MAGNETIC STRATIGRAPHY OF THE EARLY TO MIDDLE MIOCENE OLCESE SAND AND ROUND MOUNTAIN SILT, KERN COUNTY, CALIFORNIA

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Abstract—The Olcese Sand and Round Mountain Silt, northeast of Bakersfield, California, are famous for their marine fossils, especially for the vertebrates from the Sharktooth Hill bone bed. Their ages are thought to be early to middle Miocene. Magnetic samples were taken from the 70-m thick Nickel Cliff section of the Olcese Sand, and from two sections spanning 70 m of the Round Mountain Siltstone: one at Ernst Ranch and the other along Poso Creek-Round Mountain Road. The samples were demagnetized with both alternating field and thermal demagnetization, and produced stable remanence that passed a reversal test. The Olcese Sand is mostly normal in polarity, except for short reversed magnetozones at the middle and top of the section. Based on strontium-isotope ages ranging from 16.9-17.6 Ma, Relizian benthic foraminifera, and a fission-track date of 15.7 ± 1.7 Ma, we correlate the upper member of the Olcese Sand with Chrons C5Cn2-C5Cn3 (16.1-16.6 Ma), or latest early Miocene. Most of the Round Mountain Silt is reversed in polarity except for the very base of the section, and a short normal magnetzone in the upper third. Based on strontium-isotope isotope ages, Luisian benthic foraminifera, and Denticulopsis lauta A zone diatoms, the best correlation is with Chrons C5Adr to C5Cn1 (14.5-16.1 Ma). The entire middle part of the section, including the Sharktooth Hill bone bed, correlates with Chron C5Br (15.2-16.0 Ma). This confirms the middle Miocene (Barstovian) age of the unit, as has been suspected from the few terrestrial mammals recovered. The Olcese Sand at Nickel Cliff near the boundary fault with the Sierra foothills, shows an apparent counterclockwise tectonic rotation of about 35°, but the overlying Round Mountain Silt at more westerly locations does not. This rotation appears to be a local tectonic effect.

INTRODUCTION

The Cenozoic deposits of the southeastern San Joaquin Basin (Fig. 1) have long been studied for their large oil reserves (Anderson, 1911; Hoots, 1930; Addicott, 1970; Bartow and McDougall, 1984; Olson et al., 1986; Olson, 1988). They are also famous for their immense collections of fossils, especially of Miocene mollusks (Addicott, 1970), foraminifera and diatoms (Bartow and McDougall, 1984), and vertebrates (Mitchell, 1965; Savage and Barnes, 1972). In particular, the Sharktooth Hill bone bed, in the middle Miocene Round Mountain Silt, is one of the richest known vertebrate fossil deposits in the world. It yields thousands of bones representing at least 30 species of sharks (hence the name) as well as 17 species of cetaceans, 10 species of pinnipeds, 2 genera of desmostylians, sirenians (Savage and Barnes, 1972) and quite a variety of land mammals as well (Prothero et al., this volume). The underlying Olcese Sand also yields marine vertebrates and an abundant fauna of mollusks (Addicott, 1970). Despite the great importance of these fossils, the dating of these deposits has only recently been improved. For decades, the only method of dating them was the biostratigraphy of mollusks, which have very long biozones in the Miocene that limit precision, and especially are time-transgressive (Prothero, 2001). Diatom and benthic foraminiferal biozones have also been used (Barron, 1981; Bartow and McDougall, 1984), which are higher in resolution than those of mollusks. A few fission-track dates have been published (e.g., Bartow and McDougall, 1984), but the error estimates were so large (typically ± 1-2 m.y.) that precision is limited. Strontium isotope ages have been analyzed from the shell material from many of these units (Olson, 1988, Table 1), but these also give large error estimates (typically ± 1 m.y. or more), and many of the dates do not make sense in light of their stratigraphic position, suggesting that they have been altered by diagenesis. Thus, the age constraints on these units are getting better, but they do not match the <100,000-year resolution of magnetic stratigraphy.

GEOLOGIC BACKGROUND

Two formations are the focus of the present study. The Olcese Sand (defined by Ferguson, 1941) is a friable, poorly consolidated sandy unit (seldom cemented enough to be considered a true sandstone) with interbedded siltsand and pebbly sand (Addicott, 1970; Bartow and McDougall, 1984; Olson et al., 1986; Olson, 1988). Its maximum thickness is about 500 m, although no exposure of the entire formation exists at the surface. The lower member consists of gray very fine-grained marine silty sandstone about 100-280 m thick at the surface, and as thick as 310 m in the subsurface (Addicott, 1970, p. 17). The middle member is composed of fine- to coarse-grained pumiceous sandstone and gravels, with abundant cross-bedding, totaling between 8 and 70 m in thickness. The highly fossiliferous upper member, which yields most of the mollusk and vertebrate fossils, is composed of very fine-grained marine sands. The lower and middle members of the Olcese Sand are generally poorly exposed in our study area, and not suitable for long sections of magnetic sampling. The upper member is well exposed in the Nickel Cliff section (Olson et al., 1986; Olson, 1988, fig. 8), and that was the main section sampled in this study. The Olcese Sand intertongues with the Freeman Silt at its base, and with the Round Mountain Silt that overlies it. The Olcese Sand is thickest near the eastern edge of the San Joaquin basin, and gradually pinches out within a few kilometers of its surface outcrop as it plunges down into the basin in a westerly and southerly direction. This structure is consistent with the interpretation that the Olcese Sand is composed of shallow-marine shelf sand (and may even be partly non-marine), which is also consistent with the benthic foraminifera recovered from the unit (Bartow and McDougall, 1984).

The Olcese Sand yields a Relizian (and possibly Saucesian near the base of the unit) benthic foraminiferal assemblage. The Relizian Stage ranges from 15.5-17 Ma in age, but the subjacent Saucesian stage covers most of the early Miocene and part of the latest Oligocene (Barron and Isaacs, 2001; Prothero, 2001). The Temblor Stage molluscan assemblage ranges from 23 to 9 Ma, spanning almost the entire Miocene (Prothero,
Addicott (1970, p. 18) described a cross-bedded pumiceous sandstone from the middle member that yielded a fission-track date of 15.5 ± 1.7 Ma (Bartow and McDougall, 1984, p. J23). Unfortunately, the precise stratigraphic position of this sample was never recorded, and the error estimate is large. Several strontium-isotope ages were reported by Olson (1988, table 1), most of which range from 16.8 ± 1 Ma to 17.7 ± 1 Ma. However, a few ages were as old as 19 ± 1 Ma, which conflicts with the age estimates on the underlying units, as well as the benthic foraminifera and the fission-track date.

The other unit sampled in this study is the Round Mountain Silt, which overlies and interfingers with the Olcese Sand. First named by Diepenbrock (1933), it was redefined by Addicott (1970). It is overlain unconformably by the Chanac Formation or “Santa Margarita Formation” in the Kern River area, and in the western subsurface, it is overlain conformably by the Fruitvale Shale (Bartow and McDougall, 1984). The Round Mountain Silt is friable and poorly consolidated, so it is really a silt and not a true siltstone. It consists mainly of greenish-gray, micaeous, clayey-sandy silt with local white diatomite layers. Bartow and McDougall (1984, p. J28) report a total thickness of 400 m in the subsurface, although no continuous surface exposures exceed 100 m in thickness. A 55-m thick diatomaceous unit is found near the base of the formation (Olson, 1988), which shifts upward in the section as the total thickness of the unit pinches out. The Sharktooth Hill bone bed is found about 33 m above the diatomaceous layer in some sections, placing it in the middle to upper part of the section.

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The Round Mountain Silt yields a Luisian benthic foraminiferal fauna, which ranges between 14 and 15.5 Ma in age (Barron and Isaacs, 2001; Prothero, 2001). The diatomite yields characteristic of the Denticulopsis lauta A zone (Barron, 1981; Barron, in Bartow and McDougall, 1984), which is between 15 and 16 Ma in age (Barron, 1981). The Temblor Stage mollusks, as noted above, span almost the entire Miocene, and are of little use for precise correlation. Olson (1988, table 1) obtained strontium-isotope ages on a number of shells, with most samples ranging from 15.5 ± 1 Ma to 16.3 ± 1 Ma. There were a few aberrantly old dates of 17.8 ± 1 Ma and 18.0 ± 1 Ma, which are older than most of the dates from the underlying Olcese Sand, and also older than the biostratigraphic age constraints of the foraminifera and diatoms.
FIGURE 2. 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 200° to 630°C in 50°C increments. Each division equals 10⁻⁵ emu.
METHODS

Several stratigraphic sections (Fig. 1) were measured with a Jacob’s staff, and sampled during the winter and spring of 2003 wherever suitable exposures could be found for magnetic sampling. Precise locations for each of these sites and sections are given in the Appendix. The main Sharktooth Hill section was taken at Ernst Ranch (7 sites covering 80 m of section), and covered the entire exposed thickness of the Round Mountain Silt, and some of the underlying Olcese Sand. Another composite section of Round Mountain Silt and Olcese Sand was sampled from roadcuts along the Poso Creek and Round Mountain Road from Mon Bluff south to the grade north of Round Mountain (12 sites covering about 100 m of section). The thickest continuous section (8 sites covering 70 m of section) of the Olcese Sand was sampled at Nickel Cliff (Olson, 1988, fig. 8). Isolated Round Mountain exposures were sampled at the Father Garces Monument site on Highway 178, and in the classic Barker Ranch area south of the Kern River (Fig. 1). Samples (3 samples per site) were taken as oriented blocks of rock with simple hand tools, and then wrapped and carried back to the laboratory. Most samples had to be hardened in the field with sodium silicate, since they were so friable. There they were subsampled into cores by molding them into disks of Zircar aluminum ceramic. The samples were then analyzed on a 2G cryogenic magnetometer with an automatic sample changer at the California Institute of Technology. After measurement of NRM (natural remanent magnetization), they were demagnetized in alternating fields (AF) of 25, 50, and 100 Gauss to prevent the remanence of multi-domain grains from being baked in, and to examine the coercivity behavior of each specimen. AF demagnetization was followed by thermal demagnetization of every sample in 50°C steps from 200°C to 630°C to get rid of high-coercivity chemical overprints due to iron hydroxides such as goethite, and to determine how much remanence was left after the Curie temperature of magnetite (580°C) was exceeded.

Results were plotted on orthogonal demagnetization (“Zijderveld”) plots, and average directions of each sample were determined by the least-squares method of Kirschvink (1980). Mean directions for each sample were then analyzed using Fisher (1953) statistics, and classified according to the scheme of Opdyke et al. (1977).

RESULTS

Orthogonal demagnetization (“Zijderveld”) plots of representative samples are shown in Figure 2. In nearly every sample, there was a single component of remanence, with little or no overprinting. There was a slight high-coercivity component (shown by the minimal drop of intensity in the first three AF demagnetization steps in many samples in Fig. 2), probably due to some chemical remanence due to iron hydroxides, such as goethite. Apparently the overprint was not significant, because it was quickly removed by thermal demagnetization at 200°C (above the temperature at which iron hydroxides are dehydrated to hematite). The rest of the remanence appears to be held in magnetite, since it declined in intensity rapidly through thermal demagnetization, and vanished above the Curie temperature of magnetite (580°C) and no remanence was left at 600°C or 630°C (Fig. 2). For example, the sample shown in Figure 2A has single stable normal component that declined rapidly to the origin, with minimal overprinting. The sample shown in Figure 2B is also normal in polarity with no overprinting, but rotated about 45° counterclockwise. The sample shown in Figure 2C has slight overprinting during the AF steps, but then stabilized to an unrotated reversed component that disappeared above the Curie point of magnetite. Samples shown in Figures 2D and 2E are also reversed in polarity, with a slight overprint held in goethite, but then decreased steadily to the origin and lost all remanence above the Curie point of magnetite; both of these samples show a southeast and down direction (reversed with counterclockwise rotation).

Site statistics (Fisher, 1953) were calculated and are shown in Table 1. All but 3 sites were statistically significant, i.e., separated from a random distribution at the 95% confidence level (Class II sites of Opdyke et al., 1977). The exceptions failed the significance test because one sample crumbled, so only two samples remained to be measured (Class II sites of Opdyke et al., 1977). The mean for all normal sites of the Round Mountain Silt at Ernst Ranch and Poso Creek was $D = 6.3, I = 45.6, k = 15.6, \alpha_90 = 11.5, n = 12$; the mean for the reversed sites was $D = 174.6, I = -50.4, k = 23.6, \alpha_90 = 9.1, n = 13$. These directions are antipodal within error estimates, giving a reversal test that shows that the overprinting has been removed and the primary or characteristic remanence has been obtained. For the Olcese Sand (primarily at Nickel Cliff, but also a few samples at Poso Creek and Ernst Ranch), the mean for normal samples was $D = 328.3, I = 55.6, k = 7.8, \alpha_90 = 12.2, n = 21$, and the mean for reversed samples was $D = 121.5, I = -58.4, k = 43.2, \alpha_90 = 10.3, n = 6$. These directions are also antipodal (Fig. 3) within error estimates, giving a positive reversal test, and showing that the remanence is primary. However, these directions are also rotated about 35° counterclockwise from the expected direction for the Miocene (Irving, 1979), which is apparent in many of the samples (e.g., Figs. 2B, D, E). The implications of this result will be discussed further below.

The magnetic stratigraphy of the Ernst Ranch section is shown in Figure 4. Except for site 3 midway through the section, and the uppermost site 8, the entire 70 m of upper member of Olcese Sand in this section is normal in polarity (and rotated counterclockwise).

The magnetic stratigraphy of the Ernst Ranch section is shown in Figure 5. The single Olcese sample at the top of the formation was reversed in polarity, followed by a normal site at the base of the Round...
Mountain Silt. The remaining 50 m of Round Mountain Silt (including two sites on the Sharktooth Hill bone bed) were reversed in polarity. The magnetic stratigraphy of the Poso Creek section is shown in Figure 6. The site at the base of the Olcese Sand is normal in polarity, but those at the top of the Olcese are reversed in polarity. Most of the Olcese was not exposed in this area. As in Ernst Ranch, the lowest Round Mountain site is normal in polarity, but most of the rest of the Round Mountain silt (including the Sharktooth Hill bone bed) is reversed in polarity except for sites 1 and 2, high in the section. The top of the Round Mountain Silt at Mon Bluff, however, is reversed again.

The single site of Round Mountain Silt at Barker’s Ranch was reversed in polarity (Table 1), as was the single site at the Father Garces Monument.

**DISCUSSION**

Correlation of the sections is shown in Figure 7. The normal polarity of most of the Nickel Cliff section of the upper member of the Olcese Silt, plus the strontium isotope dates ranging from 16.8 ± 1 Ma to 17.7 ± 1 Ma, and the Relizian foraminiferal assemblage (15.5-17 Ma), and the fission-track date of 15.7 ± 1.7 Ma, are most consistent with a correlation of the section with Chrons C5Cn1-C5Cn3 (16.1-16.6 Ma). It is possible that the lower members of the Olcese Silt may be older than 16.6 Ma, especially given the older strontium isotope dates, but it was not possible to sample a continuous section through the lower and middle members, so their polarity is unknown.

The Poso Creek composite section and the Ernst Ranch section both have a short normal magnetozone at the very base of the Round Mountain Silt, and are reversed in polarity through the rest of the section (except for the short normal magnetozone near the top of the Poso Creek section). The Lusitan benthic foraminifera (14-15.5 Ma), the Denticulopsis lauta zone A diatoms (15-16 Ma), and the strontium isotope dates ranging from 15.5 ± 1 Ma to 16.3 ± 1 Ma are all consistent with correlation with Chrons C5Adr to C5Cn1 (14.5-16.1 Ma).

Precise correlation of the sites at Barker’s Ranch and the Father Garces Monument is not possible, since they come from isolated outcrops. However, their reversed polarity and position in the middle or upper part of the Round Mountain Silt suggest that they correlate with some part of Chron C5Br (15.2-16.0 Ma). Likewise, the Sharktooth Hill bone bed is near the middle of Chron C5Br, so it is about 15.5 Ma in age.
The apparent 35° counterclockwise rotation of the Olcese results is surprising, given that the overlying Round Mountain Silt is not rotated (Fig. 3). This rotation could be due to the fact that most of the Olcese samples came from Nickel Cliff, which is the farthest east of all the localities sampled, and closest to the boundary fault with the Sierra foothills (Fig. 1). However, the literature shows that magnetic directions and rotations are highly variable in the region. Kanter and McWilliams (1982) showed both unrotated and counterclockwise rotated results (some only a few kilometers apart) on the lower Miocene (16.5-17 Ma) Kinnick Formation, in the southern Tehachapi Mountains, only 60 km southeast of Sharktooth Hill. Coles et al. (1997), however, found no rotation on the middle Miocene (14.5-16.5 Ma) Bopesta Formation, which overlies the Kinnick Formation in the Tehachapis. Clearly, the middle Miocene rotations in this region are highly variable from one tectonic block to another. The rotation of the Olcese Sand at Nickel Cliff is probably another example of this local tectonic effect, especially given its proximity to the boundary fault with the Sierran foothills.

CONCLUSIONS

The upper member of the Olcese Sand northeast of Bakersfield correlates with Chrons C5Cn2-C5Cn3 (16.1-16.6 Ma), so it is late early Miocene in age. Although the lower and middle members of the Olcese Sand were too poorly exposed in our study area for magnetic sampling, they may be as old as 18-19 Ma based on their strontium isotope ages. The exposed outcrops of the Round Mountain Silt are correlated with Chrony C5Adr to C5Cn1 (14.5-16.1 Ma), so they are early middle Miocene in age. The Round Mountain Silt showed no evidence of tectonic rotation, but the Olcese Sand at Nickel Cliff was rotated 35° counterclockwise. This appears to be a local tectonic effect, however, since rotations of middle Miocene rocks in the southern Sierras and Tehachapis are highly variable throughout the region.

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APPENDIX: LOCATION OF PALEOMAGNETIC SITES AND SECTIONS

NICKEL CLIFF SECTION (after Olson et al., 1986; Olson, 1988, fig. 8): south-facing cliffs of Olcese Sand just north of dirt road, SE SW NW sec. 1, T29S R29E, Rio Bravo Ranch 7.5-minute quadrangle, Kern County, California.

FATHER GARCES MONUMENT SITE: upper Round Mountain Silt outcrop on south side of Highway 178 just southeast of Father Garces marker, in a shell hash bed (LACM locality 6603), about 0.25 miles west of junction with Rancheria Road, NE SW SE sec. 1, T29S R29E, Rio Bravo Ranch 7.5-minute quadrangle, Kern County, California. Latitude = N35°24.921', Longitude = W118°50.094'.

BARKER RANCH LOCALITY (USGS locality 1695 of Addicott, 1970, p. 150): shell bed in lower Round Mountain Silt in NW-SE-trending ravine just west of 800-foot contour, NE SE SW sec. 6, T29S R30E, Rio Bravo Ranch 7.5-minute quadrangle, Kern County, California. Latitude = N35°26'18.45", Longitude = W118°52'44.75"

ERNST RANCH SECTION: Round Mountain Silt and Olcese Sand in east-facing slope along north-south ravine, SW NW NW sec. 24, T28 S, R28E, Oil Center 7.5-minute quadrangle, Kern County, California. Approximately 200 m NNE of UCMP locality V99674. Latitude = 35°28'59.16", Longitude = W118°55'00.64" (except for site 1 at the main quarry, Latitude = N35°29.004', Longitude = W118°55.032')

POSO CREEK-ROUND MOUNTAIN ROAD SECTION: Round Mountain Silt and Olcese Sand collected in road cuts and outcrops at the following locations along Poso Creek and Round Mountain Road:

Mon 1 and 2: Mon Bluff (LACM locality 4563), uppermost Round Mountain Silt just below the Mon Bluff Marker Bed; site Mon 1 about 15 feet above road, Mon 2 about 15 feet below top. Located just south of bend in the road at benchmark 645, NW NE NE sec. 4, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.736', Longitude = W118°57.735'.

Poso 1: Road cut on the north side of Round Mountain Road, stratigraphically just above the Sharktooth Hill Bone Bed (exposed 200 m to west at LACM locality 4576), NE SW NE sec. 3, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.485', Longitude = W118°56.845'.

Poso 2: Road cut on the north side of Round Mountain Road, 200 m east of Poso 1. Latitude = N35°31.481', Longitude = W118°56.796'.

Poso 3: In the hills north of Round Mountain Road, from a 1 m-thick white volcanic ash bed, 1.5 m above the top of Sharktooth Hill bone bed (LACM locality 4675 here), SW NE NE sec. 3, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.598', Longitude = W118°56.635'.

Poso 4: In the hills north of Round Mountain Road, from a 1.5 m-thick silty sandstone above the Sharktooth Hill Bone Bed and below the white volcanic ash (LACM locality 4574), center NE NE sec. 3, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California.

Poso 5: Road cut on the north side of Round Mountain Road, southeast of LACM locality 4672 (a major LACM quarry in the Sharktooth Hill Bone Bed excavated in 1983), SW NW NE sec. 2, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.232', Longitude = W118°55.688'.

Poso 6: Road cut on the east side of Round Mountain Road, lower Round Mountain Silt, near LACM locality 4269, NE NW SE sec. 2, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.558', Longitude = W118°56.553'.

Poso 7: In a road cut on the north side of Round Mountain Road, in the basal Round Mountain Silt 1 m above the contact with the Olcese Sand, at LACM locality 4269, NW SW SE sec. 2, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.225', Longitude = W118°55.740'.

Poso 8: Just below Poso 7, in the top 1 m of the Olcese Sand. Latitude = N35°31.225', Longitude = W118°55.740'.

Poso 9: Road cut on the north side of Round Mountain Road, just below Poso 8 in the uppermost Olcese Sand, NW SW SW sec. 1, T28S R28E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°31.033', Longitude = W118°35.343'.

Poso 10: Road cut on the west side of Round Mountain Road, climbing the grade toward Round Mountain, near the base of the upper member of the Olcese Sand, SW NE NE sec. 7, T28S R29E, Knob Hill 7.5-minute quadrangle, Kern County, California. Latitude = N35°30.843', Longitude = W118°55.598'.
Fig. 27A. F:AM.25740, *Tatabelodon gregori*, n.sp., type, from the vicinity of Ainsworth, Nebraska. (Vertical ramus supplied from opposite; position of superior tusk adjusted.)