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MAGNETIC STRATIGRAPHY OF THE MORALES FORMATION: LATE NEOGENE CLOCKWISE ROTATION AND COMPRESSION IN THE CUYAMA BASIN, CALIFORNIA COAST RANGES

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Abstract. The Cuyama basin in the southern Coast Ranges of California underwent a transition from strike-slip to compressional faulting, synchronous with the deposition of the Pliocene-Pleistocene Morales Formation. Paleomagnetic stratigraphy was used to date the Morales Formation and, by inference, the beginning of compressional tectonics. Sections sampled below the Whiterock and Morales thrusts in the western Cuyama basin are predominantly normal and are correlated with the Gauss chron (3.57–2.60 Ma). An abrupt appearance of clasts derived from the overlying thrust sheet in the section below the Whiterock thrust suggests uplift of the Caliente Range during the middle to late Gauss chron. Seismic reflection data indicate that the eastern sections were deposited earlier. In conjunction with fossil evidence, the eastern sections are correlated to a time between the late Gilbert and early Matuyama chrons. The presence of a crystalline boulder bed midway in an eastern Cuyama basin section indicates uplift of the Mount Pinos-Frazier Mountain highlands during the Matuyama chron between 2.60 and 0.78 Ma. Paleomagnetic directions of the Morales Formation document approximately 23° clockwise rotation of the Cuyama basin.

INTRODUCTION

The Cuyama basin, located northwest of the western Big Bend of the San Andreas Fault (Figures 1 and 2), is an area of transition from strike-slip tectonics of the Coast Ranges to the northwest and compressional tectonics of the Transverse Ranges to the south. The Cuyama basin is part of the Salinian block, which is bounded by right-lateral strike-slip faults. It is north of the Big Pine fault, the northern boundary of the compressional Transverse Ranges. In the Cuyama basin, the change in tectonic styles from strike-slip to compression involves the Pliocene-Pleistocene fluvial Morales Formation.

During the Pleistocene, structural deformation of the Cuyama Valley changed from strike-slip faulting to predominantly folding and thrust faulting. The Russell strike-slip fault, known only from the subsurface of the Cuyama Valley, may be an older, inactive strand of the San Andreas fault [Yeats et al., 1989]. On the basis of decreasing offset of progressively younger beds, Yeats et al. [1989] inferred that the Russell fault was active throughout most of the Miocene but not later. The Russell fault does not involve the Morales Formation, which is cut by the Whiterock, Morales and South Cuyama thrusts and is folded in the South Cuyama and Wells Ranch synclines (Figure 2). The Caliente Range is advancing southward over the Cuyama Valley on the Whiterock and Morales thrust faults, and the Sierra Madre is advancing northward on the South Cuyama and Ozena faults.

In the absence of datable ash beds and age-diagnostic fossils, the magnetostratigraphy of the Morales Formation was studied to help constrain the timing of the transition from strike-slip to compressionl tectonics. Paleomagnetic studies resulted in age estimates of the Morales Formation and the onset of compressional tectonics. In addition, there is evidence for post-Morales clockwise rotation of 21°–23° of the Cuyama basin.

METHODOLOGY

Six sections were chosen for paleomagnetic sampling of the Morales Formation (Figure 2). They are (1) Quatal Canyon (QC) in the Cuyama Badlands, which crosses the Cuyama syncline fold axis and is our longest exposed section, (2) Ballinger Canyon (B) in the Cuyama Badlands, (3) the Wells Ranch syncline (W) on the north side of the Caliente Range, (4) Santa Barbara Canyon (S) on the north side of the Sierra Madre, (5) the Whiterock (WF) section in the Morales Canyon oil field below the Whiterock fault, and (6) the Morales (MF) section in the Russell Ranch oil field below the Morales fault.

Sites were spaced as closely as possible, while trying to sample the most fine-grained beds available, preferably siltstones and mudstones. Samples were also taken from sandstone beds; however, their remanent magnetism was usually unstable. At each site, at least three hand samples were oriented by Brunton compass. In the laboratory, hand samples were reoriented in plaster of Paris, and at least two cores were drilled from each hand sample.

The majority of samples were thermally demagnetized progressively to 650°C in 30°–50°C steps. Samples were cooled in a shielded magnetic environment with residual fields less than 10 nT. To reduce the likelihood of systematic laboratory errors, samples from each site were demagnetized in several heating batches. Some sites were also demagnetized in alternating fields (AF) to 70 mT in 5 to 10 mT increments. A comparison of the two demagnetization methods is shown in Figure 3.

The overprint by the normal, present-day field was usually removed in the first two or three demagnetization steps (Figure 4). Characteristic magnetic directions for each specimen were obtained from best line fits through consecutive points on vector projection diagrams, after omitting the lower blocking temperature/coercivity points. Highly scattered low-intensity data near the origin were also occasionally excluded from analysis. The demagnetization interval for calculating characteristic directions varied between samples.

Site mean directions and associated quality estimates, k (precision parameter) and α_{95} (95% circle of confidence) [Fisher, 1953], are listed in Table 1. Only sites with $\alpha_{95} < 25°$ were used to calculate the average paleomagnetic direction for each section. Table 2 compares the in situ vectors for each section with the bedding corrected results. For five of the six

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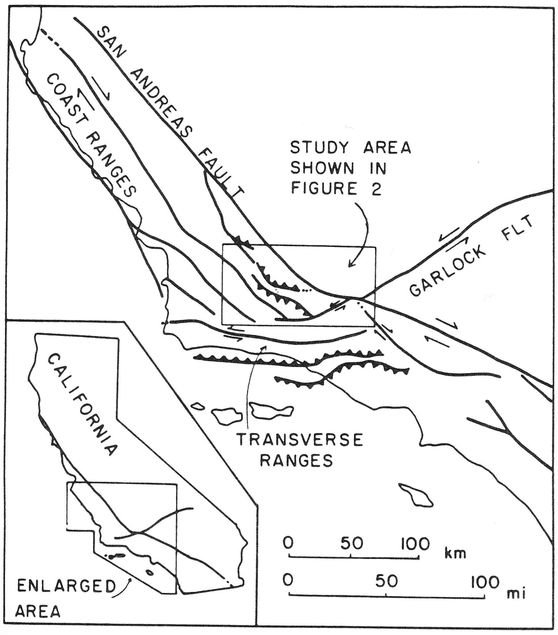

Fig. 1. Location of the study area and major faults in southern California.

sections, k and α_{95} improved after the sites were structurally corrected (Figure 5). The only exception is the Morales fault section, where only three sites were available for obtaining the average paleomagnetic direction.

A classic fold test was not possible, as most of the sections are homoclines and do not cross fold axes. Although the QC section crosses the Cuyama syncline, most of the sites are located on the eastern limb. Improvements in k and α_{95} after structural corrections imply that the remanence predates folding. Ratios of the precision parameters, k, before and after structural corrections are used to examine the statistical significance of structural corrections on the dispersion of the paleomagnetic directions [McElhinny, 1964]. At the Quatal Canyon section, the smaller dispersion after unfolding is significant at the 95% level, and at the Ballinger Canyon and Wells Ranch syncline sections they are significant at the 99% level. The results are shown in Table 2.

MORALES FORMATION

The Morales Formation is a Pliocene-Pleistocene fluvial deposit at least 1500 m thick unconformably overlying middle and late Miocene strata. It was first designated a separate formation by Hill et al. [1958]. Dibblee [1971 unpublished mapping, 1973] included all young, deformed, nonmarine sediments of the Cuyama area in the Morales Formation. Vedder [1968] and Vedder and Repenning [1975], described the upper part of Dibblee's Morales Formation as "older Quaternary alluvium."

Wells Ranch Syncline

In the Wells Ranch Syncline, the Morales Formation is approximately 600 m thick, and the top of the formation is eroded. The Morales Formation was deposited conformably on the nonmarine Quatal Formation, which is entirely composed of clay and resembles the Quatal Formation at its type locality in Quatal Canyon. The Morales Formation is coarse grained at the bottom of the section, consisting of sandstone and siltstone. In the western part of the syncline on the south limb, thick beds of coarse-grained, granular to

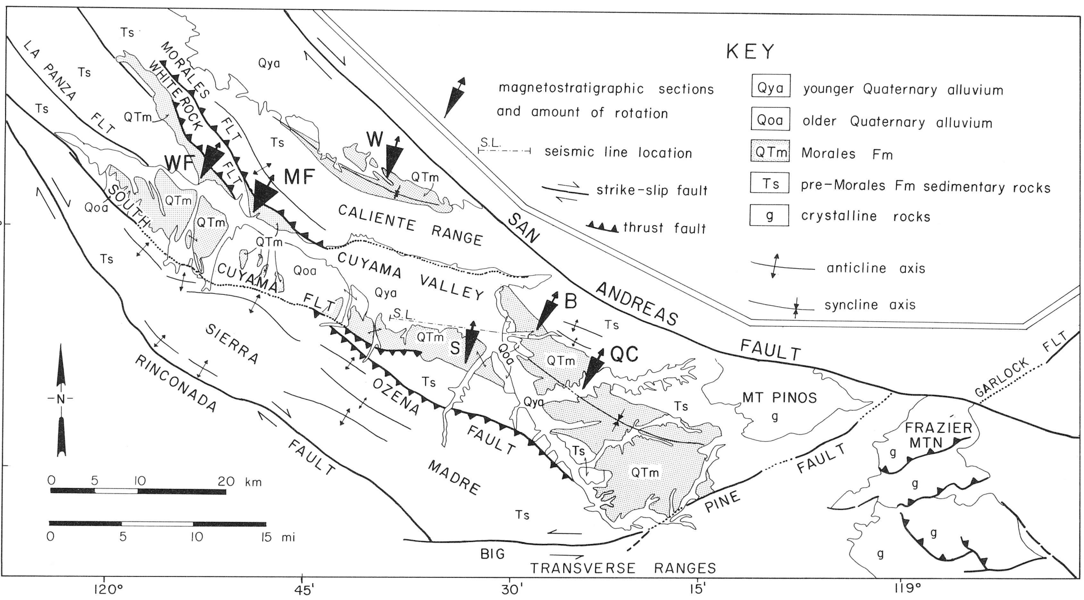

Fig. 2. Simplified geologic map of the Cuyama basin showing outcrops of the Morales Formation (shaded), magnetostratigraphic sections and rotations with 95% confidence interval. Key: WF, Whiterock fault section; MF, Morales fault section; W, Wells Ranch syncline section; S, Santa Barbara Canyon section, B, Ballinger Canyon section; and QC, Quatal Canyon section. The western Big Bend of the San Andreas fault is located northwest of the Ballinger and Quatal Canyon sections.

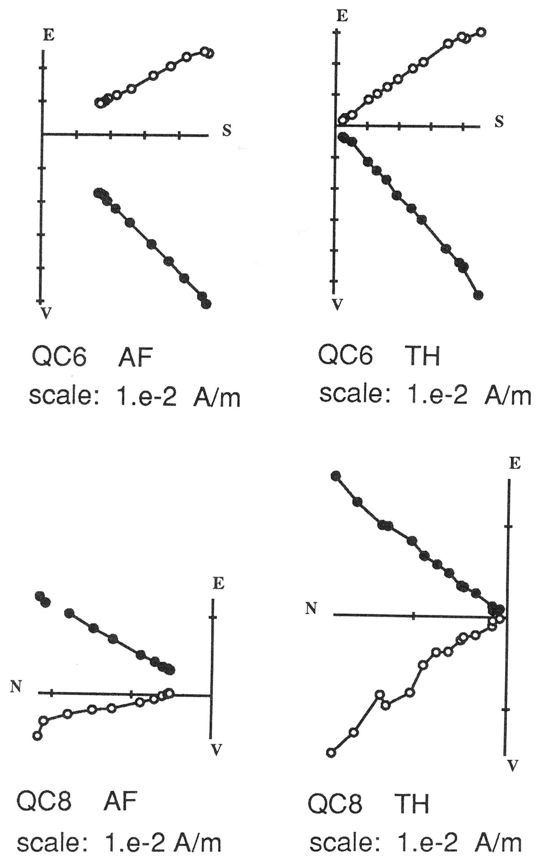

Fig. 3. Zijderveld diagrams comparing alternating fields (AF) and thermal (TH) demagnetization. In both sites, QC6 and QC8, the two specimens are from the same hand sample. Results are for in situ orientation.

pebbly sandstone and conglomerate are present. The coarse-grained strata grade upward and to the east into interbedded siltstone and claystone. Thick-bedded, blue-grey claystone is present in the axis of the syncline at the top of the section.

All sites from the Morales Formation in the Wells Ranch syncline have reversed magnetic polarity (Figure 6). One site from the Quatal Formation gave no useful results. Vedder [1970; also personal communication, 1990] found a Blancan fossil locality in the Morales Formation approximately mid-way up the section. The Blancan fossil stage lasted from about 4.4 to 1.8 Ma [Lundelius et al., 1987]. This time interval spans the late Gilbert through early Matuyama polarity chrons [McDougall et al., 1992].

Quatal and Ballinger Canyons

The Quatal Canyon section in the Cuyama Badlands is the easternmost section studied (Figure 2). It is approximately 1500 m thick, the longest exposed section of the Morales Formation, and it crosses the axis of the South Cuyama syncline. On the northeast limb, interbedded claystone and siltstone beds have an average dip of 27° and lie conformably on the Quatal Formation. In Quatal Canyon, the Quatal Formation is a lacustrine deposit of bentonitic claystone [Vedder, 1968] which interfingers with the Morales Formation. The Quatal Formation is separated from the underlying late Miocene Caliente Formation by an angular unconformity.

The Morales Formation becomes sandier and coarser-grained upsection. There is a distinctive boulder bed 885 m above the Quatal-Morales boundary. Some boulders are over a meter in diameter. Boulder lithologies correlate with crystalline basement lithologies in the Mount Pinos-Frazier Mountain highlands east of the Cuyama Badlands. Above the boulder bed, the Morales Formation becomes more coarse grained, and beds sufficiently fine-grained for paleomagnetic studies are rare (Figure 6).

Three paleomagnetism sites were sampled from the Caliente Formation. These sites occur on both sides of an anticlinal axis and all sites are reversed. Two sites were sampled in the Quatal Formation, which is very fine grained and fractures easily, making it difficult to obtain samples. One site has a reliable normal polarity, the other site is question-

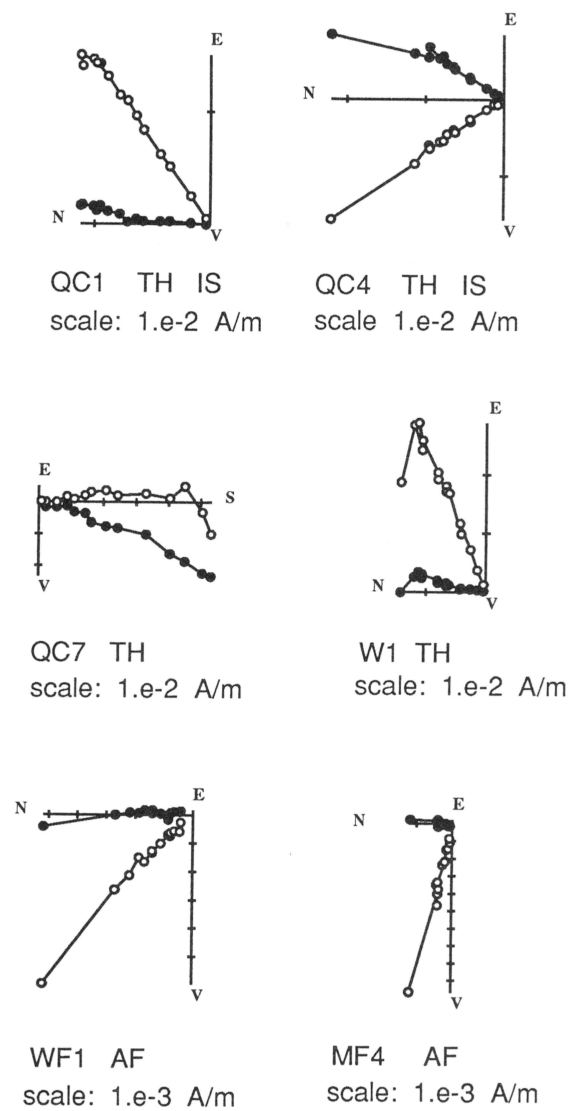

Fig. 4. Zijderveld plots, in situ (IS), showing progressive demagnetization of well behaved specimens.

TABLE 1. Cuyama Valley Summary of Paleomagnetic Results

Site	N/n	D_R, deg	I_R, deg	k	α_{95}, deg	Bedding Strike/Dip
			Quatal Canyon			
Caliente Formation						
QC1	5/5	224.5	−33.5	168.0	5.9	300°/90°
QC2	5/6	184.7	−56.6	168.6	5.9	155°/18°W
QC3	6/6	200.3	−32.9	11.2	6.4	145°/9°W
Quatal Formation						
QC4	8/9	33.7	50.5	23.8	11.6	130°/32°W
QC5*	3/6	262.9	67.2	17.5	30.4	130°/34°W
Morales Formation						
QC6	6/6	239.1	−54.2	20.0	15.4	125°/34°W
QC7	5/6	224.7	−35.8	54.6	10.4	117°/31°W
QC8	7/7	194.8	−40.1	37.4	10.0	143°/34°W
QC9	4/6	171.5	−56.4	116.0	8.6	122°/27°W
QC10*	5/6	reversed?				155°/25°W
QC11	4/6	12.5	45.3	48.5	13.3	155°/25°W
QC12	5/6	26.6	46.3	56.2	10.3	143°/33°W
QC13	7/7	203.1	−49.8	51.3	8.5	133°/20°W
QC14	6/6	197.4	−47.7	70.5	8.0	133°/20°W
QC15	6/8	213.8	−33.0	54.1	9.2	155°/16°W
QC16	7/8	221.6	−32.7	18.9	14.3	160°/15°W
QC17	6/7	212.0	−16.9	45.0	10.1	154°/43°W
QC18	5/6	207.8	−34.0	62.6	9.7	300°/22°E
QC19*		no data				340°/15°E
QC20	5/6	188.7	−29.7	41.5	12.0	140°/30°W
QC21	6/9	177.3	−24.8	109.3	6.4	355°/26°E
			Ballinger Canyon			
Morales Formation						
B3*	4/6	reversed				137°/48°W
B4*	4/6	reversed				156°/47°W
B5*	4/6	reversed				
B6	6/6	204.0	−37.0	84.0	7.0	156°/40°W
B7	5/6	202.0	−43.0	54.0	10.0	153°/43°W
B9	6/8	213.0	−49.0	52.0	9.0	147°/46°N
B10	6/6	207.0	−45.0	128.0	8.0	
QOA	4/5	33.6	47.6	1287.4	2.6	210°/7°W
			Santa Barbara Canyon			
Quatal Formation						
S1	4/9	192.8	−62.9	33.1	16.2	288°/58°N
S2*		no data				298°/58°N
Morales Formation						
S3	6/6	252.1	−50.9	38.4	10.9	312°/59°N
S4	3/5	340.5	40.9	141.2	10.4	298°/58°N
S5	6/6	174.3	−49.3	506.5	3.0	342°/60°N
			Wells Ranch Syncline			
Quatal Formation						
W1*		no data				290°/52°N
Morales Formation						
W2	4/7	200.5	−50.2	151.9	7.5	285°/54°N
W3	4/4	198.2	−48.1	649.6	3.6	282°/51°N
W4*	3/6	194.4	−34.8	18.8	29.3	255°/64°N
W5*		no data				315°/28°N
W6	5/7	176.6	−60.9	170.5	5.9	130°/60°S

Table 1. (continued)

Site	N/n	D_R, deg	I_R, deg	k	α_{95}, deg	Bedding Strike/Dip
			Below Whiterock Thrust			
Morales Formation						
WF1	6/10	37.0	52.0	38.6	10.9	6°/24°E
WF2	7/10	13.5	54.6	141.9	5.1	310°/14°E
WF3*		reversed				6°/18°E
WF4	5/9	50.5	73.3	44.4	11.6	53°/30°E
WF5*		no data				330°/37°E
WF6	6/8	23.3	45.1	12.9	19.4	315°/57°E
			Below Morales Thrust Fault			
Morales Formation						
MF1	6/10	20.4	50.5	35.1	11.5	335°/22°N
MF2*	5/9	14.7	28.2	5.4	36.2	341°/35°N
MF3	6/6	156.6	−40.0	34.0	11.7	340°/18°N
MF4	6/8	62.1	57.0	9.3	23.2	350°/61°N
MF5*	3/6	45.5	10.9	22.5	26.6	321°/26°N
MF6*		no data				235°/46°NW

N/n, number of specimens used in calculations/number of specimens measured; D_R, I_R, structurally corrected declination (D) and inclination (I), rotated to horizontal using measured bedding attitude (strike/dip); k, best estimate of precision parameter of Fisher distribution; α_{95}, radius in degrees of the 95% cone of confidence about the mean direction (Fisher, 1953); asterisk, indicates sites eliminated from calculations for average vectors due to lack of data or $\alpha_{95} > 25°$.

TABLE 2. Cuyama Valley, Average Directions by Section Comparing In Situ and Bedding Corrected Data

Section	N	D, deg	I, deg	k	α_{95}, deg	Sig
Quatal Canyon						
IS	18	207.0	−28.1	7.2	13.9	95%
BC	18	204.5	−40.3	14.5	9.5	
Ballinger Canyon						
IS	5	218.2	−14.3	19.4	17.8	99%
BC	5	207.7	−44.4	183.2	5.7	
Santa Barbara Canyon						
IS	4	69.0	−75.2	5.5	43.2	<80%
BC	4	190.9	−56.6	9.7	31.1	
Wells Ranch Syncline						
IS	3	217.9	−73.3	2.4		99%
BC	3	193.2	−53.5	64.4	15.5	
Below Whiterock Fault						
IS	4	344.4	65.5	20.3	20.9	<80%
BC	4	28.1	56.8	32.0	16.5	
Below Morales Fault						
IS	3	335.1	60.6	10.8	39.5	—
BC	3	14.4	54.5	8.5	45.1	

IS, in situ; BC, bedding corrected; N, number of sites used in calculations; D, I, declination (D) and inclination (I); k and α_{95}, as described in Table 1; Sig, significance level of F-test. (For k<3 there is no α_{95}.)

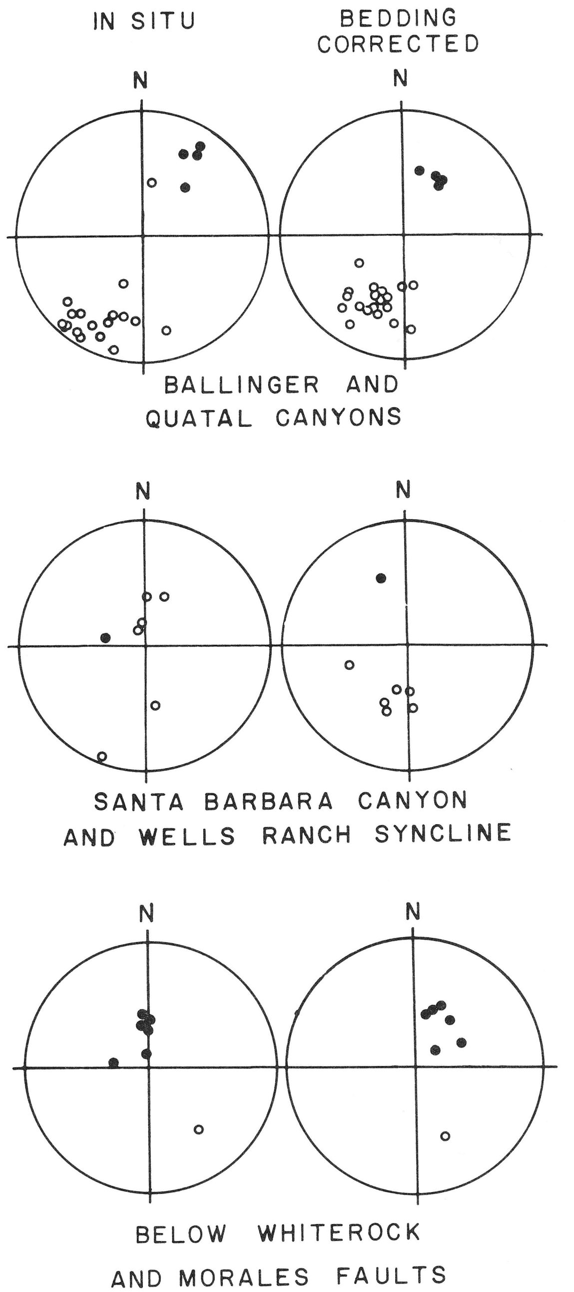

Fig. 5. Equal-area stereograms showing site data before and after bedding corrections. The directions are more tightly clustered after bedding corrections.

ably normal (Table 1, Figure 6). The Morales Formation is reversed except for two normal polarity sites approximately one third the distance up the stratigraphic section. The boulder bed from the Mount Pinos-Frazier Mountain highlands is about 380 m above the upper normal site.

In Ballinger Canyon, the stratigraphy is almost identical to Quatal Canyon. Younger fluvial sediments, the "Qoa" on Dibblee's [1971] and Vedder's [1968] maps, overlie the Morales with a 20° angular unconformity. The seven sites from the lower part of the Morales Formation are reversed and the single "Qoa" site has normal polarity.

Santa Barbara Canyon

In Santa Barbara Canyon, just west and across the Cuyama River from the Cuyama Badlands, the Morales Formation is exposed in the steep south limb of a syncline on the north flank of the Sierra Madre. It lies conformably on the Quatal Formation. In the Santa Barbara Canyon section, the Morales Formation is only approximately 200 m thick, and it may be a condensed version of the Quatal Canyon section. Here the Morales Formation is coarser grained than in other areas, which made sampling for paleomagnetism difficult. The Quatal Formation consists of poorly sorted sandstone interbedded with stringers of brown claystone. The claystone resembles the clay that forms the entire Quatal Formation in Quatal Canyon. A boulder-cobble bed 96 m above the Morales-Quatal contact is composed almost entirely of sandstone shed from the Sierra Madre. Above this boulder-cobble bed, rare stringers of siltstone and claystone are found.

Two sites were sampled in the Quatal Formation, one above and the other below the interfingered claystone. The lower site is reversed; the upper one has indeterminate polarity (Figure 6). The three sites sampled in the Morales Formation were chosen to bracket the boulder-cobble bed. The middle site, directly below the boulder bed, has normal polarity; the other two sites are reversed.

Whiterock and Morales Sections

The westernmost sections are below the Whiterock and Morales thrusts of the Caliente Range, where the Morales Formation is approximately 1030 and 1100 m thick, respectively (Figure 7). In these two sections, the Morales Formation rests unconformably on the late Miocene Santa Margarita Sandstone which interfingers with the Caliente Formation to the east. In both sections, the Morales Formation becomes coarser grained upsection. Halfway up the section below the Whiterock thrust, the clast content abruptly changes from mostly crystalline pebbles below to more than 90% angular shale chips above. The closest shale source is the Saltos Shale in the hanging wall of the Whiterock thrust. Also present are some sandstone clasts with *Turritella* fossils from the Painted Rock member of the Vaqueros Sandstone, which is also found in the hanging wall of the Whiterock thrust. The abrupt transition in clast lithology is interpreted as a change from fluvial deposition with a more distant crystalline source to localized alluvial fan sedimentation in front of the rising and eroding hanging wall of the Whiterock thrust.

AGE CORRELATION OF THE SECTIONS

The Wells Ranch syncline section contains a Blancan horse fossil near the middle of the section. The Blancan fossil age lasted from about 4.4 to 1.8 Ma [Lundelius et al., 1987], which spans the late Gilbert through early Matuyama chron. The magnetic polarity stratigraphy alone does not permit a unique age assignment for this section. However, because only reversed polarity sites were found, two correlations are most likely: (1) the the late Gilbert Chron or (2) the early Matuyama Chron. This would suggest minimum sedimentation rates of 1.5 mm/yr for the Gilbert chron interpretation and 0.85 mm/yr for the early Matuyama chron.

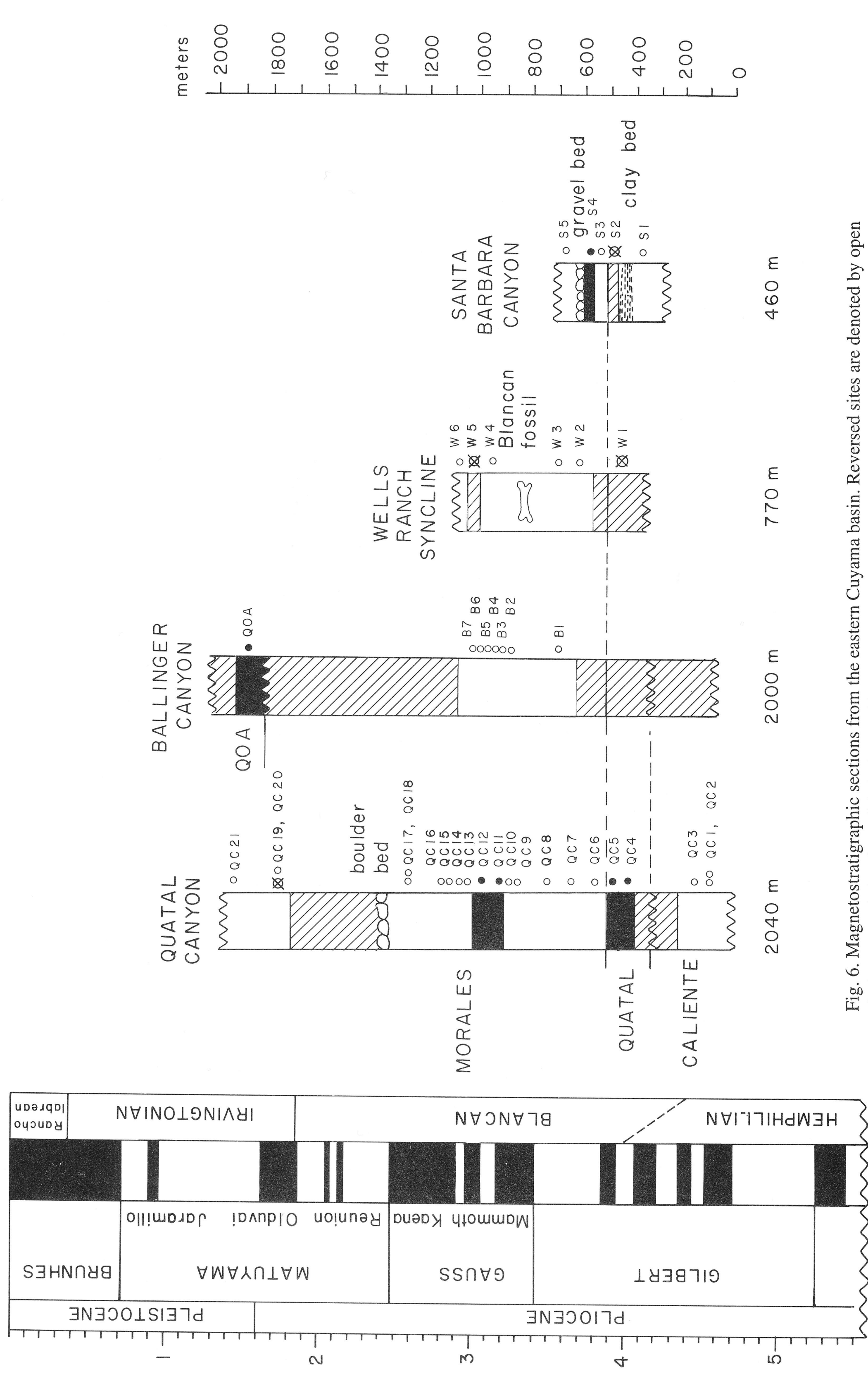

Fig. 6. Magnetostratigraphic sections from the eastern Cuyama basin. Reversed sites are denoted by open circles, normal sites by solid circles, and indeterminate sites by crosses. Diagonal line pattern indicates unknown polarity due to lack of sites.

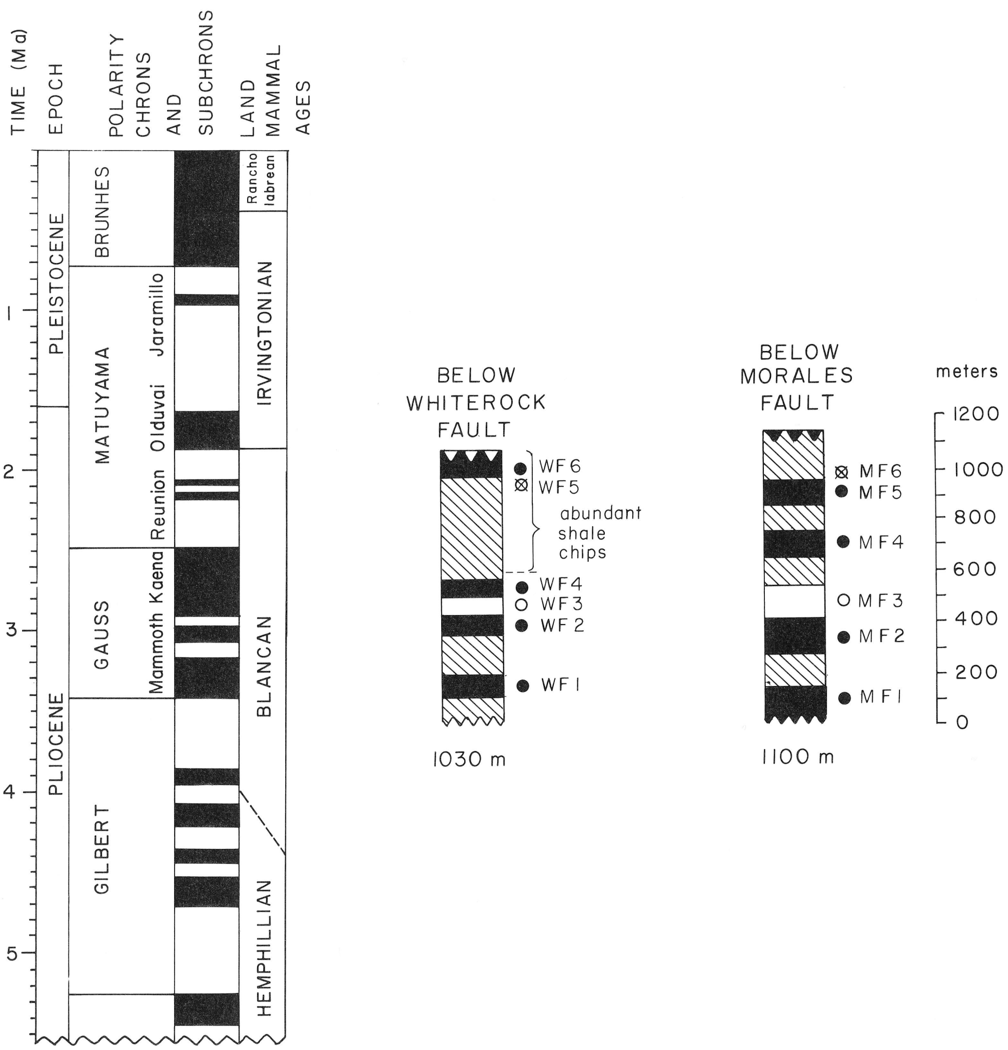

Fig. 7. Magnetostratigraphic sections from the western Cuyama basin showing the Morales Formation only. Reversed sites are denoted by open circles, normal sites by solid circles, and indeterminate sites by crosses. Diagonal line pattern indicates unknown polarity due to lack of sites.

In Quatal Canyon, an angular unconformity separates the Caliente Formation from the overlying Quatal Formation. A Clarendonian horse fossil found in the upper part of the Caliente Formation [Kelley and Lander, 1988] dates the upper Caliente Formation as upper Miocene. Therefore, the overlying Quatal Formation must be younger. The Quatal Formation has a similar lithology in both the Wells Ranch syncline and the Cuyama Badlands and can be used as a stratigraphic marker. The Quatal Canyon section is predominantly reversed, with two normal sites near the middle. No vertebrate fossils have yet been found in the Cuyama Badlands Morales Formation. There are several possible correlations for the Quatal Canyon section, and the likeliest two interpretations are (1) deposition during the late Gilbert through the Matuyama chron (4.3–0.8 Ma), with the normal sites (QC11 and QC12) representing the Gauss chron, or (2) deposition entirely during the Matuyama chron, with the normal sites representing the Olduvai subchron. Minimum sedimentation rates would be 0.5 and 0.8 mm/yr for the first and second correlations, respectively. The Quatal Formation can be used to tie the Wells Ranch syncline and Quatal Canyon sections together. Because of the discontinuous nature of continental sedimentation, gaps could exist in the stratigraphic record, and some shorter polarity subchrons, such as the Reunion, might be missing.

If the Santa Barbara Canyon section were deposited at the edge of the Morales basin, sedimentation rates could have been much lower, and the Santa Barbara canyon section might be an attenuated version of the Cuyama Badlands. The Santa Barbara Canyon section also rests on the Quatal Formation.

The age of the Morales and Whiterock sections is more ambiguous because the Quatal Formation is missing, and no fossils or ash beds are present. However, these sections must be equivalent to, or younger than the sections in the eastern Cuyama basin. An east-west seismic line (Figure 8) [Ellis and Spitz, 1987] in the eastern Cuyama basin shows that the

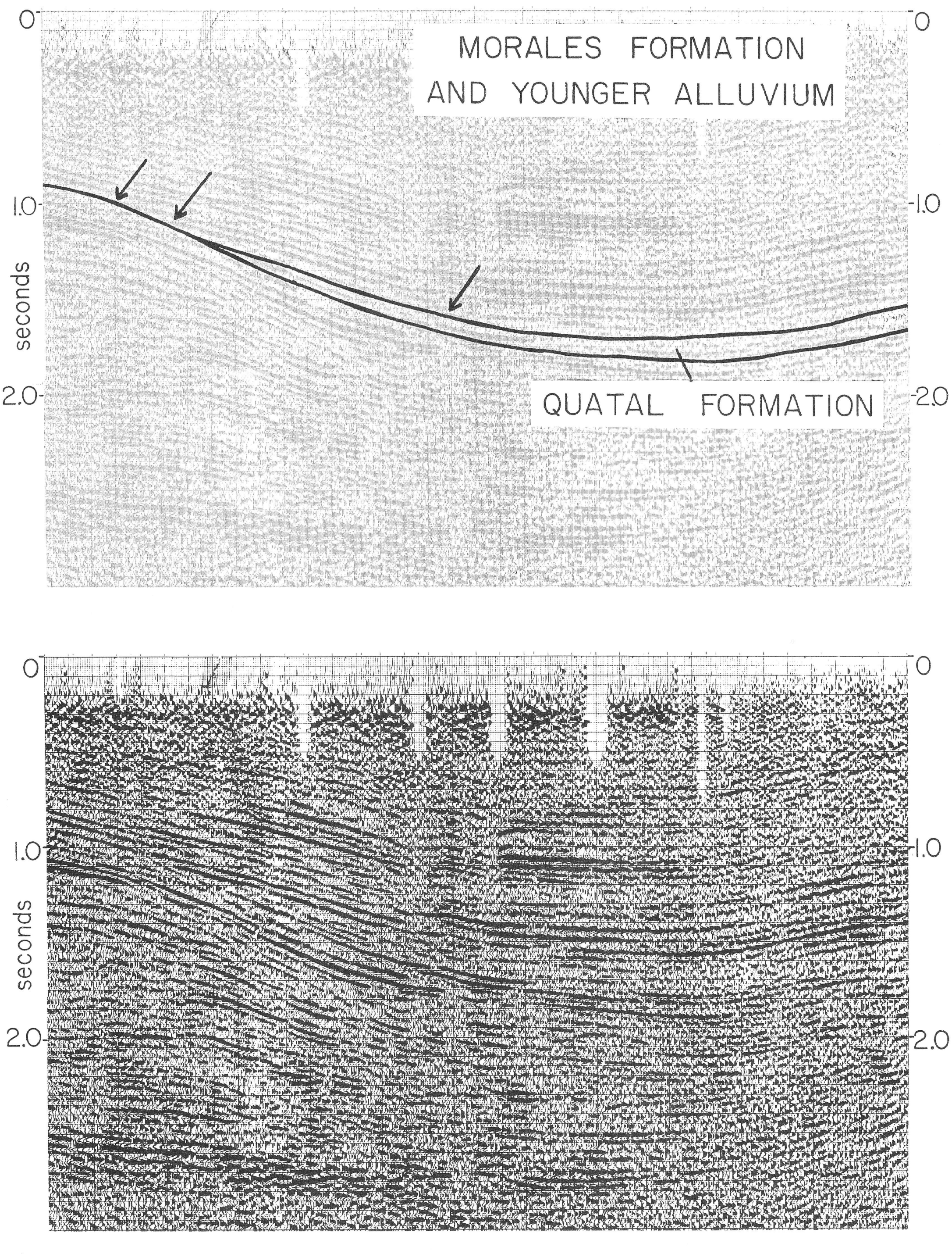

Fig. 8. East-west seismic line from the eastern Cuyama basin. See Figure 1 for location. Arrows point to onlap of individual reflectors in the Morales Formation against the Quatal Formation.

Morales Formation onlaps the Quatal Formation and lower Miocene rocks westward in the subsurface. The Quatal Formation pinches out between Santa Barbara Canyon and the Morales and Whiterock sections. Because of the onlap, the Morales beds in the western part of the basin must be younger than the lower Morales beds to the east.

The Morales fault and Whiterock fault sections are of predominantly normal polarity, and there is a reversed site near the middle of each section (Figure 7). Both sections rest unconformably on upper Miocene sandstone; they are associated with imbricate thrust faults, and both have a similar magnetic stratigraphy.

The Morales and Whiterock sections are not likely to represent the Bruhnes chron because of the reversed site in the middle of each section. Neither are they likely to correlate with the normal subchrons of the predominantly reversed Matuyama, which are more likely to go unrecorded in an area of discontinuous continental sedimentation.

By analogy with the eastern sections, the two western sections were probably deposited in a time interval between the Gilbert and Matuyama chrons. However, because the two sections are predominantly normal, we believe that it is unlikely that they were deposited during the Matuyama or Gilbert chrons. Correlating the western sections with the two youngest normal subchrons in the Gilbert cannot be totally excluded, but this interpretation would suggest unusually high minimum sedimentation rates of about 2.5 mm/yr. Deposition during the Gauss chron is the most plausible interpretation of the predominantly normal western sections, and this would translate to minimum sedimentation rates of about 1 mm/yr for the western sections during the Gauss.

If only the eastern, reversed sections are considered, deposition of the Morales Formation during either the Gilbert or the Matuyama chron is equally likely. However, in combination with the predominantly normal western sections and evidence from the east-west seismic line, deposition of the Morales Formation probably began during the late Gilbert and continued into the Matuyama chron.

TIMING OF TECTONIC EVENTS

The eastern, predominantly reversed sections are interpreted to represent the late Gilbert through early Matuyama chrons, and the western sections are correlated with the Gauss chron. In this interpretation, the appearance of the boulder bed above the normal zone in the Morales Formation of the Quatal Canyon section (Figure 6) represents the inception of uplift and erosion from the Mount Pinos-Frazier Mountain highlands in the Matuyama between 2.60 and 0.78 Ma [McDougall et al., 1992]. If the Santa Barbara Canyon section is correlative to the Quatal Canyon section, a similar boulder bed in the former may represent uplift of the Sierra Madre at about the same time.

The Wells Ranch syncline section probably predates the Gauss chron, which began at 3.57 Ma. The Gauss may be missing due to erosion of the top of the section. Alternatively, the sediment source may have been blocked by the beginning of uplift of the Caliente Range, and the area became a quiet backwater where the thick clay beds could accumulate.

The uplift and erosion of the hanging wall of the Whiterock thrust are well defined in the stratigraphic record, based on the sudden appearance of angular shale chips just above the reversed site in the Whiterock fault section (Figure 7). The interpretation that the Whiterock and Morales sections represent the Gauss chron from 3.57 to 2.60 Ma might suggest uplift of the Caliente Range during the Gauss chron after the termination of the Mammoth subchron at 3.21 Ma [McDougall et al., 1992].

TECTONIC ROTATION OF THE CUYAMA BASIN

All sections sampled in the Cuyama basin show some clockwise rotation (Tables 2 and 3), ranging from 11° for the Santa Barbara Canyon section to 28° for the section below the Whiterock fault. The regional average was calculated in two ways: (1) by combining individual sites, giving an average declination/rotation of 23.3°, α_{95} = 6.5°, for n = 37, and (2) by combining the average rotation of each section, leading to a regional rotation of 20.3°, α_{95} = 7.0°, for n = 6. The Quatal Canyon section, the longest continuous exposure, has an average rotation of 24.5°, α_{95} = 9.5° (Table 2). There is no discernible pattern of progressive rotation through time, suggesting that the clockwise rotation in the Cuyama Badlands occurred after Morales deposition.

TABLE 3. Comparison of Average Paleomagnetic Results

Sections or Combination of Sites	Bedding Corrected				
	N	D, deg	I, deg	k	α_{95}, deg
Eastern Sections (Ballinger, Quatal, Santa Barbara Canyons and Wells Ranch Syncline)					
By site	30	202.7	–45.1	21.9	5.7
By section	4	200.0	–48.9	75.5	10.6
Western Sections (Below Whiterock Fault and Morales Fault)					
By site	7	22.2	56.1	17.5	14.9
By section	2	21.0	55.8	202.8	17.6
Reversed Sites	26	202.0	–44.7	18.9	6.7
Normal Sites	11	24.3	52.9	27.2	8.9
Regional Average by Site	37	203.3	–49.0	13.9	6.5
Regional Average by Section	6	200.3	–51.2	92.0	7.0

N, number of sections or sites used in calculations. Other symbols and abbreviations are described in Table 1.

Previous studies of rotation in the western Transverse Ranges have concentrated on areas south of the Big Pine fault, the northernmost west trending left-lateral fault [Luyendyk et al., 1980; Hornafuis et al., 1986]. Luyendyk [1991] used McKenzie and Jackson's [1986] model to explain the rotation of the western Transverse Ranges. In their model, crustal blocks first underwent east-west extension, then north-south contraction as they rotated clockwise due to right-lateral shear between the Pacific and North American plates. Jackson and Molnar [1990] cite evidence from very long baseline interferometry (VLBI) for 5 years [Sauber, 1989] and the east-west orientation of crustal blocks in the western Transverse Ranges to infer that rotation in the western Transverse Ranges is continuing at a rate of 6.3° ± 3.4°/Ma. They suggested that this rate is consistent with estimates of rotation rates for the past 10 Ma, which would imply about 12° of clockwise rotation of the Cuyama basin since Morales deposition ended at about 2 Ma. The more than 20° clockwise rotation of the Cuyama basin is almost twice the predicted value.

CONCLUSIONS

The transition from strike-slip to compressional tectonics occurred since ~4 Ma, the older age estimate of the Morales Formation involved in folding and thrusting, and overlying the inactive strike-slip Russell fault. Uplift of the Mount Pinos-Frazier Mountain crystalline highlands probably began in the Matuyama chron between 2.60 and 0.78 Ma, based on the presence of crystalline boulders above the upper of two normal polarity zones in the Cuyama Badlands. The beginning of uplift of the Caliente Range may have cut off the supply of coarse sediments to the Wells Ranch Syncline, causing the Morales Formation to become finer-grained upsection. If this is so, the Caliente Range began to rise late in the Gilbert chron prior to 3.57 Ma. As uplift continued, the hanging wall of the Whiterock thrust began to shed sediments into the Morales Formation. The unroofing and erosion of the Whiterock hanging wall probably occurred during the Gauss after a normal subchron, between 3.21 and 2.60 Ma. Compressional tectonics is continuing at present; the formation of the Cuyama syncline postdates the end of Morales deposition, and borehole breakout data and space-geodetic (VLBI) data show the current direction of maximum stress is nearly perpendicular to the San Andreas Fault.

Paleomagnetism of the Morales Formation shows that the Cuyama basin has undergone about 23° of post-Morales Formation clockwise rotation, nearly twice the value predicted by present models.

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