The Use of Paleomagnetic Analysis to Assess Nonbrittle Deformation Within the San Andreas Fault Zone

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A recently developed paleomagnetic extraction technique successfully permits sample collection from unconsolidated sediments. Traditional measurement and demagnetization procedures can subsequently be performed, and several studies have already shown that soft-sediment samples yield reliable magnetic polarity information. To test the robustness of the extraction technique, as well as the resolution limits of the resultant magnetic vector directions, a total of 238 paleomagnetic samples were taken from unconsolidated strata exposed in an excavation across the San Andreas fault zone in the Carrizo Plain, California. Variable fault offset values for the most recent earthquakes at this locality favored the likelihood of rotational, nonbrittle, deformation. Such deformation could possibly be recorded in the DRM (detrital remanent magnetization) of sediment deposited across the zone. Declination directions of sample groups taken from presumably unrotated strata show general agreement with the most recent secular variation curve constructed for southern California, supporting the assumption that the stratigraphic units sampled do record an accurate DRM. However, significant variations in declination directions are found between magnetically stable samples within sample groups (i.e., taken as close as 1 cm apart within the same stratigraphic horizon). Probable causes of such declination variations include postdepositional, physical disturbances associated with rupture events and errors generated by the sampling technique. Inadvertent sample rotation about the axis of the glass holders is one of the most evident sources of error found in this study, although only samples which underwent large rotations (> 60°) could be identified. Regardless of its origin, the variability of the magnetic declination directions found for the 29 magnetically stable groups forces us to conclude that paleomagnetic results calculated in this study are not precise enough to discern reasonable (< 20°) amounts of rotation. These results question a similar soft-sediment study upon which this study was modeled which claims to have successfully detected less than 20° in rotational deformation using an identical sampling method. Additional studies are needed, preferably not within active fault zones, to better define sources of error for this relatively new soft-sediment sampling technique and to determine its resolution limits for discerning small changes in paleomagnetic vector directions.

INTRODUCTION

The purpose of this study was to determine whether fine-grained sediments in an excavation across the San Andreas fault preserve a stable detrital remanent magnetization (DRM) and if the errors associated with soft-sediment paleomagnetic sampling techniques are small enough to allow successful detection of suspected nonbrittle deformation across the fault. Such paleomagnetic detections are often desirable in regional studies of geologic rotation as well as local studies of nonbrittle deformation, such as that accompanying discrete, brittle offset within an active fault zone. Previous work by Salyards et al. [1992] suggests that this approach to discerning rotational deformation is indeed viable. The results of his study at Pallet Creek, California, [Salyards et al., 1987; Salyards, 1989; Salyards et al., 1992] suggest from 10° to 16° clockwise rotation manifested as nonbrittle warping in stratigraphic units across the San Andreas fault zone. These results are important for understanding the kinematic behavior of the San Andreas fault because the addition of dextral warp along this segment of the fault increases the average late Holocene slip rate from 9 mm/yr to 35.6 ± 6.7 mm/yr [Salyards et al., 1992]. This value is comparable to the 37.5 ± 2 mm/yr combined slip rate calculated along the San Jacinto fault and the segment of the San Andreas fault southeast of Pallet Creek to Cajon Pass [Weldon, 1986], as well as with rates determined about 200 km to the northwest at Wallace Creek of 33.9 ± 2.9 mm/yr [Sieh and Jahns, 1984].

The results of the study by Salyards et al. [1992] rely heavily upon the precision of a recently developed soft-sediment coring technique [Weldon, 1986] and especially on the ability to resolve magnetic declination changes of less than 20°. While this kind of resolution is customary in paleomagnetic analyses of drilled rock cores, quite commonly cited in conjunction with tectonic rotation studies [e.g., Chen et al., 1991], there are additional variables, e.g., sediment shifting, which must be considered. Several studies have successfully used this relatively new extraction method on unconsolidated sediments for magnetic polarity determinations [e.g., Weldon et al., 1984; Liu et al., 1988] for which precise resolution of the DRM direction is not necessary. Our study was undertaken primarily to test the robustness of the soft-sediment coring technique by performing a study similar to that of Salyards et al. [1992], carefully examining all variables, and discerning the resolution potential of the DRM directions preserved in the sediments.

For our test we chose a locality at which paleoseismic investigations were in progress in the summer of 1989 and the spring of 1990. The paleoseismic site is on the Carrizo segment of the San Andreas fault about 6.6 km southeast of Wallace Creek (Figure 1). Geomorphic work along this
segment by Sieh [1978] suggested that the most recent great-earthquake rupture here, in 1857, was associated with about 9.5 m of dextral slip. More recent work by Grant and Sieh [1991] suggests that only about 7 m of dextral slip occurred during the 1857 earthquake. One possible explanation for the smaller offset values would be the existence of nonbrittle, rotational deformation.

A laboratory experiment elucidates the physical expression of this type of deformation. In the experiment clay models were developed to simulate the formation of en échelon folds and faults caused by wrench faulting [Wilcox et al., 1973]. The upper illustration in Figure 2 (adapted from photos of Wilcox et al. [1973]) shows an undeformed clay cake marked with circles. The lower illustration shows the deformation produced by moving tin sheets below the clay cake in a strike-slip manner. The thick line drawn perpendicular to the fault zone is useful for illustrating how rotation, or warping, occurs near and within the zone of deformation. Note that two end-member types of rotational deformation are illustrated. Brittle, or rigid, block rotations yield discrete offsets such as those produced across the faults of the previously continuous circles in the lower illustration. The thick line in this sketch is also discretely offset across one of the faults. The warp of the thick line within the disturbed zone evidences elastic, or continuum, deformation as does the transformation of the circles into ellipses. In a system consisting solely of rigid block rotations, the amount of rotation inferred from paleomagnetic data should be the same at every point in the fault zone, or at least the same within each rigid block. On the other hand, continuum deformation progresses from unrotated to increasingly rotated toward some inflection point within the fault zone.

It is useful to distinguish the characteristic patterns of paleomagnetic directions which would result from each, or a combination, of these two styles of deformation. In either case potential rotations are inferred to occur about a vertical axis, and in a right-lateral strike-slip fault zone such as the San Andreas clockwise rotation is predicted for regions within the fault zone relative to points more distant from the

zone. Thus a similar pattern of clockwise rotations of the magnetic declination directions of paleomagnetic samples taken across the fault zone would provide evidence for the inferred rotational deformation. For example, a 5° clockwise rotation over a distance of 45 m, assuming a simple block rotation model, translates into 4 m of right-lateral offset. While these end-member deformation models are admittedly simple and exclude the third dimension of the displacement field, they are presented as a starting point into which more complex models of deformation can be incorporated.

METHODS

The San Andreas fault at our study site, known informally as the Bidart site, is a 16-m-wide "mole track" (Figure 3). The fault zone breaks alluvial fan deposits emanating
southwestward from the Temblor Range. The 44-m-long main trench cut perpendicular to the fault zone exposes mappable stratigraphy to a depth of 4.5 m below the surface. Predominantly sharp bedding contacts separate poorly sorted gravels from both massive and laminated, siliceous silts. Fortunately, silts tend to preserve DRM more reliably than do clays or coarser deposits. Figure 4 is a portion of the cross section of the southeast wall of the main trench. This has been simplified from K. E. Sieh and C. S. Prentice (unpublished data, 1991) to show all faults but only the two principal silt units relevant to this study. Three horizons, which correspond to the ground surface at the time of the three most recent episodes involving brittle deformation (i.e., earthquakes), are also shown and are labeled event 1, event 2, and event 3. Event 1 (1857 earthquake) occurs somewhere within the diagonally lined region. Arrows indicate the positions of events 2 and 3 and correspond to the horizons at which faults terminate upward. Two smaller trenches (also shown in Figure 3) were excavated 13 and 25 m southwest of the main trench. These are labeled trench 2 and trench 3, respectively, and exhibit the same stratigraphy as seen in the main trench. No faults occur in these smaller trenches, and our hope was that the sediments in these trenches would be unrotated.

Paleomagnetic sampling across all three trenches was performed in two phases. First a preliminary group of 79 samples was collected from nine silt beds that were traceable along most of the length of the main trench. These were tested for magnetic stability. Collection and laboratory procedures were identical to those performed on the second batch of samples and are described below. Demagnetization of these samples indicated that several beds preserve a stable magnetic remanence. Magnetic stability was assessed on the basis of least squares analyses [Kirschvink, 1980] of the demagnetization vectors.

Two silt, debris flows, designated units 92 and 60 (Figure 4), were ultimately chosen for the second phase of sampling because they were (1) magnetically stable, (2) well exposed and traceable in the main trench, (3) thick enough to prevent contamination from adjacent beds during sampling, and (4) found in at least one of the two smaller, distant trenches. Additionally, stratigraphic relationships confirm that unit 92 experienced one earthquake whereas unit 60 experienced two events. Thus, if warping occurred during the past two earthquakes, unit 60 ought to display more warping than unit 92. During this second stage of sampling, 55 additional samples were taken from unit 92, and 104 more samples were taken from unit 60. To ensure sampling consistency, these samples were extracted exclusively by one worker, and only samples acquired during this second phase of collection were utilized in the remainder of the study.

Cores are extracted from the poorly consolidated sediment by gently pounding a nonmagnetic stainless steel tube into

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**Fig. 3.** Map view showing San Andreas fault zone and the position of the trenches at the Bidart site. A cross section of the southeast wall of the main trench is shown in Figure 4.

**Fig. 4.** Simplified trench log of a portion of the southeast wall of the main trench (after K. E. Sieh and C. S. Prentice, unpublished data, 1991). See Figure 3 for orientation of the trench relative to the San Andreas fault zone. All faults within the trench are shown, but only the two principal silt units relevant to this study are included (labeled unit 92 and unit 60). Each circle within these units marks the central position of a given group of samples. The labels for each group correspond to those listed in Table 1 where the number of samples in each group is also listed. Samples 92-A, 60-A, and 60-B are located within the smaller trenches to the southwest, and samples 60-K and 60-S are located farther to the northeast in the main trench. The three most recent "event" horizons are shown and represent the approximate ground surface location during each of the three most recent earthquakes. Event 1 (1857 earthquake) occurred somewhere within the diagonally lined region, and events 2 and 3 correspond to the horizon at which faults terminate upward.
an exposure cleaned with a plastic scraper. A brass sleeve placed on the tube is oriented using standard methods. The steel tube is then extracted from the outcrop after inserting a plastic plunger to stabilize the sample within the tube. The sample is extracted into a labeled quartz glass sample holder and secured in the holder with a flexible paraffin film to keep it from rotating. Additional details of the testing and development of this technique are given by Weldon [1986]. Salyards [1989, Appendix 1] discusses the step-by-step methodology of both the extraction and laboratory preparation procedures. Alternative methods of sample collection from moderately cemented sediments include sculpting a block from an outcrop with a chisel or using compressed air instead of water to cool the drill during a standard drilling procedure. Neither of these methods could be used on the unconsolidated samples examined in this study.

Cores were usually removed from the stratum in groups of five, spaced as closely together as possible (usually within centimeters of each other), and groups were commonly spaced 1 to 2 m apart. Ten samples from each bed were extracted from trench 3 and 10 samples from unit 60 were extracted from trench 2. Unit 92 was not found in trench 2. A summary of data for the units is provided in Table 1; in total there are 10 groups in unit 92 and 19 groups in unit 60. An open circle, representing the central core in each group, locates most groups within the main trench in Figure 4. (The exceptions are group 60-R, located 8 m northeast of group 60-Q, and group 60-S, located on the northeast trench wall across from group 60-R.) Unit 92 northeast of group 92-J was too thin to be sampled.

In the laboratory the paraffin films were carefully removed and the samples were soaked with drops of sodium silicate solution to harden the sediment. Samples were placed in a magnetically shielded, μ-metal room for the remainder of the laboratory work. Once the sodium silicate solution had dried, each sample was capped with alumina cement to ensure the sample did not rotate in its holder. Samples were then subjected to the same demagnetization procedures as lithified rock cores.

All demagnetization measurements were performed using a computer-controlled cryogenic SQUID (Superconducting QUantum Interference Device) magnetometer with a background-noise level of 5 x 10^(-12) A m^2. Samples were initially subjected to alternating field (AF) demagnetization up to 15 mT in increments of 2.5 mT, followed by progressive thermal demagnetization in 50°C steps from 100°C to 500°C and four more steps between 500°C and 580°C.

Rock magnetic tests were performed on specific samples collected at the outcrop as well as samples removed during various stages in the thermal demagnetization process. These experiments are useful for determining mineralogy (via magnetic behavior) and probable grain size (via domain state) of the particles carrying the remanent magnetization. These experiments are also used to help resolve whether the nature of the magnetization is chemical or detrital. Samples were gently crushed, placed into a 1 mL plastic epinorph tube, and loaded into a cryogenic SQUID magnetometer where the following experiments could be conducted: (1) acquisition of anhysteretic remanent magnetization (ARM) in a standard 100-mT alternating field, with progressively stronger background biasing fields between 0 and 2 mT as done by Cisowski [1981], (2) progressive alternating field (AF) demagnetization of ARM after the 2-mT step, (3) progressive AF demagnetization of a 100-mT isothermal remanent magnetization (IRM), and (4) IRM acquisition in fields up to 800 mT.

### Table 1. Summary of Statistics for Paleomagnetic Samples Collected During the Second Phase of Core Collection

<table>
<thead>
<tr>
<th>Group</th>
<th>Original Samples in Each Group</th>
<th>Unstable Samples in Each Group</th>
<th>Rotated Samples in Each Group</th>
<th>Stable, Unrotated Samples in Each Group</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>92-A</td>
<td>10</td>
<td>1</td>
<td>2</td>
<td>7</td>
<td>trench 3</td>
</tr>
<tr>
<td>92-B</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-C</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-D</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-E</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-F</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-G</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>3</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-H</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-I</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>3</td>
<td>see Figure 4</td>
</tr>
<tr>
<td>92-J</td>
<td>5</td>
<td>0</td>
<td>12</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Totals</td>
<td>55</td>
<td>2</td>
<td>12</td>
<td>41</td>
<td></td>
</tr>
</tbody>
</table>

For each group samples were extracted as close together as possible, usually within a few centimeters. Determinations for magnetically unstable and rotated samples are discussed in the text. Samples in the right-hand data column are used for analysis of nonbrittle deformation across the San Andreas fault. Average magnetic declination and inclination directions for these stable, unrotated samples are listed in Table 2.
DATA ANALYSIS

Rock Magnetic Analysis

Figures 5a and 5b show graphs which summarize the rock magnetic properties. Results from a typical sample are shown. The shape of the IRM acquisition curve in Figure 5a, exhibiting only 95% saturation by 300 mT, suggests the summation of IRM curves for both magnetite, which saturates below 300 mT, and a ferric iron oxide such as hematite or goethite, which saturates at much higher fields. The low remanent coercive field ($H_{RC}$) of 30 mT also favors magnetite or maghemite over a mineral with a higher coercivity, such as hematite, as the carrier of the magnetic remanence. In addition, the value of the $H_{RC}$ does not vary substantially for samples tested after several thermal demagnetization steps have been performed. The higher peak field of the ARM demagnetization curve (AF of ARM) relative to the IRM demagnetization curve (AF of IRM) indicates a predominance of fine-grained (< 10 μm) single-domain or pseudo-single-domain magnetite. The overall shape of the demagnetization paths are also characteristic of a single-domain ferrimagnetic mineral such as magnetite. The 33% value for the crossover point $R$ (i.e., the ratio of IRM at $H_{RC}$ to the saturation IRM) indicates moderate particle interaction.

ARM acquisition experiments plotted in Figure 5b yield information about the packing geometry of the fine-grained magnetic minerals in the sediments. The end-members, shown with open circles, represent (magnetically) noninteracting chains of magnetosomes (labeled "magnetotactic bacteria") and strongly interacting clumps of magnetic particles (labeled "chiton tooth"). The sample shown in Figure 5b (solid circles) plots between these end-

![Graph showing ARM and IRM data](image.png)

Fig. 5. Rock magnetic experimental results for a typical sample. Similar results were obtained for samples tested after several thermal demagnetization steps had been performed. (a) Isothermal remanent magnetization acquisition (IRM acquisition) and alternating field demagnetization (AF of IRM) shown with open squares versus anhysteretic remanent magnetization demagnetization (AF of ARM) shown with solid squares. As discussed in the text, this plot indicates the presence of fine-grained, single-domain or pseudo-single-domain magnetite with some ferric iron oxides. (b) ARM acquisition (solid circles) plotted between noninteracting and strongly interacting end members (open circles). The position of the ARM acquisition line indicates moderate particle interaction.
members suggesting a mixture of the two types of packing geometries, confirming the above interpretation of moderate particle interaction. Although the sample plots much closer to the strongly interacting end-member, preliminary calibrations of this diagram suggest that the region between the end-members is not linearly incremental but concentrated near the strongly interacting end-member (J. L. Kirschvink, personal communication, 1992).

The results of these tests imply that a considerable fraction of the magnetic particles in these silts exists as isolated grains (i.e., not as noninteracting, highly ordered chains) of a ferrimagnetic mineral such as single-domain or pseudo-single-domain magnetite. The choice of magnetite over, say, maghemite is based upon the absence of mineralogical changes to hematite during the heating process. This would occur between 350°C and 450°C. Both the mineralogy and magnetic particle size support the existence of some type of detrital, as opposed to chemical, remanent magnetization. (Note that the absence of CRM is not unusual considering that these units were deposited only a few hundred years ago.) This is a favorable result in that it is a necessary condition for the interpretation of declinations as recorders of physical processes (i.e., rotation) and not chemical weathering.

**Demagnetization Analysis**

Figures 6 and 7 show typical demagnetization plots for two magnetically stable samples (Figures 6a, 6b, 7a and 7b).

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**Fig. 6.** Tilt-corrected orthogonal projections for three representative samples showing magnetic declinations in a horizontal plane (solid circles), magnetic inclinations in a north-south vertical plane (open circles), and magnetic intensity, which is actually the vector length from the origin, labeled along the ordinate for simplicity. Each orthogonal projection corresponds to an equal-area plot in Figure 7. (a) Magnetically stable sample from unit 92. (b) Magnetically stable sample from unit 60. (c) Magnetically unstable sample from unit 60.

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**Fig. 7.** Corresponding (tilt-corrected) equal-area plots for the three samples shown in Figure 6 (solid circles are lower hemisphere projections; open circles are upper hemisphere projections). The solid, isolated circle on each plot is the present-day field at the site locality. (a) Magnetically stable sample from unit 92. (b) Magnetically stable sample from unit 60. (c) Magnetically unstable sample from unit 60.
as well as one unstable sample (Figures 6c and 7c). The intensity of the natural remanent magnetization (NRM) of most samples is between $3 \times 10^{-5}$ and $10^{-6}$ emu. This value is moderate to low for terrigenous sediments but not unusual considering the ubiquity of marine sedimentary bedrock at the drainage heads in the Temblor Range. (Carbonates typically have only a weak remanence of less than $10^{-7}$ emu [Tarlting, 1983].) For all three samples, demagnetization steps are illustrated using both tilt-corrected orthogonal projections (Figure 6) and equal-area plots (Figure 7). Orthogonal projections show the magnetic declinations (solid circles) in a horizontal plane and magnetic inclinations (open circles) in a north-south vertical plane. Magnetic intensity, which is actually the vector length from the origin, is labeled along the ordinate for simplicity on each plot. The solid and isolated circle on each equal-area plot (Figure 7) is the present-day field at the site locality.

A sample from unit 92 (Figures 6a and 7a) becomes magnetically unstable after 525°C (just prior to the 550°C step). This is best seen on the equal-area plot. Until this temperature the demagnetization steps form a tight cluster directed down and to the northeast. In contrast, the stable demagnetization steps of a sample from unit 60 (Figures 6b and 7b) lie in a plane which includes the present-day field. Continued demagnetization gradually removes the overprint. Note that a probable VRM (viscous remanent magnetization) is also present and is removed after the first few AF demagnetization steps. The higher temperature overprint could have been interpreted as a DRM (chemical remanent magnetization) since the sample retains the overprint until almost 400°C. Such features were extremely atypical among the samples in this study (< 5%). The sample is primarily shown to illustrate the realm of demagnetization variations. Figures 6c and 7c show an example of a magnetically unstable sample from unit 60. 4% and 5% of the samples collected in units 92 and 60, respectively, were considered magnetically unstable (see Table 1). Magnetic components of the demagnetization vectors are found for each sample using the least squares method of principal component analysis [Kirschvink, 1980].

Error Analysis

Several of the magnetically stable samples have peculiar resultant vector directions, for example, south and up. Even more suspicious is the fact that usually only one or two samples in a group of five exhibits such a direction while the others are in general agreement (that is, north and down) with the present magnetic field direction. Secular variations of the Earth's magnetic field during the past several thousand years cannot account for this kind of result.

Since the orientation of the steel extraction tube is known for each sample, it is possible to test for inadvertent rotation about its axis. This might occur during the extrusion of the soft-sediment core into the glass sample holder or possibly during the securing of its position in the holder. By comparing the remanence direction of these peculiar samples with the axial direction of the extraction tube, it becomes evident that these spurious samples have indeed rotated relative to positions marked on the glass holders. On the basis of these observations, 12 samples from unit 92 and 24 samples from unit 60 were classified as rotated (see Table 1) and disregarded for the remainder of the study. All of these samples showed evidence of greater than 60° of rotation. Although it is not possible to determine whether any or all of the remaining samples underwent similar yet smaller rotations, the possibility has significant implications.

Prior to looking for evidence of warping, two multisample statistical tests [Mardia, 1972] were performed on the horizontal components (declinations) of all stable, unrotated samples in each unit. (Since the deformation analysis is based upon a simple two-dimensional model in which rotations occur about a vertical axis, such as illustrated in Figure 2, vertical components (inclinations) are not considered in the following calculations.) The first of the statistical tests examined the averaged magnetic declination directions of each group to see whether or not the means of each group were statistically distinct and thus useful for this study. The second test for homogeneity of concentration parameters to determine whether or not consistent random errors existed within each of the two populations. It was assumed that the data followed a von Mises distribution, which is the circular form of the spherical Fisher distribution. Both of these distributions are unimodal and symmetric and serve as all-purpose probability models analogous to the normal distribution for observations on a line [Fisher et al., 1987]. Inherent in the adoption of such distribution models is the assumption that the data are normally distributed, which is not necessarily true. Unfortunately, data sets containing less than about 25 elements are too small for distribution-free bootstrap statistics [e.g., Tause et al., 1991].

Results of these two tests are similar for both stratigraphic units. In the first test, the null hypothesis is rejected at the 99.9% confidence level ($F$ ratio = 8.13 with 9 and 31 degrees of freedom) that the declination directions in the 10 groups in unit 92 are not significantly different from each other, and it is rejected at the 99.5% confidence level ($F$ ratio = 3.36 with 18 and 56 degrees of freedom) for the 19 groups in unit 60 [Fisher et al., 1987]. In the second test, the null hypothesis that the concentration parameters are homogeneous cannot be rejected for either of the beds (unit 92: $\chi^2 = 6.75$ with 9 degrees of freedom; unit 60: $\chi^2 = 20.0$ with 18 degrees of freedom).

The results of each of these tests are encouraging. Significantly different mean declination directions between groups indicate the presence of variability within the beds sampled and suggest that a pattern of deformation is potentially discernible. Homogeneity of concentration parameters implies that samples have similar amounts of angular scatter, or random error, as might be expected from different locations in an isochronous stratigraphic layer. It also permits one to calculate a combined, higher confidence, standard deviation for the entire population as opposed to separate ones calculated for each group. This combined standard deviation is generally smaller than those calculated for individual groups because the population is more thoroughly sampled [Salyards, 1989; Salyards et al., 1992]. For unit 92 one standard deviation ($n - 11 = 30$ degrees of freedom) is $\pm 11.9^\circ$ and for unit 60 ($n - 20 = 55$ degrees of freedom) is $\pm 11.4^\circ$.

RESULTS AND INTERPRETATION

Resultant Magnetic Vector Directions

Tilt-corrected, resultant declination directions for all magnetically stable and unrotated samples (those in the right-hand data column of Table 1) are averaged for each
sample group. These group averages are listed in Table 2 and shown graphically in Figure 8 (solid squares). Error bars show the combined standard deviation angles derived above. For comparison, the declination values of each individual sample are also plotted in Figure 8 (open circles). Declinations are plotted against distance beginning at the farthest point from the zone of deformation (i.e., sample groups in trench 3 are plotted at zero). Note that negative declination values are plotted upward and positive values are plotted downward. The top graph shows the distribution of the 10 groups from unit 92 and the lower graph shows the 19 groups from unit 60 (note the different scales). The locations of faults are shown with solid arrows and correlate with the faults in Figure 4. The position of the fault which breaks both units (between the 32- and 33-m marks) is slightly different for each unit because the fault dips.

The distribution of mean declination directions plotted in Figure 8 suggests that there is no clear pattern of rotation across the fault zone in either unit. Both units do show a roughly sinusoidal trend with a "peak" around 27.5 m and a "trough" around 33 m, but the significance is questionable. A closer examination suggests that group declination values randomly alternate between a clockwise and counterclockwise sense of motion relative to neighboring groups. This random sense of rotation is even evident in groups straddling faults. Overall, the majority of groups have declinations indistinguishable from the assumed unrotated declinations of trench 3. It is interesting to note that variability appears to be slightly greater in unit 60, which has witnessed two earthquakes, than in unit 92, which has witnessed only one.

Also included in Table 2 are averaged group inclination values. In general, inclination values, which average 47.1 ± 6.7° and 50.3 ± 6.9° for units 92 and 60, respectively, are much less variable than declination values. This lends validity to the use of a simplified, two-dimensional deformation model. Also shown in Table 2 are group concentration parameters (κ) for both the circular von Mises distribution and the spherical Fisher distribution. Recall that Fisher parameters include inclination values. For both types of distributions the larger κ values indicate a smaller confidence circle/cone, i.e., a tighter clustering of data points, relative to smaller κ values. Note that for sample groups 92-I, 92-J, 60-B, and 60-S, which have very different inclination values from the unit averages, the values for Fisher’s κ are extremely low, indicating relatively large uncertainty. Sample group 92-G, which has both the largest inclination and declination values within unit 92, might actually represent local deformation about a nonvertical axis (see its position near a fault in Figure 4).

### TABLE 2. Average Resultant Declination and Inclination Directions for Each Group Using All Magnetically Stable and Unrotated Samples

<table>
<thead>
<tr>
<th>Group</th>
<th>Tilt-Corrected Declinations, deg</th>
<th>Tilt-Corrected Inclinations, deg</th>
<th>Concentration Parameters (κ)</th>
<th>von Mises</th>
<th>Fisher</th>
</tr>
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<tr>
<td>92-A</td>
<td>11.9-</td>
<td>53.3</td>
<td>22.6</td>
<td>47.4</td>
<td></td>
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<tr>
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<td>10.5</td>
<td>48.3</td>
<td>3.56</td>
<td>8.5</td>
<td></td>
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<tr>
<td>92-C</td>
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<td>49.1</td>
<td>19.4</td>
<td>31.5</td>
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<td>7.5</td>
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<td>73.9</td>
<td>114.2</td>
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<tr>
<td>92-E</td>
<td>19.1</td>
<td>45.7</td>
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<td>12.3</td>
<td></td>
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<tr>
<td>92-F</td>
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<td>47.1</td>
<td>27</td>
<td>35.6</td>
<td></td>
</tr>
<tr>
<td>92-G</td>
<td>25.0</td>
<td>56.6</td>
<td>50</td>
<td>25.7</td>
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Group declination values, as well as the declinations for each individual sample, are shown graphically in Figure 8. The average inclination values are 47.1 ± 6.7° (unit 92) and 50.3 ± 6.9° (unit 60). Also listed are the calculated concentration parameters (κ) for both the circular von Mises, used for the Monte Carlo simulation described in the text and shown in Figure 9, and the spherical Fisher distributions, which are based upon the entire magnetic vector direction and shown for comparison.
Although Figure 8 is an adequate summary of the average magnetic declinations, it fails to clearly illustrate any cumulative clockwise or counterclockwise deformation across the fault zone. More significantly, it fails to show the cumulative effect of the uncertainties associated with each group's declination direction. It is important to address these statistical uncertainties because it shows how this and similar studies are limited in their ability to resolve declination anomalies.

Given the assumption that physical rotations have indeed caused the observed declination variations, we have constructed "hypothetical fences" which are rotated, or bent, in the directions dictated by the magnetic declination data for each sample group. The fences are plotted with a heavy line in Figure 9 for each stratigraphic unit. The endpoints of the fences are marked with asterisks (note the different scales for each unit). We assume that the fences are initially linear and divide them into discrete lengths equal to the distance halfway between any two sample groups. Rotation is assumed uniform within these discrete blocks. Consecutive fence segments are rotated relative to the azimuthal direction of previous segments. In this way we can see where the endpoint of the fence would occur relative to the zero (unrotated) direction. (Note that because the distances to the groups in trenches 2 and 3 are so much greater than the average distance between samples in the main trench, we have not included those distant sample groups in these calculations. Large distances between these points and those of the main trench drastically increase uncertainty in the fence endpoint positions for the
superimposed scatter plots discussed below. Since the mean
declination values of the first sample groups in the main
trench (92-B, 10.5°; 60-C, 1.7°) are approximately identical
with the corresponding ones in trench 3 (92-A, 11.9°; 60-A,
1.7°), this seems to be a permissible adjustment.)

The endpoints of the fences in Figure 9 show 1.25 m of
cumulative left-lateral offset for unit 92 (over a distance of
9.47 m) and 0.70 m of cumulative right-lateral offset for unit
60 (over a distance of 23.88 m). These offsets are
equivalent to 7.5° counterclockwise rotation for unit 92 and
1.7° clockwise rotation for unit 60. Salyards et al. [1992]
calculated cumulative deformation at their study site in
essentially the same way. They found 8.5 ± 1.0 m and 14.0
± 2.8 m of cumulative right-lateral offset over a distance of
50 m for their two stratigraphic units. This is equivalent to
10° and 16° of clockwise rotation.

Secular Variation Comparisons

Ideally, a comparison between the magnetic vector
directions of each sample group and the Earth’s magnetic
field direction at the time of deposition could yield absolute
rotation values across the San Andreas fault zone. Given the
assumption that the declination values of sample groups
from trench 3 are unrotated, along with age constraints on
the timing of deposition, a comparison can be made between
the declination values plotted in Figure 8 and a secular
variation reference curve for southern California. This
comparison tests the hypothesis that the sediments have
accurately recorded the magnetic field direction at the time of
deposition.

Ages for each unit were determined from radiocarbon dates
as well as stratigraphic relationships with dated rupture
events. For example, the region labeled event 1 in Figure 4
constrains the 1857 surface rupture horizon and thus gives
the upper age constraint on unit 92. The age of unit 92 is
between 1629 and 1857 A.D. and unit 60 is dated between
1046 and 1260 A.D. Salyards [1989] compiled a secular
variation curve for southern California based upon the best
constrained archeomagnetic and paleomagnetic directions
from the southwestern United States. The age ranges of both
of our units are superimposed onto the declination portion
of his secular variation curve in Figure 10 (note that positive
declination values are plotted upward). The inclination
portion of the curve is not considered here because it
contains only a few, poorly constrained data points for the
ages of concern.

While it is beyond the scope of this study to discuss the
variables associated with the construction of secular
variation curves, it is worth noting that the general trend of
the curve presented in Figure 10 (i.e., from the present-day,
positive declination angle to a zero value roughly 600 years
BP to a negative declination angle peaking between 700 and
900 years BP) is in overall agreement with independent
decoration records from other studies such as those from
lake sediments in Blue Lake, Idaho [Hanna and Verosub,
1989]. On the other hand, there is need of improved
resolution of Holocene secular variation for western North
America, which, as Hanna and Verosub [1989, p.93] note,
"is not clearly or adequately defined through the present
group of accessible studies."

To a first approximation the declinations of distant
sample groups from both stratigraphic units plot within or

Fig. 9. "Hypothetical fences" which rotate along with discrete blocks
across the fault zone in a manner prescribed by the magnetic declination
data for each sample group found within the main trench. Each block is
equivalent to the distance halfway between any two paleomagnetic
sample groups. The endpoint of each fence (marked by an asterisk)
illustrates the cumulative deformation along the fault based upon mean
deciliation directions of each sample group (see Table 2). The final
positions of the fences are 1.25 m (left-lateral) for unit 92 and 0.70 m
(right-lateral) for unit 60. (Note the different scales.) The
distances shown, this translates into approximately 7.5° counterclockwise
rotation for unit 92 and 1.7° clockwise rotation for unit 60.
Superimposed upon each fence are contoured probability plots of the
tendpoint location. Darker shades indicate higher probabilities.
The plots are the results of a Monte Carlo simulation based upon each
group's mean direction and corresponding concentration parameter (see
text for details). These plots illustrate the cumulative affect of the large
uncertainties associated with each fence segment by showing that the
position of each endpoint cannot be resolved with a significant degree of
confidence.
Fig. 10. Secular variation curve of magnetic declination for southern California [from Salby, 1989]. The age ranges of both sampled units, blocked and stippled, are superimposed upon the curve. Unit 92 is dated between 1629 and 1857 A.D. and unit 60 is dated between 1046 and 1260 A.D. The mean declination direction of the sample groups from presumably unrotated trench 3 are 11.9° for unit 92 and 1.7° for unit 60. Data for curve are from B, Barracloough; L, IGRF; P, Panum Crater; PC, Pallet Creek; MSH, Mt. St. Helens; S, Sternerberg; and SC, Sunset Crater.

slightly clockwise of the expected regions on the southern California secular variation curve in Figure 10. The 11.9° declination value for group 92-A (from trench 3) falls within the Barracloough (B) portion of the curve as do the next three nearest groups (92-B, 92-C, 92-D; see Table 2). The distant group of unit 60 (60-A from trench 3) has an average declination of 1.7°, which is slightly clockwise of the corresponding portion of the secular variation curve. This could imply that the DRM within unit 60 did record the Earth's magnetic field direction within some margin of error or, possibly, that even this distant point from the fault is rotated in a clockwise fashion relative to the field at the time of deposition. The 16.5° declination value for group 60-B (trench 2) occurs far away from the proposed secular variation curve, while the next four groups (60-C, 60-D, 60-E, 60-F; see Table 2) fall near or within the calculated range.

These results lend support to the assumption that an accurate DRM is probably preserved within the sediments. Such interpretations, based upon a few data points falling within a relatively large range of possible values, are admittedly weak. Additionally, the large spread in individual data points (open circles in Figure 8) shows that there is a significant amount of uncertainty associated with these mean values. The correlation between the secular variation curve and mean declination values is primarily noted to stress that the data do not disagree with expected values.

Monte Carlo Simulation

A Monte Carlo simulation resulted in two-dimensional shaded probability plots for the fence endpoint positions calculated in Figure 9. The simulation allows us to evaluate the magnitude of variation in the location of the fence endpoint based upon the within-group uncertainties, that is, declination uncertainties associated with each fence segment.

The simulation proceeds as follows: an azimuthal direction is randomly chosen from a von Mises distribution for the first segment of the fence based upon that particular segment's mean direction and von Mises concentration parameter (κ; see Table 2); consecutive fence segments are similarly added to previous segments based upon each group's mean direction and corresponding concentration parameter; the final XY position of the fence is stored; the process is repeated 10^6 times. The results are the contour plots shown superimposed upon each of the fences in Figure 9. The darkest shaded regions represent the highest probability positions for the fence endpoints.

Although the plots in Figure 9 are shown exactly as produced by the Monte Carlo simulation, the fault-parallel distribution is significantly more informative than the spread produced in the fault-perpendicular direction. Because fence length was held constant for any given segment during the simulation, the plots naturally come up short of the actual fence endpoints in the direction perpendicular to the fault. Initial simulations were performed using constant block length to yield one dimensional probability plots, and these were essentially identical to the fault-parallel distributions shown in Figure 9. We prefer to show how the fault-parallel distribution looks without suppressing the second dimension because it emphasizes that vector uncertainties are problematic for deformation studies in each dimension (including the third dimension, not considered here). It is possible that the fault-perpendicular aspect of the model might be improved by substituting the constant length assumption with some sort of random scaling for fence length.

This procedure may seem a bit like an overkill considering the fact that we have already acknowledged the large uncertainties present within the sample groups; however, it
is extremely interesting to be able to visualize the cumulative effect of each group's uncertainty in this type of deformation calculation. Uncertainties associated with averaged declination directions are large in the fault-parallel direction. It is thus highly unlikely that the rotations illustrated with the "hypothetical fences" in Figure 9 are significant. Indeed, this is slightly comforting given the unexpected counterclockwise rotation suggested for unit 92. While it could be suggested that these results support a conclusion of no rotation, the correct interpretation is that the proposed rotations can be neither detected nor dismissed. This simulation basically shows that, at least for this particular study, the noise simply overwhelms any likely signal. Significantly, this poses questions for the study upon which this one was modeled [Salyards et al., 1992] in which results generated fault slip rates significant to within millimeters per year.

**Discussion**

The variables which might contribute to the observed variations in magnetic declination directions found in this study need to be understood. The fact that over 95% of the samples show stable remanent magnetic directions, which roughly correspond to the magnetic field at the time of deposition (down and to the north), suggests that one or more sources of uncertainty must exist. The reduction or elimination of such error sources could be important to the success of future studies using soft-sediment samples.

It is worth noting some of the similarities and differences between this study and the one after which it was modeled [Salyards et al., 1992]. The studies were relatively similar in terms of sample collection, demagnetization procedures, and in the calculation of cumulative deformation. Results of the two studies are obviously quite different. The authors of the Pallett Creek study basically claim that the vent was successful to the point that rotations of approximately 10°-16° were discernible. Our study, on the other hand, found that evidence for rotational deformation of this small magnitude is not identifiable.

The primary difference therefore is that while this study finds large within-group scatter, the study of Salyards and others finds a signal which is distinctly larger than the noise. This could be attributed to several possible differences between the two studies such as sediment type and average grain sizes, differing degrees of lithification, and, quite possibly, the fact that potential deformation at Pallett Creek may be significantly larger than deformation in the Carrizo Plain.

However, there is another significant reason why samples in the parent study showed much less variation than in this study. Salyards et al. [1992], who performed their sampling in groups of threes, admittedly discarded any sample which was more than 15° away from the other two samples in a group if those two samples were within 5° of each other. In this way a total of 15% of their stable samples were removed from the study. Naturally, this drastically reduced errors associated with each group's average declination direction. There are at least two problems with this kind of criteria for the removal of spurious samples. The first problem is that it is statistically unsound for groups of only three samples (what if it is the outlier which has actually recorded the true direction?). Second, if the angular spread in the data is not from inadvertent sample rotation but from some other factor, the resultant vectors and their corresponding concentration parameters are simply incorrect. It is difficult to calculate what the consequences of such an "outlier test" would be for the data set presented in this study since sample groups consist of an average of five samples each, but a quick glance at the open circles in Figure 8 suggests that the resulting data set would look quite different. Specifically, the error bars would significantly shrink.

Putting aside the different results obtained from these two studies and focusing on the variability in remanent declination directions which is clearly found in this study, we identify three variables which might contribute to such results: (1) the acquisition process of magnetization in sediments, (2) the stringency of the sampling technique, and (3) the resolving power of the statistics (i.e., could increasing the number of samples per group significantly reduce statistical uncertainties?).

**Magnetic Acquisition in Sediments**

An important variable to understand in all paleomagnetic studies of sediments are the processes involved in the acquisition of the NRM. Magnetization acquired within sediments is classified as either depositional or postdepositional remanent magnetization (DRM or PDRM). DRM is acquired within sediments [Tarling, 1983, p.52] "by the physical rotation of magnetic particles during deposition as a sediment" while PDRM is acquired "after deposition but prior to metamorphism or weathering; usually a combination of physical rotation of interstitial particles and chemical changes as sediments consolidate." Remagnetization from chemical alteration, CRM, often occurs in conjunction with cementation processes and is usually attributed to associated migrating fluids within the pore spaces of sediments. Lund and Karlin [1990] use a linear-systems approach to distinguish four factors which can affect the final NRM in deposited sediments. These are (1) the physical and biogenic processes involved in the initial lock-in of the magnetization, (2) early chemical changes such as the dissolution of magnetic minerals in anoxic environments, (3) reorientation of magnetic grains in response to compaction, and (4) chemical alteration subsequent to lithification. Of principal concern in this study are the first and third of these four factors, essentially DRM and PDRM, respectively, since indications of a CRM are absent from almost all samples.

Inclination shallowing is the most widely recognized adverse effect of sediment settling, burial, and compaction on the orientation of magnetic grains in sediments. Unfortunately, it is a common source of error in DRM studies which is not completely understood (see overview by King and Channell [1991]). This phenomenon, generally involving grain rotation about a horizontal axis, is seen in field studies [e.g., Tauxe et al., 1984; Arason and Levi, 1990a], laboratory redeposition studies [e.g., Levi and Banerjee, 1990; Deamer and Kodama, 1990], and mechanical models [Arason and Levi, 1990b]. On the basis of the axial geocentric dipole hypothesis, the inclination of the Earth's magnetic field at the latitude of our study location should be approximately 55°. All but four of the group inclinations listed in Table 2 are less than this value, supporting the likelihood of inclination shallowing. The advantage of our two-dimensional deformation model, in which rotations are
inferred to occur about a vertical axis, is that it eliminates concern of this possible affect. Although ignoring inclinations removes one dimension of the data, it does not dramatically change associated uncertainties. (Compare the values of $\kappa$ for the two-dimensional von Mises distribution and the three-dimensional Fisher distribution in Table 2).

Unusual depositional conditions (DRM) could explain the considerable spread of declination values found within some of our sample groups. Both stratigraphic units sampled in this study are debris flow deposits; in other words, a fluid-rich slurry of detritus most likely emplaced each of them. As sediment is deposited subaqueously, magnetic grains in three size ranges will behave differently: Brownian forces will most likely randomize small grains (<0.5 μm), intermediate grains will most readily align with the geomagnetic field, and large spherical grains (>30 μm), as well as elongate particles, will probably succumb to hydrodynamic and gravitational forces [Tarling, 1983]. Our rock magnetic experiments for both stratigraphic units suggested single- or pseudo-single-domain magnetic particles; this corresponds to particles no larger than a few microns in size (for axial ratios up to about 7:1) [Evans and McElhinny, 1969]. Immediately following deposition, then, these intermediate-sized grains were probably still able to rotate into alignment with the geomagnetic field because water still surrounded them. This leads us to believe that fairly optimal conditions probably existed for the preservation of a reliable DRM.

Even if a reliable DRM was initially preserved, it is quite possible that physical forces experienced during earthquakes may have played a role in changing the preserved directions. If ground shaking and/or related ground water movement produced a PDRM, one of two effects might result: (1) If these processes tend to randomize the grain orientations, and thus the magnetic directions, the sediment might simply preserve no stable magnetic direction. Since over 95% of the samples in this study clearly recorded a stable remanent direction, this scenario seems unlikely. If only some of the magnetic grains were randomized, the sediment could retain its original signal but with a relatively weaker intensity. If this were the case, however, it should not adversely affect the preservation of the original signal from sample to sample. (2) On the other hand, if these processes temporarily free the magnetic grains from their former positions and allow them to rotate freely, the geomagnetic field at the time of the event should ideally be preserved. The problem with this scenario is that such a realignment should be present and approximately the same in all samples in a given unit and, again, this does not provide a cause for the large variations observed within each unit. However, these speculations are based upon the assumption that conditions are ideal for field alignment following particle disruption. Since actual particle alignment is naturally not an ideal process, it is actually quite possible that some of the randomness found between neighboring samples might indeed be derived from such ground shaking. These complications imply that perhaps a study of unconsolidated sediments within an active fault zone is a risky venture in the first place.

**Soft-Sediment Sampling Technique**

The second important variable is the stringency of the sampling technique. As discussed above, some spurious samples were attributed to rotation (>60°) about the axis of the sampling tube and/or the glass sample holder. While all of these spurious samples were easily identified, other samples have undoubtedly undergone similar, yet smaller, rotations which are not readily discernible. Extreme care was taken during our second phase of sampling to avoid inadvertent rotations of each sample as they were transferred to holders and secured in place. Additionally, all laboratory preparation techniques for the samples were performed with special attention to avoiding rotations. However, as is apparent from the preceding discussion, rotations still occurred. This adds considerable uncertainty to the validity of the directions derived from all samples and implies an important limitation of the extraction technique for soft-sediment paleomagnetic samples.

Lithified cores which are drilled in conventional studies, by comparison, are oriented and marked while still in place, and only after the completion of this process are the cores broken off and removed from the outcrop. Obviously, sample rotation is not a concern for studies involving lithified cores. It is worth noting that if the soft-sampling technique is performed on sediment which is lithified enough to withstand and preserve an orientation mark, then this mark can be readily seen through the glass sample holder and rotations should be easily identifiable.

Additional collection processes that could potentially disturb grain orientations include the effects of pounding the sampling tube into the outcrop, pushing the sample from the tube into the glass sample holder, and any additional settling which might occur in the holder prior to cementation in the laboratory, especially during transportation from the study locality. Suspension of particles when samples are saturated with the sodium silicate solution also presents the opportunity for realignment of magnetic grains. However, performing this step in a zero-field room should simply randomize the directions of the freed grains. It is unclear whether these various sampling-related processes might randomize magnetic grain orientations or impart some sort of systematic change in orientation. Further experiments which might clarify the affects of the sampling process on the orientation of magnetic grains are undoubtedly needed. Studies of possible relationships between the sampling technique and variables such as grain size could be extremely informative. The differences in sampling technique between unconsolidated sediments and lithified sediments or rocks suggest that the former might be less precise for the reliable determination of small changes in paleomagnetic vector directions.

**Statistical Limitations**

While the use of statistics is not actually a variable, the application of statistical techniques for the quantification of results induces limits which need to be appreciated.

The first statistical procedure performed on paleomagnetic data in most studies is the use of the least squares method of principal component analysis [Kirschvink, 1980] which approximates demagnetization paths for each magnetic component by either a line or a plane based upon all available data. For each sample in this study demagnetization paths were fit to lines which were required to yield linear MAD (maximum angular deviation) values of 10° or less for all demagnetization steps.
A second statistical procedure combines the least squares results of all samples in each group and finds a mean direction and a concentration parameter (χ) for each group based upon the spread of the values and the number of samples in the group. Unfortunately, for groups with small numbers of samples, concentration parameter estimates based upon either the Fisher or von Mises distributions can be substantially biased upward [Fisher et al., 1987] resulting in deceptively small confidence cones/circles for the mean direction. Examples of this type of misrepresentation are evident in groups 92-E, 60-G, 60-K, and 60-O in Table 2. Each of these groups has only two or three samples, yet the von Mises χ values, and in some cases the Fisher χ values, are greater than 100. Simple, distribution-free bootstrap statistics [Tauxe et al., 1991] avoid the possible mistake of assuming normally distributed data but also require a larger number of samples. These examples have obvious implications regarding the number of samples taken per site for any type of paleomagnetic study. With one exception at least five samples per site were collected in this study.

The results of the test for homogeneity of concentration parameters allowed for the calculation of a combined, higher confidence, standard deviation for the entire population of samples in each unit. Again, this procedure inherently assumes that the data are normally distributed. Although such combined standard deviations are generally smaller than those calculated for individual groups, in this study they are relatively large (approximately ± 12° for each stratigraphic unit) when compared to likely rotations. The sizable magnitude of these errors represents the considerable spread of declination values within many of the groups. Salyards et al. [1992] performed a similar calculation for one of their two stratigraphic units and found a standard deviation value of ± 6.0°, while in their other unit, which failed the test for homogeneity of concentration parameters, standard deviation values ranged from ± 3.6° to ± 36.1°.

Regardless of the specifics discussed for this study, the greater the number of data points in a given group, the more confidence one has that the sample variance approximates the population variance. This implies that statistical analyses on sample groups made up of a relatively small number of samples, such as those associated with this kind of paleomagnetic study, are inherently problematic and should be considered a weak point in an analysis.

CONCLUSION

Paleomagnetic analyses of 159 soft-sediment samples taken from two stratigraphic units in the Carrizo Plain, California, show that 95% of the samples yield magnetically stable, remanent vector directions. However, variations in declination directions within any given sample group are so large that they prevent the detection of suspected declination anomalies between different sample groups. The cumulative effect of the group uncertainties (quantitatively illustrated with contoured probability plots in Figure 9) precludes possible detection of any reasonable (< 20°) amounts of deformation across the fault zone. Thus efforts to repeat and quantify an apparently successful deformation study in sediments across the San Andreas fault zone [Salyards et al., 1992] have ended with very different results. While the Pallet Creek study does show convincing evidence for nonbrittle deformation, the calculation of neotectonic deformation rates to within an accuracy of millimeters per year based upon relatively small rotations (between 10° and 16°) seems questionable given the uncertainties found in this study. This is at least partially the consequence of the dubious removal of "outlying" samples which leaves their data set with conveniently small errors.

This study has raised several important questions regarding the preservation of magnetization in sediments as well as concerns regarding a relatively new extraction technique performed on unconsolidated sediments. While sample groups distant to the fault zone show general agreement with the most recent southern California secular variation curve (Figure 9), lending support to initial preservation of an accurate DRM, postdepositional disturbances related to ground shaking during earthquakes may have played a significant role in causing variability among magnetic vector directions. Large inadvertent sample rotations (> 60°) about the axis of the glass sample holders were clearly identified in approximately 20% of the samples. Unfortunately, this appears to be difficult to avoid, and the possibility that some of the scatter in the data must be from smaller rotations cannot be ruled out. More studies need to be performed on soft-sediment samples, preferably not within fault zones, to confidently determine detection limitations related solely to the collection technique. If samples can retain some sort of orientation mark made at the outcrop, this could solve one of the uncertainties. Sediment shifting during transportation to the laboratory is still a concern which has no correlative among traditional paleomagnetic studies of lithified specimens.

On a more positive note, a study by Liu et al. [1988] illustrates the value of the soft-sediment sampling method. Workers collected soft-sediment samples near Cajon Pass, California, to perform magnetostratigraphic correlations between surface and core sections of the late early to middle Miocene Cajon Formation based upon magnetic polarity stratigraphy. In addition to polarity determinations, they looked at the declination directions in a series of samples. They noted a progressive 30° clockwise rotation in the series which was consistent with the results of a similar study conducted 12 km to the west in lithified sediments [Budney et al., 1985]. In this case, magnetic orientations from the unconsolidated samples provided a compliment to traditional paleomagnetic methods of magnetic component determinations.

The usefulness of the soft-sediment sampling technique utilized in paleomagnetic studies should not be underrated. The method allows sampling of unconsolidated strata which traditional drilling techniques would destroy. An increasing number of workers have successfully employed the technique for magnetic polarity determinations. On the basis of this study we recommend that soft-sediment paleomagnetic samples be reserved primarily for magnetic polarity studies or for the determination of only large rotations until improved sampling techniques are developed and tested. Small rotations (at least < 20°) determined exclusively from paleomagnetic analysis of unconsolidated sediments should be interpreted with extreme care until sampling methods improve or until other sources of error are better understood.

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