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Compaction-corrected inclinations from southern California Cretaceous marine sedimentary rocks indicate no paleolatitudinal offset for the Peninsular Ranges terrane

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Abstract. Paleomagnetic data have been used extensively to delineate the terrane displacement and accretion history of the western margin of North America. However, the anomalously shallow paleomagnetic inclinations used to indicate large-scale northward translation might be alternatively interpreted as due to postmagnetization tilting of batholithic rocks and compaction of marine sediments. To understand the magnitude of burial compaction effects on the post-Cretaceous motion history of the Peninsular Ranges-Baja Borderlands terrane, a rock magnetic, compaction, and paleomagnetic study of the Ladd Formation and the Point Loma Formation from southern California was conducted. The anhysteretic anisotropy of remanence of the characteristic remanence-carrying grains and individual magnetic grain anisotropy were used to correct the inclinations of each formation. Individual magnetic grain anisotropy was determined by both compaction experiments and redeposition of a magnetic separate in a DC magnetic field. Standard paleomagnetic studies of the units indicated that previous Ladd Formation results could be reproduced, and a correction was made at the sample level. We were unable to adequately reproduce earlier results of the Point Loma Formation, so the average remanence anisotropy was used to correct the previously reported mean direction. The mean inclination of the Ladd Formation was corrected from 46° (α_{95}=8°) to 58° (α_{95}=4°), and the mean inclination of the Point Loma Formation was corrected from 39.5°±5.4° (normal) and -36.4° ± 16.6° (reversed) to 56.0°±5.1° (normal) and -53.0°±16.7° (reversed). These results suggest that the Peninsular Ranges-Baja Borderland terrane has been part of the western North America since the Late Cretaceous and that clay-containing sedimentary rocks may typically experience from 10° to 15° of inclination shallowing due to burial compaction.

1. Introduction

More than 50 tectonostratigraphic terranes have been recognized in the North American Cordillera [e.g., *Coney et al.*, 1980; *Jones et al.*, 1981; *Howell*, 1989]. Rock sequences, faunal records, as well as paleomagnetic data have been used to support significant displacements and/or rotations between many of the terranes and cratonic North America [*Coney et al.*, 1980; *Jones et al.*, 1981; *Howell*, 1989]. However, a fundamental disagreement has arisen about the magnitude of allochtheneity of the Cordilleran terranes. This disagreement is best exemplified by arguments for and against the far-traveled nature of the Insular superterrane of the northern Cordillera, also known as the Baja British Columbia (Baja B.C) hypothesis [*Cowan et al.*, 1997]. The evidence for more than 3000 km of post-mid-Cretaceous offset of Baja B.C. comes primarily from paleomagnetic data while geologic data do not support significant transport. *Cowan et al.* [1997] have proposed critical tests of the competing hypotheses for and against large coastwise transport of Baja B.C. The allochtheneity of southern California terranes are part of this picture and are the focus of this paper.

The southern California and Baja California Coast Ranges are made up of two composite tectonostratigraphic terranes or superterranes (Figure 1) [*Lund and Bottjer*, 1991]. Stratigraphy indicates that these two superterranes are composed of several smaller terranes which amalgamated during the late Mesozoic. The Santa Lucia terrane, also called the Santa Lucia-Orocopia allochthon [*Vedder et al.*, 1983; *Lund and Bottjer*, 1991; *Butler et al.*, 1991; *Dickinson and Butler*, 1998], includes the area west of the San Andreas and San Gabriel faults and north of the Oak Ridge fault (Figure 1). To the north, along the coast, the Santa Lucia terrane includes the Salinian block. Sequence stratigraphy, basement rock chemistry, and fossil records from the terrane have been interpreted to support its allochthoneity [*Page*, 1982; *Vedder et al.*, 1983; *Bottjer and Link*, 1984]. Paleomagnetic studies of late Mesozoic and early Tertiary marine sediments suggest that the Santa Lucia allochthon amalgamated during the Mesozoic at an equatorial paleolatitude and traveled more than 2500 km northward since the Cretaceous [*Champion et al.*, 1984; *Kanter and Debiche*, 1985]. Subsequent compaction-correction work on the paleomagnetic results from the Cretaceous Pigeon Point Formation (Fm.) has reduced the amount of northward transport for the Salinian block to 1400±900 km. Consideration of the 95% confidence limits on the corrected Pigeon Point Fm. inclination would make the offset come into agreement with the 1000 km offset proposed

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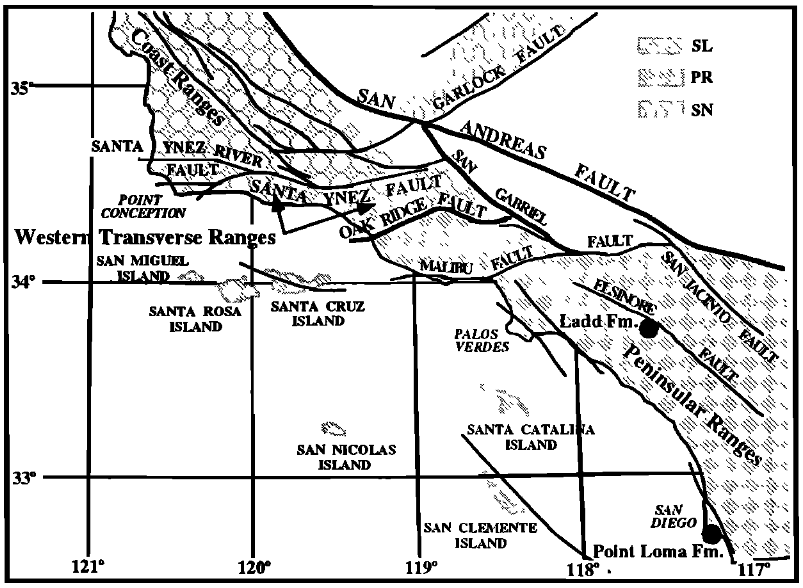

Figure 1. Simplified terrane map for southern California showing the location of the Peninsular Ranges terrane (PR) and the Santa Lucia allocthon (SL). The Sierra Nevadas are also shown (SN) Map is modified from *Lund and Bottjer* [1991] (S.P Lund and D.J Bottjer AAPG©1991, reprinted by permission of the American Association of Petroleum Geologists). The sampling localities for this study (Ladd Formation and the Point Loma Formation) are indicated by solid circles

by *Cowan et al.*'s [1997] hypothesis B for Salinia. *Dickinson and Butler* [1998], however, have taken into account rotation of the Transverse Ranges and moved the Salinian block farther to the south by ~7°. This reconstruction removes any discordance between Salinia, based on the corrected Pigeon Point inclination, and cratonic North America

The second tectonostratigraphic terrane, called the Peninsular Ranges terrane [*Bottjer and Link*, 1984] or the Baja Borderlands terrane [*Vedder et al.*, 1983], lies west of the San Andreas fault and south of the Oak Ridge and San Gabriel faults and includes all of Baja California (Figure 1). Geologic evidence for its allochthoneity is mixed. Sequence stratigraphy and fossil records on the Peninsular Ranges terrane are distinctly different from the stratigraphy and fossils in the rocks currently adjacent to the terrane along its boundaries [*Bottjer and Link*, 1984] However, Paleozoic roof pendants within the Peninsular Ranges batholith in Baja California have been correlated with rocks located nearby across the Gulf of California [*Gastil*, 1991]. Paleomagnetic data from both Late Cretaceous igneous rocks and marine sediments indicate more than 1000 km of northward displacement since the Late Cretaceous for the Peninsular Ranges *terrane [Teissere and Beck*, 1973, *Patterson*, 1984, *Fry et al.*, 1985; *Hagstrum et al*, 1985, *Morris et al.*, 1986, *Bannon et al.*, 1989].

The large-scale northward translation of these two terranes would require a megashear either on land or offshore to accommodate their motion with respect to stable North America. Since almost all the oceanic crust east of the Pacific-Farallon spreading center has been subducted, any evidence of an oceanic shear zone has been lost. A variety of geologic data across the terrane boundary do not support the existence of a megashear on land; therefore there is a lack of geological evidence that supports the motion of these terranes along the coast of western North America from low southern paleolatitudes to their present position [*Gastil*, 1991]. *Beck* [1991] reviewed a variety of possible errors in and alternative explanations for paleomagnetic data from the western North American margin which, in contradiction to the geologic evidence, do support significant northward transport. He dismissed possibilities such as remagnetization, batholith tilting, or inclination shallowing, and he argued instead that undiscovered faults or shear zones might exist which had accommodated the terranes' northward translation.

Butler et al. [1991] challenged the traditional explanation that the paleomagnetic data indicate large-scale latitudinal displacements K-Ar and U-Pb isotopic data [*Silver et al.*, 1979; *Silver and Chappell*, 1988] from the Peninsular Ranges batholith in southern California indicate a differential uplift history for the batholith. The anomalously low inclination for the paleomagnetic data from the batholith could be explained by tilting after the acquisition of its thermal remanent magnetization (TRM) [*Butler et al.*, 1991]. The agreement between the batholith and marine sedimentary paleomagnetic data had previously been used to rule out inclination shallowing in the sedimentary rocks. With the possibility that the batholithic paleomagnetic data have been affected by tilting, the supporting evidence for a tectonic explanation of shallow sedimentary inclinations has been removed Butler et al., and more recently *Dickinson and Butler* [1998], suggest that the shallow paleomagnetic inclinations for the Peninsular Ranges marine sedimentary rocks might instead have been caused by a burial compaction effect, and they suggest that these terranes have not moved at all, or less than paleomagnetic data can resolve with respect to cratonic North America.

A subsequent paleobarometric study of the Peninsular Ranges batholith suggests that tilting could account for at most only a part of its anomalous shallow inclination. The tilt-corrected paleomagnetic data could still indicate significant northward displacement (1000 ±450 km) relative to cratonic North America since the Late Cretaceous [*Ague and Brandon*, 1992]. However, the effect of tilting on a batholith's remanent magnetization depends on whether the tilting occurred at a temperature below or above the blocking temperature at which the batholith's thermal remanent magnetization was acquired [*Constanzo-Alvarez and Dunlop*, 1988, *Beck*, 1992]. *Dickinson and Butler* [1998] suggest that the paleomagnetic sites are located in a part of the batholith that acquired its TRM before tilting, but they argue that the paleobathymetrically tilt-corrected paleomagnetic inclination yields a paleolatitudinal offset of only 700±450 km, once the Neogene offset along the San Andreas fault is removed. Its significance is therefore difficult to resolve given the combined uncertainties in the paleobathymetrically determined tilt axis and the paleomagnetic data. Since the impact of the batholithic data has been reduced by the possibility of tilting explaining all or most of the shallow inclination, examining the possibility of inclination shallowing in the marine sediments becomes crucial to understanding the tectonic history of the western North American continental margin.

Most of the units indicating low paleolatitudes from the Peninsular Ranges terrane are marine sedimentary rocks, mainly turbidites. An early study by *Simpson and Cox* [1977] suggested that turbidites were immune from inclination shallowing. The inclination of the Eocene Tyee and Floumoy Formations of Oregon agreed with the inclination of the coeval Siletz River Volcanics. This result has been used, implicitly, to support the accuracy of the anomalously low inclinations from the Peninsular Ranges terrane marine sedimentary rocks. *Dickinson and Butler* [1998] carefully examined the Simpson and Cox data set and point out that the turbidite facies are about 10° shallower than the volcanics and the deltaic and shelf facies sedimentary rocks. *Kodama and Davi*'s [1995] compaction-correction work on the Pigeon Point Formation sedimentary rocks provides further evidence that indicates turbidites can suffer from over 10° of shallowing caused by burial compaction. Since almost all the sedimentary units that yield paleomagnetic data supporting northward transport for the Peninsular Ranges terrane are similar in lithology to the Pigeon Point Formation (neritic to bathyal), there is increased probability that the data indicating northward motion of the Peninsular Ranges terrane should be corrected for compaction-caused inclination shallowing.

In this study we will use bulk sample remanent magnetic anisotropy and individual magnetic particle anisotropy to recognize and correct for inclination shallowing of two units from the Peninsular Ranges terrane. The validity and accuracy of this approach, originally proposed by *Jackson et al.* [1991], have been confirmed by a detailed rock magnetic study of the anomalously shallow inclination in the Paleocene Nacimiento Formation [*Kodama*, 1997].

2. Methods

Our study comprised two parts: a standard paleomagnetic study, which isolated the characteristic remanence (ChRM) of a unit, and a detailed rock magnetic study designed to identify and correct any inclination shallowing. In this work we follow *Jackson et al.*'s [1991] theoretical approach:

$$\tan(I_c)/\tan(I_o) = \{[q_z(a+2)-1]/[q_x(a+2)-1]\} \quad (1)$$

where I_c is the inclination affected by compaction; I_o is the inclination before compaction; q_z is $\mathrm{ARM_{min}}/(\mathrm{ARM_{max}}+\mathrm{ARM_{int}}+\mathrm{ARM_{min}})$; q_x is $\mathrm{ARM_{max}}/(\mathrm{ARM_{max}}+\mathrm{ARM_{int}}+\mathrm{ARM_{min}})$ where ARM is anhysteretic remanent magnetization; and a is the individual magnetic grain anisotropy factor ($\mathrm{ARM_{easy\ axis}}/\mathrm{ARM_{hard\ axis}}$).

To use (1) to identify and correct for inclination shallowing, we needed to measure the anisotropy of anhysteretic remanence (AAR) of the samples and the individual magnetic grain anisotropy factor a. a was determined by two techniques: laboratory compaction experiments and direct measurement of a redeposited magnetic separate [see *Kodama*, 1997]. In compaction experiments the values of I_c, I_o, q_z and q_x can be measured and a is calculated by using (1). In the direct measurement method a magnetic separate is mixed into epoxy and allowed to harden in the presence of a strong DC magnetic field. It is assumed that all the magnetic particles will have their magnetic easy axes (long axes) aligned parallel to the DC field. The individual particle anisotropy is estimated by the bulk anisotropy of the epoxy sample. *Kodama*'s [1997] study of the Nacimiento Formation gives confidence that the laboratory compaction and direct measurement techniques will yield similar results for the individual grain anisotropy a.

We studied two of the marine sedimentary formations from the Peninsular Ranges terrane that have yielded anomalously low inclinations in previous studies [*Butler et al*, 1991; *Lund and Bottjer*, 1991]. Since *Hagstrum* [1990; also written communication, 1996] has suggested that most of the formations used to delineate the paleolatitude of California terranes may have been remagnetized during Late Cretaceous and Tertiary terrane accretion, we restricted our study to units with magnetostratigraphies as evidence that they have probably escaped extensive remagnetization. These formations are the Late Cretaceous Ladd Formation of Silverado Canyon, Orange County, California [*Almgren*, 1982], and the Point Loma Formation of Point Loma, San Diego County, California [*Nilsen and Abbott*, 1981]; both are marine terrigenous clastic rocks of either neritic or bathyal facies. Detailed magnetostratigraphies were reported by *Fry et al* [1985] and *Bannon et al.* [1989], for these sections, respectively

Twenty-five sites were collected from the Ladd Formation (Figure 2). Six to ten cubic (8 cm^3) samples were cut at each site using a dual-bladed, battery-powered masonry saw [*Ellwood et al.*, 1993], and 2 cm x 2 cm x 2 cm plastic boxes were fit over each sample. Samples were oriented with a Brunton compass and removed from the outcrop. Lithologies sampled included the sandstone of the Baker Canyon Member and the siltstone, sandstone, and limestone of the Holz Member. Bedding dips 30°-50° to the west in the Baker and Holz Members at the sampling locality. The Ladd Formation yields marine fossils, including ammonites and calcareous nannofossils, which indicate late Turonian to middle Campanian ages [*Fry et al.*, 1985]. These ages are supported by the magnetostratigraphic study [*Fry et al*, 1985] The section is interpreted to represent continental slope and shallow marine depositional environments based on foraminiferal assemblages [*Almgren*, 1982]

Seventeen oriented hand samples were collected from the Point Loma Formation at three localities La Jolla Cove, Sunset Cliffs, and near the sewage treatment plant at Point Loma (Figure 2) Six to ten cubic (8 cm^3) samples were cut from each hand sample with an aluminum-bladed trim saw at

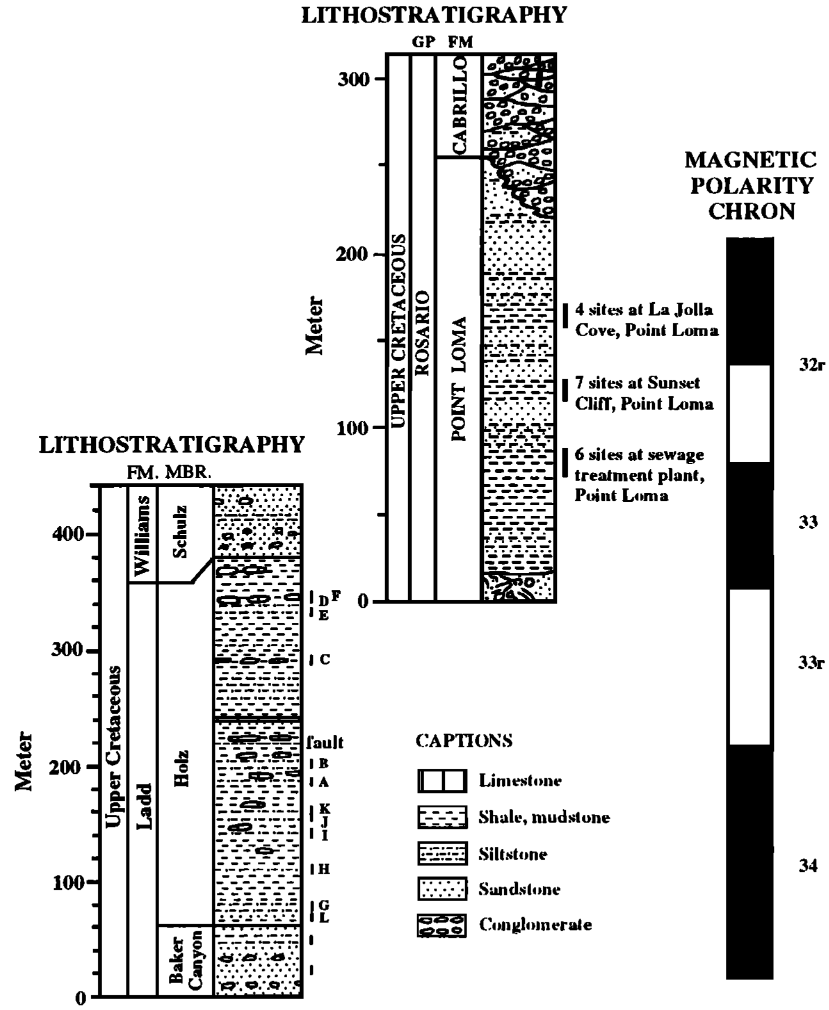

Figure 2. Lithostratigraphic sections, showing sampling localities for this study, from the Ladd and Point Loma Formations (based on *Fry et al.* [1985] and *Bannon et al.* [1989]. Reproduced by permission of the Geological Society of America. Faith Rogers Managing Editor, GSA.). Age of each section relative to the geomagnetic polarity timescale is based on Fry et al.'s magnetostratigraphic work on the Ladd Formation and Bannon et al 's magnetostratigraphic work on the Point Loma Formation.

the paleomagnetics laboratory of the University of Southern California. Lithologies in this section are mostly mudstone and shale, interbedded with thin-layered siltstones, representing a deepwater marine depositional environment. Paleontology and magnetostratigraphy indicate a late Campanian to early Maastrichtian age for the Point Loma Formation [*Bannon et al.*, 1989]. The section is folded in a gentle syncline (less than 10° dips) with an east-west trending fold axis.

In the paleomagnetic study, four representative samples from each site were subjected to either detailed progressive thermal or alternating field (af) demagnetization in 10-15 steps up to 600°C or 100 mT. The remaining samples were demagnetized in fewer steps (4-6) based on the demagnetization behavior observed in the initial pilot samples Characteristic remanences (ChRM) were calculated using principal component analysis [*Kirschvink*, 1980]. The remanent magnetization of samples was measured with a CTF Systems Inc. two-axis superconducting magnetometer. Thermal and af demagnetization was conducted using Schonstedt TSD-1 and GSD-5 demagnetizers.

In the rock magnetic study, anisotropy of anhysteretic remanence (AAR) was measured for those samples that yielded ChRMs during af demagnetization. Partial anhysteretic remanent magnetizations (pARM) were measured in 10 mT af windows (0.1 mT DC field) for one sample from each site in order to determine coercivity spectra. The pARM spectra were used in conjunction with af demagnetization results to determine the coercivity window for AAR measurements. AAR was measured following *McCabe et al.*'s [1985] procedure. Samples were given a pARM in nine orientations with a 0.1 mT DC field, and best fit AAR tensors were determined by least squares.

It is particularly important to determine if magnetic minerals in addition to those carrying the ChRM are present in the rocks. These additional magnetic minerals may not carry the ChRM, but they may contribute to a laboratory-induced magnetization, for example, pARM, which will be used to identify and correct inclination shallowing. For this reason, the isothermal remanent magnetization (IRM) acquisition and back field demagnetization curves of representative samples from every site that yielded ChRMs were used to characterize the magnetic mineralogies in the samples. Samples were given IRMs in fields up to 1.2 T in an ASC Scientific IM-10-30 impulse magnetizer. In addition to this analysis, thermal demagnetization of an IRM applied in a 1.2 T field perpendicular to a pARM acquired in a 0.1-0 T window was used to identify magnetic mineralogy, especially to determine the importance of remanence carried by high-coercivity magnetic minerals with respect to the AAR applied to samples.

Individual magnetic particle anisotropy was determined by laboratory compaction experiments and by deposition of a magnetic extract in a DC magnetic field. For the laboratory compaction experiments a hand sample from each site was carefully disaggregated so that the sediment would have a grain size distribution as close as possible to its initial, syndepositional grain size distribution. Disaggregation was accomplished by wrapping bulk rock samples in paper and crushing them into small pieces with a rock. A hammer was not used to avoid any magnetic contamination. Fragments ~5 mm in size were chosen for disaggregation in deionized water with an ultrasonic cleaner. The silt and fine sand grains were frequently checked under a light microscope (x30 magnification) to determine whether the sediment grains were composed of single particles. A slightly oversaturated slurry was made from these disaggregated sediments for compaction experiments. The slurry made from the Holz member silt was ~80 wt % water content, and the slurry made from the Point Loma Formation mud was ~280% water content. The difference in water content between these two slurries is due to their different clay contents.

Redeposition and compaction experiments were conducted in a magnetic field maintained by Helmholtz coils to have an inclination of 58°, which is close to the expected Late Cretaceous geomagnetic field inclination for the sampling localities, assuming they were part of North America. The intensity of the laboratory magnetic field was ~80 μT, the lowest field the coils could produce for a field with a 58° inclination. Although the field is stronger than the present Earth's magnetic field, it should not affect our determination of the *a* factor. The magnetic field, measured with a Bartington fluxgate magnetometer, is uniform within a 3 cm x 3 cm x 3 cm region. The sediment slurry was dripped into an acrylic, cylindrical sample holder with a small spoon. The sample holder is weakly magnetized (< 5×10^{-10} A m^2), 2 orders of magnitude less than the sample's overall magnetic intensity. After the slurry had acquired its magnetization along the ambient magnetic field, it was compacted with a water tank consolidometer, which is the same one used in previous compaction studies by *Anson and Kodama* [1987], *Deamer and Kodama* [1990], *Kodama and Sun* [1992], *Sun and Kodama* [1992], *Kodama and Davi* [1995], and *Kodama* [1997]. A detailed description of the consolidometer can be found in the work of *Hamano* [1980] and *Anson and Kodama* [1987]. The pressure on the slurry was increased at a rate of 0.008 MPa h^{-1}. The volume and remanent magnetization of the samples were measured more than 10 times at various stages of compaction.

Kodama and Davi [1995] observed that laboratory-redeposited and -compacted Pigeon Point Formation samples suffered from significant viscous overprints; hence, after compaction was completed for our samples, ChRMs were isolated by both thermal and af demagnetization. Demagnetization also served to ensure that the remanence isolated from the compacted samples was carried by the same magnetic grains that carried the natural samples' ChRM and had their fabric measured by AAR. The af demagnetized compaction samples subsequently had their AAR measured. Acquisition of IRM curves and partial ARM (pARM) spectra of the natural samples and the redeposited samples were used to monitor the magnetic mineral types and their grain size distribution before and after the disaggregation process.

For the epoxy redeposition experiments a permanent magnet was used to extract magnetic minerals from a slurry made from the disaggregated sediments. Two different magnets were used. A bar magnet was used to extract the magnetic minerals from the slurry made from the Holz Member silt and a rare earth magnet 10 times stronger was used to extract particles from the Point Loma Formation slurry The extracted magnetic minerals were mixed with epoxy, and the mixture was allowed to cure in an electromagnet maintaining a DC magnetic field with intensity between 20 and 70 mT. A suite of epoxy drying experiments was conducted with increasingly stronger magnetic fields [*Jackson et al.*, 1991; *Kodama*, 1997] to determine if magnetic grain alignment was saturated. After the epoxy samples hardened, their pARM spectra and AAR were measured. The pARMs were applied parallel and perpendicular to the direction of the applied DC field, and particle anisotropy was determined by $a=ARM_{par}/ARM_{per}$. A standard nine position AAR measurement routine of the epoxy samples was also used to determine the value of particle anisotropy. These two estimates were compared.

Scanning electron microscope (SEM) observation of the extracted magnetic minerals was used to check the value of individual particle anisotropy *a* derived from the laboratory compaction and epoxy redeposition experiments. Since these samples appear to have a ferrimagnetic mineral, probably magnetite, as their predominant magnetic mineral, shape anisotropy of the particles should be related to the individual magnetic particle anisotropy *a*. SEM observations were also used to check if incomplete dispersal, clumping, or chains of magnetic particles in the epoxy caused an unreliable estimate of the particle anisostropy. In order to prepare the epoxy samples for SEM examination, a vertical surface was cut. Each sample was wrapped by high-conductivity tape and only a 3 mm x 5 mm area was exposed for observation to avoid charging during SEM examination. To further reduce the effects of charging, a low-energy (1 keV) electron beam was chosen. All SEM work was conducted on a JEOL JSM-6300F scanning electron microscope.

Previous studies have demonstrated that clay content is an important factor causing inclination shallowing [*Anson and Kodama*, 1987; *Deamer and Kodama*, 1990; *Kodama and Sun*, 1992; *Sun and Kodama*, 1992]. For this reason we determined the composition and the clay content of the disaggregated samples from the Holz Member and the Point Loma Formation, as well as representative samples from the Pigeon Point and Nacimiento Formations for which the magnitude of inclination shallowing had been established in previous studies [*Kodama and Davi*, 1995; *Kodama*, 1997] Two techniques were used: standard grain size analysis determined the proportion of clay-sized sediment grains, and X ray diffraction of the slurry and the clay fraction identified the clay minerals. The grain size analysis included sieving to isolate the proportion of particles with $\phi\leq4$ Settling in water was used to determine the grain size distribution in the range $5\geq\phi\geq11$. To prepare the clay-sized samples for X ray diffraction, they were centrifuged at 500 rpm for 8.8 min to remove particles greater than 2 μm. The samples were then filtered through a 0.45 μm Millipore filter. The filtrate was transferred to a glass slide, air dried, then placed in a desiccator containing ethylene for 24 hours, and X rayed with a Philips XRG 3100. After the determination of individual magnetic particle anisotropy and the bulk sample remanence anisotropy (AAR), the ChRM inclination of each sample was corrected by using (1) to yield the compaction-corrected paleolatitude for the Peninsular Ranges terrane.

3. Results

3.1. Paleomagnetic Study

Both reversed and normal polarity natural remanent magnetizations (NRMs) are observed for the Holz Member siltstone and limestone samples of the Ladd Formation The normal polarity group has scattered north-northeasterly declinations and steep downward inclinations, close to the present geomagnetic field direction. The reversed polarity group has southerly declinations with both positive and negative, shallow inclinations (Figure 3). Both polarity samples yielded easily interpretable demagnetization behavior (Figure 4). Thermal demagnetization successfully isolated ChRMs in 11 sites, and alternating field (af) demagnetization was successful in 10 sites. Both thermal and af demagnetization revealed two components of magnetization. The low unblocking temperature component was removed by 300°C in the siltstones and by 200°C in the limestones. The low-coercivity component was removed by 20 mT in both lithologies. These low-stability components were scattered in declination with steep downward inclinations, probably due to the acquisition of a viscous remanence during storage. The ChRMs were isolated at temperatures up to 550°-600° C and by alternating fields of ~70 mT. The site mean directions resulting from thermal and af demagnetization are in good agreement (Figure 5 and Table 1). Magnetic susceptibility of the siltstone and limestone samples increased during thermal demagnetization above 500°C, which may indicate alteration of the magnetic minerals. These changes caused minor variations in remanent magnetization direction and greater sample measurement errors.

The limestone samples broke apart during thermal demagnetization above 300°-350° C. Therefore the remaining samples from each site were subjected to 4-6 steps of thermal demagnetization up to 500°C for siltstones and 300°C for limestones. Those remaining samples subjected to af demagnetization were demagnetized in 4-6 steps up to a 60 mT peak field.

Stepwise tilt correction of the ChRM site mean directions indicates that the precision parameter of the mean of the site means reaches a maximum at 86% untilting (Figure 5), but both *McElhinny*'s [1964] and *McFadden and Jones'* [1981] fold tests indicate that this does not represent a statistically significant synfolding or prefolding magnetization at the 95% confidence level. This result is not unexpected since the strata are exposed in a monocline with little variation in bedding tilt throughout the section. *McFadden*'s [1990] fold test, which is more sensitive to bedding distortion, yielded critical values of 4.036 and 5.624 at 95 and 99% confidence levels, respectively. The in situ statistical parameter ξ_2 is 8 826, while the 100% unfolded statistical parameter is 1 698. Thus the McFadden fold test excludes a postdeformation age for the ChRM. The magnetization may be either predeformation or syndeformation in age.

A positive reversal test [*McFadden and McElhinny*, 1990] could eliminate the possibility of syndeformational remanence. However, the precision parameters of the normal polarity mean and reversed polarity mean directions are significantly different. In this case the reversal test must be performed by simulation [*McFadden and McElhinny*, 1990]. The reversal test for the site means in geographic coordinates is negative, while the tilt-corrected normal and reversed site mean directions pass the reversal test with a C classification. The low classification may in part be due to a larger difference in declinations between reversed and normal polarity means than in inclination. The greater scatter in declination may be due to differential bedding rotations on either side of a fault cutting through the middle of the exposed section. The stratigraphic variation of polarity for our results is consistent with the magnetostratigraphy reported by *Fry et al.* [1985].

Samples from the Baker Canyon Member of the Ladd

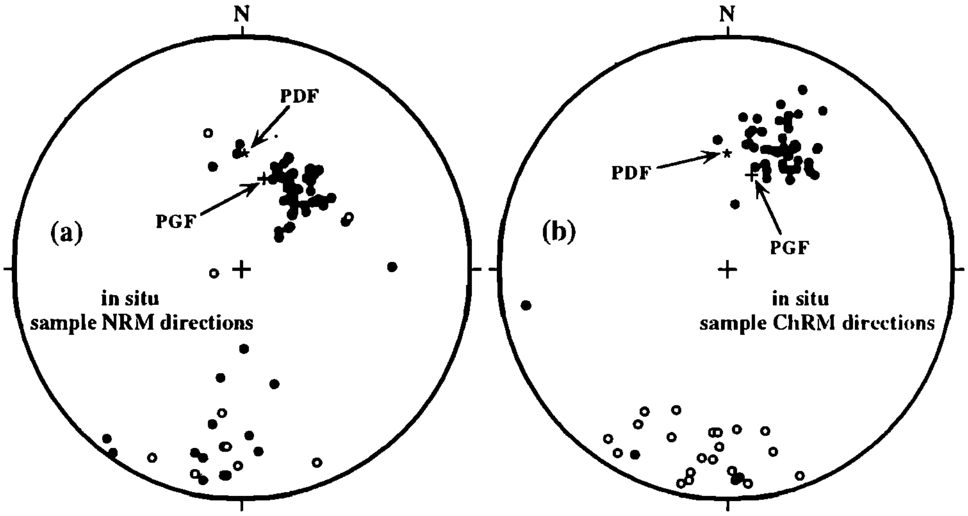

Figure 3. Natural remanent magnetizations (NRMs) and characteristic remanences (ChRMs) for the Ladd Formation with equal area stereonets showing (a) sample NRM directions and (b) ChRM sample directions in geographic coordinates. Solid circles indicate lower hemispheric projections and open circles show upper hemisphere projections. PDF, present dipole field, PGF, present geomagnetic field.

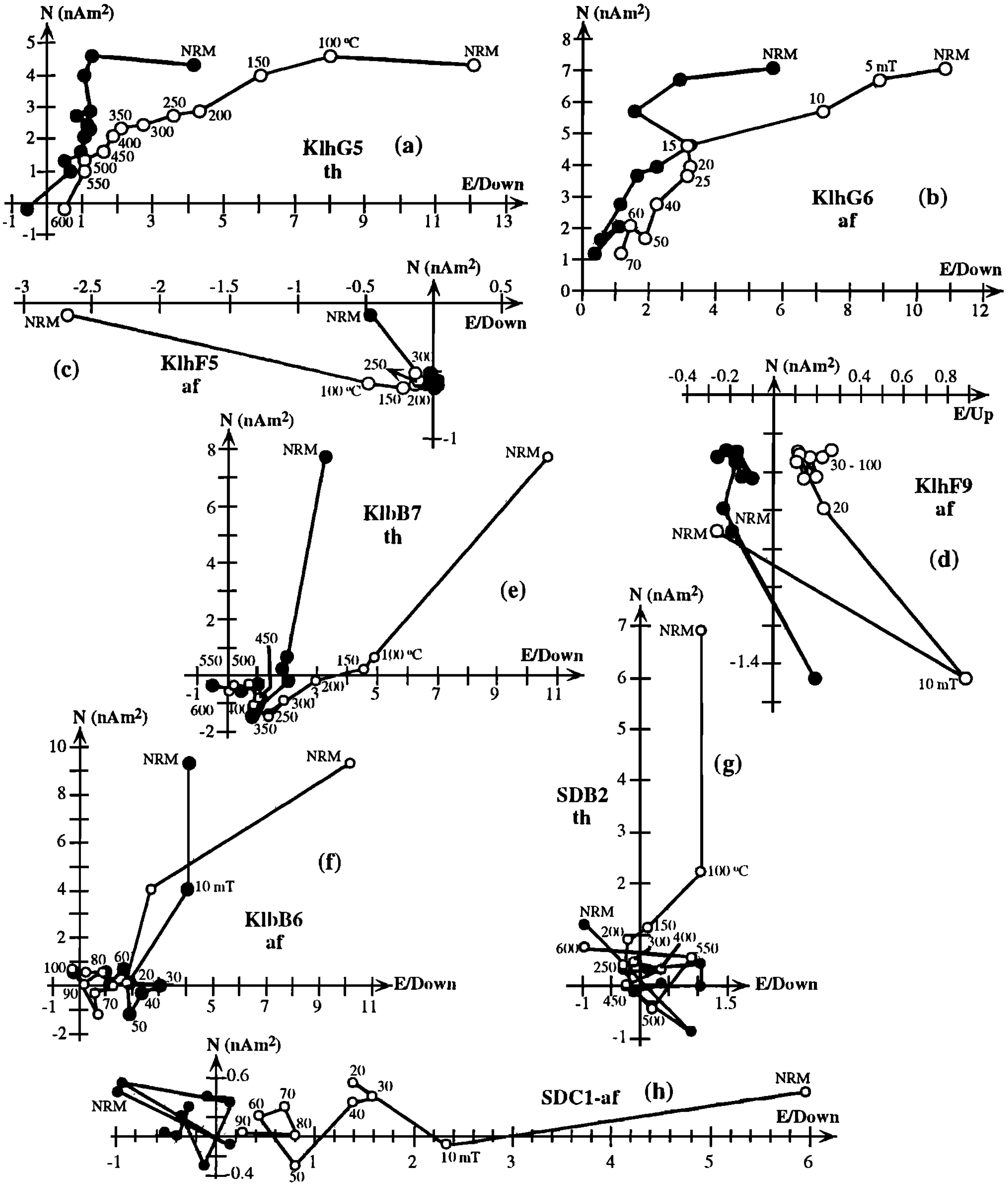

Figure 4. Representative orthogonal vector endpoint projections [*Zijderveld*, 1967] for alternating field (af) and thermal demagnetization (th) data from (a-d) the Holz Member of the Ladd Formation, (e and f) the Baker Canyon Member of the Ladd Formation, and (g and h) the Point Loma Formation. Uninterpretable demagnetograms are shown for the Point Loma Formation (Figures 4g and 4h) and for the Baker Canyon Member of the Ladd Formation (Figures 4e and 4f). Although linear decay toward the origin was not observed in Figures 4c and 4d, the directions determined from the high-temperature or high-coercivity demagnetization steps were in good agreement with ChRMs determined by principal component analysis. Solid circles indicate the horizontal component and open circles indicate the vertical component.

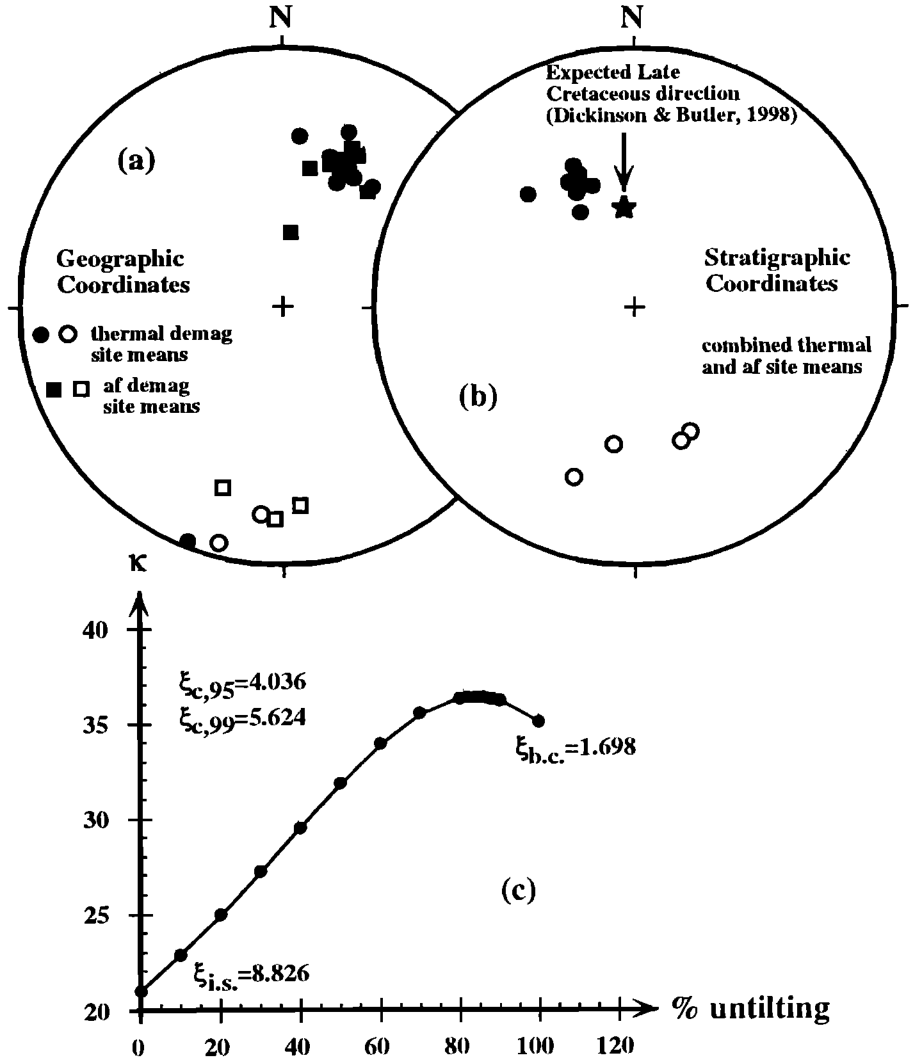

Figure 5. Equal area stereonets showing site mean directions of the Holz Member in (a) geographic and (b) stratigraphic coordinates. (c) A plot of precision parameter versus percent untilting shows that site means are best clustered at about 80% untilting; however, this direction is not statistically significant using the *McElhinny* [1964] or *McFadden and Jones* [1981] fold tests *McFadden's* [1990] fold test indicates that the magnetization is not postfolding since the in situ statistical parameter $\xi_{i.s}$ and the bedding corrected statistical parameter $\xi_{b.c.}$ bracket critical values for ξ at 95 and 99% confidence.

Formation had either uninterpretable demagnetization behavior (Figure 4) or scattered within-site and between-site directions. Therefore we only applied an inclination-shallowing correction to the sites from the Ladd Formation that produced the best paleomagnetic results. These sites are predominantly siltstones from the Holz Member.

The mean of the site means for the Holz Member of the Ladd Formation (declination (dec)=333°, inclination (inc)=47°, and α_{95}=5°) has an inclination indistinguishable from that obtained in the previous paleomagnetic study (dec=323.6°, inc=45.1°, and α_{95}=6.7°) by *Fry et al.* [1985]. Compared to a latest Cretaceous reference field direction for North America of dec=352.7° and inc=57.3°, calculated by *Dickinson and Butler* [1998] from *Diehl's* [1991] Elkhorn Volcanics paleopole and *Gunderson and Sheriff's* [1991] Adel Mountains paleopole and removing 295 km of Neogene motion along the San Andreas transform system, the mean of the site means direction indicates 10° inclination shallowing, typical for results from other marine sedimentary units from the Baja Borderland-Peninsula Ranges allochthon.

The magnetization of the Point Loma Formation proved to be very complicated. We demagnetized 107 samples from 17 sites, 64% of these samples (68) had either uninterpretable demagnetograms or no ChRMs (Figure 4). Only four site means could be obtained from the 39 samples that yielded ChRMs. Most sites had less than three sample ChRMs and no mean direction could be calculated. The 24 ChRMs that came from sites with fewer than three ChRMs were very scattered. One of the four site means had an α_{95} greater than 50°, so it was disgarded, leaving three site means, two from La Jolla Cove and one from the Point Loma locality. These three site means were better clustered in geographic coordinates rather than in stratigraphic coordinates (K_{geog}/K_{strat}=1.28), indicating strong contamination by an overprint. In fact, one of the three

Table 1. ChRM Directions From the Holz Member of Ladd Formation

		In situ				Bedding					
Site	Dem	Dec,deg	Inc,deg	Strike,deg	Dip,deg	Dec,deg	Inc,deg	n/N	R	α_{95},deg	κ
KlhF	th	194.8	-5.6	122	32			5/5	4.758	19.4	17
	af	198.0	-27.1	122	32			4/5	3.934	13.8	45
	mean	195.6	-15.3	122	32	188	-45	9/10	8.539	12.7	17
KlhE	th	201.7	0.8	122	32	199	-31	5/6	4.055	42.2	4
KlhD	af	175.1	-22.9	126	35	156	-46	4/5	3.910	16.1	33
KlhC	th	186.1	-20.3	138	42			3/3	2.956	18.6	45
	af	181.7	-18.5	138	42			3/3	2.950	19.7	40
	mean	183.5	-19.4	138	42	161	-44	6/6	5.901	9.5	50
KlhB	th	18.5	40.3	173	43	337	44	4/5	3.880	18.7	25
KlhA	th	25.6	42.6	173	43			5/5	4.905	11.9	42
	af	18.5	41.5	173	43			4/4	3.970	9.3	99
	mean	22.4	42.1	173	43	337	48	9/9	8.865	6.7	59
KlhK	th	21.2	40.3	169	45			6/6	5.874	10.8	40
	af	24.6	42.6	169	45			2/4	1.995	18.2	190
	mean	22.0	40.9	169	45	334	49	8/10	7.866	7.7	52
KlhJ	th	23.5	46.5	176	48			2/2	1.995		196
	af	24.0	34.0	176	48			1/1			
	mean	23.7	42.5	176	48	333	45	3/3	2.979	12.8	93
KlhI	th	37.9	42.5	173	50			4/4	3.979	7.8	141
	af	36.9	44.9	173	50			4/4	3.986	6.2	222
	mean	37.4	43.7	173	50	331	56	8/8	7.963	4.0	191
KlhH	th	6.0	35.0	173	45			1/1			
	af	7.5	67.0	173	45			1/1			
	mean	6.5	51.0	173	45	317	41	2/2	1.922		13
KlhG	th	28.4	43.1	173	45			3/3	2.990	8.6	207
	af	26.8	35.7	173	45			3/3	2.980	12.4	100
	mean	27.5	39.4	173	45	341	49	6/6	5.958	6.2	118
KlhL	th	21.0	29.1	173	45			3/3	2.996	5.6	490
	af	10.9	45.2	173	45			3/3	2.968	15.8	62
	mean	16.4	37.3	173	45	337	41	6/6	5.888	10.1	45
Overall ... mean		17	33					12/12	11.47	9.7	21
						342	46	12/12	11.68	7.5	34
Normal ... polarity mean		22	42					8/8	7.94	5.2	115
						333	47	8/8	7.94	5.0	125
Reversed ... polarity mean		189	-14					4/4	3.89	17.9	27
						178	-43	4/4	3.86	20.5	21

Dem,demagnetization type; af, mean alternating field direction, th,mean thermal direction. Mean is the site mean direction; strike and dip are site bedding orientation; n is the number of samples used to calculate mean direction; N is the total number of samples demagnetized; R is the resultant vector length; and κ is the precision parameter.

site means had a steep inclination (inc=65.1° and dec=9.6°); and the other two sites had sample ChRMs heavily contaminated by the present-day field since the ChRMs could only be isolated at very low unblocking temperatures (<200°C). One site mean from La Jolla Cove had a direction of inc=43.7°, dec=15.8°, and α_{95}=20.6°, with an inclination in agreement with *Bannon et al.*'s [1989] normal polarity mean direction for the Point Loma Formation. If more samples were collected and demagnetized, we probably could have reproduced Bannon et al.'s results; however, we chose, instead, to correct the mean Point Loma Formation inclination reported by Bannon et al. with the remanence anisotropy and *a* factor results measured for Point Loma samples. The Bannon et al. mean direction (normal polarity of dec=28.0°, inc=39.5°, and α_{95}=5.4°; reversed polarity of dec=214.9°, inc=-36.4°, and α_{95}=16.6°) is 16.8° (normal) to 19.9° (reversed) shallower than the expected cratonic North American direction (dec=352.8° and inc=56.3°) based on *Dickinson and Butler*'s [1998] calculations of Neogene San Andreas motion and the latest Cretaceous North American paleopole.

3.2. Rock Magnetic Study

3.2.1. Magnetic mineralogy and anisotropy of anhysteretic remanence. IRM acquisition curves show IRM increasing rapidly at low DC fields (< 0.2 T) and approaching saturation at DC fields >0.6 T (Figure 6). The back field coercivities are typically 50 mT. These results suggest a low-coercivity ferrimagnetic mineral, probably magnetite. Unblocking temperatures of ~550°-600° C support magnetite rather than a sulfide magnetic mineral. Some sites have IRMs that do not completely saturate at 1.2 T and that may contain a small amount of high-coercivity magnetic minerals (e.g., KlhI3 and KlhG6). The IRMs of the Point Loma Formation samples increase rapidly at fields <0.1T but do not saturate at the highest field applied (Figure 6). The back field experiments suggest minimum coercivities that range from 55 to 200 mT. These characteristics suggest that both low- and high-coercivity magnetic minerals coexist in the Point Loma samples

Thermal demagnetization of an IRM and an orthogonal pARM indicates that the IRM unblocks between 550° and 690°C, while the pARM component unblocks between 500° and 600° C for the Holz Member and Point Loma Formation samples (Figure 7). These results suggest the presence of hematite in both siltstone samples of the Holz Member and mudstone samples of the Point Loma Formation. Apparently, though, the pARM is carried predominantly by a low unblocking temperature magnetic mineral, probably magnetite. Despite the presence of some hematite, the AAR should be measuring the fabric of the magnetic particles carrying the shallow inclination ChRM.

All the pARM spectra of samples from the Holz Member of the Ladd Formation and the Point Loma Formation peak at 40 mT and have similar shapes (Figure 8). Because the Holz Member ChRMs were isolated at fields between 20 and 70 mT af demagnetization, the pARM window chosen for magnetic fabric measurements was between 20 and 70 mT. A pARM window between 20 and 80 mT was chosen for Point Loma Formation AARs. The Point Loma Formation pARM window was selected since most grain coercivities were in this range. Ninety percent of the best fit second-rank AAR tensor rms errors are <0.6%.

A lineation (ARM_{max}/ARM_{int}) versus foliation (ARM_{int}/ARM_{min}) plot of AAR axial ratios for the Holz Member indicates a predominant lineation, with some samples showing strong foliations (Figure 9 and Table 2). The stereonet plots of the maximum and minimum axes show that the Holz Member samples have well-grouped ARM_{max} directions with north-south declinations and shallow inclinations. There are two groups of ARM_{min} directions: one approximately perpendicular to bedding and the other orthogonal to both ARM_{max} and the other group of ARM_{min} axes. These two ARM_{min} axis groups probably result from the dominant lineation in the magnetic fabric, the small difference in the length of the ARM_{min} and ARM_{int} axes making them difficult to resolve. The AAR fabric is presumably the result of depositional (bottom current) and compaction effects and may indicate a primary origin of the ChRM magnetic carriers. Similar results and interpretations were found for the turbidites of the Cretaceous Pigeon Point Formation [*Kodama and Davi*, 1995].

For the Point Loma samples the AAR fabrics show well-grouped bedding-perpendicular ARM_{min} axes and horizontal but scattered ARM_{max} and ARM_{int} directions (Figure 9 and Table 2). Most samples have an oblate AAR ellipse with a strong foliation (1.05-1.090) indicating only a compaction fabric. This is consistent with a deepwater, quiet depositional environment.

3.2.2. Compaction experiment. The precompaction magnetization of a slurry sample was measured immediately after the slurry was dripped into the sample holder. Inclinations ranged from 53° to 58° and may have suffered a small amount of syndepositional inclination shallowing. After standing in the laboratory magnetic field for an hour, inclination increased, in most cases, by 2°-4° and intensity increased by <10%. Stirring the slurry decreased its magnetic intensity and caused the slurry's magnetization direction to deviate from the field direction Apparently, the magnetic grains are best aligned with the laboratory magnetic field by dripping the slurry into the sample holders.

For most of the compaction runs, volume loss did not begin until the load overcame the friction between the filter paper and the plunger (Figures 10 and 11). This occurred at very low pressures (<0.02 MPa), so the consolidation behavior of the samples was not affected. About half of the total volume loss occurs at pressures < 0.04 MPa for the Holz Member (Figure 10) and 0.08 MPa for the Point Loma samples (Figure 11). As pressure increases, the rate of volume loss decreases and reaches zero at the highest experimental pressures. This behavior is consistent with previous compaction work done in our laboratory [*Deamer and Kodama*, 1990; *Sun and Kodama*, 1992; *Kodama and Davi*, 1995; *Kodama*, 1997], and it suggests that the samples were not overpressured. Total volume loss for the Holz Member slurries ranged from 40 to 60%. For Point Loma Fm. slurries, maximum volume loss was 70%. Considering the initial water content (Holz Member, 80%; Point Loma, 280%) and the difference in density between water (1 gcm^{-3}) and the dry sediment (estimated at 2.8 gcm^{-3}), these results indicate that similar proportions of water were removed from the Holz Member (75%) and the Point Loma (80%) samples during compaction.

Inclination shallowing is significant for all the compaction runs (Figures 10 and 11). For the Holz Member experiments, total inclination shallowing was nearly 15°. Inclination was

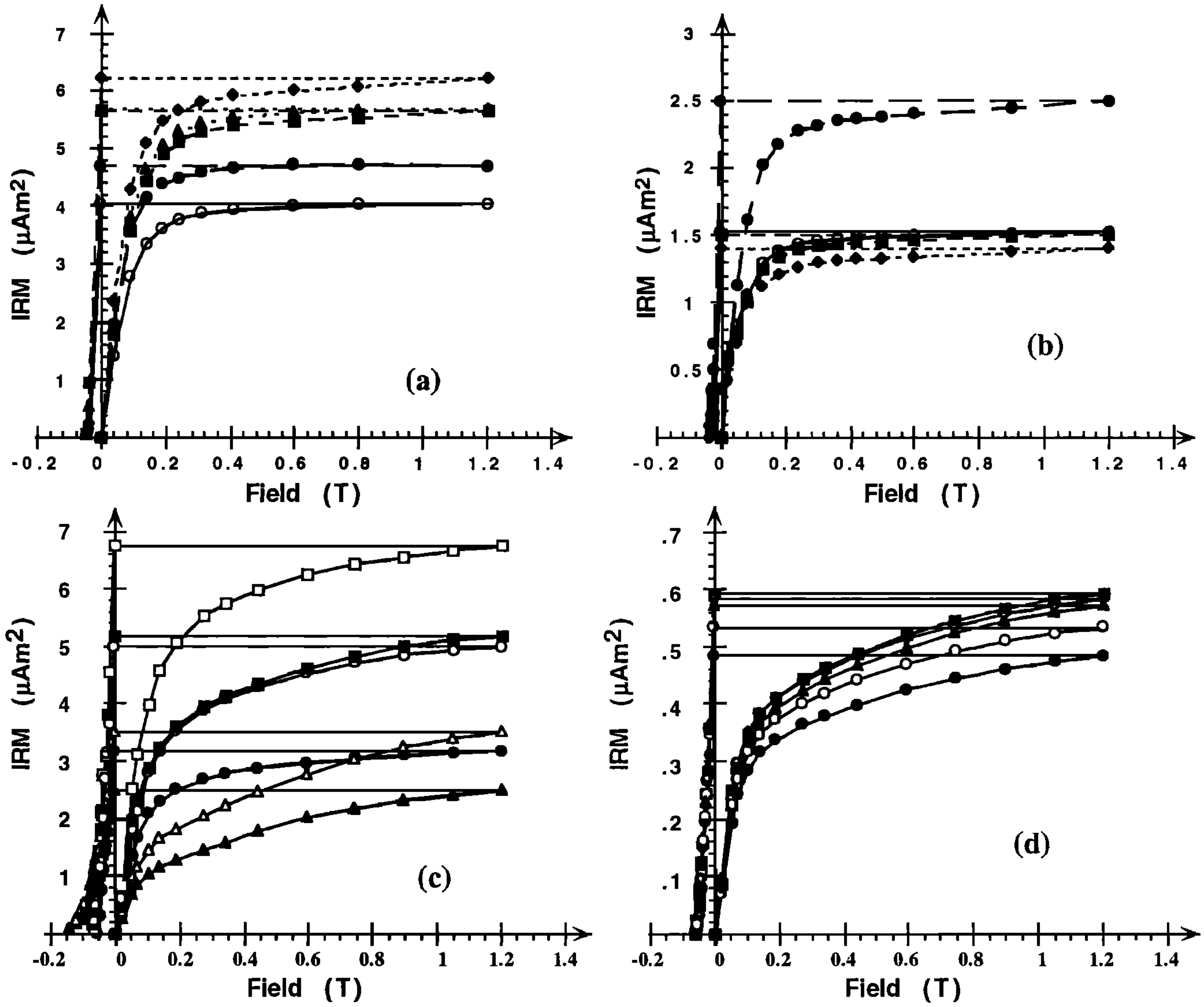

Figure 6. Isothermal remanent magnetization (IRM) acquisition and back field demagnetization plots for (a) natural and (b) laboratory compacted samples of the Holz Member of the Ladd Formation and (c) natural samples and (d) compacted samples from the Point Loma Formation. Note that all the Point Loma Formation samples and some of the Holz Member samples contain high-coercivity magnetic minerals which do not saturate by 1.2 T.

observed to decrease nearly linearly as volume decreased. For the Point Loma Formation samples, total inclination shallowing was as great as 20°. In general, inclination decreased linearly with volume; however, there is a tendency for inclination shallowing to be greater at the highest volume losses. The pattern of inclination shallowing with respect to pressure in all the compaction runs is similar to that observed in previous compaction studies [e.g., *Deamer and Kodama*, 1990; *Sun and Kodama*, 1992; *Kodama and Davi*, 1995; *Kodama*, 1997], and it shows a pronounced break in slope in the curves at a pressure of 0.03 MPa for the Holz Member and 0.07 MPa for the Point Loma Formation (Figures 10 and 11). *Jackson et al.*'s [1991] work would suggest that $\tan(I_c)/\tan(I_0)$ should be a linear function of volume loss $(1-\Delta V/V)$ rather than inclination. Our compaction results strongly support this hypothesis; however, two line segments are needed to fit the data above and below the volume loss corresponding to the break in slope observed in the inclination versus pressure plots.

Preparation of the compaction samples for demagnetization requires that they be removed from the compaction sample holders. Inclinations measured before (including the porous stone) and after extrusion (not including the porous stone) from the sample holders were within 5°, in most cases, much less. The larger differences may be due to slurry leaking into and contaminating the porous stone. Since this stone is removed for demagnetization, it will not affect the ChRM. The af and thermal demagnetization results indicate that only one remanence component exists in the compacted samples (Figure 12); hence inclination shallowing would not have been removed by demagnetization of the natural samples.

Comparison of IRM acquisition curves for the Holz Member and the Point Loma Formation samples (Figure 6) and pARM spectra for the Holz Member and Point Loma Formation

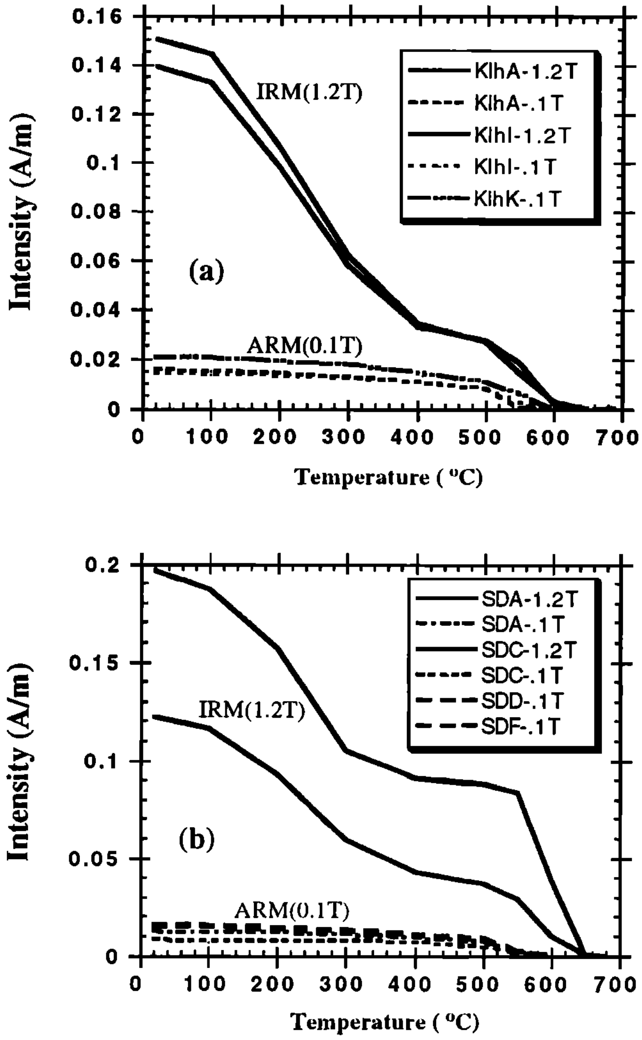

Figure 7. Thermal demagnetization of an IRM acquired in a 1.2 T field and an orthogonal anhysteretic remanent magnetization (ARM) acquired in a 0.1-0 T window for (a) Holz Member and (b) Point Loma Formation samples. Note that the ARM is carried by a magnetic mineral with unblocking temperatures <580°C, probably magnetite.

(Figure 8) shows little difference in magnetic mineral type and grain size distribution for natural and disaggregated, compacted samples. The AAR of the compacted samples shows a typical compaction fabric with vertical minimum axes and horizontally distributed maximum and intermediate axes. Axial ratio plots indicate a predominately oblate fabric (Table 3). These results indicate that the compaction experiments should provide a good model of inclination shallowing during burial compaction in nature.

The ChRM isolated by principal component analysis from the compacted samples was used to determine the a factor of individual magnetic grain anisotropy. The *a* factor for each compacted sample was calculated by

$$a=[(2q_v-1)\tan I_{initial}+(1-2q_h)\tan I_{ChRM}] \qquad$$
$$/(q_h\tan I_{compacted}-q_v\tan I_{initial}) \qquad (2)$$

where $I_{initial}$ is the inclination of the laboratory magnetic field (58°), I_{ChRM} is the inclination of the best fit ChRM of the compacted sample, q_h is the average of the normalized maximum and intermediate (horizontal) AAR axes, and q_v is the normalized AAR minimum (vertical) axis. The maximum and intermediate axes were averaged to ensure the best estimate of the horizontal AAR axis for the oblate fabric resulting from laboratory compaction. The initial field inclination, rather than the initial inclination measured for the sample, was used since many of the samples suffered from a slight syndepositional inclination error. Both syndepositional and compaction errors should be used to determine the *a* factor since both effects contribute to the bulk anisotropy of the sample. The *a* factor for each formation was determined by least squares fit of inclination correction curves derived from *Jackson et al.* [1991] by *Kodama and Davi* [1995] to the inclination shallowing observed in the compaction experiments (Figure 13). This was done separately for the Holz Member and Point Loma samples and follows the technique outlined by *Kodama* [1997]. The resulting *a* factors are 1.41±0.12 and 1.47±0.028 for siltstone samples of the Holz Member and mudstone samples of the Point Loma Formation, respectively.

3.2.3. Magnetic extract orientation experiment. The pARM spectra of the epoxy-magnetic separate samples indicate that the magnetic extracts were dominated by coarse grains of low coercivity (< 20 mT) although some higher-coercivity, finer magnetic grains were also detected. We attempted to measure the AAR of the epoxy-magnetic extract samples with the same coercivity window used for the natural and compacted samples, but because the epoxy samples had acquired a large IRM during drying, which could not be removed by af demagnetization at a 100 mT peak af demagnetization field, the AAR rms error was very large (>20%). Consequently, we were only able to measure the pARM in three directions: $\mathrm{pARM_{par}}$, which is parallel to the aligning magnetic field, and $\mathrm{pARM_{per1}}$ and $\mathrm{pARM_{per2}}$, both orthogonal to $\mathrm{pARM_{par}}$ and to each other. The *a* factor was calculated by

$$a=2\,\mathrm{pARM_{par}}/(\mathrm{pARM_{per1}}+\mathrm{pARM_{per2}}) \qquad (3)$$

A plot of *a* versus aligning field strength for the Holz Member slurries shows that *a* increases from 1.04 at a 25 mT field to around 1.4 at a 45 mT field and that it remains at a value near to 1.4 at a 55 mT field (Figure 14). The *a* value derived is very similar to the value determined in the compaction experiments (Figure 13). This gives us confidence that we have obtained a good approximation of the individual magnetic particle anisotropy *a* for the Holz Member of the Ladd Formation. We will use the laboratory compaction-derived *a* factors for each site for the compaction correction of the Holz Member.

For the Point Loma extracts, *a* is around 1.6 at fields <50 mT, but at higher fields it increases significantly and does not saturate (Figure 14). There appears to be a "local saturation" of the *a* factor at fields comparable to those that caused saturation of the Holz Member slurry. This *a* factor (*a*=1.6) would be reasonably close to that obtained by the compaction experiment. The large increase at higher fields, though, suggests that the Point Loma magnetic extract-epoxy experiments do not provide a reliable estimate of individual magnetic grain anisotropy. The *a* factor derived from the compaction experiments will be used for the Point Loma compaction correction.

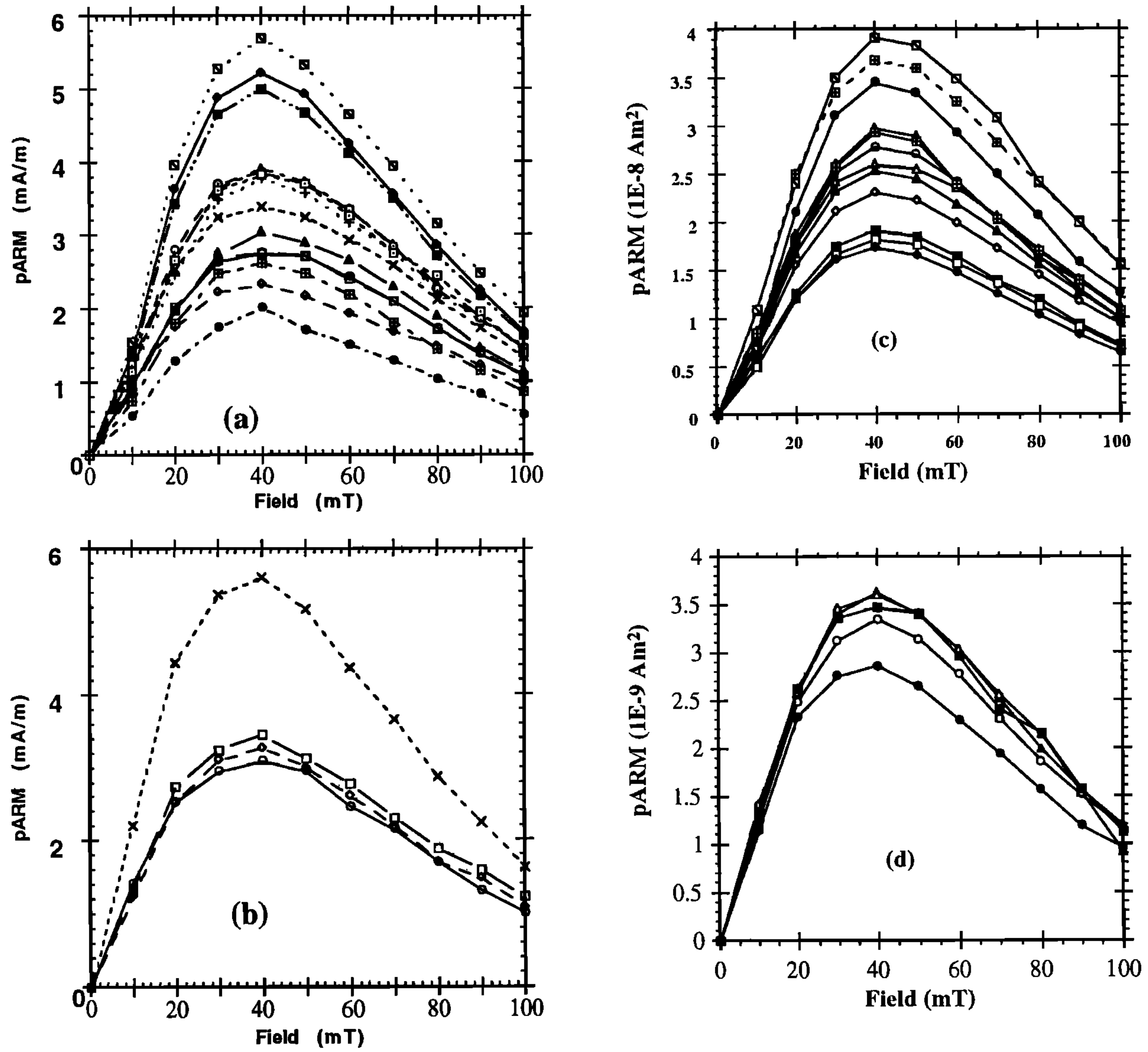

Figure 8. Partial anhysteretic remanent magnetization (pARM) spectra for (a) natural and (b) laboratory compacted samples for the Ladd Formation and (c) natural and (d) laboratory compacted samples for the Point Loma Formation Note the similarity of the spectra before and after disaggregation for the compaction experiments. Read 1E-8 as 1 x 10^{-8}.

3.3. SEM Observations

SEM backscatter images (Figure 15) of the epoxy-magnetic extract samples can be used to check the estimates of a, the magnetic particle orientation, and the possibility of magnetic interactions. SEM micrographs of the Holz Member indicate grain sizes less than about 100 μm and greater than 1-2 μm. These grains are nearly equidimensional. This observation supports the a value of ~1.4 obtained by the compaction and epoxy-magnetic separate drying experiments. The micrographs in Figure 15 were made for a sample allowed to dry in a 45 mT magnetic field. The alignment of the long axes nearly parallel to the magnetic field direction supports the observation that the a value had saturated. The SEM micrographs of the Point Loma Formation extracts show a wider range of magnetic grain size, 1-200 μm, than that seen for the Holz Member. The SEM micrographs show that for a 20 mT aligning field the large grains were not aligned parallel to the field direction. Small particles (1-10 μm) stick together to form large aggregates, and other small particles apparently form chains. The large aggregates were poorly aligned in the magnetic field direction at both low and high field strength. These observations of magnetic interactions may explain why the a value for the Point Loma epoxy-magnetic extract samples did not saturate at high fields. Since the Point Loma Formation magnetic particles were extracted using a rare earth magnet 10 times stronger than the magnet used for the Holz Member, the individual magnetic particles are likely to have acquired strong IRMs, which made magnetic interactions more probable. Magnetic interactions greatly reduce the accuracy of the epoxy-magnetic extract technique for determining individual magnetic particle anisotropy a. The nearly equidimensional shape observed for the Point Loma magnetic minerals, though, does support the low a factor of 1.47 derived from the laboratory compaction experiments.

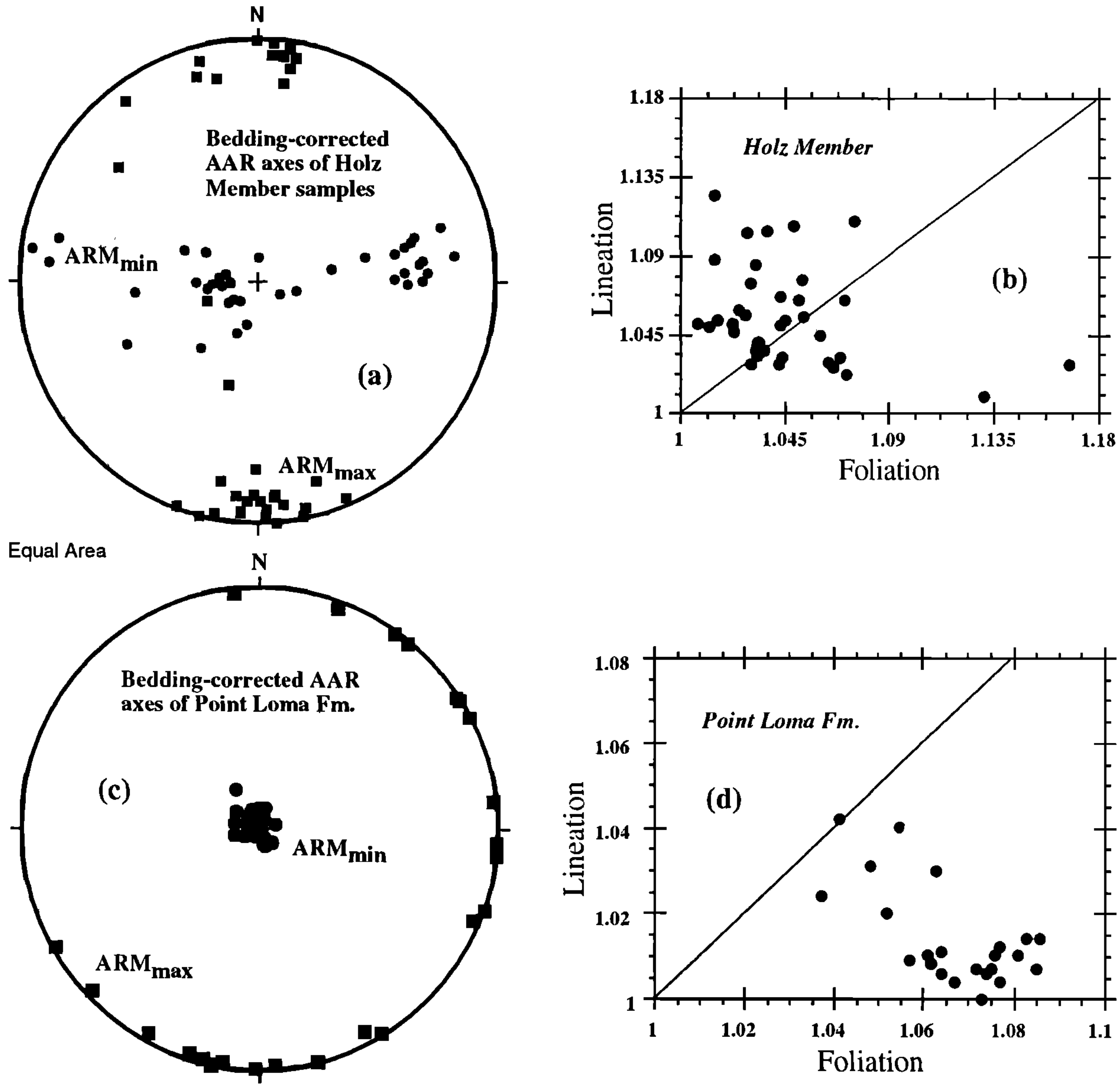

Figure 9. Equal area stereonet plots of the principal axis directions (ARM_{max} and ARM_{min}) for natural samples from the (a) Holz Member of the Ladd Formation and the (c) Point Loma Formation. Solid circles indicate lower hemisphere plots. Principal axis ratios for the (b) Holz Member and the (d) Point Loma Formation indicate a mixture of lineations and foliations for the Holz Member samples and only a strong foliation for the Point Loma Formation samples. AAR, anisotropy of anhysteretic remanence.

3.4. Grain Size Distribution and Clay Content

Grain size distributions indicate that the Holz Member is composed of 17.1% fine sand, 67.6% silt, and 15.3% clay-sized particles. The Point Loma Formation has much more clay-sized particles with a grain size distribution of 0.5% fine sand, 53.5% silt, and 46% clay-sized particles. X ray diffraction of slurries made of Holz Member and Point Loma Formation material shows that both slurry types consist mainly of quartz and plagioclase with minor amounts of carbonate, halide minerals, and potassium feldspar. The X ray diffractograms of the fine grains separated by centrifuge reveal that the clay-sized fraction of the Holz Member slurry consists of the clay minerals smectite, kaolinite, illite, and chlorite, and the clay-sized fraction of the Point Loma Formation slurry contains illite and chlorite. The Pigeon Point Formation samples are composed of 2.3% sand, 52.3% silt, and 45.4% clay, while the Nacimiento Formation samples are 0.9% sand, 79.7% silt, and 19.4% clay.

4. Discussion

4.1. Remanence Anisotropy Correction of ChRM

In using (1) to correct for inclination shallowing, it is assumed that compaction causes an oblate fabric, which should have minimal effects on sample declination. However, prolate and triaxial magnetic fabrics are observed for some samples of

Table 2. AAR of Holz Member and Point Loma Formation Samples

Sample	q_x	D_x, deg	I_x, deg	q_y	D_y, deg	I_y, deg	q_z	D_z, deg	I_z, deg	L	F
KlhA1	0.3489	178.0	3.3	0.3324	269.6	25.5	0.3188	81.2	64.2	1.05	1.043
KlhA2	0.3487	345.0	6.7	0.3302	254.2	6.3	0.3211	121.1	80.8	1.056	1.028
KlhA5	0.3489	14.4	0.0	0.3296	284.4	14.4	0.3215	104.4	75.6	1.059	1.025
KlhA6	0.3454	168.1	4.6	0.3326	77.3	10.0	0.3220	282.6	78.9	1.039	1.033
KlhB2	0.3528	8.4	18.7	0.3317	99.7	3.7	0.3155	200.6	70.9	1.064	1.051
KlhB6	0.3616	172.9	8.1	0.3268	263.1	1.7	0.3116	4.9	81.7	1.107	1.049
KlhC1	0.3458	325.5	9.0	0.3385	60.5	28.8	0.3157	219.8	59.5	1.022	1.072
KlhC2	0.3525	348.2	16.2	0.3306	95.7	46.1	0.3168	244.4	39.4	1.066	1.043
KlhC7	0.3467	342.5	12.9	0.3293	74.2	7.7	0.3240	194.2	74.9	1.053	1.016
KlhD1	0.3539	0.2	0.9	0.3253	90.4	9.0	0.3208	264.8	80.9	1.088	1.014
KlhD2	0.3528	3.9	2.1	0.3284	94.5	14.8	0.3188	266.1	75.0	1.074	1.03
KlhD4	0.3511	3.9	7.7	0.3329	95.1	8.8	0.3160	233.4	78.2	1.055	1.053
KlhD6	0.3466	8.9	12.1	0.3368	109.2	40.0	0.3167	265.4	47.4	1.029	1.064
KlhD7	0.3461	10.2	7.6	0.3374	100.8	4.5	0.3165	220.8	81.1	1.026	1.066
KlhE1	0.3550	175.1	1.1	0.3335	84.7	20.9	0.3115	268.0	69.1	1.064	1.071
KlhE2	0.3499	168.5	0.9	0.3321	78.2	16.9	0.3180	261.4	73.0	1.053	1.045
KlhE3	0.3489	157.2	3.2	0.3456	66.6	11.3	0.3054	262.8	78.3	1.01	1.131
KlhE8	0.3564	167.6	4.4	0.3468	76.6	12.6	0.2968	276.3	76.6	1.028	1.168
KlhF1	0.3555	6.9	8.1	0.3304	128.3	74.7	0.3141	275.0	12.9	1.076	1.052
KlhF2	0.3599	8.4	3.8	0.3259	134.3	83.6	0.3142	278.0	5.2	1.104	1.037
KlhF4	0.3554	199.9	0.9	0.3274	109.4	26.9	0.3172	291.7	63.1	1.085	1.032
KlhF7	0.3613	6.6	7.2	0.3215	97.4	6.9	0.3172	230.8	80.1	1.124	1.014
KlhF9	0.3587	190.8	3.0	0.3253	180.0	74.2	0.3161	281.6	15.5	1.103	1.029
KlhG2	0.3427	190.4	17.3	0.3335	305.8	54.0	0.3238	89.8	30.5	1.028	1.03
KlhG6	0.3453	185.9	11.8	0.3332	290.2	49.8	0.3216	86.6	37.8	1.036	1.036
KlhH2	0.3651	308.5	26.7	0.3289	204.8	25.1	0.3060	78.3	51.9	1.11	1.075
KlhI1	0.3443	174.9	12.4	0.3331	282.1	53.2	0.3226	76.4	33.9	1.033	1.033
KlhI3	0.3448	177.3	6.3	0.3328	277.3	57.7	0.3224	83.5	31.6	1.036	1.032
KlhI5	0.3442	179.2	9.7	0.3346	284.9	57.6	0.3212	83.4	30.5	1.028	1.042
KlhI7	0.3453	182.5	10.2	0.3344	290.1	59.4	0.3202	86.9	28.5	1.032	1.044
KlhJ1	0.3470	180.3	23.3	0.3301	299.4	48.5	0.3230	74.6	32.1	1.051	1.022
KlhK1	0.3454	184.1	4.1	0.3285	279.4	52.4	0.3261	91.0	37.3	1.051	1.007

Table 2. (Continued)

Sample	q_x	D_x, deg	I_x, deg	q_y	D_y, deg	I_y, deg	q_z	D_z, deg	I_z, deg	L	F
KlhK3	0.3467	184.2	5.4	0.3302	280.2	47.9	0.3231	89.4	41.6	1.05	1.022
KlhK7	0.3455	163.4	14.6	0.3293	69.7	13.9	0.3252	297.7	69.6	1.049	1.012
KlhK9	0.3460	181.0	12.8	0.3308	284.6	45.8	0.3232	79.4	41.4	1.046	1.023
KlhL2	0.3478	195.1	53.2	0.3371	331.8	28.5	0.3152	73.9	21.1	1.032	1.069
KlhL3	0.3459	175.6	11.0	0.3325	279.3	50.6	0.3216	77.0	37.3	1.04	1.034
KlhL6	0.3494	248.8	71.6	0.3348	351.5	4.2	0.3158	82.8	17.9	1.044	1.06
SDA2	0.3471	56.7	1.5	0.3330	326.5	6.5	0.3199	159.5	83.3	1.042	1.041
SDA4	0.3454	239.9	1.6	0.3350	330.1	6.5	0.3196	135.8	83.3	1.031	1.048
SDA7	0.3480	57.9	1.2	0.3348	147.9	0.7	0.3172	267.9	88.6	1.04	1.055
SDA8	0.3468	62.4	0.9	0.3366	332.3	5.7	0.3166	160.9	84.2	1.03	1.063
SDB1	0.3421	354.0	2.4	0.3387	84.3	5.4	0.3192	240.2	84.1	1.01	1.061
SDB3	0.3425	152.2	5.9	0.3410	62.2	0.0	0.3165	332.2	84.1	1.004	1.077
SDB5	0.3441	165.6	0.1	0.3402	75.6	8.8	0.3157	256.0	81.2	1.012	1.077
SDB7	0.3427	83.4	1.3	0.3405	173.5	6.4	0.3167	342.4	83.4	1.007	1.075
SDC1	0.3438	197.6	2.9	0.3415	107.1	9.1	0.3147	304.9	80.4	1.007	1.085
SDC4	0.3454	226.1	3.4	0.3408	135.2	14.7	0.3138	328.9	74.9	1.014	1.086
SDC5	0.3451	181.0	0.9	0.3405	1.0	4.0	0.3144	283.0	85.9	1.014	1.083
SDC8	0.3435	113.2	2.9	0.3403	203.5	6.3	0.3162	358.4	83.0	1.01	1.076
SDD2	0.3434	208.7	3.5	0.3366	299.0	4.5	0.3200	81.0	84.3	1.02	1.052
SDD3	0.3414	39.2	1.7	0.3384	309.1	3.3	0.3202	156.9	86.3	1.009	1.057
SDD5	0.3426	35.1	1.7	0.3346	125.2	3.0	0.3228	275.1	86.5	1.024	1.037
SDD7	0.3415	20.0	3.2	0.3400	110.0	0.2	0.3185	203.5	86.7	1.004	1.067
SDE1	0.3426	193.9	1.9	0.3390	103.8	4.6	0.3185	306.4	85.0	1.011	1.064
SDE3	0.3418	148.8	1.5	0.3391	238.8	2.6	0.3192	28.0	87.0	1.008	1.062
SDE4	0.3414	191.8	0.1	0.3394	101.7	8.4	0.3191	282.7	81.6	1.006	1.064
SDE6	0.3411	93.5	0.2	0.3410	183.5	4.9	0.3179	0.9	85.0	1.0	1.073
SDF1	0.3441	175.8	2.4	0.3407	85.6	3.1	0.3152	303.3	86.1	1.01	1.081
SDF4	0.3425	109.7	0.0	0.3404	199.7	7.1	0.3171	19.5	82.9	1.006	1.074
SDF5	0.3426	188.8	2.3	0.3402	98.7	2.0	0.3173	328.4	86.9	1.007	1.072
SDF9	0.3426	96.9	0.0	0.3401	186.9	6.7	0.3172	6.8	83.3	1.007	1.072

Klh sites are from the Holz Member; SD sites are from the Point Loma Formation. The q_x, q_y, and q_z, are the normalized maximum, intermediate, and minimum axes of the anisotropy of anhysteretic remanence (AAR), and (D_i, I_i) (i=x, y, z) are their corresponding directions. Lineation is $L = q_x/q_y$, and foliation is $F = q_y/q_z$.

the Holz Member and ARM_{max} axes do not always align with a sample's ChRM declination. Therefore some modification of the correction procedure suggested by *Jackson et al.* [1991] is necessary. Both declination and inclination need to be corrected using a sample's AAR. The correction method used was

$$\tan D_{field} / \tan D_{ChRM} = [q_N(a+2)-1] / [q_E(a+2)-1] \qquad (4)$$

$$\tan I_{field} / \tan I_{ChRM} = [q_H(a+2)-1] / [q_V(a+2)-1] \qquad (5)$$

where all the parameters are in stratigraphic coordinates and q_N, q_E, q_V, and q_H are the lengths of each sample's normalized AAR ellipse in north, east, vertical, and horizontal (along the ChRM declination) directions, respectively. When the ChRM direction is corrected by (4) and (5) for each individual sample, using the appropriate site *a* factor, and the site mean directions

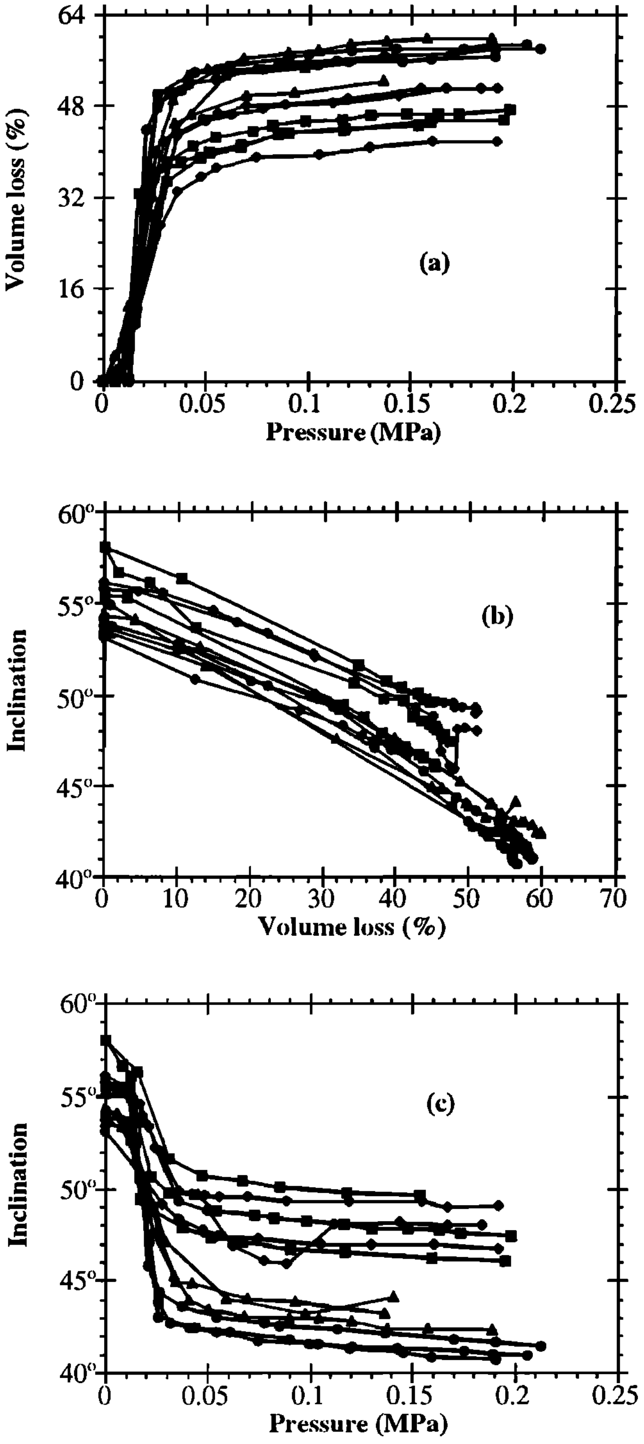

Figure 10. (a) Volume loss versus pressure, (b) inclination versus volume loss, and (c) inclination versus pressure plots for the laboratory compaction experiments conducted with disaggregated samples of the Holz Member of the Ladd Formation. Note that most inclination shallowing occurs at low pressures Different symbols designate different samples.

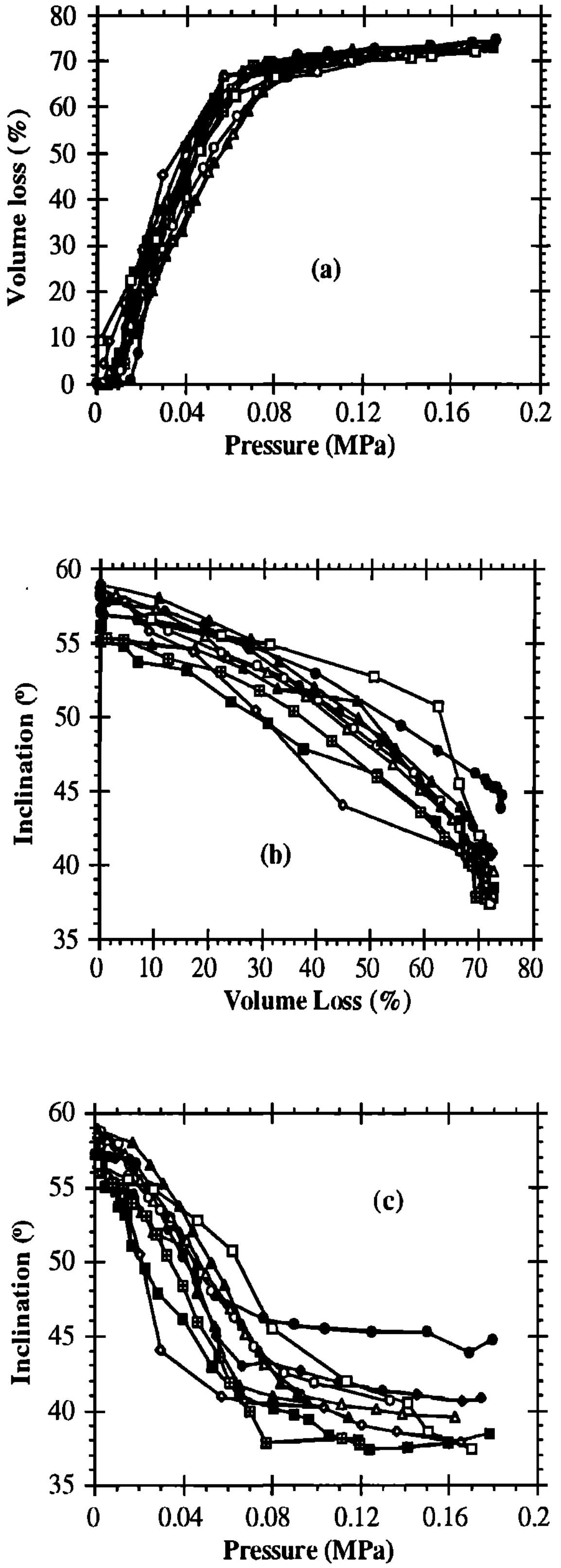

Figure 11. (a) Volume loss versus pressure, (b) inclination versus volume loss, and (c) inclination versus pressure plots for the laboratory compaction experiments conducted with disaggregated samples of the Point Loma Formation. While most inclination shallowing occurs at low pressures for these samples, there is evidence for increased inclination shallowing at the highest volume losses Different symbols designate different samples.

based on these corrected sample directions are calculated, the mean of the site means is corrected from dec=333° and inc=47° (α_{95}=5°) to dec=324°and inc=58° (α_{95}=4°) (Table 4 and Figure 16). This direction is based on the corrected means from eight sites; seven siltstone and one sandstone site. Four additional limestone sites were not corrected because compaction ex-

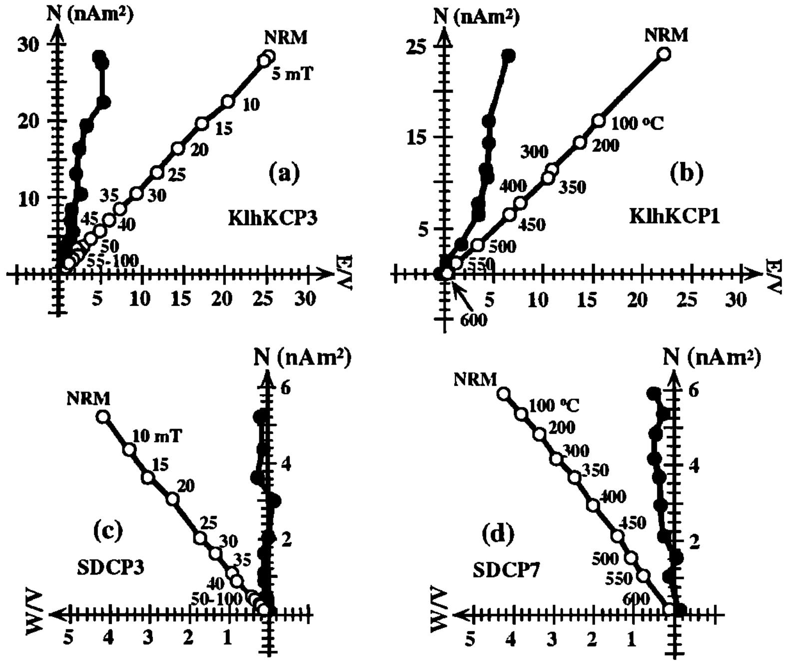

Figure 12. Orthogonal vector endpoint diagrams for alternating field demagnetization of laboratory-compacted samples from the (a and b) Ladd Formation and (c and d) the Point Loma Formation. Solid circles indicate the horizontal component, and open circles indicate the vertical component. Note that the vertical component is plotted in the vertical plane including the sample's declination to show the true inclination of the sample during demagnetization Minimal viscous overprinting has occurred during compaction.

periments could not be used to determine their *a* factors and insufficient magnetic extract could be obtained for epoxy drying experiments. The limestone sites had mean directions similar to the siltstone site means (Table 1). Using the siltstone *a* factors would have provided similar corrected directions. The sample AARs for the limestones (Table 2) suggest that they have suffered equivalent amounts of compaction shallowing as the siltstones suffered. This result

Table 3. AAR, ChRM Inclination, and *a* Factors of Laboratory Compaction Samples

Sample	q_x	D_x, deg	I_x, deg	q_y	D_y, deg	I_y, deg	q_z	D_z, deg	I_z, deg	I_{ChRM}, deg	*a*
KlhG-2	0.341	225.2	10.8	0.339	316.1	4.6	0.320	69.0	78 2	43.1	1.427
KlhG-3	0.339	220.9	7.4	0.337	311.2	2.5	0.324	59.7	82.2	43.9	1.306
KlhJ-2	0.337	342.7	10.1	0.335	245.6	34.8	0.328	86.6	53.4	49.2	1.232
KlhJ-3	0.344	245.2	9.0	0.336	339.0	22.8	0.321	135.1	65.3	46.1	1.509
KlhK-3	0.342	40.5	12.4	0.337	307.3	14.0	0.321	170.5	71.1	43.5	1.388
KlhK-4	0.342	43.7	8.3	0.336	312.6	7.4	0.322	181.2	78.9	49.1	1.60
KlhL-2	0.339	163.7	3.1	0.336	73.6	2.6	0.325	303.6	85.9	45.8	1.314
KlhL-3	0.340	313.9	7.0	0.337	223.6	2.6	0.323	113.4	82.5	48.7	1 505
SDCP-1	0.346	272.6	5.5	0.343	2.7	1.3	0.311	105.9	84.4	33.4	1 478
SDCP-2	0.344	265.8	7.7	0.342	355.9	0.8	0.315	91.9	82.3	37.8	1.473
SDCP-3	0.344	180.5	1.1	0.341	270.5	2.0	0.316	62.2	87.7	38.7	1.457
SDCP-4	0.342	280.3	7.4	0.341	189.9	2.8	0.317	79.5	82.1	40.2	1.446
SDCP-5	0.342	21.5	1.5	0.340	291.3	5.5	0.318	126.6	84.3	43.0	1.488
SDCP-6	0.345	235.5	1.7	0.341	145.4	0.4	0.313	41.7	88.2	38.7	1.533
SDCP-9	0.343	302.7	6.0	0.342	212.5	2.1	0.315	103.1	83.6	38.0	1.470
SDCP10	0.342	25.7	1.2	0.341	295.6	6.4	0.317	126.6	83.5	39.4	1.4

Klh indicates Holz Member samples; SD indicates Point Loma samples. The q_x, q_y, q_z, and (D_i, I_i) are the same as in Table 2. I_{ChRM} is the inclination of the characteristic remanence of a laboratory-compacted samples and *a* is the individual magnetic particle anisotropy factor.

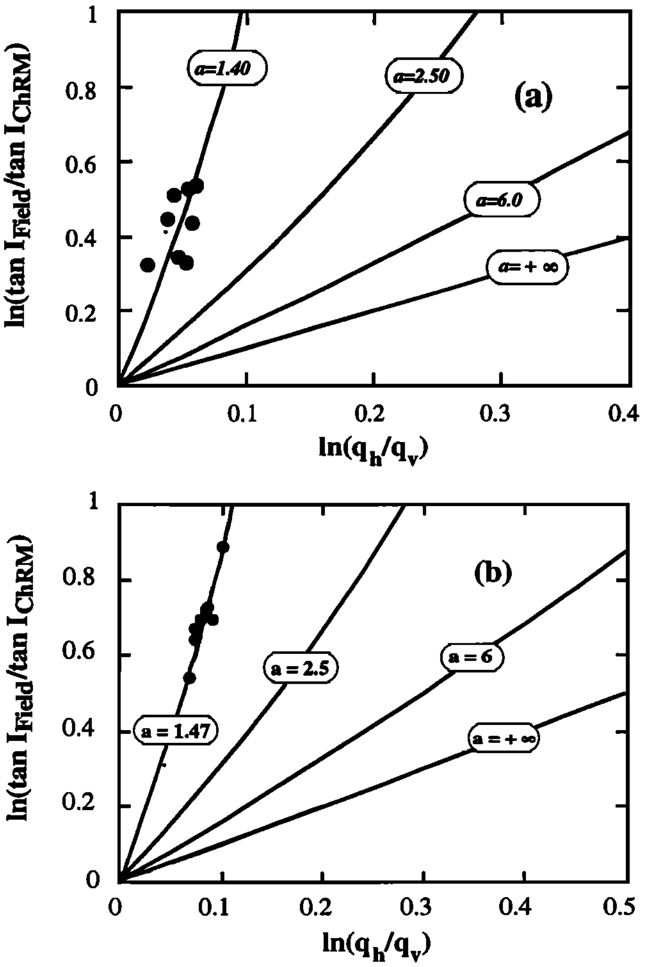

Figure 13. Laboratory compaction experiment determination of individual magnetic particle anisotropies (*a* factors) for (a) the Holz Member of the Ladd Formation and (b) the Point Loma Formation. Note that $q_h = (q_x+q_y)/2$ and $q_v=q_z$ (see text). The Holz Member and Point Loma yield similar *a* factors close to 1 4 - 1 5 for the compaction experiments.

is consistent with evidence for compaction in limestones [e.g., *Elgindy et al.*, 1998; *Anastas et al.*, 1998] and previous work which identified compaction-caused inclination shallowing in deep-sea limestones [*Hodych and Bijaksana*, 1993].

Since we were unable to isolate ChRM directions from the Point Loma samples, we corrected the mean inclination data of *Bannon et al.* [1989] on the basis of the average magnetic fabric measured on Point Loma samples and the *a* factor we obtained using compaction experiments with Point Loma material. The accuracy of using the mean AAR to correct the mean inclination of a formation was tested with our Nacimiento Formation results [*Kodama*, 1997]. The uncorrected Paleocene Nacimiento Formation direction (dec=341° and inc=49°) is 9° shallower than the expected Paleocene direction for North America (dec=351° and inc=58°). A sample by sample correction of inclination results in a mean corrected direction of dec=341° and inc=57° (α_{95}=6.6°), which contains the expected North American direction within its 95% cone of confidence. Averaging the Nacimiento AAR data to correct the formation mean direction gives a corrected direction of dec=341°, inc=59° which is in good agreement with the sample by sample correction and the expected Paleocene direction.

Since the Point Loma Formation *a* factor is small, the inclination correction will be a strong function of sample remanence anisotropy. The strong oblate fabric of the Point Loma suggests that there should have been little effect on paleomagnetic declination. The foliation parameter of the natural samples is just slightly (~0.01) less than the laboratory-compacted samples; hence the magnitude of inclination shallowing in the compaction experiments should be a first-order estimate of the natural compaction shallowing. This would suggest that almost all of the Point Loma's anomalously shallow inclination is due to rock magnetic effects rather than tectonic effects.

A detailed inclination correction of the Point Loma Formation mean of the site means direction was made using (1) and the mean AAR measured for the Point Loma. *Bannon et al.* [1989] only report normal polarity and reversed polarity mean

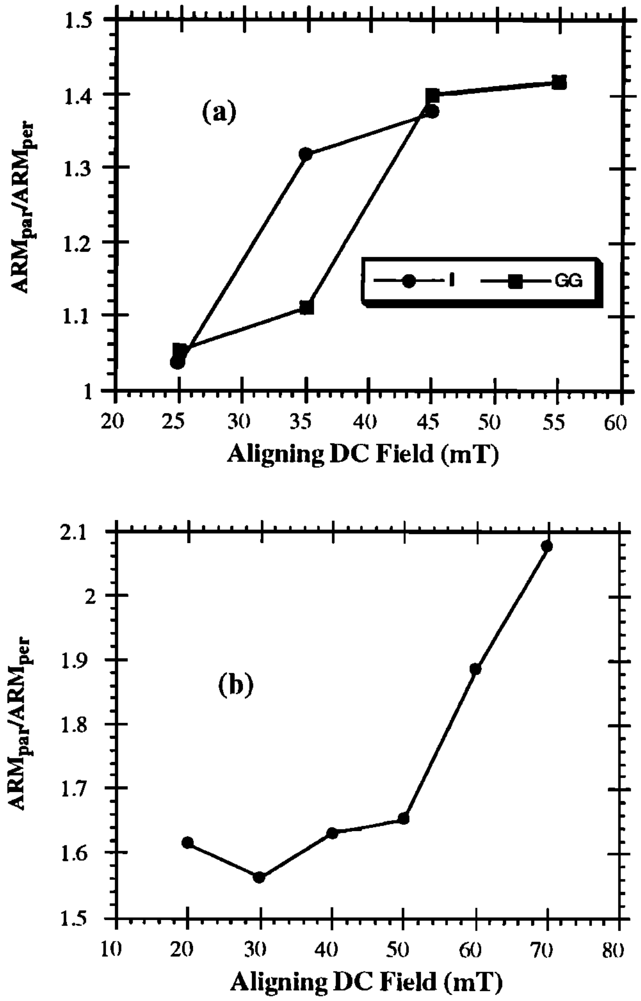

Figure 14. Epoxy-magnetic separate drying experiments to determine the *a* factor for the (a) Holz Member samples and the (b) Point Loma Formation samples. While the Holz Member samples show saturation of a factor at fields of 40 mT, the Point Loma Formation samples appear to saturate at 50 mT but then increase up to the highest field used, 70 mT Note that the a factor obtained for the Holz Member (1 4) is similar to the value derived from the compaction experiments. GG, separate from site KlhG; II, separate from site Klhl

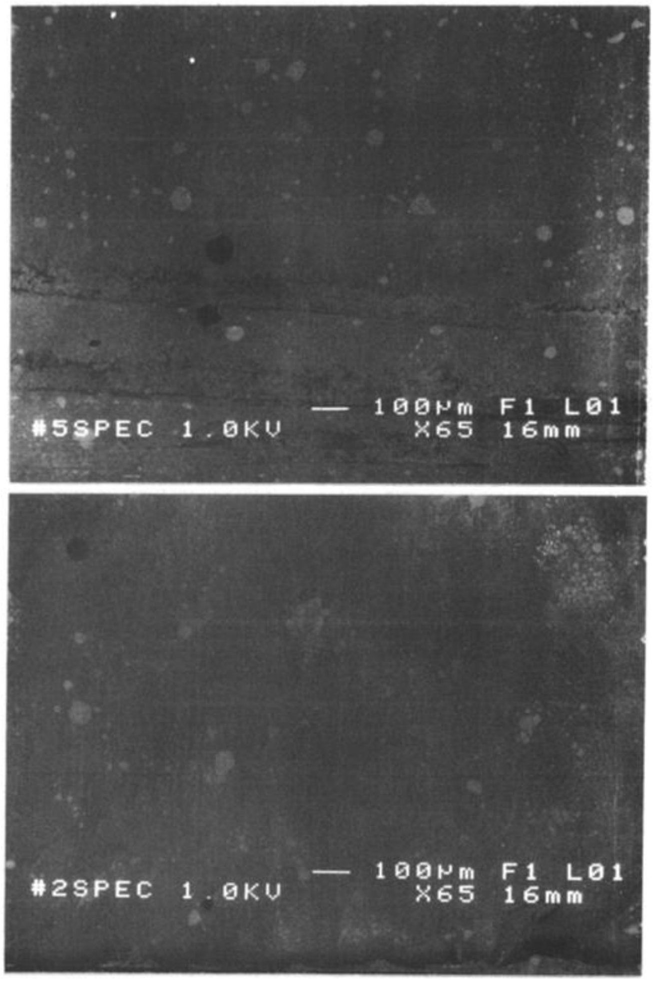

Figure 15. Scanning electron micrographs of epoxy samples made with magnetic separates from (top) the Holz Member of the Ladd Formation and (bottom) the Point Loma Formation. Note the nearly equidimensional shape of the Holz Member and Point Loma Formation magnetic particles and the clumping of the Point Loma Formation magnetic particles. The scribed line nearly parallel to the bottom of the Holz Member micrograph is parallel to the applied field direction. The applied field direction in the Point Loma sample is parallel to the bottom edge of the micrograph.

directions. Their inclinations are 39.5°±5.4° and -36.4°±16.6°, respectively. The remanence anisotropy corrected normal and reversed polarity inclinations are 56.0°±5.1° and -53.0°±16.7°, respectively. The confidence limits for the corrected inclinations are calculated by

$$\begin{aligned}\delta \mathrm{I}_{\mathrm{field}} = {} & \cos^2 I_{field}[q_H(a+2)-1]/\{\cos^2 I_{\mathrm{ChRM}}[q_V(a+2)-1]\}\delta I_{ChRM} \\ & + \cos^2 I_{field}(a+2)/[q_V(a+2)-1](\tan I_{ChRM}\delta q_H - \tan I_{field}\delta q_V) \\ & + \cos^2 I_{field}/[q_V(a+2)-1](q_H \tan I_{ChRM} - q_V \tan I_{field})\delta a \qquad (6)\end{aligned}$$

where $\delta \mathrm{I}_{\mathrm{ChRM}}$ is the 95% confidence limits on the mean ChRM inclination [*Demarest*, 1983]; δq_H and δq_V are standard errors of the mean normalized remanence anisotropies in horizontal and vertical directions, respectively. δ_a is the standard error of the a factor.

4.2. Tectonic Implications

Our corrected paleomagnetic directions for the Ladd and Point Loma Formations suggest that the Peninsular Ranges terrane has not moved with respect to stable North America since the Late Cretaceous. The predicted paleolatitudes, based on the AAR-corrected inclinations, are 38°N for the Ladd Formation and 37°N (normal) and 34°N (reversed) for the Point Loma Formation. When compared to the latest Cretaceous paleopole for North America calculated by *Dickinson and Butler* [1998], after Neogene San Andreas transform motion has been removed, the paleolatitudes indicate no movement for the Silverado Canyon locality (predicted paleolatitude is 38°N) and no movement for the normal polarity Point Loma area (predicted paleolatitude is 37°N). The reversed polarity Point Loma results have a large error, probably due to an incompletely removed normal polarity overprint, but they are statistically consistent with the predicted paleolatitude. These conclusions are in agreement with *Butler et al.*'s [1991] and Dickinson and Butler's suggestion that the Peninsular Ranges terrane's anomalously shallow inclinations can be completely explained by postmagnetization tilting of batholithic rocks and compaction-caused inclination shallowing in sedimentary rocks.

The depositional environments of the Holz Member of the Ladd Formation and the Point Loma Formation (neritic and bathyal) are typical of the other sedimentary units which provide anomalously shallow inclinations for the Peninsular

Table 4. Compaction-Corrected Site Means for the Holz Member

Site	a Factor	Dec, deg	Inc, deg	n	R	α_{95}, deg	κ
KlhA	1.50	328.6	60.0	9	8.903	5.7	82.9
KlhB	1.52	330.3	63.7	4	3.885	18.3	26.1
KlhG	1.41	330.7	55.4	6	5.950	6.7	99.7
KlhH	1.41	316.7	61.9	2	1.966		29.7
KlhI	1.41	317.0	61.6	8	7.965	3.9	200.8
KlhJ	1.41	320.6	53.5	3	2.991	5.4	224.2
KlhK	1.41	323.2	58.5	8	7.858	8.0	49.1
KlhL	1.41	326.9	50.5	6	5.874	10.7	39.8
Mean		324.4	58.2	8	7.968	3.7	221.0

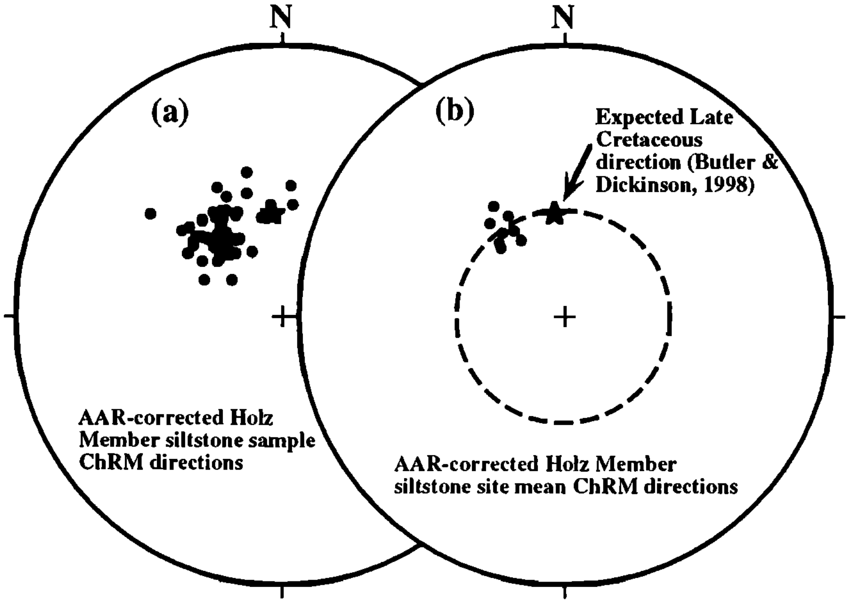

Figure 16. Equal area stereonet showing the compaction-corrected (a) sample ChRMs and (b) site means for the Holz Member. The dashed circle indicates the locus of inclinations equal to the inclination of the expected Late Cretaceous direction (star) for the Holz Member if it were part of cratonic North America. Note that the compaction-corrected data indicate that no northward transport for the Holz Member locality is needed and that a counterclockwise vertical axis rotation of the site is indicated.

Ranges terrane [*Butler et al.*, 1991; *Dickinson and Butler*, 1998]. Our results should be representative of the magnitude of inclination correction (10°-15°) that should be applied to these units. Since the paleomagnetically determined paleolatitudinal offset for Peninsular Ranges sedimentary units can be attributed to inclination shallowing of the order of 10°-15°, a correction of this size would indicate that none of the units can provide evidence for northward motion of the Peninsular Ranges terrane since the Cretaceous.

Dickinson and Butler [1998] conclude that deeper water facies, i.e., turbidites, may suffer from greater inclination shallowing than nearshore deltaic or shelf facies. This interpretation is based on a reexamination of *Simpson and Cox*'s [1977] data from the Eocene Tyee and Flournoy Formations of Oregon. They argue that reworking by currents on the shelf may allow magnetic grains to settle more effectively into pore spaces and avoid subsequent compaction effects. However, our results from the Holz Member of the Ladd Formation, which is interpreted to have been deposited in a shallow marine (shelf/slope) environment, do not support this hypothesis. *Smith and Busby* [1993] tried to determine whether the shallow inclinations of the Valle Formation from Baja California were caused by compaction from a grain size and inclination comparison. They reasoned that fine-grained lithologies should suffer from greater compaction and have shallower inclinations than coarser grained lithologies if compaction has affected a sample's remanence direction. Their results from the Valle Formation show no correspondence between inclination shallowing and sample grain size. We believe, however, that the reason lithology is not observed to control inclination shallowing is because clay content of the sediments plays a critical role in determining the magnitude of inclination shallowing. Previous work in our laboratory [*Sun and Kodama*, 1992] indicates that magnetite particles become attached to and incorporated into the developing clay fabric during compaction. This effect appears to significantly overshadow the effects of mean grain size or environment of deposition.

A plot of inclination shallowing, derived from the inclination correction work we have completed on four different formations, versus percent clay content reveals that the magnitude of inclination shallowing appears to be directly related to clay content (Figure 17). The Ladd Formation (Holz

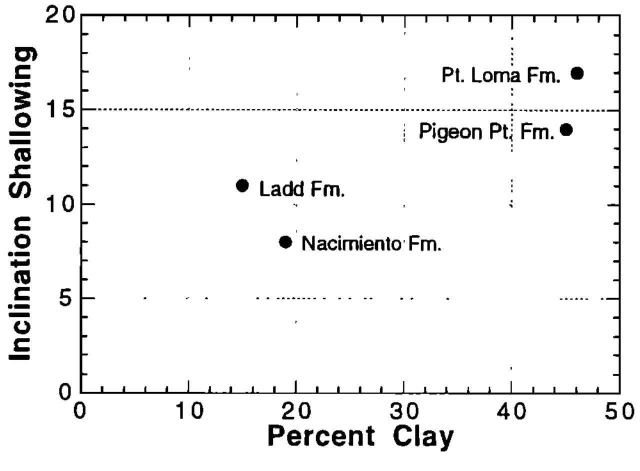

Figure 17. Inclination shallowing as a function of percent clay content for four different formations. The Ladd and Point Loma Formation inclination shallowing is reported in this paper. The Pigeon Point Formation and Nacimiento Formation inclination shallowing results are reported by *Kodama and Davi* [1995] and *Kodama* [1997], respectively Inclination shallowing increases from ~10° for 15% clay content to 15° and greater for clay contents close to 50%. These results suggest that clay content is an important control on compaction-caused inclination shallowing.

Member) and Nacimiento Formation have relatively low clay contents of 15-19%, yet suffer from 8° to 10° of inclination shallowing. The Point Loma and Pigeon Point Formations have higher clay contents (~45%) and correspondingly higher inclination shallowing (14°-17°). The magnitude of inclination shallowing for these plots is based on the anisotropy of remanence from at least 50 samples from each formation, so it should be a representative value. The percent clay content is based on only one or two samples, but the samples were from lithologies from which the bulk of the paleomagnetic data were collected. Higher clay contents may not lead to a greater degree of inclination shallowing since *Deamer and Kodama*'s [1990] work with synthetic sediments indicates comparable degrees of inclination shallowing during laboratory compaction of natural muddy marine sediments (percent clay content is ~50%) and samples containing 100% clay (kaolinite or montmorillonite) and magnetite.

The precompaction inclinations for the four formations studied are assumed to be ~50°-60°. These intermediate inclinations have been shown to produce the greatest inclination shallowing [*Anson and Kodama*, 1987; *Deamer and Kodama*, 1990]. Steeper initial inclinations will be shallowed by burial compaction by perhaps 50% less. Initial inclinations as shallow as 30° can still suffer from inclination shallowing nearly as great as that observed for 45°-60° initial inclinations [*Deamer and Kodama*, 1990]. It appears, then, that inclination shallowing is a function of clay content. Clay contents as low as 15-20% can still produce significant inclination shallowing (~10°), and the maximum inclination shallowing, for initial inclinations ranging from 30° to 60°, can approach 20° for high-clay contents (50-100%).

Our results can be applied to the current discussion of the far-travelled nature of Baja British Columbia (Baja B.C.). The paleomagnetic results from the Insular superterrane, which indicate significant paleolatitudinal offset, are from the Cretaceous Nanaimo Group sediments [*Ward et al.*, 1997] and the Duke Island ultramafic complex [*Bogue et al.*, 1995]. Only the data from the Nanaimo Group have good paleohorizontal control. The siltstones and mudstones of the Nanaimo Group are similar lithologies to those of the Holz Member and Point Loma Formations. *Ward et al.*'s [1997] results suggest over 2400 km of northward motion due to ~25° anomalously shallow inclinations. If 15° of the shallowing is due to burial compaction, this would put the Insular superterrane at a latitude of 35°N, rather than 25°N, in the latest Cretaceous, more consistent with plate kinematic models [*Cowan et al.*, 1997]. Of course, until detailed rock magnetic and compaction experiments are conducted on Nanaimo Group sediments, a more accurate estimate is not possible.

Our compaction-corrected inclinations from sedimentary rocks argue for no paleolatitudinal offset for the Peninsular Ranges terrane, however, this is not in agreement with *Ague and Brandon*'s [1992] recent paleobathymetrically tilt-corrected paleomagnetic results from the Peninsular Ranges batholith. Given the uncertainties in the paleomagnetic direction and the paleobathymetrically determined tilt axes and two compaction corrections from different, geographically separated sedimentary units which yield consistent paleolatitudinal results, we believe that the evidence from the batholith is not strong enough to support northward motion for the Peninsular Ranges terrane.

Other evidence for the Peninsular Ranges terrane being in place since the Late Cretaceous comes from the Pozo redbeds. *Whidden et al.* [1991] reported paleomagnetic results from upper Cretaceous redbeds on Pozo Summit in the La Panza Range located in the central Salinian block. The results indicate that Salinia was within 4°±7° of its expected North American position in the Late Cretaceous if Neogene San Andreas transform motion is restored.

The post-Cretaceous paleolatitudinal offset history for the Santa Lucia terrane remains controversial. *Kodama and Davi*'s [1995] compaction correction of the Cretaceous Pigeon Point turbidites indicates that approximately half of their 25° anomalously shallow inclinations were due to compaction while the remainder were probably due to tectonic transport. They proposed that the Santa Lucia terrane was at the southern end of the Sierra Nevada batholith, in agreement with *Dickinson* [1983]. However, in a more recent analysis, *Dickinson and Butler* [1998] have removed the rotation of the Transverse Ranges in a tectonic reconstruction for the Santa Lucia terrane, and they conclude that Kodama and Davi's compaction correction for the Pigeon Point Formation now puts it, and the Salinian block, concordant with North America in the Cretaceous. This conclusion is supported by a paleomagnetic study [*Hagstrum and Murchey*, 1996] of Jurassic radiolarian chert above the Coast Range Ophiolite at Stanley Mountain which indicates no latitudinal offset since Late Jurassic time.

The declination of the corrected formation mean directions indicates a 28.7° counterclockwise vertical axis rotation of the Silverado Canyon area and a 35.2° (normal) and 42.2° (reversed) clockwise vertical axis rotation of the Point Loma locality when the corrected and predicted directions are compared. Coherent clockwise declination rotations from the Peninsular Ranges terrane have been used to support a paleolatitudinal transport model; however, both *Butler et al.* [1991] and *Dickinson and Butler* [1998] have examined the complete declination dataset and have shown no consistent pattern of declination rotations. The Silverado Canyon and Point Loma rotations are probably the result of local block rotations or fault motions, rather than large-scale block rotations.

4.3. Magnetic Fabric

The magnetic fabric of the Holz Member is very similar to that observed for the Pigeon Point turbidites. A north-south lineation with distributed minimum axes is superimposed on a foliation. In contrast, the Point Loma sediments exhibit only a foliation. These results are consistent with each unit's depositional environment. The depositional environment of the Holz Member changes from shelf (siltstone) to slope (shale and limestone) to shelf (sandstone), probably responding to Late Cretaceous eustatic sea level changes [*Almgren*, 1982; *Bottjer and Link*, 1984]. The Point Loma Formation is typical of continental slope and ocean basin plain environments [*Nilsen and Abbott*, 1981]. The Holz Member lineation is probably, like the Pigeon Point Formation's, due to either bottom currents or possibly prelithification tectonic dewatering due to offshore plate convergence [*Paterson and Tobisch*, 1993]. Since the fold test and reversal tests support a depositional age for the ChRM-carrying magnetic grains, a tectonic AAR lineation which is significantly younger (10^7 years) than deposition is unlikely. The fabric also suggests a more active depositional environment for the Holz Member than for the Point Loma Formation. This result contradicts *Dickinson and Butler*'s

[1998] hypothesis that more active shelf-deltaic facies may not suffer from significant compaction shallowing due to constant reworking of the sediment.

5. Conclusions

The compaction-corrected inclinations from two Late Cretaceous marine sedimentary formations of southern California indicate that the Peninsular Ranges-Baja Borderlands terrane was in its present position with respect to North America by the Late Cretaceous. No post-Cretaceous paleolatudinal offset is indicated by the corrected paleomagnetic data. It appears from our studies of the Ladd and Point Loma Formations, as well as from previous studies of the Pigeon Point turbidites [*Kodama and Davi*, 1995] and the Nacimiento Formation [*Kodama*, 1997], that sediments containing clay have a high probability of suffering from 10° to nearly 20° inclination shallowing caused by burial compaction. The data from these four formations also indicate that there is a direct relationship between clay content and degree of inclination shallowing. The energy of the depositional environment does not appear to have a large control on the presence or significance of inclination shallowing. The high-energy environment for the deposition of the Holz Member, as indicated by a strong AAR lineation, did not significantly reduce the effects of burial compaction on inclination. Correction of inclination shallowing using remanence anisotropy of the ChRM-carrying magnetic grains and individual magnetic grain anisotropy should be routinely used to quantify the effects of burial compaction on the paleomagnetic inclination of clay-containing sedimentary rocks.

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