Refining the relative displacement of the southern California and Baja California coast ranges terrane: an application of the compaction correction to the remanent magnetization of marine sedimentary rocks

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Refining the Relative Displacement of the Southern California and Baja California Coast Ranges Terrane: An Application of the Compaction Correction to the Remanent Magnetization of Marine Sedimentary Rocks

by

Xiaodong Tan

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Abstract

Paleomagnetic data have been used extensively to delineate the terrane displacement and accretion history of western North America. However, some of the paleomagnetic data which could indicate large scale northward translation might be alternatively interpreted as due to tilting of batholiths or compaction of marine sediments. Recently, a paleobarometric study of the late Cretaceous Peninsular Batholith and a laboratory compaction study of marine sedimentary rocks from the Late Cretaceous Pigeon Point Formation show that the significant inclination shallowing observed in these rocks may not be all due to paleolatitudinal offset. In order to refine the displacement history of the southern and Baja California composite terrane, a detailed rock- and paleomagnetic study of the Ladd and Williams Formations from Silverado Canyon, Orange County, CA and the Point Lorna Fm. from Point Lorna, San Diego County, CA was conducted. Previous paleomagnetic studies have shown magnetostratigraphy in those late Cretaceous sections and their characteristic remanent magnetizations (ChRMs) are most probably primary. The study followed Jackson et al.'s (1991) approach to correct the site mean directions of the Ladd Fm. from Dec=342°, Inc=46° (α95=8°) in stratigraphic coordinates to Dec=324°, Inc=58° (α95=4°), and the inclination data of Point Lorna Fm. from 39.5°±5.4° and -36.4° ± 16.6° to 56.0°±5.1° and -53.0°±16.7°, respectively. The corrected inclination data suggest that the Baja Borderland terrane has been part of the western North America since Late Cretaceous. There was no significant latitudinal offset with respect to North American craton, while the Silverado Canyon area may have experienced significant counterclockwise vertical axis rotation. This study also suggests that rock magnetic fabric (AAR) experiment should be made as a routine technique in paleomagnetic studies. For tectonic purposes, in the case of a strong AAR fabric, the remanent magnetization should be corrected.
Introduction and Geologic Background

The North American Cordillera is composed mainly of allochthonous terranes (e.g., Coney et al., 1980; Jones et al., 1981; Howell, 1989). More than 50 terranes have been recognized from Alaska to Mexico. Although convergence and collisional events might have occurred as early as the mid-Paleozoic, most of the events of terrane collision and accretion occurred in Mesozoic and early Cenozoic time. Rock sequences, faunal records, as well as paleomagnetic data, suggest large latitudinal displacements and/or rotations between the terranes and between the terranes and cratonic North America (Coney et al., 1980; Jones et al., 1981; Howell, 1989).

The southern California and Baja California Coast Ranges are made up of two composite terranes, or superterranes (Figure 1) (Lund and Bottjer, 1991). These two superterranes are composed of several smaller terranes which amalgamated during the Late Mesozoic as indicated by sedimentary stratigraphy. One composite terrane was initially named the Santa Lucia-Orocopia allochthon by Vedder et al. (1983). Subsequently the Late Mesozoic paleomagnetically-determined paleolatitude (40°N) for the Orocopia-Chocolate Mountains thrust system was found to be consistent with the North American craton (Tosdal, 1990). Since the Orocopia area had already accreted to the North American craton in the Mesozoic, the allochthon was renamed simply the Santa Lucia terrane (Lund and Bottjer, 1991). The Santa Lucia terrane includes the area west of the San Andreas and San Gabriel faults and north of the Oak Ridge fault (Figure 1). Sequence stratigraphy, basement rock chemistry, and fossil records from the terrane indicate 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 2000 km northward since the Cretaceous (McWilliams and Howell, 1982; Champion et al., 1984; Kanter and Debiche, 1985).

The second allochthonous terrane, called the Peninsular Ranges terrane (Bottjer and Link, 1984) or the Baja Borderland terrane (Vedder et al., 1983), lies west of the San Andreas fault and south of the Oak Ridge and San Gabriel faults. It also includes all of Baja California (Figure 1). 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). 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 in land or in ocean to accommodate their motion with respect to southwestern North America. Since almost all the oceanic crust east to the spreading center of the oceanic plates has been subducted, i.e., the Pacific Plate, Faralon Plate, the trajectory of terrane movement in oceanic crust cannot be defined, and any northward translation of the terranes before docking to North America is unable to test. A variety of geologic data across the terrane boundary do not support the existence of a megashear in land; therefore, no reasonable geological scenario that would have these terranes move along coast of western American continents from low southern paleolatitudes to their present position (Gastil, 1991). Beck (1991) reviewed a variety of possible error sources for paleomagnetic data and argued that there might exist long range stratigraphic
correlation and an undiscovered megashear which had accommodated the terranes’ northward translation. To solve this controversy, both geological and paleomagnetic reinvestigation are needed. While there is no new geological discovery, several paleomagnetic reexamination has underscored the extent of northward translation of these terranes.

Butler et al. (1991) have 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 Range batholith in southern California indicate a differential uplift history for the batholith, showing that tilting of the paleohorizontal plane of the batholith after the acquisition of thermal remanent magnetization has occurred, and the anomalously low inclination for the paleomagnetic data from the batholith might have been caused by tilting subsequent to magnetization (Butler et al., 1991). Because the paleomagnetic data from the batholith are generally consistent with paleomagnetic data from the late Cretaceous and early Tertiary marine strata, Butler et al. (1991) suspect that the shallow paleomagnetic inclinations for the Peninsular Ranges marine sedimentary rocks might have been caused by a burial compaction effect, and the actual latitudinal displacement of these terranes might be small or insignificant. A subsequent paleobarometric study of the Peninsular Range batholith suggests that tilting could account for at most only a part of the inclination shallowing and the tilt-corrected paleomagnetic data still indicate significant northward displacement (1000 ±450 km) relative to cratonic North America since the late Cretaceous time (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 Curie temperature at which the batholith's thermal
remanent magnetization was acquired (Constanzo-Alvarez and Dunlop, 1988; Beck, 1992). Thus, the effect of compaction on paleomagnetic inclination in these marine sediments, is more critical in solving this controversy.

**Previous Work on Compaction-Caused Inclination Shallowing**

Compaction-caused inclination shallowing is observed both in laboratory compaction experiments (Anson and Kodama, 1987; Deamer and Kodama, 1990; Kodama and Sun, 1992; Sun and Kodama, 1992; Kodama and Davi, 1995) and in natural marine sediments (Celaya and Clement, 1988; Arason and Levi, 1990; Tarduno, 1990; Gordon, 1990). The compaction-caused inclination shallowing depends on the grain size, clay content, pore water chemistry (e.g., the Eh-pH values), and the volume loss of the sediments. It is larger in fine-grained sediments with a high clay content. Although the classic study, in which the remanent magnetization of marine turbidites from the Tyee and Flournoy Formations of Oregon was compared to the remanence of the coeval Siletz River volcanics, showed no inclination errors for the sedimentary rocks (Simpson and Cox, 1977), this result may not be universal. A laboratory compaction study on the late Cretaceous Pigeon Point Formation from the Santa Lucia terrane recognizes significant (about 10°) compaction-caused inclination shallowing (Kodama and Davi, 1995), however the compaction correction of the inclination only accounts for half of the inclination difference between the late Cretaceous Santa Lucia inclination and the inclination for the stable North American Craton (Kodama and Davi, 1995). Recently, well-controlled laboratory compaction experiments on Paleocene Nacimiento Formation samples, which are known to have 8° of inclination shallowing, demonstrate that detailed rock magnetic and laboratory compaction experiments can indicate the exact amount of inclination shallowing (Kodama, 1997).
The compaction correction for the Pigeon Point Formation inclination suggests that the paleolatitude of the Santa Lucia terrane was similar to that of the Peninsular Ranges terrane (Kodama and Davi, 1995) in the Late Cretaceous and could indicate that these two terranes were amalgamated at that time (Figure 2). Kodama and Davi suggested the possibility that the Peninsular Ranges terrane has also been affected by 10° of inclination shallowing and was not displaced with respect to the North America since the Late Cretaceous. To test this possibility, it is necessary to study whether the compaction-caused inclination shallowing has affected the characteristic remanent magnetization of the Late Cretaceous marine strata of the Peninsular Ranges terrane and to make a compaction correction, if necessary.

Jackson et al. (1990) have developed a conceptual method in which inclination errors in detrital remanent magnetization (DRM) can be recognized by measurement of the anisotropy of anhysteretic remanent magnetization (AAR). According to Jackson et al.'s model, the inclination error should only depend on the magnitude of the AAR and the magnetic anisotropy of the individual magnetic particles.

Jackson et al.'s model may be expressed as:

$$\tan(I_{\text{compacted}}) / \tan(I_{\text{initial}}) = \left( q_x (a+2) - 1 \right) / \left( q_x (a+2) - 1 \right)$$

(1)

where $I_{\text{compacted}}$ is the inclination affected by compaction; $I_{\text{initial}}$ is the inclination before compaction; $q_x$ is the ratio of $\text{ARM}_{\text{min}} / (\text{ARM}_{\text{max}} + \text{ARM}_{\text{int}} + \text{ARM}_{\text{min}}$); $q_x$ is the ratio of $\text{ARM}_{\text{max}} / (\text{ARM}_{\text{max}} + \text{ARM}_{\text{int}} + \text{ARM}_{\text{min}}$); and $a$ is the individual grain anisotropy factor: $\text{ARM}_{\text{easy axis}} / \text{ARM}_{\text{hard axis}}$.

To use Jackson et al.'s model to identify and correct for any compaction-caused inclination shallowing, we need to measure the AAR of sediment samples to determine
ARM_{min} and ARM_{max} and the individual magnetic grain anisotropy factor, a. ‘a’ may be determined either by compaction experiments or by direct measurement of the magnetic fraction separated from the sediment. In compaction experiments, the values of I_{compacted}, I_{initial}, q_x, and q_y can be measured, and a is calculated by using eq.(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. If all the particles have their magnetic easy axes (long axes) aligned parallel to the DC field, the individual particle anisotropy is best estimated by the bulk anisotropy of the epoxy sample.

Methods

In order to determine an accurate Late Cretaceous paleolatitude for the Peninsular Ranges terrane, we must conduct a detailed rock magnetic study to isolate compaction effects and a standard paleomagnetic study to determine the characteristic remanence that must be corrected. Our targets were two of the marine sedimentary formations that have shown low inclinations in previous studies (Butler et al., 1991; Lund and Bottjer, 1991) because, recently, Hagstrum (1990a,b; 1996, private communication) has suggested that most of the formations studied to delineate the paleolatitude of California terranes may have been remagnetized during late Cretaceous and Tertiary terrane accretion. The two formations we chose to study from the Peninsular Ranges terrane have stratigraphically-constrained magnetic polarity variations and, hence, have probably escaped extensive remagnetization. These formations are the Late Cretaceous Ladd and Williams Fms. of Silverado Canyon, Orange County (Almgren, 1982) and the Point Loma Fm. of Point Loma, San Diego County (Nilsen and Abbott, 1981), both marine strata. Detailed magnetostratigraphies were reported by Fry et al. (1985) and Bannon et
al. (1989), respectively, for these sections. Three types of site directional behavior were reported by both Fry et al. (1985) and Bannon et al. (1989). These directional behaviors were used to classify sites for magnetostratigraphic interpretation. Class 1 sites have well-defined polarity and direction; class 2 sites have well-defined polarity, but not well-defined directions; and class 3 sites have poorly-defined directions and polarity. About half of the sites are class 1 sites. Because of the complexity of the remanent magnetization carried by the formations, our compaction correction study could not be simply conducted on randomly selected samples, but on samples having a stable characteristic remanent magnetization (ChRM). It is obvious that both rock- and paleomagnetic studies are critical to identify and to correct, if necessary, any compaction-caused inclination shallowing for the Peninsular Ranges terrane's Late Cretaceous marine strata.

In order to determine if the sediments in these formations have had their inclination affected by compaction, several steps must be taken. First, detailed progressive thermal and alternating field demagnetization was used to isolate the ChRMs. The remanent magnetization of samples was measured by a CTF two-axis superconducting magnetometer. Thermal and af demagnetization was conducted using TSD-1 and GSD-5 demagnetizers. AAR (McCabe et al. 1985) was subsequently measured on those af demagnetized samples which yielded ChRMs. Next, the individual particle anisotropy was determined. This was done in two ways, one by laboratory compaction experiments and the other by deposition of a magnetic extract in a strong magnetic field.

For the laboratory compaction experiment, a hand sample from each site was disaggregated in an ultrasonic cleaner so that the disaggregated sediment would have a grain size distribution as close as possible to the original grain size distribution.
Laboratory redeposition and compaction in a controlled magnetic field will be conducted to mimic the acquisition of a natural pDRM and the effects of burial compaction on it. The AAR of the compacted sediment sample was measured following compaction to different degrees. Thermal and alternating field demagnetization was also used to isolate the ChRM of the laboratory-compact-compacted samples. Isothermal remanent magnetization (IRM) applied using an impulse magnetizer (ASC Scientific IM-10-30) and partial ARM (pARM) spectra of the natural samples and the redeposited samples could be used to monitor possible changes in the magnetic minerals and grain size distribution due to the disaggregation process.

For the epoxy redeposition experiment, a permanent magnet was used to extract magnetic minerals from a slurry made from the disaggregated sediments. The extracted magnetic minerals were mixed in with epoxy and the mixture was allowed to harden in a strong magnetic field so that all the particles orient with their easy axes of magnetization (long axes) parallel to the magnetic field. The IRMs acquired by samples were demagnetized before pARMS were imparted to the samples in the direction parallel to and then perpendicular to the assumed direction of the particle long axes, and particle anisotropy was thus determined (a=ARM∥/ARM⊥). A standard 9 position AAR measurement routine of the epoxy samples could also be used to determine the value of particle anisotropy, and these two estimates can be compared.

Scanning electron micrograph (SEM) observation of the extracted magnetic minerals can also be used to check the particle anisotropy derived from the laboratory compaction and epoxy redeposition experiments, because the shape anisotropy of the particles should be related to the individual particle anisotropy, a. One reason for the SEM check...
is that incomplete dispersal of magnetic particles in the epoxy would result in an unreliably low estimate for the particle anisotropy (Jackson et al., 1990), which would then lead to overcorrection for inclination shallowing. Chains formed by magnetic particles would result in an exaggerated individual grain anisotropy factor leading to an undercorrection of inclination shallowing.

After the determination of individual particle anisotropy, the ChRM direction of each sample is corrected by using eq. (1) to yield the corrected paleolatitude for the Peninsular Ranges terrane.

Sampling

Twenty five sites of samples were collected from the Ladd Fm. in Silverado Canyon, Orange County, CA, including the sandstone of the Baker Canyon Member, and the siltstone, sandstone, and limestone of the Holz Member. Six to ten cubic (8 cm³) samples were cut at each site using a dual blade, battery powered, hand saw. Samples were oriented with a Brunton compass. The stratigraphic distribution of sites is shown in Fig. 3. Bedding dips south to south-southeast at 30° to 50° in the Baker Member and in the Holz Member. The Ladd Fm. yields typical marine fossils, including ammonites and other calcareous nannofossils which indicate Late Turonian to Middle Campanian ages (Fry et al., 1985). A previous magnetostratigraphic study also indicated late Turonian to middle Campanian stage ages, about 90-70 Ma for the Ladd Fm. (Fry et al., 1985). This section represents continental slope and shallow marine depositional environments.

Sixteen oriented hand samples were collected from the Point Loma Fm., from La
Jolla Cove, Sunset Cliff and a cliff behind the sewage treatment plant at Point Loma, San Diego County. Six to ten cubic (8 cm$^3$) samples were cut from each hand sample with an aluminum blade saw at the paleomagnetics laboratory of USC. Lithologies in this section are mostly mudstone, shale, interbedded with thin-layered siltstones, representing a much deeper depositional environment than the Ladd Fm. Fig. 4 shows the stratigraphic position of our sampling sites. Paleontology and magnetostratigraphy indicate a late Campanian to early Maastrichtian age for the Point Loma Fm. (Bannon et al., 1989). The structure of the section is a gentle syncline (less than 10° dips) with a fold axis trending east-west.

Results

1. Paleomagnetism

Four representative samples from each site were subjected to either detailed progressive thermal or af demagnetization in 10-15 steps. The Holz member siltstone and limestone samples of the Ladd Fm. yielded straightforward demagnetization behavior with consistent within-site and between-site ChRM directions, while the samples from the Baker Canyon Member of the Ladd Fm. and of the Point Loma Fm. had either uninterpretable demagnetization behavior or scattered within-site and between-site directions. Our data are consistent with the previously published formation mean direction for the Ladd and Williams Fms.; our best sites have directions which correspond to the class 1 sites of Fry et al. (1985). We have decided to only correct the inclination for the sites from the Ladd Fm. that produced the best paleomagnetic results. These sites are predominantly from the Holz shale member. The magnetization of the Point Loma Fm. is very complicated; for some sites we were unable to obtain any
interpretable demagnetization results, while for other sites the ChRM are rather dispersed. Therefore, we measured samples’ AAR of 6 sites from the Point Loma Fm. and used the mean AAR to correct the mean Point Loma inclination reported by Bannon et al. (1989).

The demagnetization behavior of representative siltstone and limestone samples of the Holz member are shown in Fig. 5. Thermal demagnetization was successful 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 stability component was removed by 300° C in siltstone and by 200° C in limestone, and by 20 mT in both lithologies. The low stability component was very scattered with steep downward inclinations, which may be due to the acquisition of viscous remanence. The low field magnetic susceptibility of siltstone and limestone samples increased significantly during thermal demagnetization after heating above 500° C (Fig. 6), which may indicate a magnetic mineralogy change and caused minor variation of remanent magnetization and greater measurement error at higher temperature. The limestone samples broke apart during thermal demagnetization after heating above 300-350° C. Therefore, the remaining samples were either subjected to 4 to 6 steps of thermal demagnetization up to 500° C for siltstone samples and 300° C for limestone samples or to af demagnetization up to a 60 mT peak field to isolate the ChRM of each sample. The ChRM was then calculated by principal component analysis (Kirchvink, 1980).

NRM have two groups of directions (Fig. 7). One is distributed in the north-northeast with a steep downward inclination, close to the present geomagnetic field direction; the other points south with both positive (downward) and negative (upward) shallow inclinations (Fig. 7 (a)). After removal of the overprint (low coercivity, low
unblocking temperature) component, the normal direction gets shallower and the reversed direction gets more negative Fig. 7(b)). The ChRM site mean directions resulting from thermal and af demagnetization are in quite good agreement (Fig. 7(c) and Table 1). Progressive tilt correction of the ChRM site mean directions indicate that the precision parameter of the mean of the site means increases from in situ, and reaches a maximum at 86% untilting (Fig. 8), but both McElhinny's (1964) and McFadden & Jones' (1981) fold tests are negative. Since the section is a monocline and the geometry of the strata was not greatly distorted, the mean directions before and after tilt correction could not be statistically distinguished from each other between these tests. McFadden's fold test (1990), which is more sensitive to bedding distortion, was applied to test the relative age of the ChRM. The critical values are 4.036 and 5.624 at 95% and 99% confidence level respectively. The in situ statistic parameter, $\xi_2$, is 8.826, greater than the critical value, while the unfolded statistic parameter is 1.698, less than the critical value. The fold test may exclude the post-deformation age of ChRM, and the ChRM may be either pre-deformation or syn-deformation, since the precision parameter, $k$, reaches maximum at 86% unfolding and there is no apparent correlation at that point. A positive reversal test (McFadden & McElhinny, 1990) will exclude the possibility of syn-deformation origin of the ChRM because of its generally short period of remagnetization. Because the precision parameters of the normal mean and reversed mean directions are significantly different, the reversal test (McFadden & McElhinny, 1990) has been performed by simulation. The reversal test for the in situ directions is negative, while the bedding corrected normal and reversed mean directions pass the reversal test, classified C. Since the positive and negative mean inclinations are nearly equal in magnitude ($I_R = -43^\circ$; $I_N = 47^\circ$) (Table 1) the scatter of mean directions can be attributed to the declination difference between reversed and normal polarity means,
which may be indicative of differential bedding rotation or due to the relatively large scatter of the reversed directions. The stratigraphic variation of polarity of the sampled section is the same as previously reported by Fry et al. (1985) and the overall mean inclination is indistinguishable from their results. Compared to a reference field direction, which is Dec=336.4°, Inc=62.5° (Irving & Irving 1982), or Dec=354°, Inc=57.7° (Diehl, 1991) (Fig. 7 (d)), the mean ChRM direction shows 12° to 17° inclination shallowing, typical for the Baja Borderland allochthon.

2. Magnetic mineralogy

The low unblocking temperature and coercivity of the ChRM in the samples from the Holz member of the Ladd Formation suggest that it is carried mainly by magnetite. It is important to know if other magnetic minerals are present in the rocks. These minerals may not contribute to the ChRM but could contribute to a laboratory-induced magnetization, e.g., ARM, which will be used to correct the ChRM directions.

The IRM acquisition and back field demagnetization curves of representative samples from every site which yielded good ChRM directions show that IRM increases rapidly at low DC fields (< 0.2 T) and approaches saturation at high DC fields (> 0.6 T) (Fig. 9 (a)). The coercivities are around 50 mT for most of samples except for one sample from site KlhE. Its coercivity is about 0.2 T. The characteristics of IRM saturation and coercivity suggest the dominance of low coercivity magnetic minerals. Samples from site KlhD, KlhE, KlhG and KlhI, may contain a small amount of high coercivity magnetic minerals, because their IRMs are not completely saturated at 1.2 T.

The IRMs of the Point Lorna Fm. samples increase rapidly at low DC fields, and gradually increase at high fields (Fig. 10 (a)). IRM does not saturate at highest field and
the back field experiments suggest minimum coercivities that range from 55 mT to 200 mT. These characteristics suggest that both low and high coercivity magnetic minerals coexist in the Point Loma rock samples.

Thermal demagnetization of an IRM applied perpendicular to an ARM can also provide a means for identifying multiple magnetic minerals in a sample, especially to determine the contribution of high coercivity magnetic minerals to the pARM applied to samples. Thermal demagnetization of an IRM acquired at 1.2 T and a pARM acquired in either a 20 to 70 mT window for the Holz member samples or 20 to 80 mT window for the Point Loma samples indicates that the unblocking temperature of the IRM ranges from 550° to 690°C, while ARM component unblocks from 500° to 600° C (Figure 11 (a, b)). It confirms the existence of hematite in both siltstone samples of the Holz member and mudstone samples of the Point Loma Fm., but the pARM resides in magnetite particles. Therefore, following pARM acquisition, and AAR measurement are targeting mainly to magnetite particles, which are supposed to be the ChRM carriers since the unblocking temperatures of ChRM of our samples and Bannon et al.'s samples are less than 580° C.

3. Magnetic fabrics (of natural samples)

A pARM curve represents the coercivity spectrum of a sample which is related to magnetic grain size distribution in the sample. All the pARM curves of samples from the Holz member and the Point Loma Fm. samples peak at 40 mT, and have a similar shape of their coercivity spectrum (Fig. 12 (a), 13 (a)). Because ChRM is isolated after 20 mT of af demagnetization, the pARM window chosen for magnetic fabric measurements was between 20 to 70 mT for the Holz member samples and 20 to 80 mT
for the Point Loma Fm. Samples.

Following McCabe et al.'s (1985) procedure, samples were imparted a pARM sequentially in 9 orientations with a 0.1 mT DC field, and a least squares method was applied to calculate the best-fit 2nd order tensor. For all the tensors, the RMS errors are less than 0.6%, most of them are less than 0.4%. The eigenvectors and eigenvalues of the tensor are the directions and relative lengths of the three axes of the magnetic fabric ellipse. The ellipse is a function of the shape anisotropy and distribution of magnetic particles within a certain coercivity (grain size) range.

The directions of maximum and minimum axes of the magnetic fabric ellipse were projected onto an equal area stereonet (Fig. 14(a)). For the Holz member samples the $K_{\text{max}}$ direction is best determined. It points in a north-south direction and has a shallow inclination. There are two groups of $K_{\text{min}}$ directions. One is approximately perpendicular to bedding; the other is orthogonal to both $K_{\text{max}}$ and the other group of $K_{\text{min}}$ axes. These two $K_{\text{min}}$ axis groups probably result from the dominant lineation in the fabric, and hence the minor difference between the length of the $K_{\text{min}}$ and $K_{\text{int}}$ axes making them hard to resolve. The shape parameters of magnetic fabric were plotted on a Flinn diagram (Fig. 14(b)) and indicate oblate, prolate, and triaxial ellipsoid shapes. The magnetic fabrics show both lineation and foliation features, which presumably represent depositional (bottom current) and compaction effects, respectively. Since no strain was observed in the section and our rock samples, tectonic fabric can be ruled out. These fabrics corroborate a primary origin of the ChRM magnetic carriers.

For the Point Loma samples, the AAR fabrics show well-grouped bedding-perpendicular minimum axes and horizontal but scattered $K_{\text{max}}$ and $K_{\text{int}}$ directions (Fig. 16).
Most samples have an oblate AAR ellipse with a strong foliation (1.05-1.090) and a weak lineation (Fig. 15(b)) indicating a large influence by compaction effects and small current effects, suggesting a quiet depositional environment. The average $K_{\text{max}}$, $K_{\text{int}}$, and $K_{\text{min}}$ values are 0.3435±0.0019, 0.3388±0.0024, 0.3176±0.0021, respectively. The average foliation and lineation values are $F=1.074±0.0005$, $L=1.014±0.0016$.

4. Determination of individual grain anisotropy factor 'a'

The magnetic remanent anisotropy of individual magnetic grains, a, is critical for correcting remanent magnetization. Two different methods were used to derive the 'a' factor. One is laboratory compaction of a sediment slurry made of distilled water (the water composition should not affect the determination of the a factor) and sediments disaggregated from natural rock samples. The other is the direct measurement of pARMs along the easy and hard axes of magnetic extracts which were aligned in a strong DC field during drying of an epoxy medium.

4.1 Compaction experiment

a. Disaggregation

The bulk rock samples were wrapped in clean papers and crushed into small pieces by a hard rock. A hammer was not used to avoid any magnetic contamination. Fragments of about 5 mm in size were chosen for disaggregation in deionized water with an ultrasonic cleaner. The grain shape and structure of silt and fine sand grains were frequently checked under a light microscope with a magnification of 30 to determine whether the sediment grains were composed of single particles. A slightly
oversaturated slurry is made from these disaggregated sediments for subsequent experiments. The slurry made from the Holz member silt is about 80% water content and that made from the Point Loma Fm. mud is about 280% water content. The difference in water content between these two slurry is due to their different grain size. The muddy slurry has higher water content and due to its higher clay content.

b. Redeposition and DRM/pDRM acquisition

Redeposition and compaction experiments were conducted in a magnetic field using an inclination of 58°, which is very close to the expected Late Cretaceous paleofield inclination for the sampling localities assuming they were part of North America at that time. The intensity of the laboratory magnetic field was about 80 μT, the lowest field the coils could produce for a field with 58° of inclination. Although the field is stronger than the present Earth's magnetic field, it should not affect our determination of the α factor. The magnetic field was measured with a Bartington flux-gate magnetometer and is quite uniform within a cubical space 3 cm on each side. The sediment slurry was dripped into an acrylic, cylindrical sample holder with a small spoon. The sample holder is weakly magnetized (< 5E-10 Am²), two orders of magnitude less than the sample's overall intensity.

The magnetization of the slurry was measured right after being dripped into the sample holder. The inclination ranged from 53° to 58° and may have suffered a small amount of syn-depositional inclination shallowing. After standing in the laboratory magnetic field for an hour, in most cases, inclination increased by 2° to 4° and intensity increased less than 10%. Since stirring the slurry did not increase the intensity, but decreased the intensity, and the direction of the slurry's magnetization after stirring was
in most cases further away from the field direction than for dripping alone, most of the magnetic grains have aligned very close to the magnetic field by using the drip technique.

c. Compaction

After the slurry had acquired its magnetization along the ambient magnetic field, it was compacted with a water tank consolidometer, which is the same as that used in previous compaction studies by Anson and Kodama (1987), Deamer and Kodama (1990), Kodama and Sun (1992), Sun and Kodama (1992), and Kodama and Davi (1995). A detailed description of the consolidometer can be found in Hamano (1980) and Anson and Kodama (1987). The pressure on the slurry sample increased at a rate of 0.008 MPa per hour, which is controlled by adjusting the rate at which water fills the tank. The volume and remanent magnetization of the samples were measured more than ten times at various stages of compaction.

The volume loss as a function of pressure is shown in Fig. 16(a), 17(a) for all the compaction runs. For most of the compaction runs, volume loss did not start until the pressure overcame the friction between the filter paper and the plunger. This occurred at very low pressures (<0.02 MPa), so the consolidation behavior of the samples was not affected. Most of the volume loss occurs at low pressures. About half of the total volume loss occurs at a pressure less than 0.04 MPa. As pressure increases, the rate of volume loss decreases and reaches zero at the highest experimental pressures. Total volume loss for the Holz member slurries range from 40% to 60%, because of variations in grain size and water content. For Point Loma Fm. Slurries, total volume loss reaches just above 70%.
The inclination shallowing of a slurry's remanent magnetization is shown in Fig.s 16 (b), 17 (b). Inclination shallowing is significant for all the compaction runs. For the Holz member runs, total inclination shallowing was about 5° to 15°, and inclination declines gradually during volume loss. For the Point Loma Fm. experiments, total inclination shallowing was between 13° to 20°, and the inclination vs. Volume loss curves are convex in shape, indicating that the inclination shallowing is more significant at the highest volume losses. The inclination vs. pressure curves indicate that most of inclination shallowing occurs at low pressures, less than 0.08 MPa. At higher pressures, inclination decreases very slightly. The pattern of inclination shallowing and volume loss with respect to pressure in all the compaction runs are similar to previous compaction studies (eg. Deamer and Kodama, 1990; Sun and Kodama, 1992).

d. Demagnetization

Kodama and Davi (1995) have shown that the remanent magnetization of their laboratory redeposited and compacted magnetite-bearing Pigeon Point Fm. samples consists of two remanence components one of which is a large viscous magnetic overprint. We conducted alternating field (AF) and thermal demagnetization on the compacted samples after compaction to determine whether they had acquired a large secondary overprint during compaction and more importantly to obtain the remanent magnetization carried by the same grains that carry the natural samples’ ChRM and the AAR used for inclination correction.

For most of the compacted samples, their inclinations were almost the same before and after extrusion out of the sample holder. For a few samples, e.g., SDCP1, about 5° further inclination shallowing was observed after the sample was extruded, which might
be an effect of the remanence of the porous stone. The porous stone may in some cases acquire a remanence from contamination by sediments if the filter paper did not seal the space between porous stone and the sample holder completely. The ChRM of compacted samples were not affected by porous stone since it had been removed prior to demagnetization, so the samples are still useful in determining the a factor. The AF and thermal demagnetization results are plotted in orthogonal vector end point projections (Zijderveld, 1967) in Figs. 18 and 19 for the Ladd Fm. silt slurry samples and Point Loma Fm. mud slurry samples respectively, indicating only one remanence component in the compacted samples. This also suggests that inclination shallowing would not have been removed by demagnetization of the natural samples. The best fit direction in the same coercivity window as the natural samples’ ChRM or as those used to measure the AAR was chosen to calculate the ‘a’ factor.

e. Comparison of magnetic properties between disaggregated samples and their natural samples

One critical aspect in deriving the ‘a’ factor is that the magnetic mineralogy and magnetic grain size distribution is the same for the natural samples and the laboratory compacted samples. The IRM acquisition and back field demagnetization curves of both disaggregated and natural samples were compared to determine if any magnetic mineral shape and size distribution changes occurred. The pARM spectra can also be used to indicate variations in the magnetic grain size distribution. All of these parameters for the laboratory-compacted samples (Figs. 9(b), 10(b), 12(b), 13(b)) are quite similar to their natural counterparts and suggest the same magnetic grain composition, shape, and size distribution as the natural samples.
f. Magnetic fabric of laboratory compacted samples

To derive the 'a' factor, AAR measurements of the compacted samples are necessary. The pARM for AAR was acquired in the same coercivity window as that used for imparting a natural sample's pARM. The magnetic fabric results show a strong oblate ellipsoid with well clustered vertical minimum axes and horizontally-distributed maximum and intermediate axes (Fig.s 20, 21), typical of a compaction fabric.

g. Calculation of the 'a' factor

The 'a' factor was calculated by:

$$ a = [(2q_z - 1) \tan I_{\text{initial}} + (1 - 2q_z) \tan I_{\text{compacted}}]/(q_z \tan I_{\text{compacted}} - q_z \tan I_{\text{initial}}) $$  (2)

where $I_{\text{field}} = 58^\circ$, and $I_{\text{ChRM}}$ is the inclination of the best fit ChRM inclination for the compacted sample, the ChRM was based on the same coercivity window as used for the AAR measurement. All the 'a' factor data were plotted on the inclination correction curves derived from Jackson et al. (1991) by Kodama and Davi (1995) (Fig. 22). The average 'a' factors that resulted are 1.41±0.12 and 1.47±0.028 for siltstone samples of the Holz member and mudstone samples of the Point Loma Fm.

h. X-ray diffractometry

Previous studies have demonstrated that clay content is an important factor in inclination shallowing (Anson and Kodama, 1987; Deamer and Kodama, 1990; Kodama and Sun, 1992; Sun and Kodama, 1992). It is important to know the composition and the clay content of the disaggregated samples. Each slurry sample of
the Holz member or the Point Lorna Fm. was analyzed using X-ray diffraction. Results (Fig. 23(1)) show that both slurries consist mainly of quartz, plagioclase, supplemented with carbonate, halide minerals, and potash feldspar. Slurries were further treated in centrifuge at 500 RPM for 8.8 minutes to separate particles greater than 2 \( \mu \text{m} \) from the suspensoid which was then filtered through a 0.45 \( \mu \text{m} \) Millipore filter. The particles were placed on the small glass slide which fits into the x-ray sample holder. After they were air-dried, samples were placed in a desiccator containing ethylene for 24 hours. The x-ray diffractograms (Fig. 23 (2)) of the separated fine grains reveal that the Holz member slurry also consists of smectite, kaolinite, illite, and chlorite, and the Point Loma slurry contains illite and chlorite.

4.2 Orientation of magnetic extracts

a. ‘a’ factor vs. Magnetic field strength

An alternative way to determine the ‘a’ factor is to directly measure the pARMS along the magnetic particles’ easy and hard axes of magnetization. To do this the magnetic minerals were extracted from the disaggregated sediments with a permanent magnet. Two different magnets were used. A bar magnet producing a magnetic field up to 20 mT was used to extract the magnetic minerals from the slurry made from the Holz member silt, and a rare earth magnet producing a magnetic field up to 200 mT was used to extract particles from the slurry made from the Point Loma Fm. The extract is enough for subsequent experiment, except the extract from Ladd Fm. limestone sample, which is so little that the pARM is negligible compared with their IRM and correction for limestone ChRM inclination is impossible. After the extract was dried, the magnetic particles were mixed with epoxy and the mixture was placed in a strong DC magnetic
field in an electromagnet. The easy axis of magnetic particles should be able to rotate parallel to the magnetic field direction. The efficiency of the alignment of easy axes depends mainly on the viscosity of the epoxy used and the magnetic torque on the grain's magnetic moment caused by the applied magnetic field. The magnetic field produced by the laboratory electromagnet is adjustable up to about 0.3 T. It is best to avoid applying too strong a magnetic field to the mixture, since the strong IRM that results from high DC field will make pARM measurements difficult to resolve. However, the field must be strong enough to align the magnetic grains as perfectly as possible. Therefore, a suite of epoxy drying experiments with increasingly stronger magnetic fields was conducted (Jackson et al., 1991; Kodama, 1997). After the epoxy samples hardened, their coercivity spectrum and AAR were measured. The pARM spectrum of the epoxy samples indicate that the magnetic extracts were dominated by coarse grains of low coercivity (< 20 mT) although the higher coercivity, finer grains also exist in epoxy. We attempted to measure the AAR of the magnetic extracts using the same coercivity window as used for measuring the AAR of the natural and compacted samples, but because the samples had acquired a large IRM which could not be cleaned by a 100 mT peak af demagnetization field, the AAR error was very large (>20%). Consequently we were only able to measure the pARM in three directions, termed as \( p\text{ARM}_{\text{EASY}} \), \( p\text{ARM}_{\text{HARD1}} \), and \( p\text{ARM}_{\text{HARD2}} \). \( p\text{ARM}_{\text{EASY}} \) is along the external magnetic field direction (assumed to be along the easy axes of the magnetic particles), and the other two were orthogonal to the first and to each other and were assumed to be the two hard axes. The 'a' factor was calculated by:

\[
a = 2 \frac{p\text{ARM}_{\text{EASY}}}{(p\text{ARM}_{\text{HARD1}} + p\text{ARM}_{\text{HARD2}})}
\]  

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A curve of ‘a’ versus DC field was plotted to see at what magnetic field strength ‘a’ reaches a maximum, indicating that the easy axes were completely aligned parallel to the external field.

Fig. 24 (a) shows two ‘a’ vs. magnetic field curves for the Holz member magnetic extracts. ‘a’ increases from 1.04 at a 25 mT field to around 1.4 at a 45 mT field, and then does not increase at higher fields. The ‘a’ value derived in this manner is very close to the value derived from the compaction experiments (Fig. 22 (a)). Since these two different methods yielded the same result, it gives us confidence that we have obtained a good approximation of a for the Holz member compaction correction. For the Point Lorna extracts, ‘a’ is around 1.6 at fields less than 50 mT, but at higher fields, it increases significantly (Fig. 24 (b)). This may be due to magnetic interaction between magnetic grains. Since the magnetic particles were extracted using a very strong magnet, the individual magnetic particles acquired strong IRMs, which made the grain alignment easier and magnetic interactions more prevalent. At low fields, magnetic grains are clumped and partially aligned while at higher fields alignment would cause the magnetic particles to form a chain which resulted in an amplified ‘a’ factor value. The low field ‘a’ factor is greater than that derived from compaction study by more than 0.1, so particle interactions and limited alignment might have existed even at the lowest alignment field. The ‘a’ factor value determined by compaction experiment will be used in correcting the inclination of the Point Lorna Fm.

b. **SEM observation**

SEM backscatter images (Fig. 25) provide evidence for magnetic particle orientation and magnetic interactions. The magnetic grains extracted from the Holz member slurry
have grain sizes less than about 50 μm and greater than 1-2 μm, and are mostly oval in shape. A 35 mT magnetic field did not align the long axes of the oval-shaped grains (Fig.25 (a)), while a 45 mT magnetic field was able to align the long axes nearly parallel to the magnetic field direction (Fig. 25 (b)), thus confirming the assumption that the ‘a’ value had saturated (Fig. 24(a)). The Point Loma extracts have a wider range of magnetic grain size than the Holz shale, 1 to 200 μm. The SEM micrographs show that at a 20 mT field, the large grains did not align parallel to the field direction while at a 60 mT field, they aligned in the DC field direction and formed particle chains (Fig. 25 (c), (d)). Small particles did stick together to form large aggregates. Those large aggregates were poorly aligned in the magnetic field direction at both low and high field strength.

5. Correction for ChRM

5.1 Correction for ChRM directions of the Holz member siltstone

We essentially used eq. (1) to make a correction for the Holz member siltstone ChRM directions. Implicit in the use of eq. (1) is the assumption that the $K_{\text{max}}$ direction is the same as the paleomagnetic field declination and that the magnetic fabric of the natural sample is oblate. However, prolate and triaxial magnetic fabrics do exist in some samples of the Holz member. In addition, the maximum axes do not always align with the paleomagnetic declination of a sample. Therefore, some modification of the correction procedure suggested by Jackson et al. (1991) is necessary and both declination and inclination need to be corrected for the ChRMs of the Holz member samples. The correction method used is:

$$\tan \text{Dec}_{\text{Field}} / \tan \text{Dec}_{\text{ChRM}} = (K_N(a+2)-1) / (K_E(a+2)-1)$$

(4)
\[
\frac{\tan \text{Inc}_{\text{Field}}}{\tan \text{Inc}_{\text{ChRM}}} = \frac{(K_H(a+2)-1)}{(K_V(a+2)-1)}
\]  
\quad (5)

Where all the parameters are in stratigraphic coordinates, and \(K_N\), \(K_E\), \(K_V\), and \(K_H\) are the lengths of the normalized AAR ellipse in north, east, vertical, and horizontal (along the paleolongitude) directions respectively. The tilt-corrected ChRM direction is corrected by eqs. (4) and (5) for each individual sample and the site mean directions based on these corrected sample directions are listed in Table 2. This procedure changes the site mean normal direction from \(\text{Dec}=333^\circ, \text{Inc}=47^\circ (\alpha_{95}=5^\circ)\) (before fabric correction) to \(\text{Dec}=324^\circ, \text{Inc}=58^\circ (\alpha_{95}=4^\circ)\) (after correction). The change in both declination and inclination is about 11°.

5.2 Correction for mean inclination of the Point Loma Fm.

Since we were unable to obtain ChRM directions for the Point Loma samples, we decided to correct the mean inclination data of Bannon et al. (1989) based on the magnetic fabric and ‘a’ factor data we collected from the Point Loma. The magnetic fabric from the Point Loma is oblate in shape, and ‘a’ factor (based on compaction experiments) is small, therefore an inclination correction should significant. Since the lineation in the fabric data is very weak, there would be little fabric effect on the paleomagnetic declination. The foliation parameter of the natural samples is just slightly (~0.01) less than the laboratory compacted samples, hence the compaction experiments indicate the magnitude of the compaction effect for the Point Loma Fm. By comparing the inclination data of natural and laboratory compacted samples, we conclude that most of the inclination shallowing observed in the Point Loma could be attributed to a compaction effect.

Eq. (1) was used to correct the mean inclination data. Bannon et al.’s normal
polarity inclination and reversed polarity inclination are $39.5^\circ \pm 5.4^\circ$, and $-36.4^\circ \pm 16.6^\circ$. The fabric-corrected normal and reversed polarity inclinations are $56.0^\circ \pm 5.1^\circ$, and $-53.0^\circ \pm 16.7^\circ$. The confidence limit for the corrected inclination is calculated by:

$$dI_{\text{Field}} = \cos^2 I_{\text{Field}}(K_H(a+2)-1)/\cos^2 I_{\text{ChRM}}(K_V(a+2)-1) dI_{\text{ChRM}}$$

$$+ \cos^2 I_{\text{Field}}(a+2)/(K_V(a+2)-1)(\tan I_{\text{ChRM}} dK_H - \tan I_{\text{Field}} dK_V)$$

$$+ \cos^2 I_{\text{Field}}/(K_V(a+2)-1)(K_H \tan I_{\text{ChRM}} - K_V \tan I_{\text{Field}}) da$$

where $dI_{\text{ChRM}}$ is the error of the mean ChRM inclination with 95% confidence (Demarest, 1983); $dK_H$, $dK_V$ are standard errors of the mean normalized remanence susceptibilities in horizontal and vertical directions respectively; $da$ is the standard error of the 'a' factor.

**Discussion**

1. **Tectonic implications**

   We were able to correct the paleomagnetic directions for the Ladd & Williams Fms. and the Point Loma Fm. of the Baja Borderland terrane. The corrected inclination for Silverado Canyon and Point Loma localities are $58^\circ \pm 4^\circ$, and $56.0^\circ \pm 5.1^\circ$ and $-53.0^\circ \pm 16.7^\circ$, respectively. The inclination correction is $11^\circ$ for the Ladd and Williams Fms. and $17^\circ$ for the Point Loma Fm. The reference pole for North America did not move significantly during 130-85 Ma; however, significant apparent polar wandering did occur between 85 to 75 Ma. Since the ages of our samples range from about 90 Ma to 70 Ma, both the stand-still pole (e.g., Irving and Irving, 1982; Globerman and Irving, 1988) and the 80 Ma pole (Diehl, 1991) were selected to derive the field direction for Baja Borderland. The reference inclination is about $62.5^\circ$ (Irving and Irving, 1982;
Globerman and Irving, 1988), or 57.7° (Diehl, 1991); if the 300 km northward translation in Neogene (Butler et al., 1991) is considered, the expected inclination is about 59.5° for the Holz member and 54.7° for the Point Lorna Fm. There is no inclination difference between the corrected value of the allochthon and the expected inclination; therefore, the Baja Borderland terrane had already accreted to North America by the Late Cretaceous. This supports Butler et al.’s (1991) model and Kodama and Davi’s (1995) suggestion.

Ague and Brandon (1992) reported tilt-corrected paleomagnetic data for the Peninsular Ranges batholith, and concluded that the inclination shallowing of the batholith is partly due to tilting of the batholith due to differential uplift and also due to the northward transport. The paleolatitudinal offset suggested is 1000±450 km. Since both stratigraphic correlation across the San Andreas fault system (Gastil, 1991) and faulting restoration (Butler et al. 1991) suggest only about 300 km of Neogene fault slip for the Baja Borderland terrane these data would suggest at least 250 km and as much as 1150 km of northward translation of the terrane in the Late Cretaceous before the deposition of the Holz member. However, other uncertainties exist. A 250 km offset in field geology is substantial, while it would be well within typical errors in paleomagnetism. In addition, because the crystallization or annealing temperature of Hornblende is close to the highest unblocking temperature of magnetite, if the magnetization was syn-uplifting of the batholith the method is inappropriate. The situation is more complicated if the geotherm, the cooling rate or the initial emplacing depth was different within the batholith. Although Ague and Brandon’s data may suggest some degree of northward displacement, we believe that Baja Borderland terrane has already been part of the western north American continental margin since the
Late Cretaceous.

Other evidence for Baja Borderland’s already being in place in Late Cretaceous may be from the Pozo redbeds. Whidden et al. (1991) reported the paleomagnetic results of the upper Cretaceous redbeds on Pozo Summit in the La Panza Range of the central block of Salinia, suggesting that the central block of Salinia was within 5° of its expected position as part of the North American craton in Late Cretaceous if the San Andreas Fault motion during Neogene was restored. The 15° inclination shallowing of other upper Cretaceous and Paleocene marine and non-marine stratigraphic sequences from the Peninsular Ranges Terrane reported by Lund et al. (1991) may also be contributed to compaction, since the compaction correction for inclination shallowing ranges from 10° to 17° from Kodama and Davi (1995) and this study.

The latitudinal translation history of the Santa Lucia allochthon remains controversial. Kodama and Davi (1995) conducted a compaction correction for the inclination shallowing of the Late Cretaceous Pigeon Point Fm. They concluded that the 25° inclination shallowing observed from the Pigeon Point Fm. (Champion et al., 1984) could be attributed to 10° of compaction shallowing and 15° of northward transport. Other evidence supporting large scale northward movement for the Santa Lucia terrane is the Jurassic marine radiolarian chert which is usually considered of equatorial origin (Hagstrum et al., 1996). Hagstrum et al. (1996) reported a paleomagnetic study of the lower Jurassic radiolarian chert in the Franciscan Complex, San Rafael Mountains, Southern California. Their results support its equatorial origin which requires more than 20° of northward translation. In contrast, another paleomagnetic study (Hagstrum and Murchey, 1996) of Jurassic radiolarian chert above the Coast Range Ophiolite at Stanley Mountain suggested no latitudinal offset since late Jurassic time. The tectonic
history of the Santa Lucia allochthon appears to be quite complicated.

The declination results indicate a counterclockwise vertical axis rotation of the Silverado Canyon area and a clockwise vertical axis rotation of the Point Loma locality. Butler et al. (1991) have collected all the declination data available from the Coastal California terranes. Most of the localities studied paleomagnetically in southern and Baja California show various degrees of vertical axis clockwise rotation and two areas, the Santa Anna Mountains of southern California and the Vizcaino Peninsula of Baja California, show counterclockwise rotation. Since the declination may have been affected by preferential alignment of magnetic particles as shown by the Holz member samples, more AAR data may need to account for this effect. However, these different senses of rotation at various localities of the Baja California may reflect local vertical axis rotations as a result of different fault movements, rather than large scale block rotations.

2. Depositional implications

The magnetic fabric data of the Holz member of the Ladd Fm. show both lineation and foliation, indicating an active depositional environment, while the Point Loma Fm. only shows foliation, probably suggesting a quiet deposition environment. These features are reasonable with respect to their depositional environments. The depositional environment of the Holz member changes from shelf (siltstone), slope (shale, limestone), to shelf (sandstone), probably responding to Late Cretaceous eustatic sea level changes (Almgren, 1982; Bottjer and Link, 1984). The Point Loma Fm. is typical of continental slope and ocean basin-plain environments (Nilsen and Abbott, 1981). The magnetic particles' long axes may either be parallel to current flow when current

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velocity is small or be perpendicular to current flow when the current velocity is high. The lineation may also be tectonic origin, or the combination of depositional and tectonics origin (Kodama and Davi, 1995). Although currently it is impossible to resolve the origin of the lineation, the tectonic related lineation is most unlikely. Because the remanent magnetization is primary, if the lineation is related to deformation, the remanent magnetization would have either been rotated or been remagnetized, and would not pass the fold and reversal tests. Thus, we believe that the lineation fabric of the Holz member is depositional. The slight deviation of the Holz member’s $K_{\text{min}}$ axes from vertical could indicate an imbrication dipping toward the east. This result could indicate either the general slope of the basin or a local bathymetric variation. In the former case, the sediment would have come from the west-northwest of the basin (the 25° counterclockwise tectonic rotation is restored) and the basin might have been isolated or semi-isolated. X-ray diffractometry shows the presence of halide, carbonate minerals, and plagioclase and potash feldspar in sediments indicating that the basin might be isolated. Crouch and Suppe (1993) suggested that the Los Angeles basin was an extensional basin in Late Cenozoic time. It may have been a back-arc extensional basin in Late Cretaceous. Further fabric data from other localities and provenance studies are necessary to better constrain the depositional environment.

3. Implications for the compaction effect on paleomagnetic direction of marine sediments

Laboratory studies and some natural marine sediments have shown that clay minerals play an important role in depositional inclination error and compaction caused inclination shallowing (e.g., Anson and Kodama, 1987; Deamer and Kodama, 1990; Sun and Kodama, 1992; Lu et al. 1990). Laboratory compaction study has shown that clay-rich
sediments lose their volume and suffer inclination shallowing mainly at pressures below 0.05 Mpa (Anson and Kodama, 1987; Deamer and Kodama, 1990; Sun and Kodama, 1992). The compaction experiments on sedimentary slurries demonstrate a similar relationship between volume loss, inclination shallowing and pressures. However, since most inclination shallowing of Quaternary marine sediments were observed from samples below 100 m depth and greater pressure (e.g., Arason and Levi, 1990; Celaya and Clement 1988), there may have some difference in compaction behavior between laboratory compaction experiments and compaction in natural environment. However, since the porosity of laboratory compacted samples which show significant inclination shallowing is similar to natural samples at great depth (>100 m) (Deamer and Kodama, 1991), the laboratory compaction-caused inclination shallowing is a good analog to marine sedimentary rocks. The difference in compaction behavior should not affect the estimation of individual particle anisotropy factor and the correction for natural samples' ChRM. Inclination shallowing usually occurs in fine grained sediments, e.g., mudstone, shale. This study reveals that siltstone may also suffer significant inclination shallowing, as well as declination error. Grain size analysis of the Holz member disaggregated sample shows the dominance of silts (67.6%), with 17.1% of fine sands, and 15.3% of clay-size grains. Although the silt sediments may not experience compaction very much, since the mechanism of inclination shallowing is that magnetic particles attach to clay mineral and flatten with the formation of clay domain (Deamer and Kodama, 1991; Sun and Kodama, 1992), a small amount of clay minerals can play an important role in causing significant inclination error. Therefore, a rock magnetic fabric test should be conducted in routine paleomagnetic studies in addition to laboratory and field tests and, in some cases, a correction for ChRM directions may be necessary.
Conclusion

The compaction corrected inclination data of the Late Cretaceous marine sedimentary rocks of southern California indicate that the Baja Borderland terrane was already accreted to North American craton by the Late Cretaceous, and does not require northward transport. The declination data indicate different local vertical axis rotation of the Silverado Canyon area with respect to other areas of the terrane and to the North American craton. The Holz member sediments show strong lineation fabric which may indicate that the sediments were deposited in the occurrence of a current flow either from the west-northwest or the east-southeast of the basin. Silt-sized marine sediments may also suffer significant inclination shallowing and declination error, and therefore, AAR fabric method should be used as a routine technique for testing magnetic stability and as a rough estimation of inclination shallowing or declination variation caused by fabric. For tectonic purposes, correction of the ChRM is necessary if fabric is significant.
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Table 1. Site mean ChRM directions from the Holz member of Ladd Formation (upper Cretaceous) from Silverado Canyon, California.

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<th>Dip (°)</th>
<th>Bedding Dec(°)</th>
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<th>R</th>
<th>α95(°)</th>
<th>κ</th>
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<td>Dec(°)</td>
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<td>1/1</td>
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Table 2. Fabric-corrected site mean ChRM directions (in stratigraphic coordinates) for siltstone sites of the Holz member of Ladd Fm.

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<th>Site</th>
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<th>Dec (°)</th>
<th>Inc (°)</th>
<th>n</th>
<th>R</th>
<th>α&lt;sub&gt;95&lt;/sub&gt; (°)</th>
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<td>5.874</td>
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<td>58.2</td>
<td>8</td>
<td>7.968</td>
<td>3.7</td>
<td>221.0</td>
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Figure 1. Map of southern California showing the location of the Peninsular Ranges terrane (PR) and Santa Lucia allochthon (SL) (after Lund and Bottjer, 1991), sample localities are indicated by solid dots, Silverado Canyon (Svr) and Point Loma (Plm).
Figure 2. Paleolatitudinal offset versus age for paleomagnetic studies from coastal California (Kodama and Davi, 1995). The Pigeon Point (PP) offset of the Santa Lucia terrane is distinguishable from that of Peninsular Ranges terrane (PR). The compaction corrected PP shown by the arrow of PP is consistent with that of PR. This result indicates that either these two terranes had already amalgamated in the Late Cretaceous or the Late Cretaceous marine strata of PR had been affected by burial compaction.
Figure 3. Stratigraphic section and magnetic polarity column of the Ladd and Williams Fms. (from Fry et al., 1985), Silverado Canyon, Orange County, CA. Sampling sites in this study are shown by vertical bars. The results of labeled sites will be reported in Table 1.
Figure 4. Stratigraphic section and magnetic polarity column (from Bannon et al., 1989) of the Point Loma Fm., Point Loma, San Diego County, CA. Sampling sites are shown by vertical bars right to the stratigraphic column.
Figure 5. Orthogonal projections of remanent magnetization during progressive thermal and af demagnetization of siltstone (top) and limestone (bottom) samples of the Holz member of the Ladd Formation.
Figure 6. Low field magnetic susceptibility of siltstone (a) and limestone (b) samples of the Holz member measured at room temperature after samples were thermally demagnetized. Increase of susceptibility at higher temperature corresponds to minor variation of remanent magnetizaton and greater measurement error due to induced magnetization.
Figure 7. Stereonet projection of magnetization of (a) in situ sample NRMs, (b) in situ sample ChRMs, (c) in situ site mean ChRMs resulting from thermal or af demagnetization, respectively, (d) tilt corrected site mean ChRMs, (e) AAR fabric corrected siltstone sample ChRMs, (f) AAR corrected siltstone site mean ChRM directions. The limestone and sandstone directions are not corrected, because of the difficulty in deriving the '+a' factor, also see text.
Figure 8. Variation of the precision parameter of the formation mean direction as a function of percent tilt correction. For a positive McElhinny's (1964) fold test, the precision parameter must be greater than 55.7. The mean direction also fails McFadden and Jones (1981) fold test, but it passes McFadden's (1990) new fold test, because the later method is more sensitive to distortion of bedding attitudes.
Figure 9. IRM acquisition and back field demagnetization curves of the Holz member samples, (a) natural samples and (b) compacted samples.
Figure 10. IRM acquisition and back field demagnetization curves of the Point Loma samples, (a) natural samples and (b) compacted samples.
Figure 11. Thermal demagnetization of IRM (one order stronger) and pARM components of samples from (a) the Holz member and (b) the Point Loma Fm.
Figure 12. pARM curves of (a) natural and (b) compacted samples from the Holz member of Ladd Fm.
Figure 13. pARM curves of (a) natural and (b) compacted samples from the Point Loma Fm.
Figure 14. Results of magnetic fabric measurement of the Holz member samples showing (a) equal area stereonet projection of the maximum and minimum axes of ellipse and (b) Flinn diagram of AAR fabric.
Figure 15. Results of magnetic fabric measurement of the Point Loma Fm. samples showing (a) equal area stereonet projection of the maximum and minimum axes of the AAR ellipse and (b) Flinn diagram of AAR fabric.
Figure 16. Results of a compaction study of the silt slurry made from the Holz member siltstone showing (a) volume loss as a function of burial pressure, (b) inclination shallowing as a function of volume loss of the slurry and as a function of pressure (c).
Figure 17. Results of the compaction study of the mud slurry made from the Point Loma Fm. mudstone showing (a) volume loss as a function of burial pressure, (b) inclination shallowing as a function of volume loss of the slurry and as a function of pressure (c).
Figure 18. Orthogonal projection of the magnetization of the compacted Holz member silt slurry samples subjected to progressive (a) af and (b) thermal demagnetization.
Figure 19. Orthogonal projection of magnetization of the compacted Point Loma Fm. mud slurry samples subjected to progressive (a) af and (b) thermal demagnetization.
Figure 20. Results of magnetic fabric measurements of the compacted silt slurry of Holz member samples showing (a) equal area stereonet projection of the maximum and minimum axes of AAR ellipse and (b) Flinn diagram.
Figure 21. Results of magnetic fabric measurements of the compacted mud slurry of Point Loma Fm. samples showing (a) equal area stereonet projection of the maximum and minimum axes of the AAR ellipse and (b) Flinn diagram.
Figure 22. Inclination correction curves as a function of individual grain anisotropy factor for (a) the compacted Holz member silt slurry and (b) the compacted Point Loma mud slurry. The coordinates of each point on the curve are from individual compacted samples.
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<td></td>
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Figure 23 (1). X-ray diffractograms from samples of (a) the Holz member silt slurry and (b) the Point Loma mud slurry.
Figure 23 (2). Diffractograms from samples with very fine grains (less than 2 micron) separated from Holz member silt slurry (L&W) and Point Loma mud slurry (Plm).
Figure 24. Curves of individual grain anisotropy factor as a function of aligning DC field for magnetic extracts from (a) siltstone samples of the Holz member and (b) mudstone samples of the Point Loma Fm.
Figure 25. Scanning Electron Microscope backscatter images show the shape and distribution of magnetic extracts within epoxy at different DC field. Magnetic extracts of Holz member silt slurry oriented at (a) 35 and (b) 45 mT, and magnetic extracts of Point Loma mud slurry at (c) 20 and (d) 60 mT.
Figure 25. Scanning Electron Microscope backscatter images show the shape and distribution of magnetic extracts within epoxy at different DC field. Magnetic extracts of Holz member silt slurry oriented at (a) 35 and (b) 45 mT, and magnetic extracts of Point Loma mud slurry at (c) 20 and (d) 60 mT.
Vita

Tan, Xiaodong, born on November 8, 1963, to Fushen Tan and Caiyin Jing, in Hangzhou, Zhejiang Province, China, obtained his Bachelor degree and Master degree in 1985 and 1988, respectively, in the field of geology and structural geology from Zhejiang University. He served as a lecturer assistant during 1988-1990, and a lecturer during 1990-1994. He was selected as an outstanding young teacher in 1993-1994 at Zhejiang University. He has participated in several research grants during the Chinese 7th and 8th five-year projects awarded by NSF and industry, and was awarded a grant by Chinese NSF in 1994. His research was also awarded the third prize in 1992 and 1995 by the Chinese Education Committee. In 1994, he joined the paleomagnetic group at Lehigh University as a graduate student working with Dr. Kodama.
END
OF
TITLE