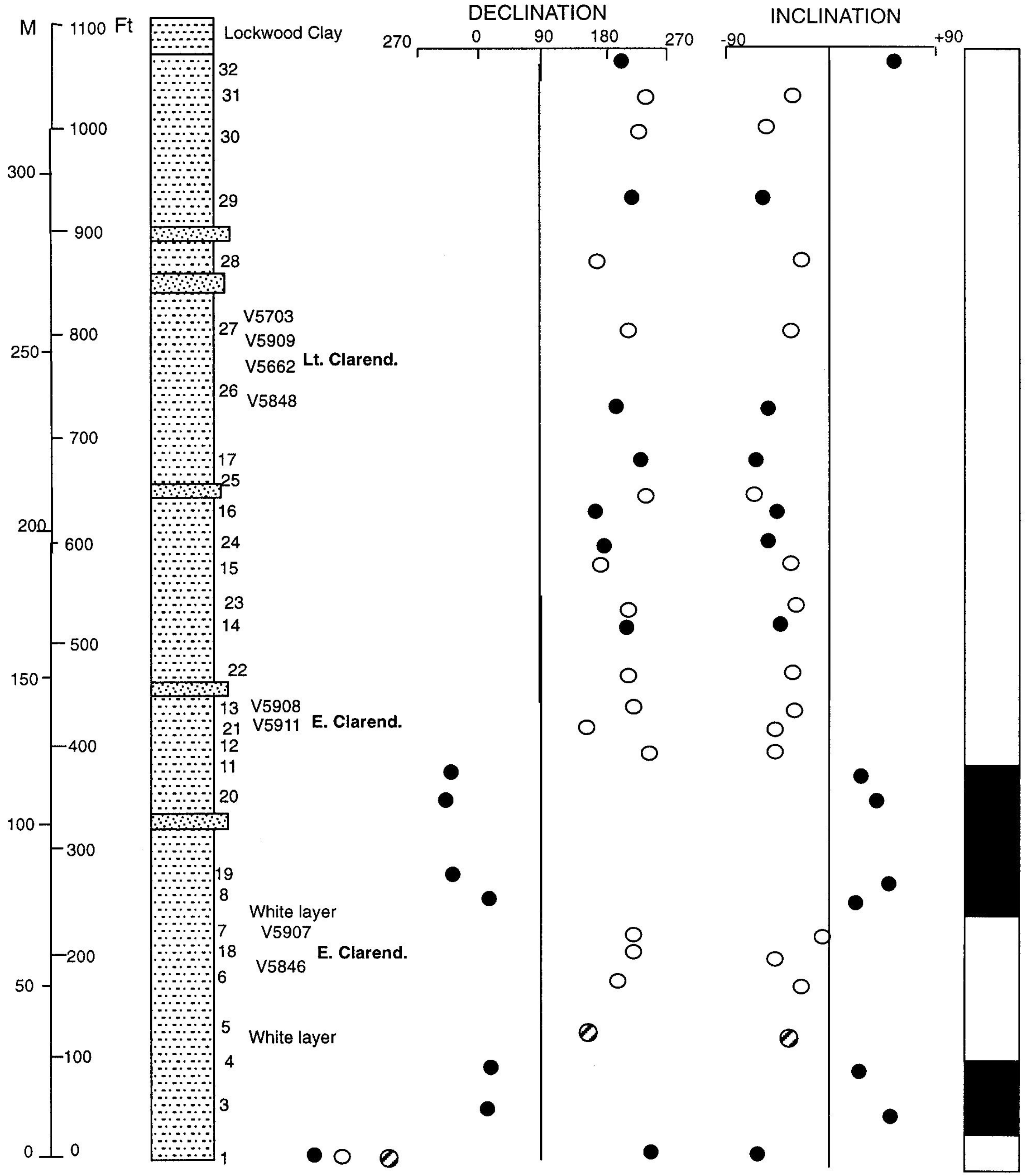

FIGURE 7. Lithostratigraphy, biostratigraphy, and magnetic stratigraphy of the section at Apache Canyon. Conventions as in Figure 6.

lowing Hemphillian faunas; the Rattlesnake, Bartlett, and Rome Faunas of Oregon, the Juniper Creek and Little Valley localities of Oregon, the Smith Valley and Yerington Faunas of Nevada, and the Mulholland Fauna of California (Stirton, 1939, 1940; Creely et al, 1982; Tedford et al, 1987, 2004; Alroy, 2002). Alroy (2002) questionably referred material from the late Clarendonian Nettle Spring l.f. of California to *Dinohippus* ?*spectans* and also stated that the age range of "*D.*" *spectans* is 23.8–5.3 Ma. However, except for the Nettle Spring locality, all of the localities listed by Alroy that yielded "*D.*" *spectans* are regarded by most investigators to be early to late early (= medial) Hemphillian in age (Hh1 or Hh2, see Tedford et al, 1987, 2004). Based on examination of horse material from the Caliente Formation by one of us (Kelly), no specimens

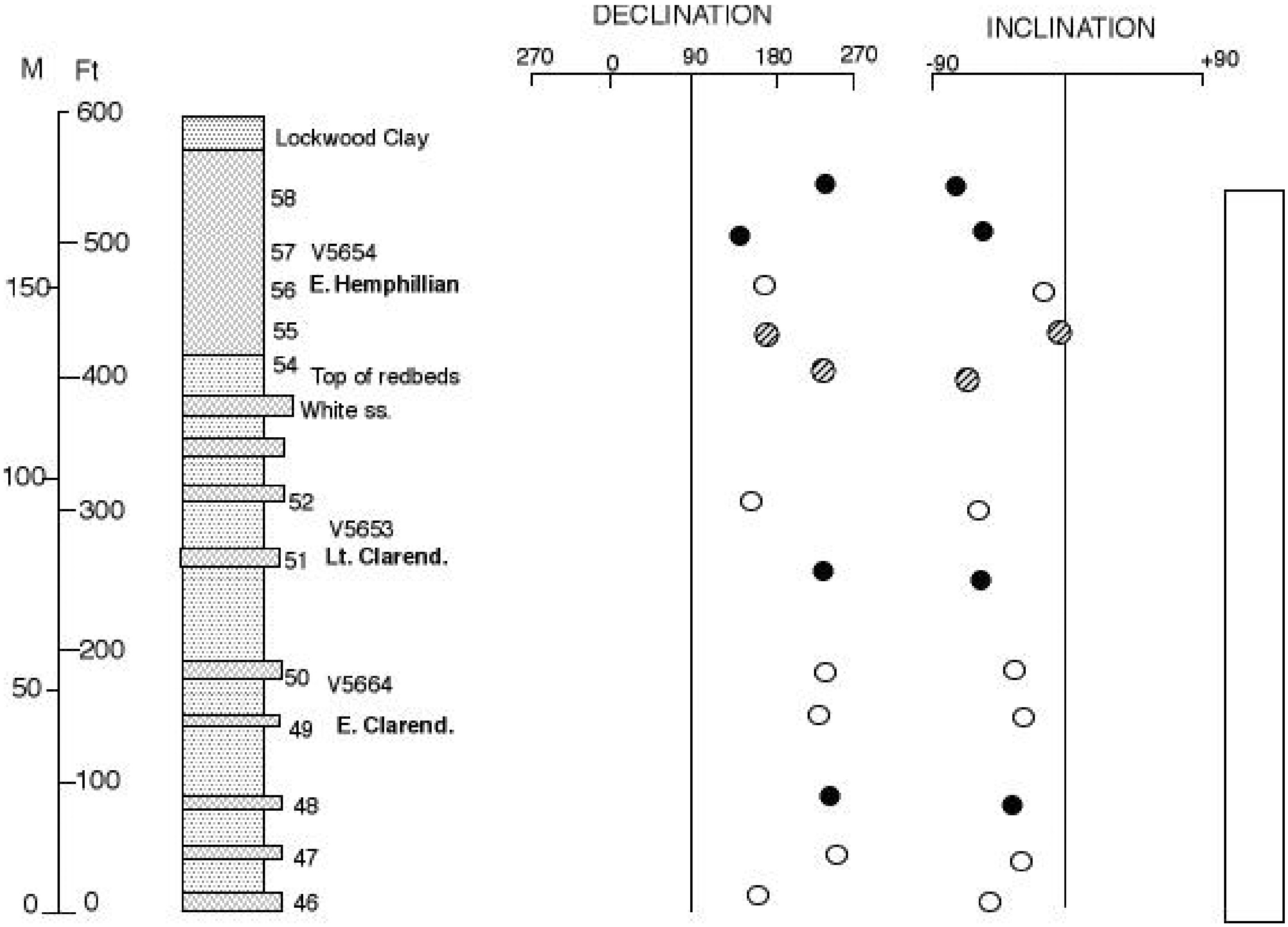

FIGURE 8. Lithostratigraphy, biostratigraphy, and magnetic stratigraphy of the section at Sequence Canyon. Conventions as in Figure 6.

that have the suite of dental characters exhibited by "*D.*" *spectans* (Kelly, 1998) are known from the Nettle Spring l.f. and the questioned indentification of "*D.*" *spectans* from this local fauna is rejected.

The type material of "*Dinohippus*" *spectans* comes from the Rattlesnake Formation of eastern Oregon. The Rattlesnake Fauna occurs below the Rattlesnake Tuff, dated by various methods from between 6.6 to 7.2 Ma (Tedford et al, 1987, 2004; Tedford and Martin, 2001; Alroy, 2002). Tedford et al (1987, 2004) regard the Rattlesnake Fauna as late early Hemphillian (Hh2) in age, dated from about 7.0 to 7.5 Ma. Prothero et al. (2006) used magnetic stratigraphy and newer ^{40}Ar/^{39}Ar dates to establish the age of the Rattlesnake Formation between 6.9 and 7.3 Ma.

Evernden et al (1964), using conventional K-Ar methods, dated biotite from a tuff underlying the Smith Valley Fauna in Smith Valley, Nevada, at 9.6 Ma (corrected for new constants). Swisher (1992) dated plagioclase from the Wilson Canyon Tuff (WCT) at 7.52 ± 0.08 Ma (corrected for new Fish Canyon Tuff constants) using the more accurate single-crystal laser-fusion ^{40}Ar/^{39}Ar dating method. The WCT occurs within the fossil bearing strata of the Coal Valley Formation that yielded the Smith Valley Fauna (Swisher, 1992; Kelly and Secord, in press). Tedford et al (1987, 2004), apparently using the older 9.6 Ma date, place the Smith Valley Fauna in their correlation charts in the beginning of the Hemphillian (Hh1). Kelly and Secord (in press) re-evaluated the biostratigraphy of the Coal Valley Formation that yielded the Smith Valley Fauna in Smith Valley. They recognize three mammalian assemblages in the Smith Valley Fauna spanning the early to late Hemphillian (Hh1 to Hh3) as follows; a lower assemblage from below the WCT (Hh1), a middle assemblage from between the WCT and the marker shale (Hh2), and an upper assemblage from above the marker shale (Hh3). They reported also two new ^{40}Ar/^{39}Ar dates of 7.08 ± 0.01 and 6.98 ± 0.01 Ma on sanidines from two tuffs that occur between the WCT and the marker shale (130 and 160 m above the WCT, respectively). Thus, based on the new dates and biostratigraphy, the Smith Valley Fauna appears to span the early to late Hemphillian (Hh1-Hh3), or about 6.5-8.5 Ma.

In the Coal Valley Formation of Smith Valley, *"D." spectans* is abundantly represented below the WCT, but a few specimens referable to this species have been recorded up to 30 m below the marker shale (Kelly and Secord, in press). Thus, the geochronologic range of *"D." spectans* in the Smith Valley Fauna is about 7.0–8.5 Ma. In the Yerington area, the Coal Valley Formation yielded the Yerington Fauna, which was originally stated to occur stratigraphically higher that the Smith Valley Fauna. Field examination of the stratigraphic positions of the Yerington localities by one of us (Kelly) indicates that these localities are laterally equivalent to those of the Smith Valley Fauna that occur below the marker shale and above the WCT, or about 7.0–7.5 Ma. The Barlett l.f. and the stratigraphically lower Otis Basin l.f. from the Drewsey Formation of Oregon occur below the Drinkwater Basalt, dated at 7.1 ± 1.09 Ma. Tedford et al (1987, 2004) correlate these faunas to the early and early late (= medial) Hemphillian (Hh1 and Hh2) at about 7.0-8.4 Ma. The age of the Rome Fauna of Oregon lacks radiometric dating constraints. Tedford et al (1987) regard the Rome Fauna as early Hemphillian in age. The Rome Fauna contains *Pliozapus* and *Lutravus*, whose first occurrences are used by Tedford et al (2004) to characterize subdivisions of the early late and late Hemphillian (Hh2 and Hh3), respectively. *Pliozapus* first occurs also in middle assemblage of the Smith Valley

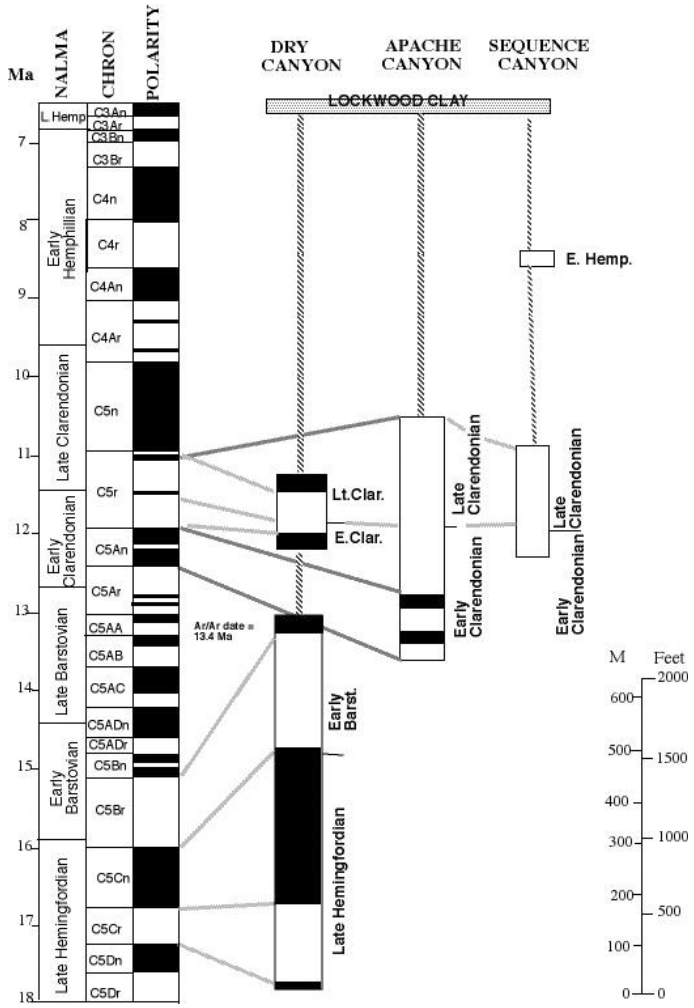

FIGURE 9. Correlation of the Caliente Formation paleomagnetic sections, based on the dates and age constraints discussed in the text. Time scale after Berggren et al. (1995), Woodburne, (1996), Tedford et al. (2004), and Woodburne and Swisher (1995).

Fauna between the WCT and the marker shale (Wilson, 1936). Based on microtine biochronology, Repenning (1987) regarded the Rome Fauna as older than 6.7 Ma. Contrary to Shotwell (1970), the tooth fragments and limb elements assigned by Shotwell from the Hemphillian Little Valley localities in the Chalk Butte Formation, Oregon, are too fragmentary to confirm the presence of *"D." spectans* in the fauna.

The sample of *"D." spectans* from the Hemphillian Juniper Creek Canyon localities from the "Grassy Mountain Formation" of Oregon is difficult to place age constraints on because the fossils came from sediments that are locally faulted and redeposited (Shotwell, 1970). The age of the sample of *"D." spectans* from the Mulholland Formation of California is constrained by a K-Ar date of 7.91 Ma (corrected) on the laterally equivalent Bald Peak Basalt (Evernden et al, 1964; Creely et al, 1982, Alroy, 2002). Thus, *"D." spectans* appears to have a restricted geochronologic range of about 7.0-8.5 Ma and, where radiometric and detailed biostratigraphic controls are available, is most common in sediments that date from about 7.5 to 8.5 Ma. These data strongly suggest that the reversed interval containing the Sequence Canyon l.f. does not represent Chron C4Ar, but most likely represents Chron C4r, dated at 8.1-8.4 Ma. However, assignment of this interval to Chron C3Br cannot be ruled out.

Tectonic Rotation

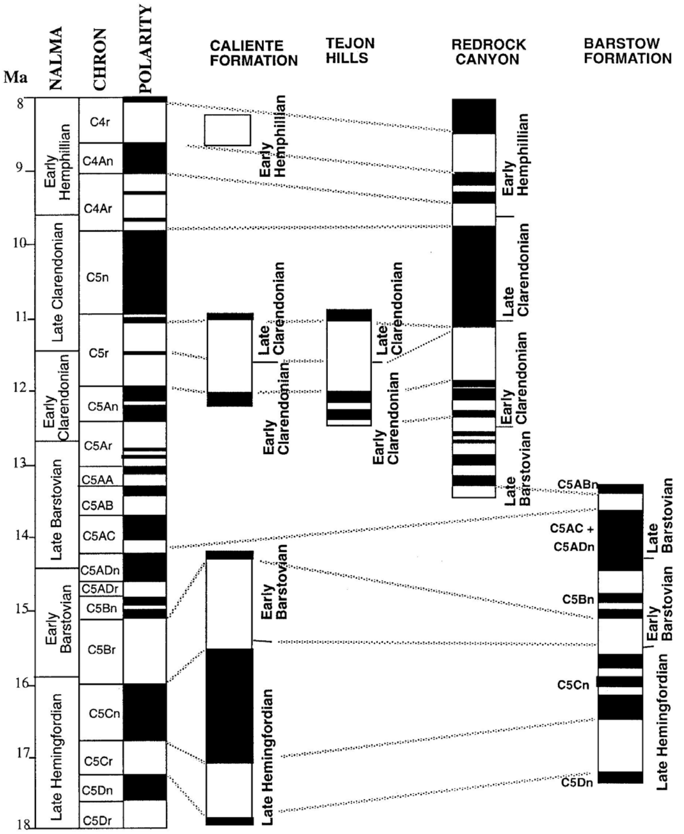

FIGURE 10. Correlation of the Caliente Formation composite paleomagnetic section (based on correlations shown in Figure 9) with other important localities. Tejon Hills after Wilson and Prothero (1997); Redrock Canyon after Whistler and Burbank (1992); Barstow Formation after MacFadden et al. (1990) and Woodburne (1996). Time scale after Berggren et al. (1995), Tedford et al. (2004), and Woodburne and Swisher (1995).

Analysis of mean declinations of the polarity zones indicated that the block indeed rotated during the 10 million years of deposition (Fig. 11). During the period of 18-11 Ma, no statistically significant trend in rotation occurred, although amounts of rotation in the samples varied from 34°± 10° to 46°± 23°. Because the lowest part of section (Chron C5Dn, 17.5-18 Ma) was rotated 37°± 19° and the Chron C5Br (11-12 Ma) portion of the section was rotated almost the same amount (37°± 13°), it is inferred that this section was rotated primarily after 11 Ma. Between 11 and 9 Ma, a hiatus in sedimentation occurred that apparently coincides with approximately 7° of rotation. Strata between 9 and 8 Ma are rotated 30°± 20°, and samples between 4 and 1.7 Ma are rotated 23° ± 7° (Ellis et al., 1993), indicating that the remaining 23° of rotation occurred in the last 1.7 Ma, and no progressive rotation occurred between 9 and 1.7 Ma.

When the average rotation of the Cuyama basin is compared to the original models of Hornafius et al. (1986), it is apparent that the rotational history indicated by the Caliente data is consistent with their paleomagnetic data. Hornafius et al. (1986) and Luyendyk (1991) suggested that most clockwise rotation occurred between 15 and 10 Ma, coincident with the capture of the Arguello microplate (Nicholson et al, 1994), and the period of transrotation of the Los Angeles Basin (Rumelhart and Ingersoll, 1997). While all of these rotations were occurring to the south between 11 and 18 Ma, the Cuyama Basin apparently pulled open and subsided and accumulated hundreds of meters of sediment, but did not undergo rotation. Rotation of the Caliente Formation began in earnest about 11 Ma, coincident with onset of motion on the San Gabriel fault (Crowell, 1982). Ehlig et al. (1975) state that the Caliente Formation began accumulating between 20 and 18 Ma, before the inception of San Gabriel fault motion, and Carman (1964) indicates that late Miocene

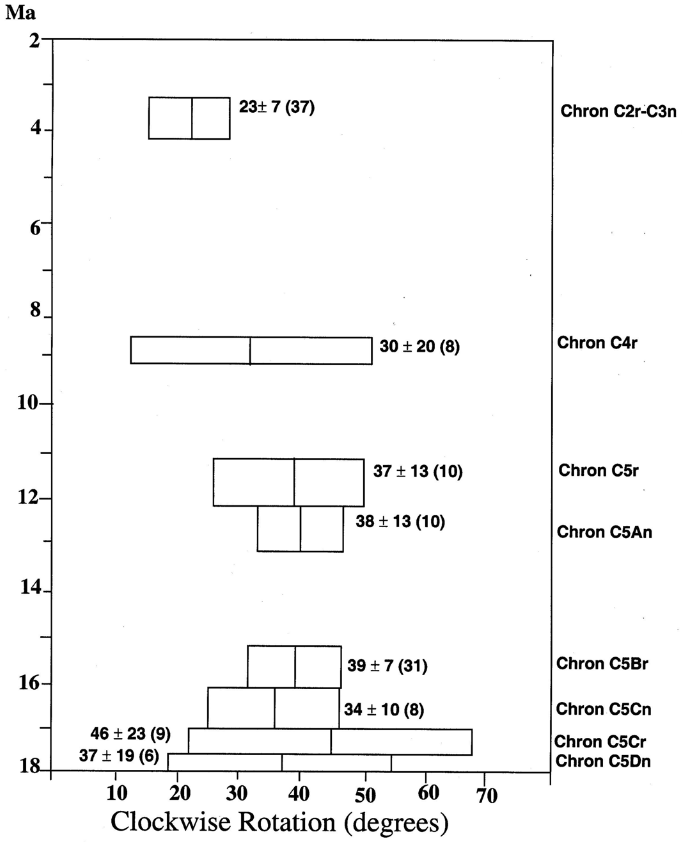

FIGURE 11. Summary of tectonic rotation of different polarity zones within the Caliente Formation, based on correlations shown in Figure 9. Mean of each level shown by the central vertical line, and the 95% confidence interval around the mean shown by the width of the rectangle. Temporal duration of the polarity zone shown by the vertical height of the rectangle. The degree of rotation and the error is also given next to the rectangle, with the sample size shown in parentheses. Note that the rotation is consistently around 34-39° degrees without a net trend between 18 and 11 Ma, then rotation begins 11 Ma. The uppermost data (23 ± 7°) are from Ellis et al. (1993).

beds of the Caliente Formation contain locally derived clasts that indicate the onset of movement on the San Gabriel fault. San Gabriel fault motion occurred between 14 to 13 Ma and 10 to 9 Ma according to Powell (1993). Thus it is plausible that the rotation seen in the Caliente sediments was initiated by the commencement of San Gabriel fault motion, although more research is needed to resolve this matter. The period between 11 and 12 Ma is also significant because it marks the beginning of the transtensional tectonics of the Los Angeles Basin (Rumelhart and Ingersoll, 1997), and the capture of the Guadalupe and Magdalena microplates (Nicholson et al,. 1994).

This clear signature of rotation in the block north of the Big Pine fault is in sharp contrast to models that suggest that all the clockwise rotation of the Western Transverse Range block occurred south of that fault and argue that the blocks to the north have undergone only northwesterly translation along the San Andreas fault without any vertical-axis rotation (Hornafius et al., 1986; Luyendyk, 1991; see discussion by Dickinson, 1996). Terres (1984) and Hornafius et al. (1986) mentioned a single paleomagnetic result from the Plush Ranch Formation, which underlies the Caliente Formation to the southeast; this result seemed to indicate no tectonic rotation of this unit. We resampled the Plush Ranch Formation in several places, and found mostly samples that were overprinted by modern normal magnetic polarity held in a chemical remanence of diagenetic hematite, so we do no regard the Plush Ranch data of Terres (1984) or Hornafius et al. (1986) to be valid. Instead, recent resampling of the Plush Ranch Formation in its type area (Prothero, 2006) shows that it is indeed rotated. In addition, Prothero and Hoffman (2001) found 60° of clockwise rotation on the Oligocene-Miocene Soda Lake Shale Member of the Vaqueros Formation, which locally underlies the Caliente Formation in the Caliente Range to the northwest of the Cuyama Badlands, but on the same tectonic block. Similarly, Prothero and Vacca (2001) found 60° of clockwise rotation in the Paleocene Pattiway Formation in the southeastern Caliente Range, not far from the Cuyama Badlands, further confirming the fact that large clockwise tectonic rotations are widespread in the blocks to the north of the Big Pine fault and west of the San Andreas fault (see Prothero, 2006).

CONCLUSIONS

Paleomagnetic analysis of samples from the Caliente Formation in the Cuyama Badlands of northern Ventura County, California, have allowed the magnetostratigraphic dating of strata yielding fossils from four Miocene land-mammal “ages” (Hemingfordian through Hemphillian). The Dry Canyon section corresponds to Chrons C5Cr through C5Bn (17.2 to 14.8 Ma) and C5An through C5r (12.3 to 11 Ma), which places the Hemingfordian-Barstovian boundary near the Chron C5Cn/C5Br boundary (16.2 Ma). The Apache Canyon sequence correlates to Chrons C5An to C5r (12.4 to 11 Ma), which suggests that the local early-late Clarendonian boundary occurs within Chron C5r (11.5 Ma). The rocks at Sequence Canyon corrrelate with Chrons C5r (11.4 to 11 Ma) and C4r (8.1-8.4 Ma), and there is a large hiatus covering the interval between 8.5-11 Ma throughout the Cuyama Badlands.

Although error estimates to not rule out the possibility of continuous rotation, clustering of mean magnetic declinations indicate that there was no rotation between 11 and 18 Ma, and tectonic rotation of this block occurred after 11 Ma (14° of clockwise rotation between 4 and 11 Ma, and 23° of additional rotation since 1.7 Ma). These episodes of rotation apparently coincided with hiatuses in sedimentation, suggesting that tectonic rotation triggered uplift and erosion. Most deposition occurred during episodes of subsidence prior to the time when rotation took place. The rotation between 9 and 11 Ma may have been induced by the onset of the San Gabriel fault motion, and recent rifting in the Gulf of California may have affected the system since 2 Ma.

ACKNOWLEDGMENTS

We thank D. Lundquist, J. Erskine, S. Shula, J. Resseguie, and J. Sutton for help with field sampling. We thank J. Kirschvink for access to the Caltech paleomagnetics lab. We thank W. Dickinson, R. Tedford, M. Woodburne, R. Ingersoll and S. Lucas for helpful comments on the manuscript. This research was supported by grants to Prothero from the NSF (EAR94-05942), and by grants from the Donors of the Petroleum Research Fund, administered by the American Chemical Society.

REFERENCES

Alroy, J., 2002, Synonymies and reidentifications of North American fossil mammals: The Paleobiology Database, www.paleodb.org.

Atwater, T., 1989, Plate tectonic history of the northeast Pacific and western North America; *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The Eastern Pacific Ocean and Hawaii: The Geology of North America, v. N., p. 21-72. Boulder, Colorado: Geological Society of America.

Berggren, W.A., Kent, D. V., Swisher, C. C., III, and Aubry, M.-P., 1995, A revised Cenozoic geochronology and chronostratigraphy: SEPM Special Publication, v. 54, p. 129-212.

Carman, M.F., Jr., 1964, Geology of the Lockwood Valley area, Kern and Ventura Counties, California: California Division of Mines and Geology Special Report, v. 81, p. 1-62.

Creely, S., Savage, D. E., and B. A. Ogle, 1982, Stratigraphy of upper Tertiary nonmarine rocks of central Contra Costa basin, California; *in* Ingersoll, R. V. and Woodburne, M. O., eds., Cenozoic nonmarine deposits of California and Arizona: Pacific Section SEPM, p. 23-34.

Crowell, J.C., 1982, The tectonics of Ridge Basin, California; *in* Crowell, J.C., and Link, M.H., eds., Geologic history of the Ridge Basin, southern California: Pacific Section SEPM, p. 25-41.

Crowell, J.C., 1987, Late Cenozoic basins of onshore southern California: complexity is the hallmark of their tectonic history, *in* Ingersoll, R.V. and Ernst, W.G., eds., Cenozoic Basin Development of Coastal California: Englewood Cliffs, NJ, Prentice-Hall, Inc., p. 207-241.

Dalrymple, G.B., 1979. Critical tables for conversion of K-Ar ages from old to new constants: Geology, v. 7, p. 558-560.

Dickinson, W.R., 1996, Kinematics of transrotational tectonism in the California Transverse Ranges and its contribution to the cumulative slip along the San Andreas transform system: Geological Society of America Special Paper, v. 305, p. 1-45.

Eaton, J. E., 1939, Geology and oil possibilities of the Caliente Range, Cuyama Valley, and Carrizo Plain, California: California Journal of Mines and Geology, v. 35, p. 255-274.

Eaton, J. E., Grant, U.S., IV,, and Allen, H.B., 1941, Miocene of the Caliente Range and environs, California: American Association of Petroleum Geologists Bulletin, v. 25, p. 193-262.

Ehlig, P.L., Ehlert, K.W., and Crowe, B.M., 1975, Offset of the upper Miocene Caliente and Mint Canyon Formations along the San Gabriel and San Andreas faults; *in* Crowell, J.C., ed., The San Andreas fault in Southern California: California Division of Mines and Geology Special Report, v. 118, p. 83-92.

Ellis, B.J., Levi, S., and Yeats, R.S., 1993, Magnetic stratigraphy of the Morales Formation: Late Neogene clockwise rotation and compression in the Cuyama Basin, California Coast Ranges: Tectonics, v. 12, p. 1170-1179.

English, W.A., 1916, Geology and oil prospects of Cuyama Valley, California: U.S. Geological Survey Bulletin, v. 621M, p. 191-215.

Evernden, J.L., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potassium argon dates and the Cenozoic mammalian chronology of North America: American Journal of Science, v. 262, p. 145-198.

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

Fremd, T., Bestland, E.A., and Retallack, G.J., 1994, John Day Basin Paleontology Field Trip Guide and Road Log. Society of Vertebrate Paleontology Field Trip Guide, 56 pp.

Green, R. C., Walker, G. W., and Corcoran, R.E., 1972, Geologic map of the Burns Quadrangle, Oregon: U.S. Geological Survey Professional Paper 797.

Hill, M.L., Carlson, S.A., and Dibblee, T.W., Jr., 1958, Stratigraphy of the Cuyama Valley-Caliente Range area, California: American Association of Petroleum Geologists Bulletin, v. 42, p. 2973-3000.

Hornafius, J.S., 1985, Neogene tectonic rotation of the Santa Ynez Range, western Transverse Ranges, California, suggested by paleomagnetic investigation of the Monterey Formation: Journal of Geophysical Research, v. 90, p. 12503-12522.

Hornafius, J.S., Luyendyk, B.P., Terres, R.R., and Kamerling, M.J., 1986, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges: Geological Society of America Bulletin, v. 97, p. 1476-1487.

James, G.T., 1963, Paleontology and nonmarine stratigraphy of the Cuyama Valley Badlands, California: University of California Publications in Geological Sciences, v. 45, p. 1-162.

Johnson, H.P., Lowrie, W.P., and Kent, D.V., 1975, Stability of anhysteretic remanent magnetization in fine and coarse magnetite and maghemite particles: Geophysical Journal of the Royal Astronomical Society, v. 41, p. 1-10.

Kamerling, M.J., and Luyendyk, B.P., 1979, Tectonic rotation of the Santa Monica Mountain region, western Transverse Ranges, California, suggested by paleomagnetic vectors: Geological Society of America Bulletin, v. 90, p. 331-337.

Kamerling, M.J., and Luyendyk, B.P., 1985, Paleomagnetism and Neogene tectonics of the northern Channel Islands, California: Journal of Geophysical Research, v. 90, p. 12485-12502.

Kelly, T.S., 1992, New middle Miocene camels from the Caliente Formation, Cuyama Valley Badlands, California: PaleoBios, v. 13, p. 1-22.

Kelly, T.S., 1995, New Miocene horses from the Caliente Formation, Cuyama Valley Badlands, California: Natural History Museum of Los Angeles County, Contributions in Science, v. 455, p. 1-33.

Kelly, T.S., 1998, New Miocene equid crania from California and their implications for the phylogeny of the Equini: Natural History Museum of Los Angeles County, Contributions in Science, v. 473, p. 1-44.

Kelly, T.S., and Lander, E.B., 1988, Biostratigraphy and correlation of Hemingfordian and Barstovian land mammal assemblages, Caliente Formation, Cuyama Valley area, California: Pacific Section SEPM Guidebook, v. 59, p. 1-19.

Kelly, T.S., and Lander, E.B., 1992, Miocene land mammal faunas from the Caliente Formation, Cuyama Valley Badlands, California: Paleobios, v. 14, p. 3-8.

Kelly, T. S., and Secord, R., in press, Biostratigraphy of the Hunter Creek Sandstone, Verdi Basin, Washoe County, Nevada: *in* Oldow, J., and Cashman, P., eds., Western Great Basin, Walker Lane Volume, Geological Society of America Special Papers.

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.

Lander, E,B., 1985, Early and middle Miocene continental vertebrate assemblages, central Mojave Desert, San Bernardino County, California: *in* Reynolds, R.E., ed., Geological Investigations along Interstate 15, Cajon Pass to Manix Lake: San Bernardino County Museum, p. 127-144.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtension, and transpression in southern California: Geological Society of America Bulletin, v. 103, p. 1528-1536.

Luyendyk, B.P., and Hornafius, J.S., 1987, Neogene crustal rotations, fault slip, and basin development in southern California; *in* Ingersoll, R.V., and Ernst, W.G., eds., Cenozoic Basin Development of Coastal California: Englewood Cliffs, N.J.: Prentice-Hall, p. 259-283.

Luyendyk, B.P., Kamerling, M.J., and Terres, R.R., 1980, Geometric model for Neogene crustal rotations in southern California: Geological Society of America Bulletin, v. 91, p. 211-217.

Luyendyk, B.P., Kamerling, M.J., Terres, R.R., and Hornafius, J.S., 1985, Simple shear of southern California during Neogene time suggested by paleomagnetic declinations: Journal of Geophysical Research, v. 90, p. 12454-12466.

Macdonald, J. R. and Pelletier, W.J., 1958, The Pliocene mammalian faunas of Nevada, USA: Paleontologia, taxonomia, y evolucion. Cuidad de Mexico: International Geological Congress, 1956 Report of the 7th Session, v. 7, p. 365-388.

MacFadden, B.J., Swisher, C.C., III, Opdyke, N.D., and Woodburne, M.O., 1990. Paleomagnetism, geochronology, and possible tectonic rotation of the middle Miocene Barstow Formation, Mojave Desert, southern California: Geological Society of America Bulletin, v. 102, p. 478-493.

Nicholson, C., Sorlien, C.C., Atwater, T., Crowell, J.C., and Luyendyk, B.P., 1994, Microplate capture, rotation of the western Transverse Ranges, and initiation of the San Andreas transform as a low-angle fault: Geology, v. 22, p. 491-495.

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.

Powell, R.E., 1993, Balanced palinspastic reconstruction of pre-late Cenozoic paleogeology, Southern Califronia: Geological Society of America Memoir, v. 178, p.1-106.

Prothero, D.R., 2006, Paleomagnetism and tectonic rotation of the southern Coast Ranges, California: Pacific Section SEPM Special Publication, v. 101, p. 215-236.

Prothero, D. R., and Tedford, R.H., 2000, Magnetic stratigraphy of the type Montediablan Stage (late Miocene), Black Hawk Ranch, Contra Costa County, California: implications for regional correlations" Paleobios, v. 20, p. 1-10.

Prothero, D.R., and Hoffman, J.M., 2001, Magnetic stratigraphy of upper Oligocene-lower Miocene Soda Lake Shale Member of the Vaqueros Formation, Caliente Range, San Luis Obispo County, California: Pacific Section SEPM Special Publication, v. 91, p. 254-262.

Prothero, D.R., and Vacca, R., 2001, Magnetic stratigraphy and tectonic rotation of the upper Paleocene Pattiway Formation, Caliente Range, San Luis Obispo County, California: Pacific Section SEPM Special Publication, v. 91, p. 20-26.

Prothero, D. R., Hoffman, J. M., and Foss, S.E., 2006 Magnetic stratigraphy of the upper Miocene (Hemphillian) Rattlesnake Formation, central Oregon: Paleobios, v. 26, no. 1, p. 31-35.

Reed, R.D., and Hollister, J.S., 1936, Structural Evolution in Southern California: American Association of Petroleum Geologists, Tulsa, Oklahoma.

Repenning, C. A., 1987, Biochronology of the microtine rodents of the United States; *in* Woodburne, M.O., ed., Cenozoic Mammals of North America, Geochronology and Biostratigraphy: Berkeley, University of California Press, p. 236 – 268,

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. 424-C, p. C235-C239.

Rumelhart, P.E., and Ingersoll, R.V., 1997, Provenance of the upper Miocene Modelo Formation and subsidence analysis of the Los Angeles basin, southern California: implications for paleotectonic and paleogeographic reconstructions: Geological Society of America Bulletin, v. 109, p. 885-899.

Savage, D.E., 1955, Nonmarine lower Pliocene sediments in California: a geochronologic-stratigraphic classification: University of California Publications in Geological Sciences, v. 31, p. 1-26.

Shotwell, J. A., 1970, Pliocene mammals of southeast Oregon and adjacent Idaho: Bulletin of the Museum of Natural History, University of Oregon, v. 17, p. 1-103.

Stirton, R. A., 1939, The Nevada Miocene and Pliocene mammalian faunas as faunal units: Proceedings of the Sixth Pacific Science Congress, v. 2, p. 627 –640.

Stirton, R. A., 1940, Phylogeny of North American Equidae: University of California Publications, Bulletin of the Department of Geological Sciences, v. 25, p. 165-198.

Swisher, C.C., III, 1992, ^{40}Ar/^{39}Ar dating and its application to the calibration of North American land-mammal ages: Unpubl. Ph.D. dissert., University of California, Berkeley, 239 pp.

Tedford, R.H., and Hunter, M.E., 1984, Miocene marine-nonmarine correlations: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 47, p. 129-151.

Tedford, R.H., and Martin, J., 2001, *Plionarctos*, a tremarctine bear (Ursidae: Carnivora) from western North America: Journal of Vertebrate Paleontology, v. 21, p. 311-321.

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, p. 153-210,

Tedford, R.H., Albright, L.B., III, Barnosky, A.D., Ferrusquia-Villafranca, I., Hunt, R.M., Jr., Storer, J.E., Swisher, C.C., III, Voorhies, M.R., Webb, S.D., and Whistler, D.P., 2004. Mammalian biochronology of the Arikareean through Hemphillian interval (late Oligocene through early Pliocene epochs); *in* Woodburne, M.O., ed., Late Cretaceous and Cenozoic Mammals of North America: Biostratigraphy and Geochronology. Columbia University Press, New York, p. 169-231.

Terres, R.R., 1984, Paleomagnetism and tectonics of the central and eastern Transverse Ranges: Unpubl. Ph.D. dissert., University of California, Santa Barbara, 325 p.

Terres, R.R., and Luyendyk, B.P., 1985, Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors: Journal of Geophysical Research, v. 90, p. 12467-12484.

Whistler, D.P., and Burbank, D.W., 1992, Miocene biostratigraphy and biochronology of the Dove Spring Formation, Mojave Desert, California, and the characterization of the Clarendonian land mammal age (late Miocene) in California: Geological Society of America Bulletin, v. 52, p. 1-48.

Wilson, E.L., and Prothero, D.R., 1996, Magnetic stratigraphy and tectonic rotation of the middle-upper Miocene "Santa Margarita" and Chanac Formations, north-central Transverse Ranges, California: Pacific Section SEPM Special Publication, v. 82, p. 35-48.

Wison, R. W., 1936, A Pliocene rodent fauna from Smiths Valley, Nevada: Carnegie Institution of Washington Publication no. 473, p. 15-34.

Woodburne, M.O., 1975, Cenozoic stratigraphy of the Transverse Ranges and adjacent areas, Southern California: Geological Society of America Special Paper, v. 162.

Woodburne, M.O., 1996, Reappraisal of *Cormohipparion* from the Valentine Formation of Nebraska: American Museum Novitates, no. 3163, p. 1-56.

Woodburne, M.O., and Swisher, C.C., III, 1995, Land mammal high-resolution geochronology, intercontinental overland dispersals, sea level, climate, and vicariance: SEPM Special Publication, v. 54, p. 335-364.

Woodburne, M.O., Tedford, R.H., and Swisher, C.C., III, 1990, Lithostratigraphy, biostratigraphy, and geochronology of the Barstow Formation, Mojave Desert, southern California: Geological Society of America Bulletin, v. 102, p. 459-477.

APPENDIX 1

Distribution of mammalian taxa in local faunas of the Caliente Formation, Cuyama Badlands, California. Abbreviations are as follows: HTS, Hidden Treasure Spring l.f.; WDC, West Dry Canyon l.f.; LDS, Lower Dome Spring l.f.; UDS, Upper Dome Spring l.f.; DS, Doe Spring l.f.; MR, Mathews Ranch l.f.; NS, Nettle Spring l.f.; and SC, Sequence Canyon l.f.

Taxon	HTS	WDC	LDS	UDS	DS	MR	NS	SC
Lagomorpha								
Hypolagus spp. indet.	x	x						
Hypolagus cf. *parviplicatus*			x					
Hypolagus tedfordi							x	
Pronotolagus apachensis						x	x	
Alilepus sp.							x	
Rodentia								
Petauristodon uphami				x	x			
Petauristodon mathewsi						x		
Ammnospermophilus fossilis						x		
Eutamias ateles						x	x	
Protospermophilus quatalensis						x	x	
Perognathus furlongi				x		x	x	
Perognathus minutus						x		
Proheteromys maximus				x				
Cupidinimus cuyamaensis							x	
Pliosaccomys wilsoni							x	
Copemys cf. dentalis				x				
Copemys russelli						x	x	
Carnivora								
Tomarctus hippophaga				x				
Amphicyon sp.				x				
Pseudalurus spp.				x	x	x	x	
Martes sp.				x	x	x		
Borophagus littoralis						x	x	
Borophaginae				x				
Caninae						x	x	
Actiocyon leardi							x	
Bassarsicus sp.						x		
Stenicitis sp.						x	x	
Erinaceomorpha								
Lanthanotherium sawini				x		x	x	
Lanthanotherium dehmi						x		
Metechinus sp.						x		
Domninoides sp.						x		
Soricomorpha								
Linmoecus tricuspis						x		

APPENDIX 1 CONTINUED

TAXON	HTS	WDC	LDS	UDS	DS	MR	NS	SC
Chiroptera								
Chiroptera, gen. indet.						x		
Proboscidea								
Gomphotherium sp.					x	x	x	
Perissodactyla								
Parahippus sp.	x							
Archaeohippus mourningi				x				
Megahippus sp.						x		
Megahippus matthewsi							x	
Parapliohippus carrizoensis	x	x						
"Merychippus" brevidontus				x				
Hipparion tehonense						x		
Cormohipparion occidentale s.l.							x	
Acritohippus cf. *tertius*	x							
Acritohippus quinni		x	x	x	x			
"Pliohippus" tehonensis						x		
Heteropliohippus hulberti						x	x	
Pliohippus sp.						x	x	
"Dinohippus" spectans								x
Chalicotheriidae, gen. indet.	x							
Artiodactyla								
"Cynorca" occidentale			x	x				
Brachycrus buwaldi		x	x					
Ticholeptus zygomaticus	x							
?Ustatochoerus sp.						x		
Aepycamelus sp.		x	x	x				
Hesperocamelus cf. *alexandrae*				x				
Miolabis fricki		x	x	x				
Paramiolabis taylori				x				
Cuyamacamelus jamesi			x					
Protolabis sp.							x	
cf. *Megatylopus* sp.							x	
Procamelus sp.					x	x		
Bouromeryx cf. *americanus*		x	x	x				
Rakomeryx sinclairi			x					
Crainoceras sp.						x		
Merycodontinae, gen. indet.	x							
Paracosoryx cf. *furlongi*					x	x	x	
Ramoceras sp.					x			
Ramoceras ramosus						x		