PALEOMAGNETISM OF THE UPPER PALEOCENE LOCATELLI FORMATION, SANTA CRUZ COUNTY, CALIFORNIA: IMPLICATIONS FOR TECTONIC ROTATION OF THE NORTHERN SALINIAN BLOCK

DONALD R. PROTHERO AND RUBEN A. LOPEZ
DEPARTMENT OF GEOLOGY, OCCIDENTAL COLLEGE, LOS ANGELES, CA 90041

ABSTRACT

The upper Paleocene Locatelli Formation consists of about 300 m of marine sandstones and siltstones which unconformably overlie Cretaceous granites on the Ben Lomond Block of the northern Salinian terrane in the Santa Cruz Mountains, California. Magnetic analysis of samples from the Smith Grade section west of Felton showed that the formation is entirely reversed in polarity. Based on the occurrence of late Paleocene planktonic foraminifera of the P4 zone, and molluscs of the *Turritella infragranulata pachecoensis* zone ("Martinez Stage"), this reversed polarity best correlates with magnetic Chron C26r (58.1-60.9 Ma). The Locatelli Formation yields a paleolatitude of 22.5°, which is about 15° farther south than its present position, and consistent with previous studies of over 2000 km of northward translation since the late Paleocene. In addition, it is rotated about 136 ± 9° clockwise, consistent with results reported from Paleocene rocks at Point San Pedro, about 60 km to the northwest on the same tectonic block. Since the overlying lower Eocene-Oligocene rocks are unrotated, such large clockwise rotations on widely separated regions within the same tectonic block suggest that either the entire block underwent rotation during docking of the terrane, or that different portions of the block underwent the same degree of dextral shear and rotation prior to the early Eocene.

INTRODUCTION

The Salinian block (Howell et al., 1977; Howell and Vedder, 1978; Blake et al., 1982; McWilliams and Howell, 1982; Page, 1982; Vedder et al., 1983) is an exotic terrane approximately 400 km in length that lies west of the San Andreas fault in the Coast Ranges of California (Fig. 1). Several analyses have suggested that this terrane has undergone as much as

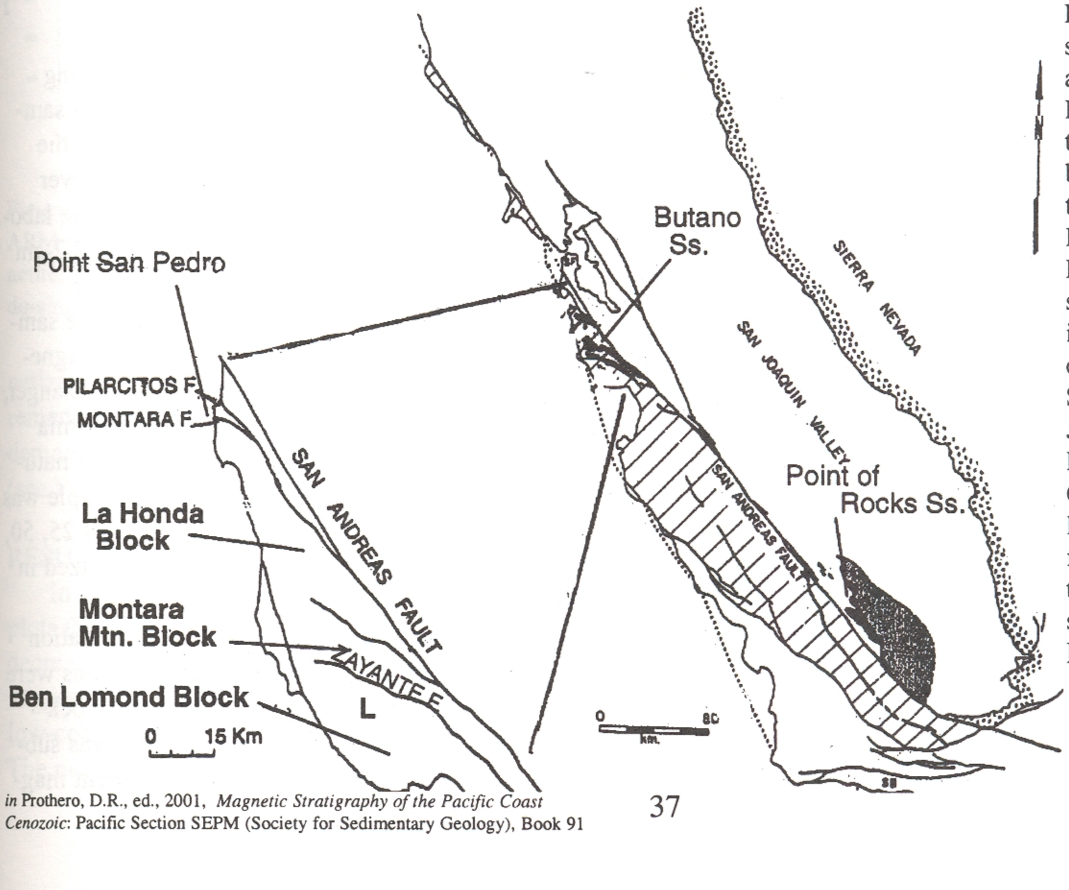

Figure 1. Index map showing location of areas mentioned in text. Diagonally ruled area is the Salinian block. Solid black areas show location of lower-middle Eocene Butano and Point of Rocks sandstones; dark gray area indicates subsurface extent of Point of Rocks Sanstone in the San Joaquin Basin. Enlargement of Santa Cruz Mountains (lower left) shows location of features mentioned in text. L = Smith Grade section of Locatelli Formation.

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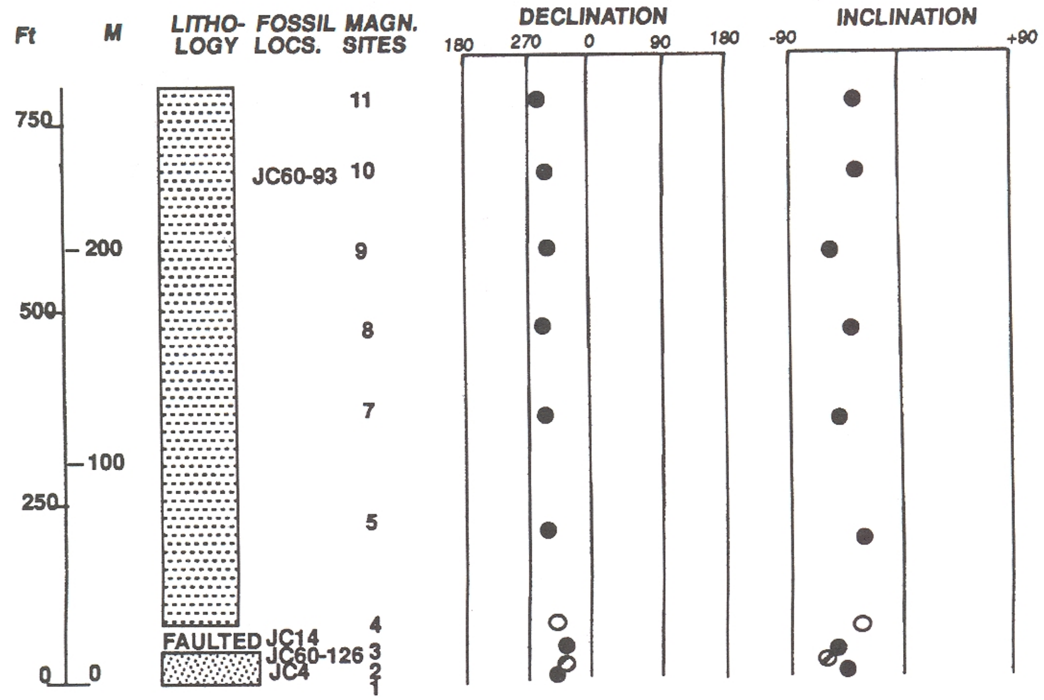

Figure 2. Magnetic stratigraphy of the Locatelli Formation at Smith Grade. Stratigraphy and fossil localities after Clark (1966). Solid circles indicate Class I sites of Opdyke et al. (1977), which are statistically distinguished from a random distribution at the 95% confidence level; circle with diagonal pattern is a Class II site, where one sample was missing, so no statistics could be calculated; open circle is a Class III site, where one sample was divergent, but the other two gave a clear polarity indication.

2500 km of northward transport since the Late Cretaceous (Blake et al., 1982; McWilliams and Howell, 1982; Champion et al., 1984; Lund et al., 1991). By the early Eocene, the Salinian terrane was apparently sutured to North America, and has undergone only northward translation along the San Andreas fault since then.

Paleomagnetic studies (Champion et al., 1984; Kanter and Debiche, 1985; Kanter, 1988) of early Cenozoic rocks from the northern Salinian terrane in the Santa Cruz Mountains have consistently shown about 15-20° of northward latitudinal displacement. Kanter (1988) demonstrated that the lower-middle Eocene Butano Sandstone could be matched up both lithostratigraphically and paleomagnetically with the Point of Rocks Sandstone, 315 km to the south in the southern San Joaquin Basin on the east side of the San Andreas fault (Fig. 1). However, there are relatively few outcrops of Paleocene and Eocene rocks in most of the region that would yield suitable paleomagnetic data for refining the transport history of the Salinian block.

One such unit is the upper Paleocene Locatelli Formation (Cummings et al., 1962; Clark, 1966, 1981; Nilsen and Brabb, 1979), located on the north flank of Ben Lomond Mountain about 5 km west of Felton, California (Fig. 1). The Locatelli Formation consists of about 300 m of marine sandstones, siltstones, with minor conglomerates, which nonconformably overlies Upper Cretaceous granitic rocks; it is disconformably overlain by the lower-middle Eocene Butano Sandstone. In areal extent, however, the Locatelli Formation covers only a few square kilometers, and most of its outcrop is covered by dense vegetation (Clark, 1966, 1981). In no place is a complete section through the formation exposed, but the Smith Grade section of Clark (1966) is the thickest and best exposed, with almost 300 m of strata available for sampling (Fig. 2).

METHODS

Oriented block samples were collected using simple hand tools at 11 paleomagnetic sites (3 samples per site), spanning the entire thickness of the Locatelli Formation along Smith Grade wherever suitable outcrops were available (Fig. 2). In the laboratory, each block was then subsampled into 2.2-cm diameter cores with a air-cooled drill press, or ground into a cylinder using a disk sander. The samples were then analyzed on a 2G cryogenic magnetometer, equipped with an automatic sample changer, at the paleomagnetics laboratory of the California Institute of Technology. After measurement of natural remanent magnetization (NRM), each sample was demagnetized using alternating fields (AF) of 25, 50, and 100 Gauss, and then thermally demagnetized in multiple steps from 300-600°C.

In addition to AF and thermal demagnetization of every sample, about 0.1 g of several samples were powdered and placed in epindorph tubes for rock magnetic analyses. Each powdered sample was subjected to increasing IRM (isothermal remanent mag-

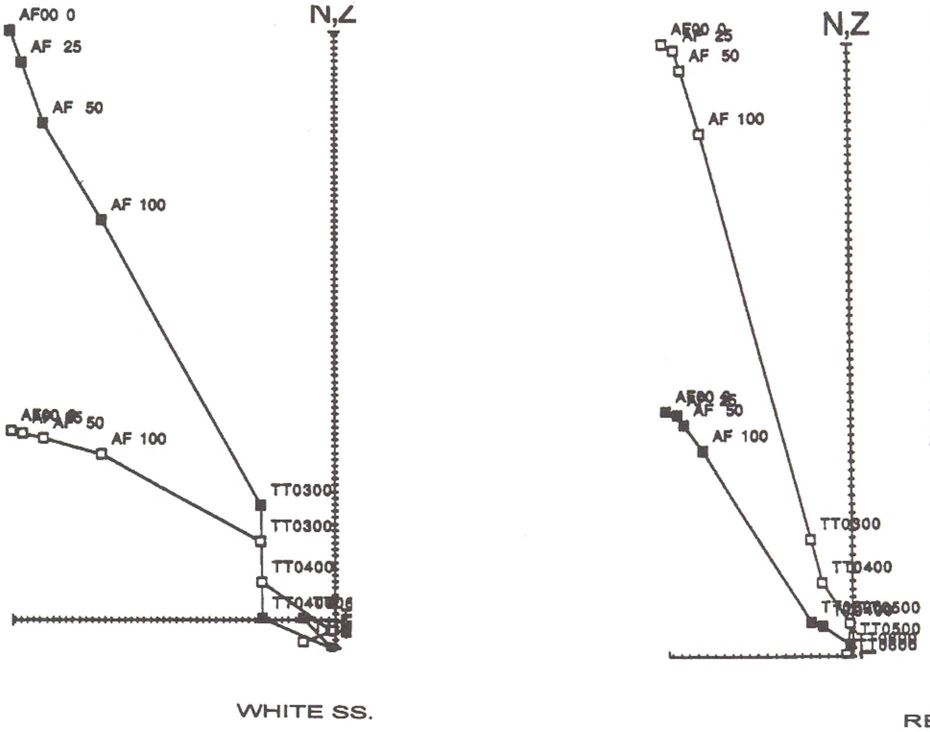

Figure 3. Orthogonal demagnetization plots of representative samples. Solid squares indicate horizontal component; open squares indicate vertical component. AF demagnetization steps ("AF") in Gauss; thermal demagnetization steps ("TT") in degrees Centigrade. Each division = 10^{-7} emu. Both samples show a single component of reversed polarity which was apparent at NRM, and disappeared at 600°C.

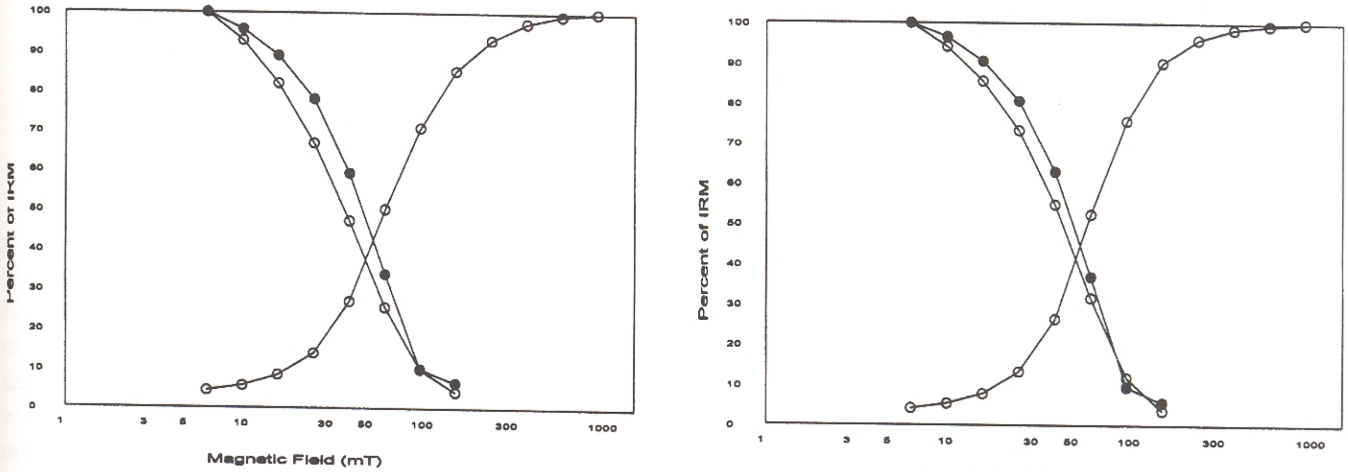

Figure 4. IRM acquisition and Lowrie-Fuller tests of a representative sample. Open boxes are IRM steps; solid boxes are ARM values. The IRM nearly saturates about 300 mT (millitesla), showing that the remanence is carried mostly by magnetite. The ARM is more resistant to AF demagnetization than the IRM, showing that the grains are single-domain or pseudo-single-domain.

netization), and peak IRM and ARM (anhysteretic remanent magnetization) was subjected to AF demagnetization in a modified Lowrie-Fuller test (see Pluhar et al., 1991, for further details).

RESULTS

In most samples, orthogonal demagnetization plots ("Zijderveld" plots) showed significant decrease in intensity during AF demagnetization, suggesting that the remanence is largely held in a low-coercivity mineral such as magnetite (Fig. 3). The nearly complete loss of remanence above the Curie point of magnetite (580°C) is consistent with this interpretation. Most of the samples showed a single stable component of magnetization that was oriented northwest and up after dip correction (Fig. 3). This component was determined using the least squared method of Kirschvink (1980), and then all three vectors at each site were averaged using Fisher (1953) statistics and ranked according to the scheme of Opdyke et al. (1977). The formational mean direction was D = 306.6, I = -40.2, k = 25.4, α_{95} = 9.2 (n = 30).

IRM acquisition studies (Fig. 4) showed that the

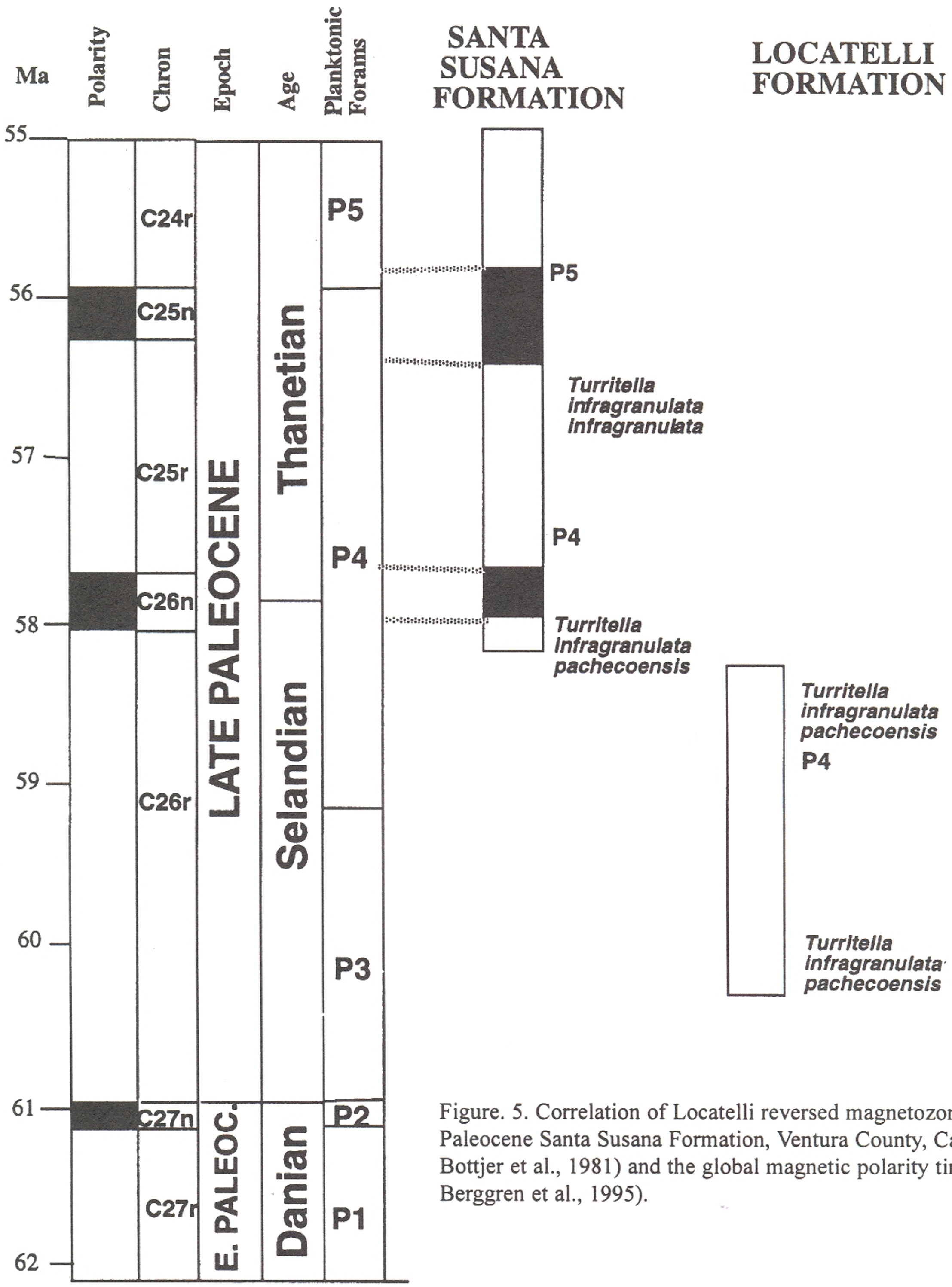

Figure. 5. Correlation of Locatelli reversed magnetozone with the upper Paleocene Santa Susana Formation, Ventura County, California (after Bottjer et al., 1981) and the global magnetic polarity time scale (after Berggren et al., 1995).

IRM starts to plateau at 300 mT, suggesting that magnetite is a major carrier of the remanence, with a minor component of hematite or goethite. In the modified Lowrie-Fuller test, the ARM was more resistant to AF demagnetization than was the IRM, showing that the remanence is held in single-domain or pseudo-single-domain grains.

DISCUSSION

Magnetic Correlation

Since the inclinations were negative (up) after dip correction, the entire Locatelli Formation appears to be of reversed polarity (Fig. 2). The Locatelli Formation yields late Paleocene ("Martinez stage") molluscs such as *Turritella infragranulata*

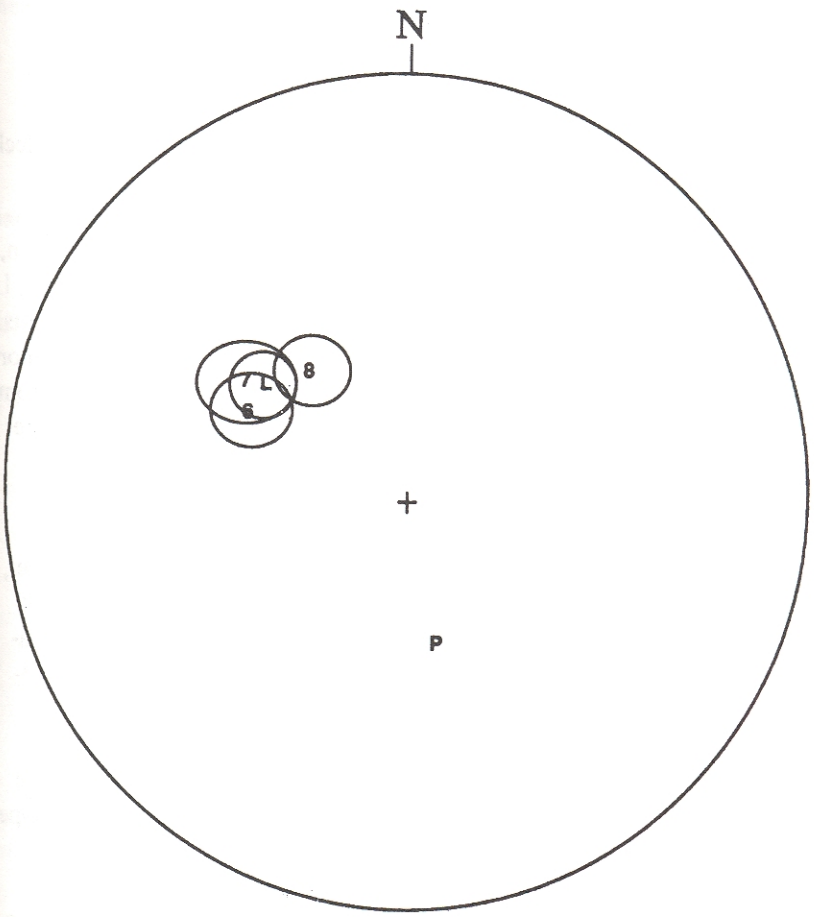

Figure 6. Stereonet showing mean and circle of confidence for the Locatelli Formation (L) and sites 6, 7, and 8 in the Paleocene rocks of Point San Pedro (Champion et al., 1984, Table 2). "P" indicates position of expected reversed polarity Paleocene direction for the Locatelli Formation (based on the Paleocene cratonic pole—Diehl et al., 1983). All means and circles of confidence are upper hemisphere projections, and are corrected for dip.

pachecoensis, as well as Zone P4 planktonic foraminifera, and Ynezian benthic foraminifera (Cummings et al., 1962; Clark, 1966, 1981). Based on the occurrences of these taxa in the Santa Susana and Silverado Formation (Prothero and Lopez, this volume), we correlate the Locatelli Formation with magnetic Chron C26r (58.1-60.9 Ma) (Fig. 5).

Tectonic Translation

The inclination of 40.2° corresponds to a paleolatitude of 22.9°, which is about 15° south of its present latitude of 37.5°. This is consistent with the paleolatitudes reported by Champion et al. (1984, Table 2) for the upper Paleocene rocks at Point San Pedro, about 60 km to the northwest, which they interpreted as evidence for about 2000 km of northward transport since the Late Cretaceous. These rocks were entirely reversed in polarity, and contain the same molluscan and benthic foraminiferal faunas as the Locatelli Formation, so it is reasonable to assume that they are correlative. Kanter (1988) found a mean paleolatitude of 36 ± 2.5° on the early-middle Eocene Butano Sandstone, which unconformably overlies the Locatelli Formation, showing that Santa Cruz Mountain rocks had migrated from the latitude of central Mexico to that of Bakersfield between the late Paleocene and early Eocene. Whidden et al. (1998) argued that the Salinian terrane has been transported only 6° northward, based on Upper Cretaceous redbeds from the La Panza Range in San Luis Obispo County. However, these data come from the central block of the Salinian terrane, which is separated from the northern block (including the Point San Pedro and Locatelli rocks) by several major faults. Our data from the northern block could easily have their own transport history independent of the central block.

Tectonic Rotation

In addition, the declination suggests a clockwise rotation of 136 ± 9° (Fig. 6) after corrections and comparison to the Paleocene cratonic pole (Demarest, 1983; Diehl et al., 1983). Champion et al. (1984) reported declinations in the Paleocene rocks at Point San Pedro ranging from 254-320°, so this extreme rotation is found in both Paleocene units in this region (Fig. 6). Champion et al. (1984) dismissed the large degree of apparent rotation in their rocks as Neogene dextral rotation along the nearby Pilarcitos fault. However, the presence of the same degree of clockwise rotation over 60 km to the southeast (and far from the Pilarcitos fault) shows that the rotation is not a local feature, but found throughout this portion of the Salinian block in the late Paleocene. In addition, Wakabayashi (1999) argued that the Pilarcitos fault does not show the recent activity or proper sense of motion to explain the scatter of the data of Champion et al. (1984) in terms of local rotations by that fault. Instead, we note that only two sites (5 and 6A) show less than 110° of clockwise rotation, while the rest (sites 6B, 7, and 8 of Champion et al., 1984, Table 2) show at least 110° of rotation or more, consistent with our results. Finally, we note that Champion et al. (1984) did no thermal demagnetization of their Point San Pedro samples. Based on the presence of goethite overprints in our samples, we suspect that the anomalously underrotated sites 5 and 6A of Champion et al. (1984) represent insufficient removal of CRM overprints due to goethite.

Apparently, this tectonic rotation was over by the early Eocene, because the lower-middle Eocene Butano Sandstone (D = 148.6, I = -38.8, k = 10.0, α_{95} = 41.0, n = 10) and upper Eocene-Oligocene San Lorenzo Formation (D = 7.5, I = 33.4, k = 16.3, α_{95} = 7.1, n = 55) show no significant tectonic rotation (Prothero, Sutton, and Brabb, this volume).

Two models might explain this major pre-Eocene rotation of the northern Salinian terrane. If the region behaved as a single tectonic block, it might be an exotic terrane that underwent clockwise rotation as it docked during the late Paleocene. However, this model is inconsistent with prevailing ideas about Salinian terrane, which tie it closely to rocks in southern California before its northward transport. Alternatively, the region might be broken into smaller blocks that have rotated together as they underwent dextral slip between the late Paleocene and early Eocene. Certainly, there are many faults in the region which could accommodate such slip. McLaughlin and Clark (in press) suggest that the Zayante fault (Fig. 1) is a major terrane boundary, separating two blocks with very different basement rocks and stratigraphies (the Ben Lomond block, with its Salinian granite basement, and La Honda block, with its gabbroic basement). Currently, we favor the latter interpretation, although this conflicts with the remarkably consistency of the declination values at Point San Pedro and in the Locatelli Formation.

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REFERENCES CITED

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

Blake, M.C., Jr., Howell, D.G., and Jones, D.L, 1982, Preliminary tectonostratigraphic terrane map of California: U.S. Geological Survey Open File Report 82-593.

Bottjer, D.J., Lund, S.P., Power, J.E., and Steele, M.C., 1991, Magnetostratigraphy of Paleogene strata in San Diego and in the Simi Valley, southern California: Pacific Section SEPM, v. 68, p. 115-124.

Champion, D.E., Howell, D.G., and Gromme, C.S., 1984, Paleomagnetic and geologic data indicating over 2500 km of northward displacement for the Salinian and related terranes, California: Journal of Geophysical Research, v. 89, p. 7736-7752.

Clark, J.C., 1966, Tertiary stratigraphy of the Felton-Santa Cruz area, Santa Cruz Mountains, California [Ph.D. dissertation]: Stanford, California, Stanford University.

Clark, J.C., 1981, Stratigraphy, paleontology, and geology of the central Santa Cruz Mountains, California Coast Ranges: U.S. Geological Survey Professional Paper, v. 1168, pp. 1-51.

Cummings, J.C., Touring, R.M., and Brabb, E.E., 1962, Geology of the northern Santa Cruz Mountains, California: California Division of Mines and Geology Bulletin, v. 181, p. 20-24.

Demarest, H.H., Jr., 1983, Error analysis for the determination of tectonic rotation from paleomagnetic data: Journal of Geophysical Research, v. 88, p. 4321-4328.

Diehl, J.F., Beck, M.E., Jr., Beske-Diehl, S., Jacobson, D., and Hearn, B.C., Jr., 1983, Paleomagnetism of the Late Cretaceous-early Tertiary north-central Montana alkalic province: Journal of Geophysical Research, v. 88, p. 10593-10609.

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

Howell, D.G., and Vedder, J.G., 1978, Late Cretaceous paleogeography of the Salinian block, California, *in* Howell, D.G., and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States: Los Angeles, Pacific Section SEPM, p. 532-534.

Howell, D.G., Vedder, J.G., McLean, H., Joyce, J.M., Clarke, S.H., Jr., and Smith, G., 1977, Review of the Cretaceous geology, Salinian and Nacimiento blocks, Coast Ranges of central California, *in* Howell, D.G., Vedder, J.G., and McDougall, K.A., eds., Cretaceous Geology of the California Coast Ranges West of the San Andreas Fault: Los Angeles, Pacific Section SEPM, p. 1-46.

Kanter, K.R., 1988, Paleolatitude of the Butano Sandstone, California, and its implications for the kinematic histories of the Salinian terrane and the San Andreas fault: Journal of Geophysical Research, v. 89, p. 11699-11710.

Kanter, L.R., and Debiche, M., 1985, Modeling the motion histories of the Point Arena and central Salinian terranes, *in* Howell, D.G., ed., Tectonostratigraphic Terranes of the Circum-Pacific Region: Houston, Circum-Pacific Council for Energy and Mineral Resources, p. 227-238.

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.

Lund, S.P., Bottjer, D. J., Whidden, K.J., Powers, J.E., and Steele, M.C., 1991, Paleomagnetic evidence for Paleogene terrane displacements and accretion in southern California: Pacific Section SEPM, v. 68, p. 99-106.

McLaughlin, R.J., and Clark, J.C., in press, Stratigraphy and structure of rocks across the San Andreas fault zone near Loma Prieta, California: their relation to deformation during the October 17, 1989, earthquake: U.S. Geological Survey Professional Paper, v. 1550-E (in press).

McWilliams, M.O., and Howell, D.G., 1982, An exotic origin for terranes of western California: Nature, v. 297, p. 215-217.

Nilsen, T.H., and Brabb, E.E., eds., 1979, Geology of the Santa Cruz Mountains: Cordilleran Section of the Geological Society of America, Field Trip Guidebook.

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.

Page, B.M., 1982, The southern Coast Ranges, *in* Ernst, W.G., ed., The Geotectonic Development of California: Englewood Cliffs, N.J., Prentice-Hall, p. 329-417.

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, p. 31-42.

Vedder, J.G., Howell, D.G., and McLean, H., 1983, Stratigraphy, sedimentation, and tectonic accretion of exotic terranes in the southern Coast Ranges, California: Memoirs of the American Association of Petroleum Geologists, v. 34, p. 471-496.

Wakabayashi, J., 1999. Distribution of displacement on and evolution of a young transform fault system: the northern San Andreas fault system, California: Tectonics, v. 18, p. 1245-1274.

Whidden, K.J., Lund, S.P., Bottjer, D.J., Champion, D., and Howell, D.G., 1998, Paleomagnetic evidence that the central block of Salinia (California) is not a far-traveled terrane: Tectonics, v. 17, p. 329-343.

TABLE 1—Site statistics

	N	D	I	k	α_{95}
1	3	308.4	-43.3	18.1	29.9
2	2	320.6	-64.3	32.1	45.6
3	3	320.6	-43.9	11.7	37.8
4	3	300.5	-21.3	3.8	74.2
5	3	309.8	-22.3	11.6	38.0
7	3	289.9	-49.3	33.7	21.6
8	3	309.0	-33.8	6.4	53.6
9	3	319.6	-61.6	35.0	21.2
10	3	307.0	-32.7	9.8	41.8
11	3	292.0	-33.7	49.0	17.8