AN ABSTRACT OF THE DISSERTATION OF

Barbara Jean Ellis for the degree of Doctor of Philosophy in Geology presented on May 12, 1994, Title: Changing Tectonic Regimes in the Southern Salinian Block: Extension, Strike-Slip Faulting, Compression and Rotation in the Cuyama Valley, California

Abstract approved: Signature redacted for privacy.

Robert S. Yeats

During the Cenozoic, tectonics in the Cuyama basin of the southeastern Salinian block changed from extension to strike-slip faulting to compression and rotation. During the Oligocene-early Miocene, the Cuyama basin was adjacent to the southern Mojave region and part of that extensional tectonic regime. Many present-day reverse faults have an extensional history.

At ~23 Ma, strike-slip faulting began, and the Cuyama basin was part of a zone of distributed shear between the North American and Pacific plates. The Russell fault, which is the oldest documented right-lateral fault in the region, began movement at ~23 Ma which continued until 4 Ma. Tracing its 29 km of slip south of the Big Pine fault is problematic. It may connect with the Blue Rock fault below the Cuyama Badlands, and then correlate with the Clemens Well-Fenner-San Francisquito fault segments, another early strand of the San Andreas fault system to the south. An associated left-lateral fault is proposed to underlie the southeast Caliente Range. The Cox normal fault, which was active during deposition of the Saltos Shale member of the Monterey Formation, is another structure associated with the early right-lateral shear.

Compressional tectonics have occurred more recently. The Caliente Range is moving south on the Whiterock and Morales thrusts; the Sierra Madre is moving north on the South Cuyama and Ozena faults. A blind thrust that may be a southern extension of the Morales thrust is postulated to underlie the folds of the Cuyama Badlands. The Plio-Pleistocene Morales Formation was

deposited during the onset of folding and thrust faulting. Magnetostratigraphy was used on the Morales Formation to date uplift of the Caliente Range, which began between 3.0 and 2.5 Ma. Recent uplift of the Frazier Mountain-Mt. Pinos highlands began between 2.6 and 0.78 Ma.

Paleomagnetism also revealed 23° of post-Morales Formation clockwise rotation. The rotation may be due to the movement of material west of the San Andreas fault around the Big Bend of the San Andreas fault.

Changing Tectonic Regimes in the Southern Salinian Block: Extension, Strike-Slip Faulting, Compression and Rotation in the Cuyama Valley, California

by

Barbara Jean Ellis

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Completed May 12, 1994

Commencement June 1995

APPROVED:

Signature redacted for privacy.

Professor of Geology in charge of major

Signature redacted for privacy.

Head of Department of Geosciences

Signature redacted for privacy.

Dean of Graduate School

Date dissertation is presented May 12, 1994

Typed by Barbara J. Ellis for Barbara J. Ellis

For my father,

Merald D. Ellis,

who always supported and encouraged my educational endeavors
and "non-traditional" career choices.

ACKNOWLEDGEMENTS

I would like to thank Drs. Robert Yeats, Shaul Levi, Gary Huftile, Robert Lillie and Pierrick Roperch for their helpful comments and insights. G.W. Charlton of COHO Resources, Ltd., and Coleman Morton provided the seismic lines. T.W. Dibblee Jr. made available his unpublished maps. Dennis Shultz assisted in paleomagnetic sampling and laboratory analysis. Grants from ARCO, the Geological Society of America, Sigma Xi, the Bureau of Land Management, the National Earthquake Hazards Reduction Program and the Oregon State University Geology Department made this study possible.

I would also like to thank my parents, Merald and Bernadette Ellis, who supported my academic endeavors. My friends, collegues and supervisors on the Siuslaw National Forest gave me their encouragement and understanding, and allowed me to take time off to finish the dissertation. Wayne Sugai allowed me the use of his computer and computer expertise, thus saving me the expense of buying my own. The Reyes family of the Cuyama Valley provided me with a place to stay during three seasons of field work, and made me feel welcome. Their hospitality and friendship will always be remembered. Cheryl Beam and Robert Miller were able field assistants during the first field season.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Changing Tectonic Regimes in the Southern Salinian Block: Extension, Strike-Slip Faulting, Compression and Rotation in the Cuyama Valley, California

Chapter 1:
Subsurface Cross-Section of the Southeastern Cuyama Basin, Southern California

Barbara J. Ellis
Department of Geosciences
Oregon State University
Corvallis, OR 97331-5506

and

Herbert M. Spitz
621 Lantana #20
Camarillo, California 93010

ABSTRACT

Subsurface data shows the middle to late Cenozoic transition from predominantly marine strata in the southeastern Cuyama basin to nonmarine strata in the Cuyama Badlands. The marine Saltos Shale, Branch Canyon Sandstone and Santa Margarita Formation all grade eastward into the nonmarine Caliente Formation. Only the late Oligocene-early Miocene Vaqueros Formation is continuous throughout the area.

East of the South Cuyama oil field, the eastern edge of the Cox trough is a half-graben which is bordered by a hinge line, not a fault, on its eastern side. Subsidence of the Cox trough occurred during the early Miocene deposition of the Saltos Shale, which thickens significantly across the hinge line. Strata above and below the Saltos Shale maintain a relatively uniform thickness.

At the end of the Miocene, the area east of the Cox trough, the Cuyama syncline, subsided to receive a thick sequence of the Pliocene Quatal and Plio-Pleistocene Morales Formations. The formation of the syncline is coincident with the deposition of the Morales Formation and is truncated by younger north-directed thrust faults.

A postulated pre-Pliocene fault in the subsurface of the Cuyama Badlands explains contrasts in the pre-Vaqueros geology. The Vaqueros Formation rests on the Simmler Formation and crystalline basement in the Badlands and on Paleogene sedimentary rocks in the Cuyama basin.

INTRODUCTION

Seismic and well data from the southeastern Cuyama basin were evaluated to map the eastern boundary of the Cox trough and to trace the transition from the marine to nonmarine Miocene strata.

The Cuyama basin contains a sequence of middle to late Cenozoic marine and nonmarine strata that unconformably overlie early Tertiary sedimentary rocks (Hill et al., 1958). The marine strata are dominant in the western part of the basin (Schwing, 1984; Spitz, 1985), and interfinger with nonmarine rocks to the east in the Cuyama Badlands (James, 1963; Dibblee, 1982; Davis, 1983).

The Cuyama Valley is transitional between the Transverse Ranges and the Coast Ranges (Figs. 1-1 and 1-2). The present-day valley has an east-southeast trend, almost parallel to that of the Transverse Ranges. Older structures in the Cuyama basin, such as the Russell fault and Cuyama syncline, trend northwest, almost parallel to the Coast Ranges. The valley is bounded by east-west trending thrust faults, the Morales and Whiterock faults to the north and the South Cuyama and Ozena faults to the south Late Cenozoic movement along these faults has given the Cuyama Valley its present-day trend (Spitz, 1985).

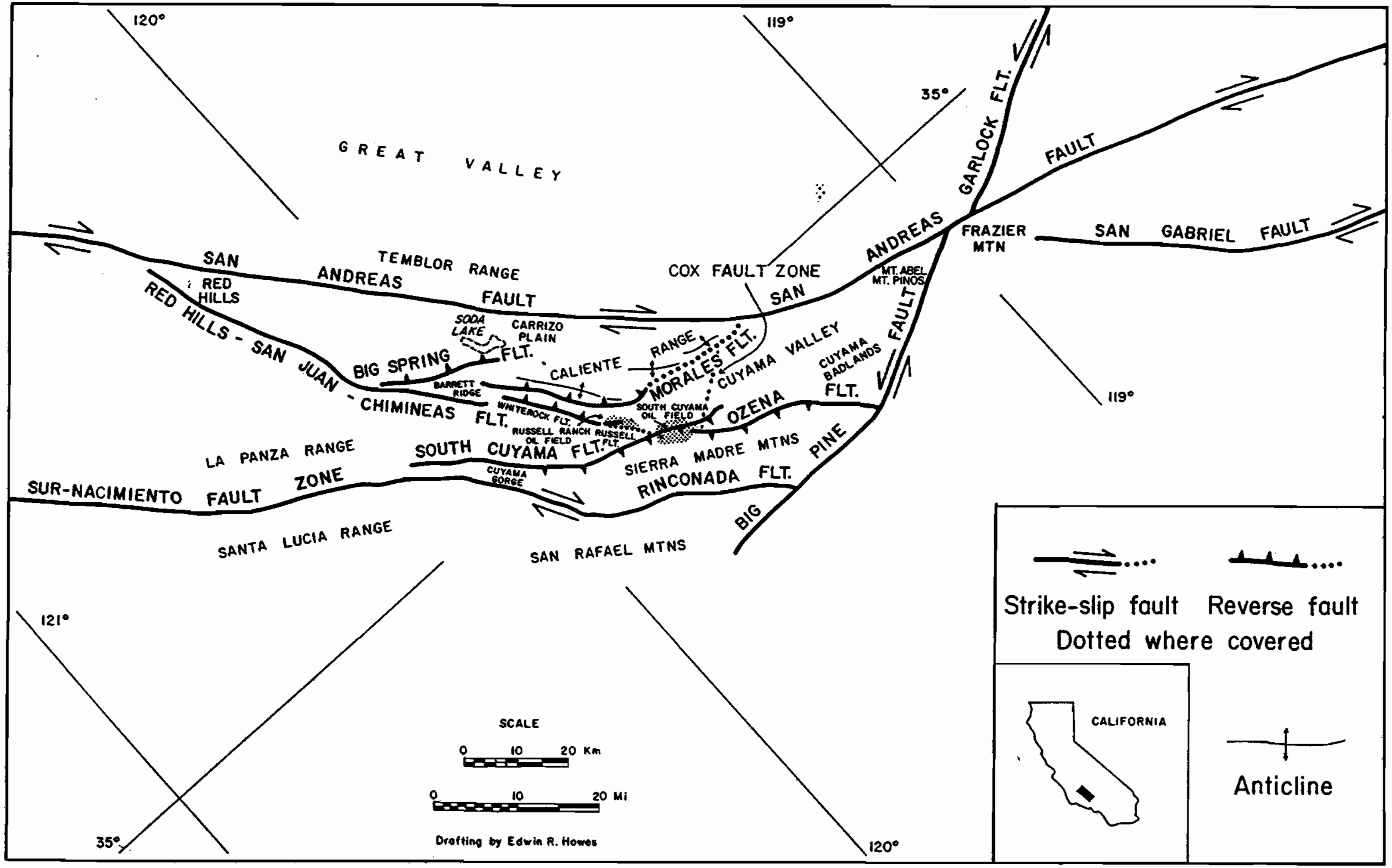


Figure 1-1. Tectonic map of the Cuyama basin and adjacent areas.

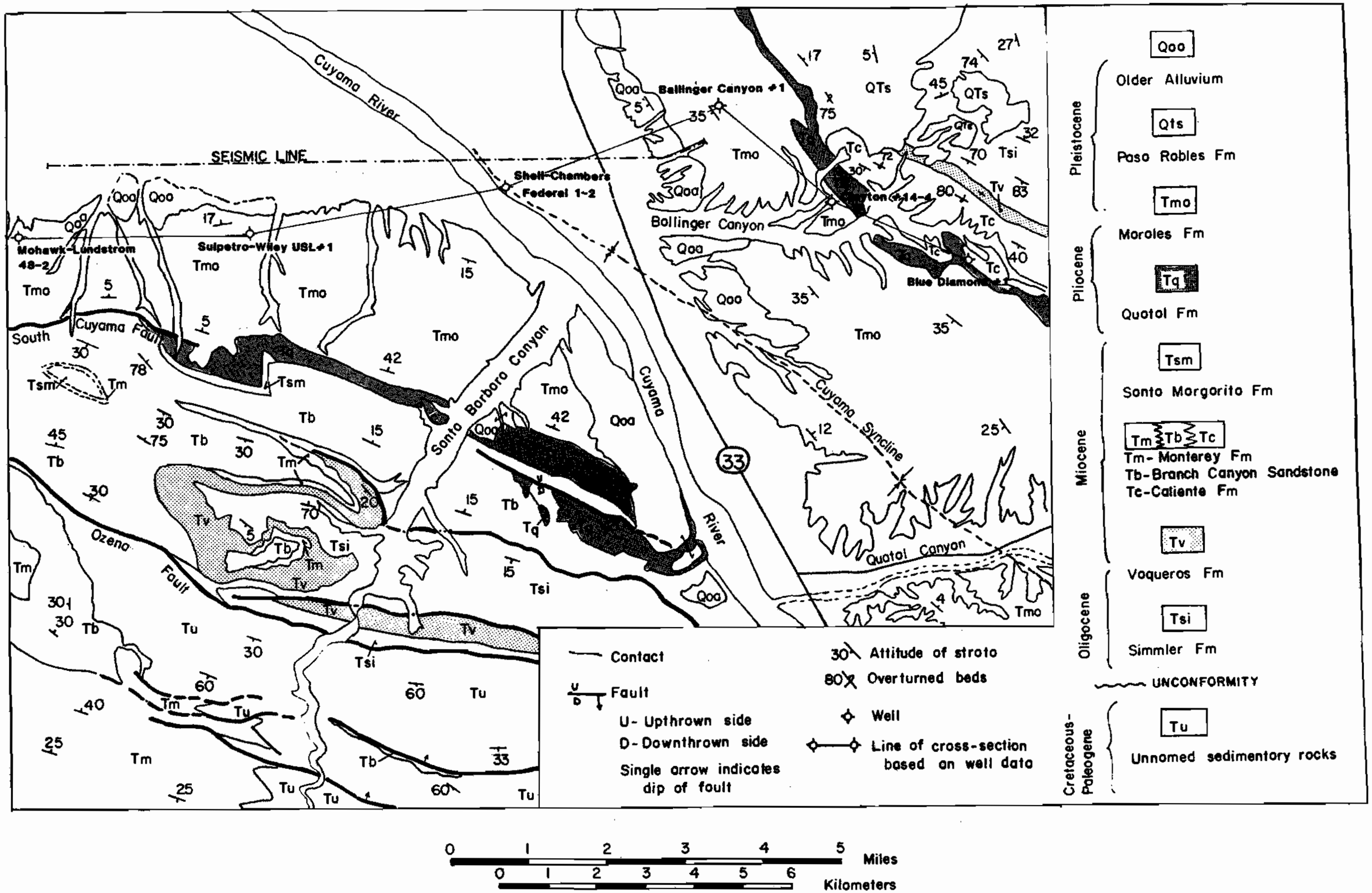


Figure 1-2. Geologic map of the southeastern Cuyama basin and western Cuyama Badlands. Note location of the cross-section based on well data (Fig. 1-3) and the seismic line (Fig. 1-4) (after Dibblee, 1971a and 1971b).

METHODS

A cross-section based on well data (Fig. 1-3) was drawn to parallel the seismic line as closely as possible. Data from Spitz (1985) were correlated to wells near the western part of the line; surface exposure in the Cuyama Badlands was used to support the correlation of rock units in wells to the east. Paleontological data provided by Texaco gave age constraints on the Shell-Chambers well.

The migrated seismic line (Fig. 1-4) in this study used Vibrosis as the energy source, with a frequency spectrum of 10-48 hertz. The sample rate is 4 milliseconds. Both the geophone group interval and the Vibroseis point interval are 330 feet (100.6 meters). The common depth point stack is 24-fold.

The interpretation of the seismic line was based on well-top correlation and depth-to-time conversions. Depths in time to key stratigraphic horizons in the Shell-Chambers well are based on a synthetic seimsic trace produced from the sonic-log data. Interpretations of the line were validated by checking intersecting seismic lines.

STRATIGRAPHY

The subsurface stratigraphic sequence in the southeastern Cuyama basin changes from predominantly marine strata in the west to mainly nonmarine strata in the east. This change is similar to that exposed in the northern side of the Caliente Range and described by Clifton (1973). The subsurface facies change can be seen in an east-west cross section based on well data (Fig. 1-3). The non-marine Oligocene-early Miocene Simmler Formation is exposed in the Cuyama Badlands; however, it is not present in the Shell-Chambers well or in the South Cuyama oil field farther west (Schwing, 1984; Spitz, 1985). The early Miocene marine Saltos Shale member of the Monterey Formation is over 5000 feet (1524 m) thick in the Cox trough (Spitz, 1985), less than 100 feet (30 m) thick in the Shell Chambers well, and absent in the Cuyama Badlands. During the middle to late Miocene, the fluvial Caliente Formation was deposited in the Cuyama Badlands at the same time the marine Branch Canyon Sandstone and Santa Margarita Formation were being deposited to the west. Between the Caliente Range (Vedder, 1970) and the southeastern Cuyama Basin, the Branch Canyon Sandstone-Caliente Formation facies change trends approximately N50°W, giving an orientation on the paleo-shoreline at this time. The overlying Pliocene Quatal Formation pinches out to the west between the Chevron Sulpetro-Wylie and Mohawk-Lundstrom wells.

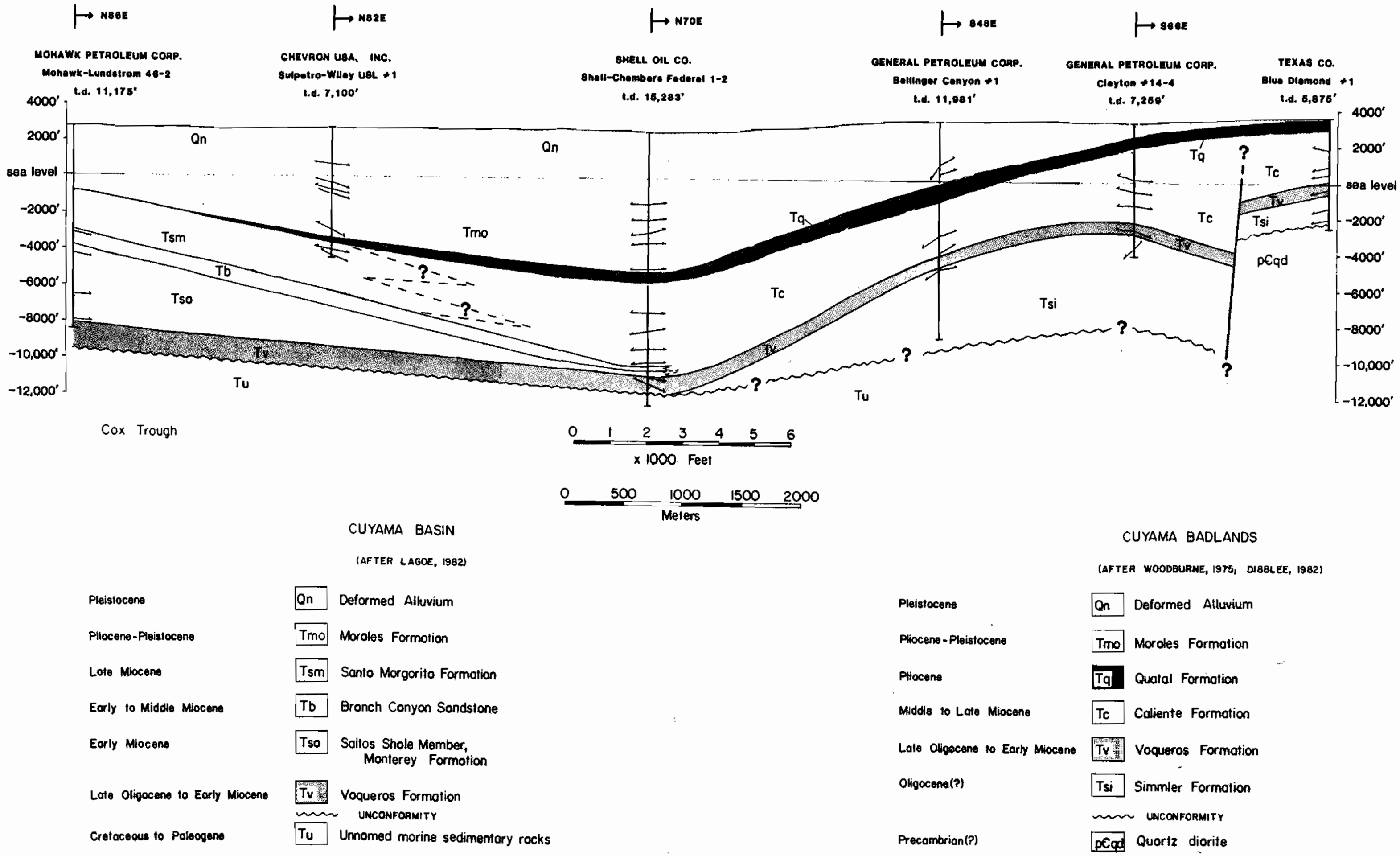


Figure 1-3. Cross-section based on well data. The marine Saltos Shale, Branch Canyon Sandstone and Santa Margarita Formation grade into the nonmarine Caliente Formation. The Saltos Shale thickens into the Cox trough. The Quatal Formation pinches out to the west.

THE COX TROUGH

The northeast-trending Cox trough is a prominent structural feature in this area, and is easily recognized by the abrupt thickening of the early Miocene Saltos Shale. The Saltos Shale, less than 100 feet (30 m) thick in the Shell-Chambers well, rapidly increases to over 5000 feet (1524 m) within the Cox trough to the east (Spitz, 1985). Close to the southern edge of the Cuyama basin, the Cox trough is bound by faults on both the eastern and western sides (Lagoe, 1981; Spitz, 1985), and the western boundary fault can be traced northeast into the center of the basin. However, the seismic line located in the center of the basin shows no evidence of faulting on the eastern side of the Cox trough. Instead, the Cox trough there appears to be a half-graben with the Saltos Shale thickening across a fault zone to the west (Spitz, 1985) and a hinge line on the east.

The Cox trough was not active during the deposition of the late Oligocene-early Miocene Vaqueros Formation, which maintains approximately the same thickness both within and outside of the Cox trough. Localized subsidence of the Cox trough was limited to the time of deposition of the early Miocene Saltos Shale, as can be seen by its rapid thickening across the Cox trough. Subsidence had almost ceased by the time the middle Miocene Branch Canyon Sandstone was deposited. However, one of the faults on the western side of the Cox trough continued to be active through the deposition of the Branch Canoyn Sandstone. The Branch Canyon Sandstone is approxiamtely 400 feet (122 m) thicker on the downthrown (eastern) side of the fault (Spitz, 1985). The branch Canyon Sandstone thins from 900 feet (274 m in the Mohawk-Lunstrom well to 400 feet (122 m) in the Shell Chambers well. Onlap on the eastern edge of the Cox trough across the hinge line may be responsible for the Branch Canyon Sandstone thinning in that direction.

THE CUYAMA SYNCLINE

At the end of the Miocene, the area east of the Cox trough subsided, and the Cox trough underwent relative uplift, with a subsequent shift of the depocenter to the east into the Cuyama syncline. The axis of the Cuyama syncline, as mapped and named by Frakes (1959), trends approximately N50°W, plunges 13°NW, and is on line with the Shell-Chambers well.

There are three possibilities for the time of uplift of the Cox trough: 1) It occurred after the Santa Margarita Sandstone was deposited, thus forming a high which limited the extend of deposition of the Quatal Formation, 2) it occurred after the deposition of the Quatal, with subsequent erosion of the Quatal and part of the Santa Margarita Sandstone from the resulting uplift, or 3) the Quatal Formation changed facies to sandstone to the west, thus not requiring post-Santa Margarita, pre-Morales Formation uplift. Because the Quatal Formation is not found in outcrop in the northern Sierra Madre farther west than the Cox trough (Vedder, 1968; Fritsche, 1969; Vedder and Repenning, 1975), the first hypothesis is preferred. Frakes (1959) also believed it is a pre-Pliocene feature because of the unconformity at the base of the Morales Formation. The Cuyama syncline remained the site of sediment accumulation during the deposition of the Morales Formation, as can be seen by the greater thickness of the Morales in the vicinity of the Shell-Chambers well (Figs 1-3 and 1-4).

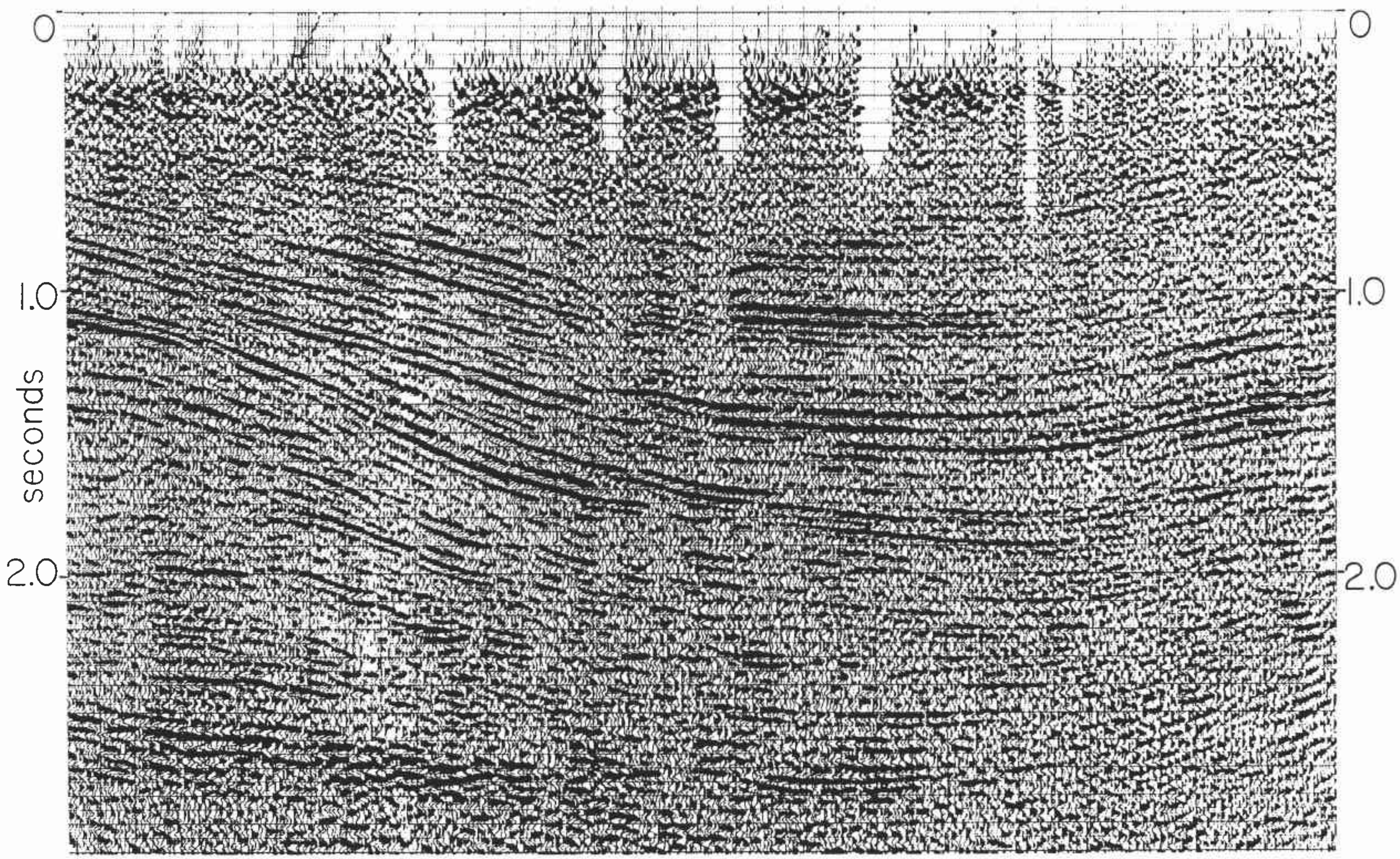


Figure 1-4a. Seismic line from the southeastern Cuyama basin, uninterpreted.

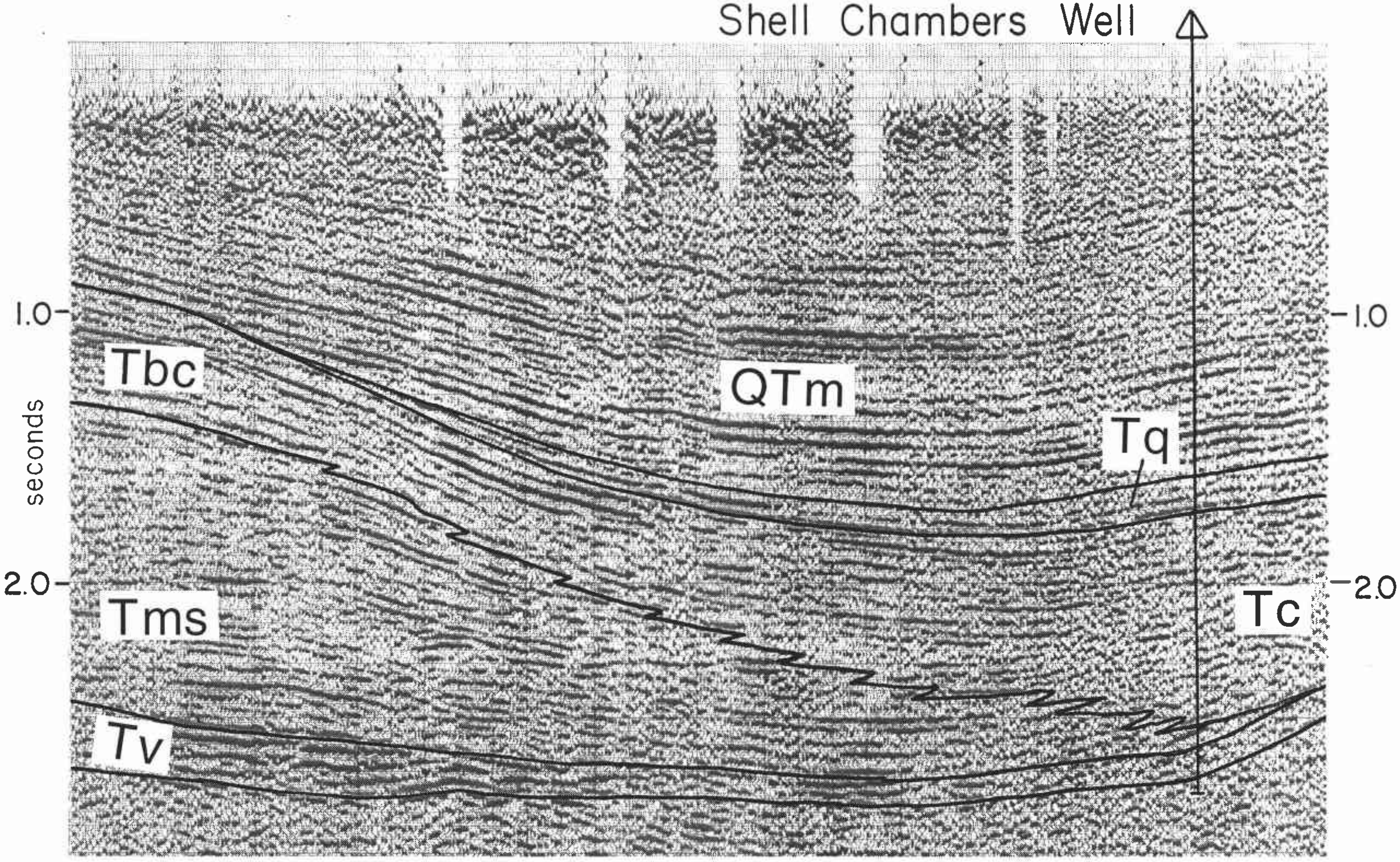


Figure 1-4b. Seismic line from the southeastern Cuyama basin, interpreted.

FAULTING IN THE CUYAMA BADLANDS

A subsurface fault is postulated between the Clayton 14-4 and the Blue Diamond wells. Precambrian(?) (Kistler, et al., 1973) crystalline basement, with the composition of quartz diorite (Ross, 1974), occurs at 5989 feet (1764 m) well depth in the Blue Diamond well, but is absent in the Clayton 14-4 well. The Clayton 14-4 well is not deep enough to completely support or rule out the presence of a fault; basement may be located just below the bottom of the hole. This fault would explain two discrepancies between the wells: 1) The Vaqueros Formation rests on Paleogene sedimentary rocks in the Shell-Chambers well, and in wells farther to the west, but it overlies crystalline basement and Oligocene Simmler Formation in the Blue Diamond well. 2) There is a shart contrast in dips between the wells. This could be explained by either a fault or a tight fold. A fault seems the better choice because it avoids mapping folded basement between the wells, although granitic rocks appear in the core of an anticline in Quatal Canyon (Dibblee, 1971a). Also the basement rock in the Blue Diamond well is extensively sheared, chloritized and slickensided (Ross, 1974), which supports the presence of a fault nearby.

The overlying Qualtal Formation appears undisturbed, suggesting that the postulated fault is pre-Pliocene in age.

CONCLUSIONS

1. Tertiary marine strata, predominant in the western part of the area, grade into predominaltly nonmarine strata in the Cuyama Badlands to the east. The facies changes are comparable to those on the north side of the Caliente Range (Vedder, 1970; Clifton, 1973), thus giving a N50°W orientation on the paleoshoreline, assuming no late Tertiary strike-slip on the Morales fault.

2. In the center of the Cuyama Valley, the Cox trough is a half-graben with a fault only on its western flank.

3. The Cox trough subsided only during the deposition of the early Miocene Saltos Shale.

4. The Cuyama syncline remained a depocenter during the deposition of the Pliocene-Pleistocene Morales Formation, therefore it is a relatively young feature. The superposition of east-west trending structures, such as the South Cuyama fault and the present trend of the Cuyama Valley is still younger, probably Quaternary in age.

5. A fault is postulated between the Clayton 14-4 and Blue Diamond wells to explain the contrast in pre-Vaqueros geology. Quartz diorite and Simmler Formation are present in the Blue Diamond well, whereas Paleogene marine strata occurs in the Shell-Chambers well and wells farther west.

ACKNOWLEDGEMENTS

We would like to thank Drs. Robert Yeats, Robert Lillie, and W.J.M. Bazeley for their helpful comments and insights. G.W. Charlton of COHO Resources, Ltd., and Coleman Morton provided the seismic lines. T.W. Dibblee, Jr. made available his unpublished maps. Grants from Arco, the Geological Society of America, and the Oregon State University Dept. of Geology mde this study possible. I would also like to thank the Reyes family for their warm hospitality in providing a base camp for the field work, and Cheryl Beam and Robert Miller for being congenial field assistants.

This chapter was originally published as: Ellis, B.J. and Spitz, H.M., 1987, Subsurface cross-section of the southeastern Cuyama basin, southern California, *in* T.L. Davis and Namson, J.S., eds., Structural Evolution of the Western Transverse Ranges, Society of Economic Paleontologists and Mineralogists, vol. 48A, p. 77-84. It is included here with permission from the publisher.

Chapter 2:
Magnetic Stratigraphy of the Morales Formation: Late Neogene Clockwise Rotation and Compression in the Cuyama Basin, California Coast Ranges

Barbara J. Ellis
Department of Geosciences

Shaul Levi
School of Oceanography

Robert S. Yeats
Department of Geosciences
Oregon State University
Corvallis, OR 97331-5506

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 Morales and Whiterock thrusts in the western Cuyama basin were 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 through 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 23° of clockwise rotation of the Morales Formation.

INTRODUCTION

The Cuyama basin, located northwest of the western Big Bend of the San Andreas Fault (Fig. 2-1 and 2-2), is an area of transition between the strike-slip tectonics of the Coast Ranges to the northwest and the 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 (Fig. 2-2). 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 an age-diagnostic fossil record, the magnetostratigraphy of the Morales Formation was studied to help constrain the timing of the transition from strike-slip to compressional 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° in the Cuyama basin.

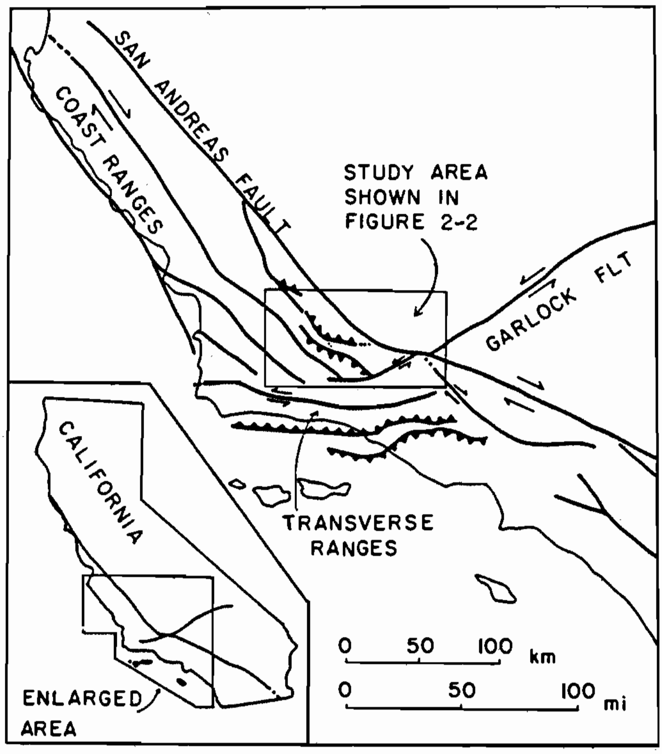


Figure 2-1. Location of study area and major faults in southern California.

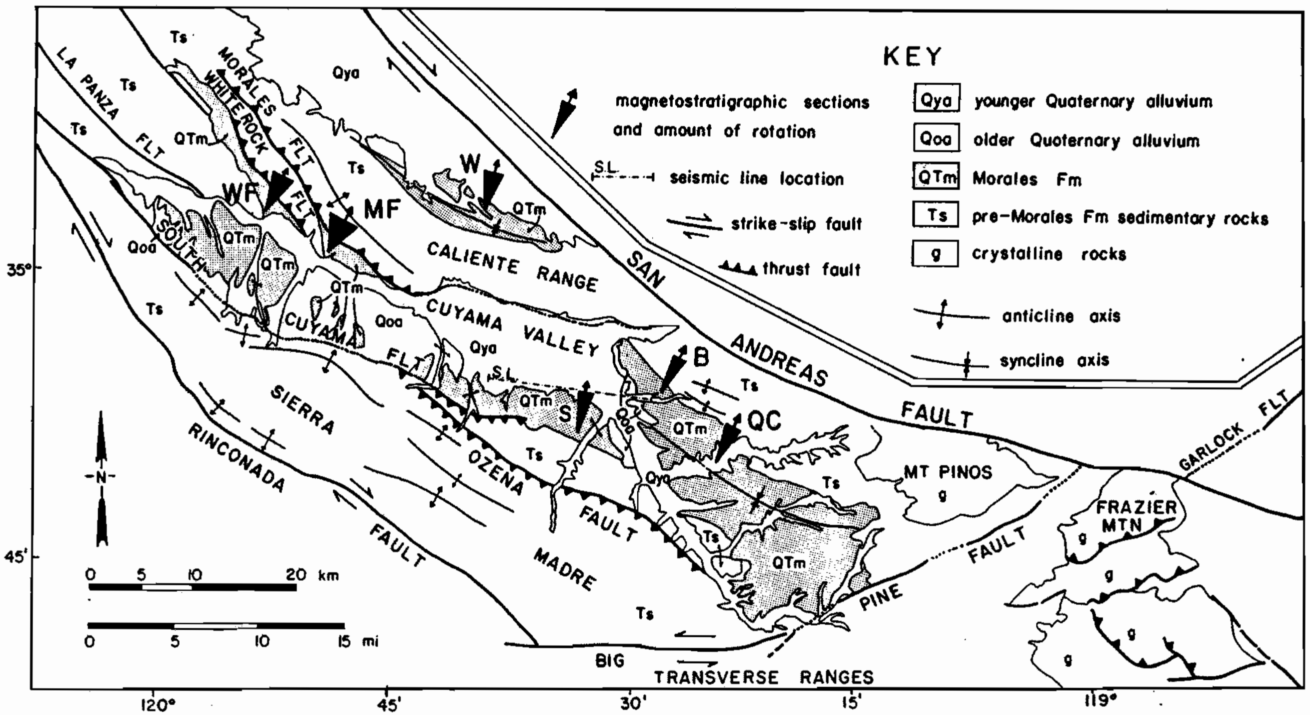


Figure 2-2. Simplified geologic map of Cuyama basin showing outcrops of Morales Formation (shaded). Magnetostratigraphic sections shown with amount of rotation with 95% confidence interval. WF = Whiterock fault section, MF = Morales fault section, W = Wells Ranch syncline section, S = Santa Barbara Canyon section, B = Ballinger Canyon section, QC = Quatal Canyon section. The western Big Bend of the San Andreas fault is located northwest of the Ballinger and Quatal Canyon sections.

METHODOLOGY

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

Sample sites were spaced as closely as possible, while trying to sample the finest 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 3 hand samples were oriented by Brunton compass. In the lab, hand samples were reoriented in plaster of Paris, and at least 2 oriented cores were drilled from each hand sample. The majority of samples were thermally demagnetized progressively to 650° Centigrade in 30°-50° 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 at 5-10 mT increments. A comparison of the two demagnetization methods is shown in Figure 2-3.

The overprint by the normal, present-day field was usually removed in the first two or three demagnetization steps (Fig. 2-4). 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 the analyses. The demagnetization interval used 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 sampled sections, k and α_{95} improved after the sites were structurally corrected (Fig. 2-5). The only exception is the section below the Morales fault, where only three sites were available for obtaining the average paleomagnetic direction.

A classic fold test was not possible, as most of the sections were homoclines and did not cross fold axes. 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 correction imply the magnetization 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, 1963). At the Quatal Canyon section, the smaller dispersion after unfolding is significant at the 95% level, at the Ballinger Canyon and Wells Ranch syncline sections they are significant at the 99% level. The results are shown in Table 2.

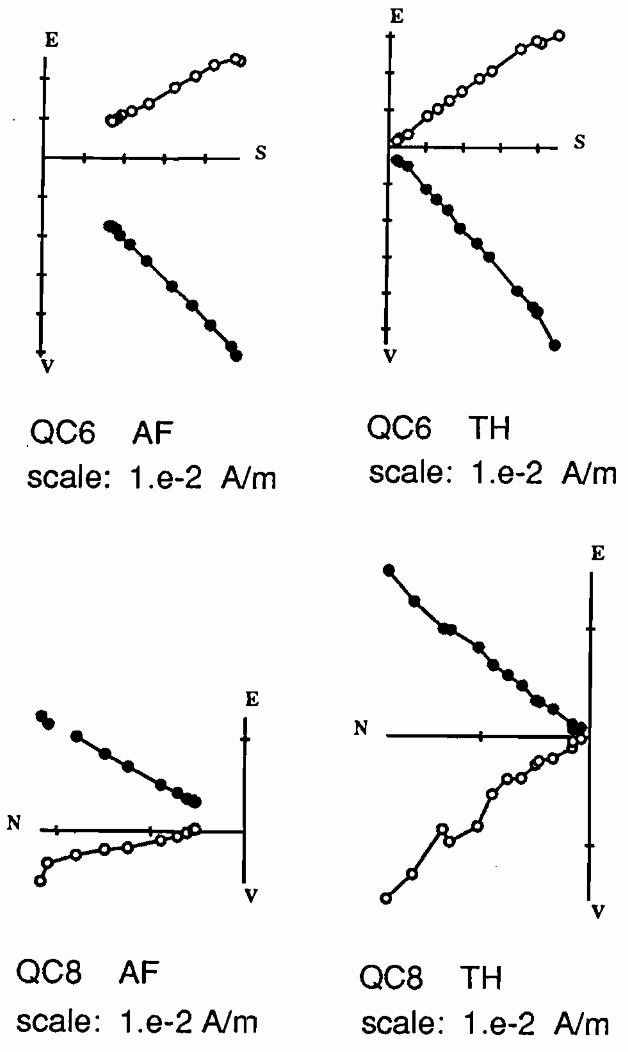


Figure 2-3. Zijderveld diagrams comparing alternating fields (AF) and thermal (TH) demagnetization. In both sites, QC6 and QC8, the two specimens are from the same hand sample. Results are for in situ orientation.

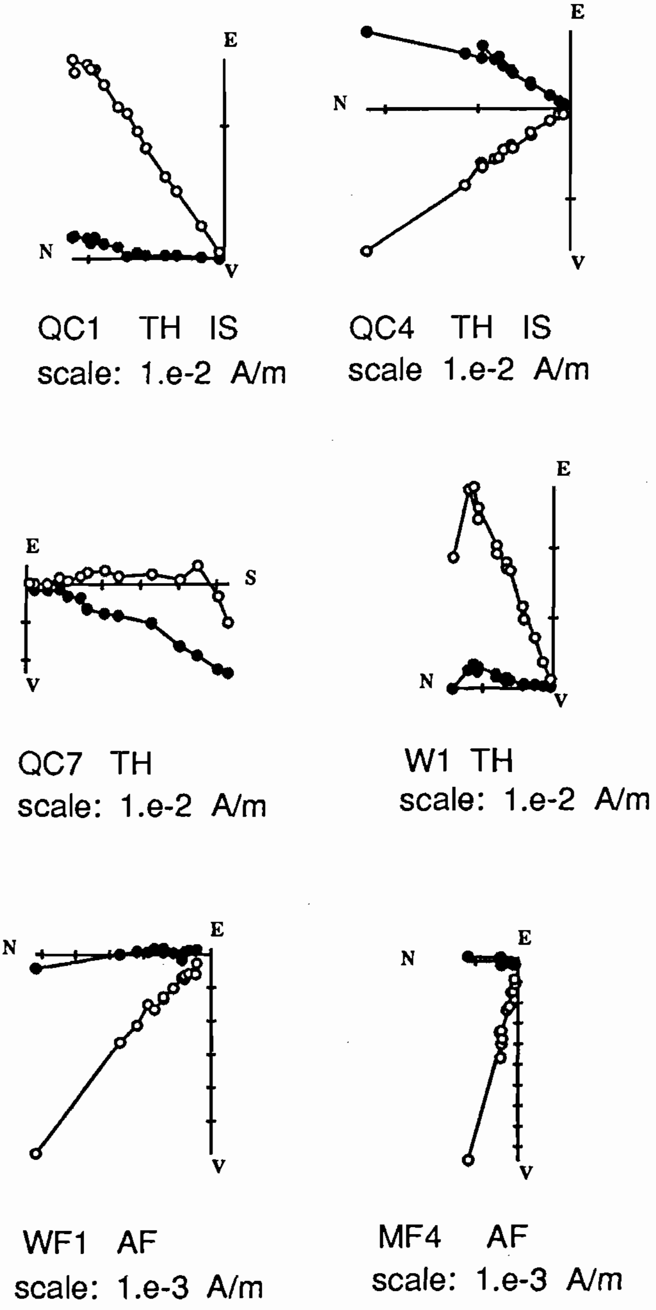


Figure 2-4. Zijderfeld plots, in situ (IS), showing progressive demagnetization of well behaved specimens.

TABLE 1

CUYAMA VALLEY SUMMARY OF PALEOMAGNETIC RESULTS

Site No.	N/n	D_R(°)	I_R(°)	k	α_{95}(°)	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	probably 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*		weak site				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

TABLE 1 (CONTINUED)

CUYAMA VALLEY SUMMARY OF PALEOMAGNETIC RESULTS

Site No.	N/n	D_R(°)	I_R(°)	k	α_{95}(°)	Bedding Strike/Dip
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*	weak site, indeterminate					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*	weak site, indeterminate					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*			weak site, reversed?			315°/28°N
W6	5/7	176.6	-60.9	170.5	5.9	130°/60°S

TABLE 1 (CONTINUED)

CUYAMA VALLEY SUMMARY OF PALEOMAGNETIC RESULTS

Site No.	N/n	D_R(°)	I_R(°)	k	α_{95}(°)	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*		weak site, inderminate				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*		weak site, indeterminate				235°/46°NW

N/n, number of specimens used in calculations/number of specimens measured.

DR, IR, 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.

a95, radius in degrees of the 95 percent cone of confidence about the mean direction.

* Site eliminated from calculations for average vectors due to lack of data or A95>25.

TABLE 2

CUYAMA VALLEY , AVERAGE DIRECTIONS BY SECTION
COMPARING IN SITU AND BEDDING CORRECTED DATA

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

IS, in situ

BC, bedding corrected
N, number of specimens used in calculations
D, I, declination (D) and inclination (I);
k, best estimate of precision parameter of Fisher distribution.
a95, radius in degrees of the 95 percent cone of confidence about the mean direction.
* k less than 3, no A95

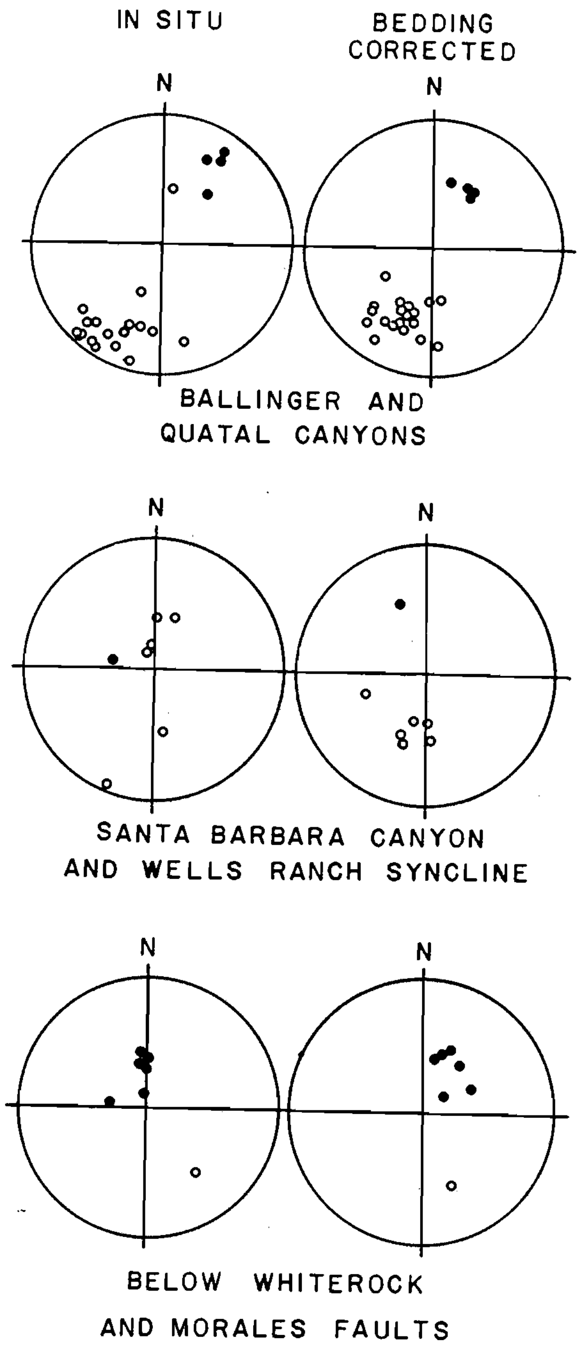


Figure 2-5. Equal-area stereonets showing site data before and after bedding corrections. The directions are more tightly clustered after bedding corrections.

THE MORALES FORMATION

The Morales Formation is a Pliocene-Pleistocene fluvial deposit at least 1500 meters thick unconformably overlying middle and late Miocene strata. It was first designated a separate formation by Hill et al. (1958). Dibblee (1971a, 1973) included all young, deformed, non-marine 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 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 (Fig. 2-6). One site from the Quatal Formation gave no useful results. Vedder (1970; pers. comm., 1990) found a Blancan fossil locality in the Morales Formation approximately midway 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 the early Matuyama polarity chrons (McDougall et al., 1992).

Figure 2-6. Magnetostratigraphic correlation of 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.

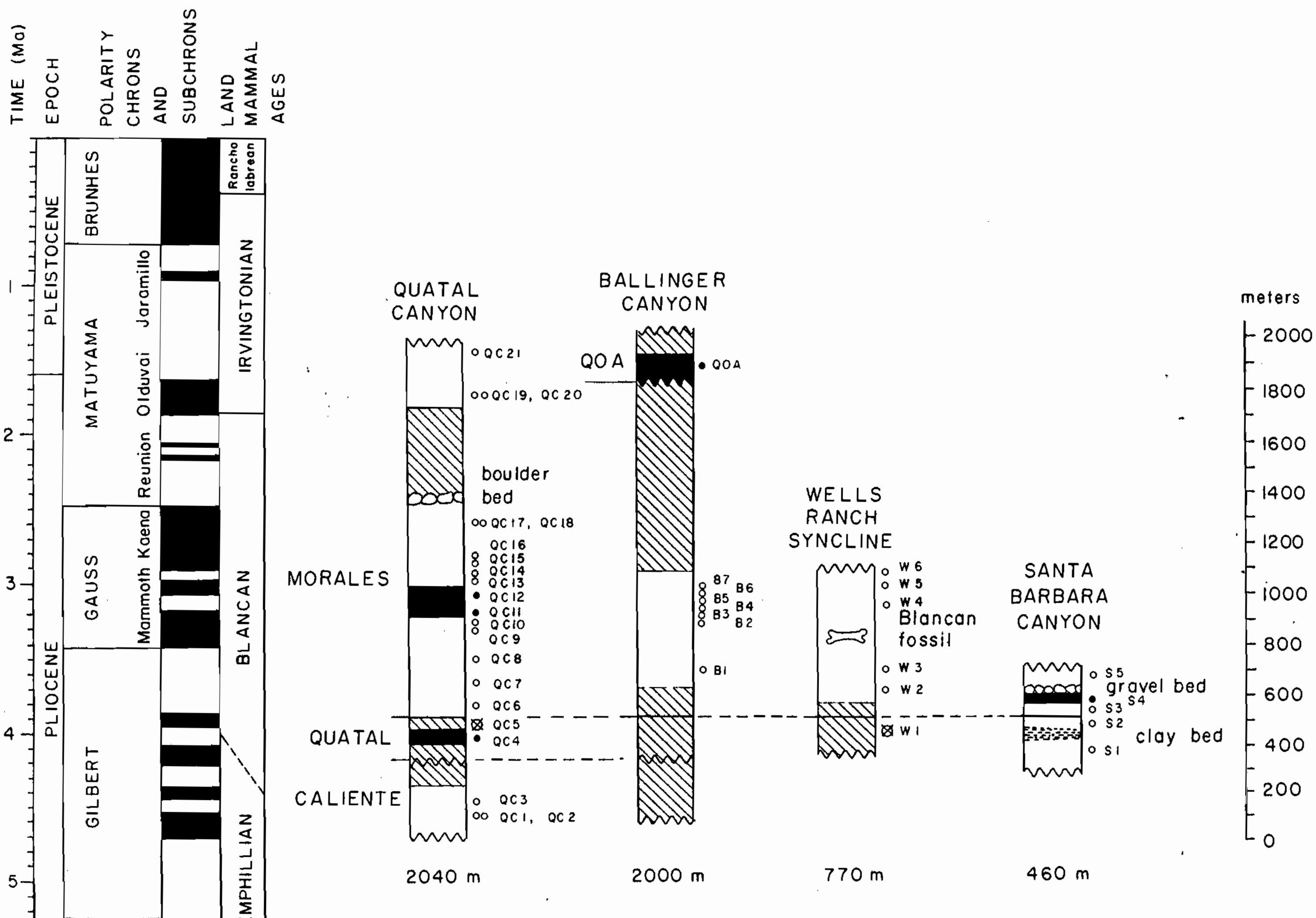

TIME (Ma)
EPOCH
POLARITY CHRONS AND SUBCHRONS
LAND MAMMAL AGES
PLEISTOCENE
PLIOCENE
BRUNHES
MATUYAMA
GAUSS
GILBERT
Jaramillo
Olduvai
Reunion
Kaena
Mammoth
Rancho labrean
IRVINGTONIAN
BLANCAN
HEMPHILLIAN
1
2
3
4
5
QUATAL CANYON
BALLINGER CANYON
WELLS RANCH SYNCLINE
SANTA BARBARA CANYON
meters
2000
1800
1600
1400
1200
1000
800
600
400
200
0
QC21
QC19, QC20
boulder bed
QC17, QC18
QC16
QC15
QC14
QC13
QC12
QC11
QC10
QC9
QC8
QC7
QC6
QC5
QC4
QC3
QC1, QC2
MORALES
QUATAL
CALIENTE
QOA
B7
B6
B5
B4
B3
B2
B1
W6
W5
W4
Blancan fossil
W3
W2
W1
S5
gravel bed
S4
S3
S2
clay bed
S1
2040 m
2000 m
770 m
460 m

Figure 2-6

Quatal and Ballinger Canyons

The Quatal Canyon section in the Cuyama Badlands is the easternmost section studied (Fig. 2-2) 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 clay (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 include a pink feldspar augen gneiss, Pelona Schist, granitic gneiss, a marble boulder almost 2 m in diameter, a white granitic fine-grained gneiss with garnets, and a greenschist with amphibole and garnets. Boulder lithologies correlate with crystalline basement lithologies in the Mt. Pinos-Frazier Mountain highlands east of the Cuyama Badlands. Above the boulder bed, the Morales Formation is coarser grained, and beds sufficiently fine-grained for paleomagnetic studies are rare.

Three paleomagnetism sites were sampled from the Caliente Formation. These sites occur on both sides of an anticlinal axis and all sites were 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 gave a reliable normal polarity, the other site is questionably normal (Table 1, Fig. 2-6). The Morales Formation is reversed except for two normally magnetized sites approximately one third of the distance up the stratigraphic section. The boulder bed from the Mt. Pinos-Frazier Mountain highlands is about 384 meters above the upper normal site.

In Ballinger Canyon, the stratigraphy is almost identical to Quatal Canyon. Younger fluvial sediments, the "Qoa" on Dibblee (1973) and Vedder's

(1968) maps, overlie the Morales with a 20° angular unconformity. The seven sites from the lower part of the Morales Formation were reversed and the single "Qoa" site has normal polarity.

Santa Barbara Canyon

In Santa Barbara Canyon, just west of 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 beds. The lower site is reversed;the upper one has indeterminate polarity (Fig. 2-6). 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 have reversed magnetization.

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 m and 1100 m thick, respectively (Fig. 2-7). 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. Half-way 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.

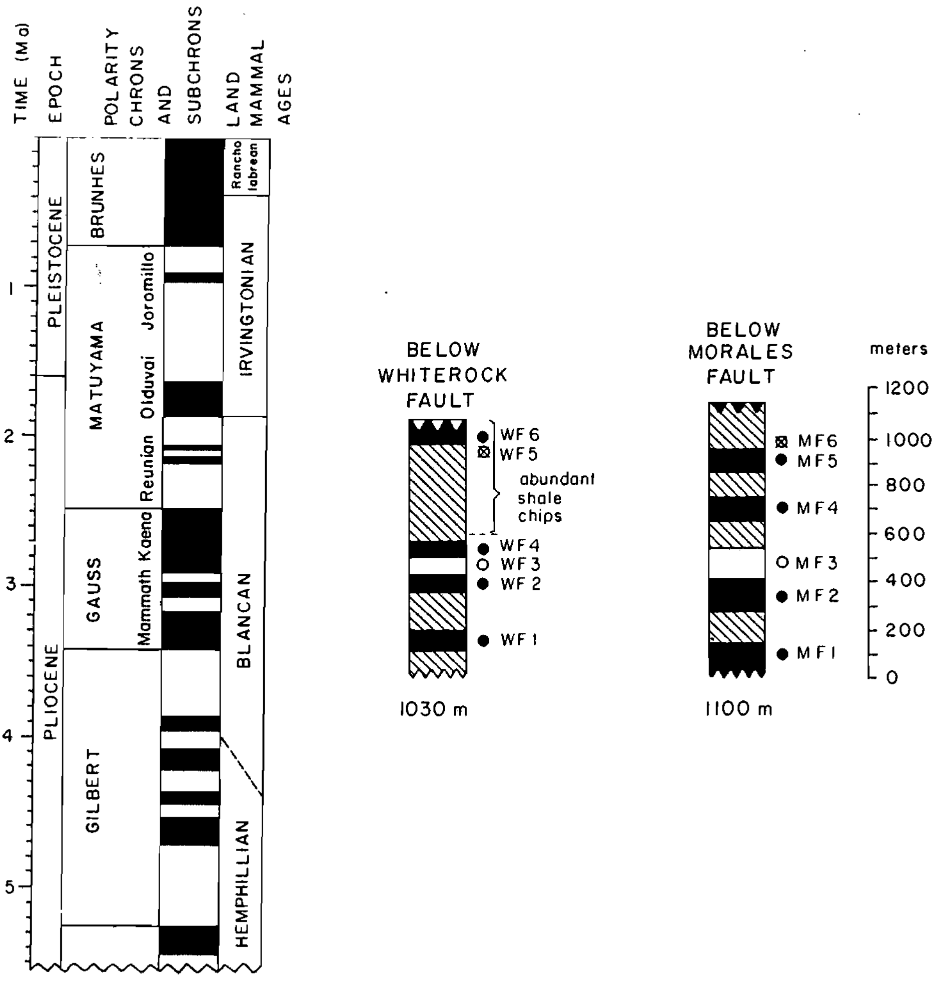


Figure 2-7. Magnetostratigraphic sections from the western Cuyama basin showing the Morales Formation only. Reversed sites are denoted by open circles, normal sites by solid circles, and indeterminate sites by crosses. Diagonal line pattern indicates unknown polarity due to lack of sites.

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 (Lundalius, 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 late Gilbert Chron or 2) the early Matuyama Chron. This would suggest minimum sedimentation rates of 1.5 mm/yr for the Gilbert chron, and 0.85 mm/yr for the early Matuyama chron.

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 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 been found in the Cuyama Badlands Morales Formation. There are 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 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 could 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 there are no fossils or ash beds present. However, they must be equivalent to, or younger than, the sections in the eastern Cuyama basin. An east-west seismic line (Fig. 2-8) (Ellis and Spitz, 1987) in the eastern Cuyama basin shows that the 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 (Fig. 2-6). Both sections rest unconformably on upper Miocene sandstone; they are associated with imbricate thrusts faults, and both have a similar magnetic stratigraphy. If they are correlative, one section can be used to fill in gaps in the other, giving a more complete, composite section.

The Morales and Whiterock sections are not likely represent the Bruhnes 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 usually 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 chrons is equally likely. However, in combination with the western, predominantly normal sections, and evidence from the east-west seismic line, deposition of the Morales Formation in the Cuyama basin probably began during the late Gilbert and continued into the Matuyama Chron.

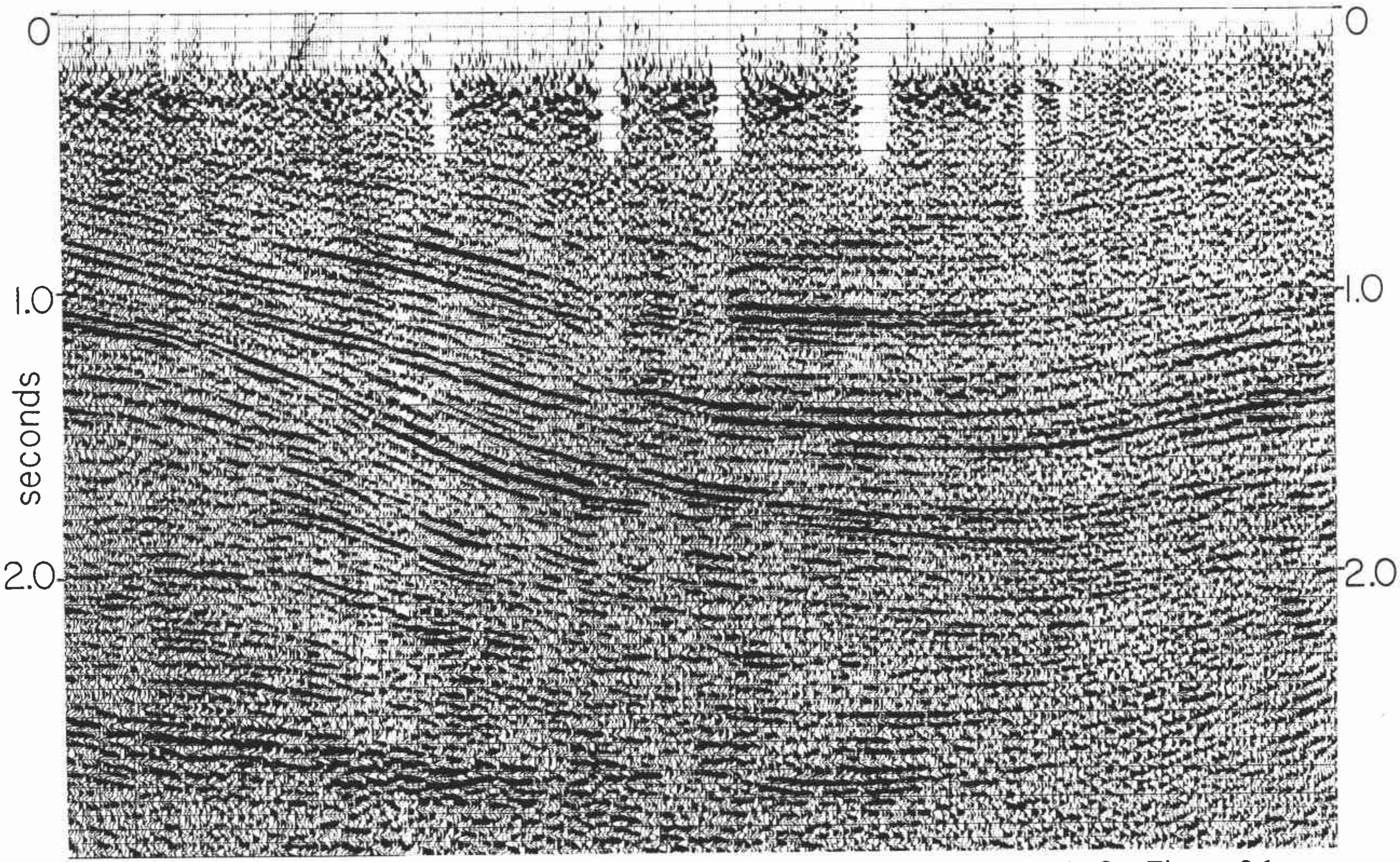


Figure 2-8a. East-west seismic line from the eastern Cuyama basin, uninterpreted. See Figure 2-1 for location.

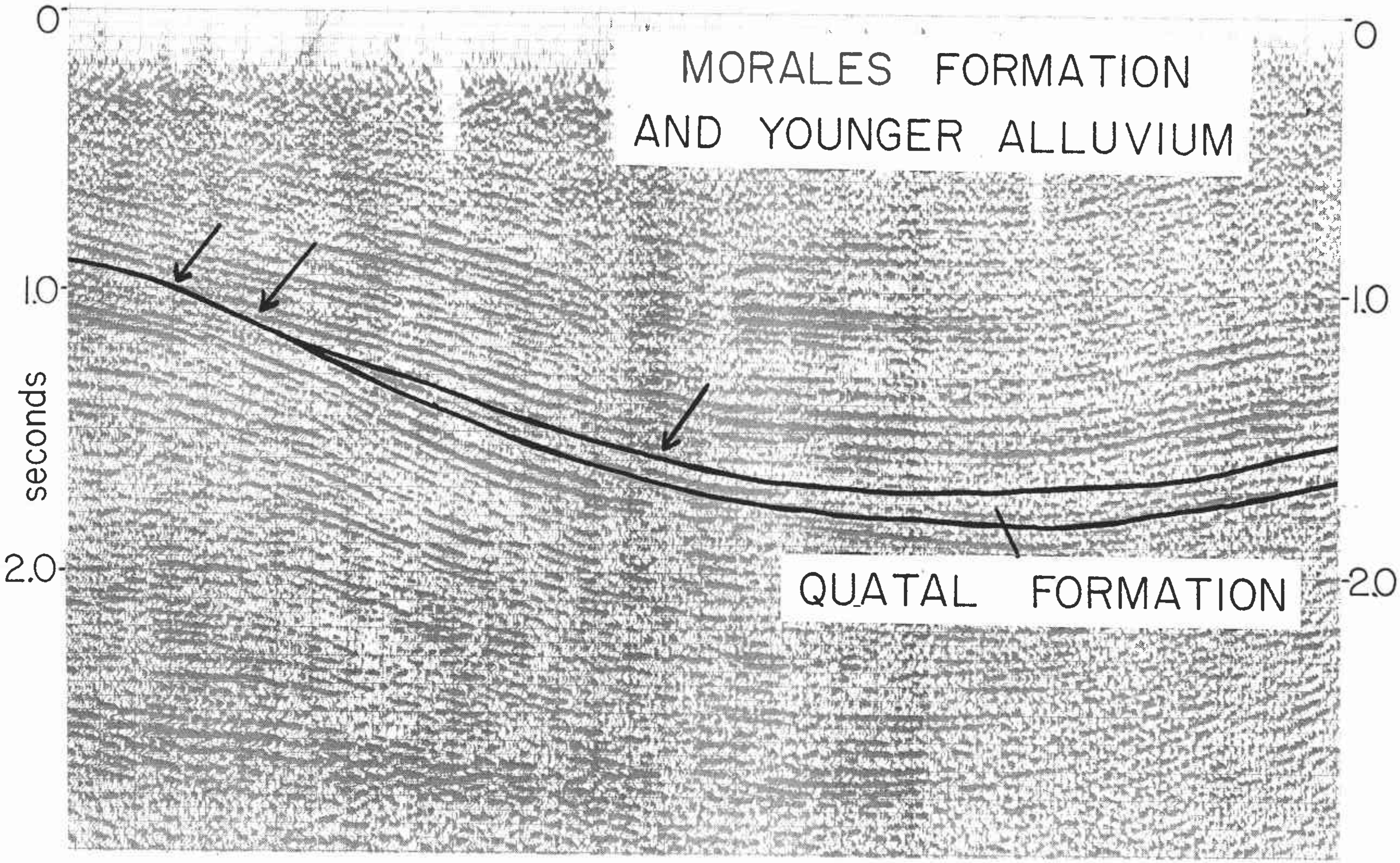


Figure 2-8b. East-west seismic line from eastern Cuyama basin, interpreted. Arrows point to onlap of individual reflectors in the Morales Formation against the Quatal Formation.

TIMING OF TECTONIC EVENTS

The eastern, predominantly reversed sections are interpreted to correlate with the late Gilbert through early Matuyama chron, and the western sections are correlated with the Gauss chron. In this interpretation, the appearance of the boulder bed just above the normal site in Quatal Canyon (Fig. 2-6) represents the inception of uplift and erosion from the Mt 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 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 thrust section (Fig. 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 began 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 two ways: 1) by combining averages of all site samples, which gave an average declination/rotation of 23.3, α_{95}=65°, n=37, and 2) by combining the average rotation of each section, which gave a regional average rotation of 20.3°, α_{95}=7.0°, n=6. The Quatal Canyon section, the longest continuous exposure, has an average rotation of 24.5°, α_{95}=17.1° (Table 2). There is no discernable pattern of progressive rotation through time, suggesting that rotation in the Cuyama Badlands occurred after Morales deposition.

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; Hornafius et al., 1986) Luyendyk (1991) uses McKenzie and Jackson's (1986) model to explain the rotation of the western Transverse Ranges. In their model, crustal blocks first undergo 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° $\pm$ 3.4°/Ma. They suggest this rate is consistent with estimates of rotation rates for the past 10 Ma, which would imply about 12° degrees of clockwise rotation of the Cuyama basin since Morales deposition ended about 2 Ma. However, the Cuyama basin is rotated 20°-23°, almost twice the predicted value.

TABLE 3

COMPARISON OF AVERAGE PALEOMAGNETIC RESULTS

Sections or Combination of Sites	N	D(°)	I(°)	k	α_{95}(°)
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
D, I, declination (D) and inclination (I);
k, best estimate of precision parameter of Fisher distribution.
a95, radius in degrees of the 95 percent cone of confidence about the mean direction.

CONCLUSIONS

The transition from strike-slip to compressional tectonics occurred since approximately 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 Mt. 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 sites 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; the formation of the Cuyama syncline post-dates 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.

Paleomagnetic data from the Morales Formation shows the Cuyama basin has undergone an average of 23° of post-Morales clockwise rotation, nearly twice the value predicted by present models.

ACKNOWLEDGEMENTS

This work was supported by grants from the Geological Society of America, Sigma Xi, ARCO, the Bureau of Land Management, and the National Earthquake Hazards Reduction Program. Dr. Shaul Levi provided laboratory facilities to analyze the paleomagnetic samples, and greatly improved the manuscript through discussions and editing comments. Dennis Schultz assisted in sampling and paleomagnetic analysis. Discussions with Pierrick Roperch were helpful. Wayne Sugai provided computer support in manuscript preparation.

This chapter was first published as:

Ellis, B.J., Levi, S. and Yeats, R.S., 1993, Magnetic stratigraphy of the Morales Formation: Late Neogene clockwise rotation and compression in the Cuyama basin, California Coast Ranges: Tectonics, v. 12, no. 5, p. 1170-1179. It is included here with permission from the publisher, the American Geophysical Union.

CONTRIBUTIONS OF THE AUTHORS

Barbara J. Ellis gathered and analyzed the data, and is the primary author of the paper.

Dr. Shaul Levi provided access to the laboratory facilities that made it possible to analyze the paleomagnetic samples. He also provided guidance in interpreting the resulting data, and critiqued the manuscript.

Dr. Robert Yeats first suggested paleomagnetism as a method to date the Morales Formation, and provided helpful discussions on the tectonic significance of the paleomagnetic data.

Chapter 3: Tectonic History of the Southeastern Cuyama Basin and Cuyama Badlands, Southern California

Barbara J. Ellis
Department of Geosciences
Oregon State University
Corvallis, OR 97331-5506

ABSTRACT

During the Cenozoic, the tectonics of the Cuyama basin changed from extension to strike-slip faulting, and most recently, to compression and rotation. The Cuyama basin was adjacent to the Mojave region 320 km to the south during the Oligocene. Many of the present-day reverse faults of the Cuyama basin have an earlier extensional history. At ~23 Ma, extensional tectonics changed to strike-slip faulting, and the Cuyama basin became part of a distributed shear zone between the North American and Pacific plates. Right- and left-lateral strike-slip faults, normal faults (e.g., the Cox fault) and en echelon folds were part of this shear zone. The Russell fault is the oldest documented dextral fault in the Cuyama basin. It began to move at 23 Ma and has ~29 km of slip. Tracing the Russell fault south of the Big Pine fault has been problematic. I propose that the Russell fault joins with the Blue Rock fault under the Cuyama Badlands, which then correlates with the Clemens Well-Fenner-San Francisquito fault to the south. A left-lateral fault that was also active during the early phase of strike-slip faulting is postulated to underlie the southeast Caliente Range.

More recently, east-west trending compressional structures overrode and deformed earlier structures. The Caliente Range is moving south on the Whiterock and Morales thrusts, and the Sierra Madre is moving north on the South Cuyama and Ozena faults. The beginning of uplift of the Caliente Range is dated at ~3.0-2.5 Ma, based on the magnetostratigraphy of the Morales Formation, which is cut by the thrusts.

Paleomagnetic data also revealed ~23° of clockwise rotation in the Cuyama basin. A plan-view model, similar to the cross-section model for the formation of a fault-bend fold above a thrust fault ramp (Suppe, 1983), is proposed to explain the rotation. Material west of the San Andreas fault rotates as it moves around the Big Bend of the San Andreas fault, which has a 27° change in strike.

INTRODUCTION

The Cuyama basin is in the southern Coast Ranges, north of the western Transverse Ranges, and immediately west of the Big Bend of the San Andreas fault (Fig. 3-1). It is part of the Salinian block, which is characterized by granitic basement. The Salinian block is separated from the Franciscan Formation, Jurassic ophiolites and Mesozoic forearc basin deposits by the San Andreas fault to the northeast, and the Sur-Nacimiento (Rinconada) faults to the southwest (Fig. 3-1). The Cuyama basin is separated from the western Transverse Ranges to the south by the Big Pine fault (Yeats et al., 1988, 1989) (Fig. 3-2).

The Cenozoic tectonic history of the Cuyama basin is complex and has changed from extension to strike-slip faulting to compression and rotation. During the early Tertiary, the Cuyama basin was 320 km southeast of its present position and adjacent to the Mojave extensional terrane on the other side of the San Andreas fault. Many of the modern reverse faults in the Cuyama basin were normal faults at that time. Crouch and Suppe (1993) suggest that the Cuyama basin was part of an extensional terrane in the hanging wall of a low-angle normal fault. The initial break-away zone for the low-angle normal fault was the Nacimiento (Rinconada) fault zone. Extensional faulting in the Cuyama basin ended in the upper Oligocene at approximately 24 Ma (Bohannon, 1975, 1976).

The oldest documented strike-slip movement in the Cuyama basin involved the Russell fault, which began at 23 Ma (Yeats, et al. 1989). Powell (1993, p. 32, his Figure 8) suggests that the San Andreas fault north of the Western Transverse Ranges may have been active as early as 22 Ma. Sims (1989) dates the beginning of the San Andreas fault in central California as 22-18 Ma. During the early phase of strike-slip faulting, the Cuyama basin may have been part of a diffuse shear zone as described by Atwater (1970). Dextral shear was distributed across two or more strike-slip faults, and a complex of structures, including normal and left-lateral faults, were formed. As the dextral shear zone evolved, it became narrower with one dominant fault, the San Andreas fault (Weldon et al., 1993).

Yeats et al. (1988, 1989) documented 26-29 km of right-lateral slip on the Russell fault in the northwest part of the Cuyama Valley (Fig. 3-2). To continue the right-lateral movement to the south, they connected the Russell fault with the Ozena fault. But as Powell (1993, p. 51) points out, it is not possible to continue 29 km of dextral slip directly south of the Big Pine fault. It seems unlikely that 29 km of slip abruptly ends in the Cuyama Valley; thus, tracing the fault southeast of the Cuyama Valley is a major problem.

More recently, compressional tectonics have been superimposed over earlier structures created by extension and strike-slip faulting. The Caliente Range is being thrust south over the Cuyama Valley on the Morales and Whiterock thrusts, and the Sierra Madre is moving north on the South Cuyama and Ozena faults. The Russell fault is overlain unconformably by the Morales Formation. In turn, the Morales Formation is cut by the Morales and Whiterock thrusts. Based on the magnetostratigraphy of the Morales Formation, uplift of the Caliente Range began between 3.0 and 2.6 Ma, the middle to late Gauss chron. Recent uplift of the Mt. Pinos-Frazier Mountain crystalline highlands east of the Cuyama Badlands began between 2.6 and 0.78 Ma (Ellis et al, 1993). Twenty-three degrees of clockwise rotation occurred after the Morales Formation was deposited. A section sampled in Quatal Canyon in the Cuyama Badlands (Fig. 3-2) ranged from the upper Miocene upper Caliente Formation to the "older Quaternary alluvium" on the edge of the Cuyama Valley. No progressive rotation through time was found, implying all rotation occurred after deposition of the Morales Formation (Ellis et al., 1993). Previous rotation models for southern California have not predicted that rotation would occur north of the Big Pine fault (e.g. Luyendyk et al., 1980; Luyendyk, 1991). The rate of rotation in the Cuyama basin appears to be twice as fast as that south of the Big Pine fault (Jackson and Molnar, 1990; Luyendyk, 1991). To explain the clockwise rotation of the Cuyama basin, I propose that the rotation is due to the movement of the Cuyama basin around the Big Bend of the San Andreas fault.

New data in the form of a paleomagnetic study of the Plio-Pleistocene Morales Formation, and a previously unpublished grid of seismic lines has been used to refine the current understanding of the Cuyama basin's geologic evolution. Other data that were used in this study includes numerous oil well logs and new interpretations of existing geologic maps. Some of the wells have synthetic seismograms, which were used to correlate the wells to the seismic lines.

Problems addressed include the continuation of the Russell fault southeast of the Cuyama basin, and the timing of transitions from extension to strike-slip faulting, and most recently, to compression.

In a regional context, the Cuyama basin records the development of part of a diffuse shear zone along the western North American continental margin. More recently, the paleomagnetic data from the Morales Formation allow a refinement in dating the onset of compressional tectonics, and show that clockwise rotation is not confined to the western Transverse Ranges south of the Big Pine fault.

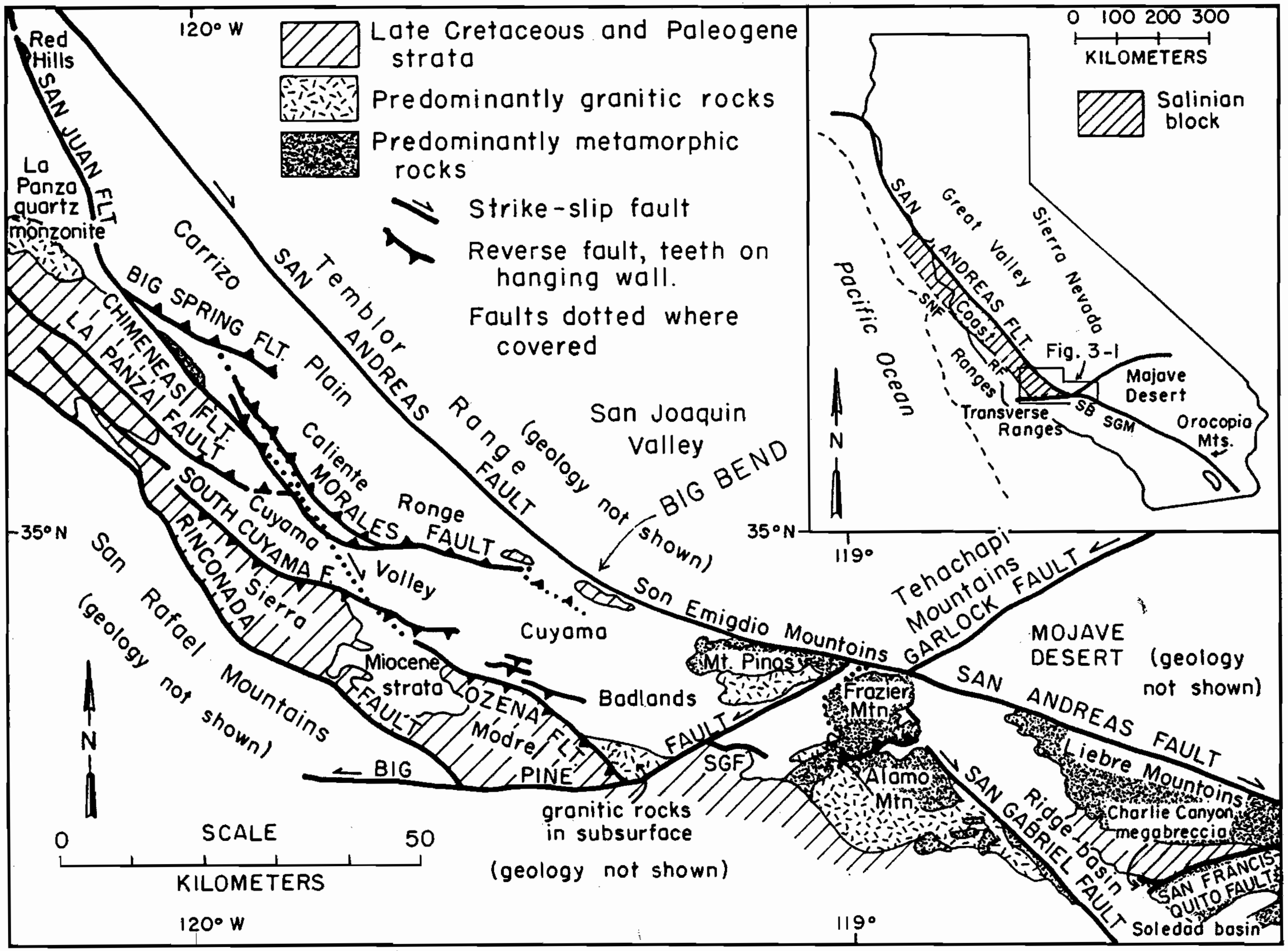


Figure 3-1. Index map of the Cuyama basin area. Inset Map: RF = Rinconada fault, SB = Soledad basin, SGM = San Guillermo Mountains, SNF = Sur-Nacimiento fault. Large map: SGF = San Guillermo fault.

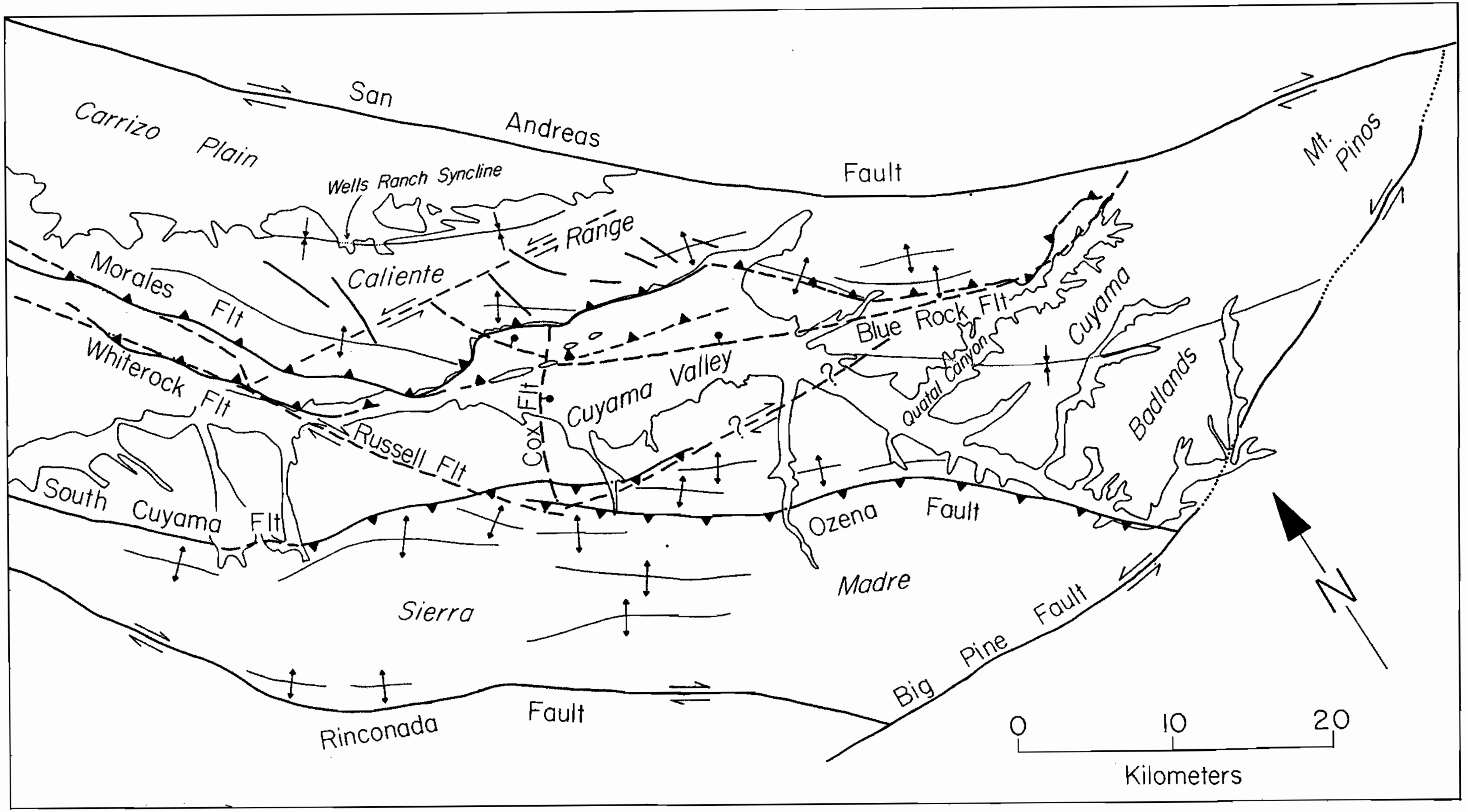


Figure 3-2. Tectonic map of the Cuyama basin area. Subsurface faults are dashed lines. Solid teeth point toward hanging wall of reverse faults. Place names are in italics.

STRATIGRAPHY

Basement

The Salinian block is underlain by crystalline rocks that include the gneiss of Barrett Ridge (Howell et al., 1977; Vedder, 1967), quartz monzonite of the La Panza Range (Ross, 1972, 1978) and Mesozoic granite, Precambrian gneiss and Pelona Schist of Mt. Pinos and Frazier Mountain (Dibblee, 1987). Davis (1983) found the northernmost known exposure of Pelona Schist in an outcrop northwest of the Cuyama Badlands and just south of the San Andreas fault (Fig. 3-3).

The Frazier Mountain-Mt. Pinos crystalline highlands have been correlated to the eastern Orocopia Mountains in the Mojave region (Crowell, 1975; Powell, 1993, p. 9) (Fig. 3-1). Both areas have Proterozoic igneous and metamorphic rocks that have been intruded by Mesozoic granite. The Proterozoic rocks consist of metasedimentary rocks, amphibolite, granitic orthogneiss and augen gneiss. Mesozoic igneous rocks include hornblende gabbro, diorite, granodiorite, and distinctive Jurassic and/or Cretaceous units of very coarse grained granite, granite with muscovite $\pm$ biotite $\pm$ garnet and a fine grained granitoid rock with a distinctive "polka-dot" texture. The "polka dots" consist of 0.5-4.0 cm long dark grey quartz-biotite-muscovite $\pm$ garnet spherules with light grey quartz feldspathic rims (Pelka, 1971; Smith 1977; Joseph et al., 1982). These granitic units are distinctive and are the primary evidence that links the Frazier Mountain-Mt. Pinos area to the Orocopia Mountains. In both areas, the basement is unconformably overlain by Eocene through upper Oligocene sedimentary strata.

Upper Cretaceous-Eocene Marine Strata

In the western part of the Cuyama basin, the crystalline basement is overlain by upper Cretaceous-Eocene marine strata (Chipping, 1972; Howell et al., 1977). Regionally, this sequence dips to the southwest. In the La Panza (Fig. 3-1) and Santa Lucia Ranges, it is over 30,000 feet (9230 m) thick. In the

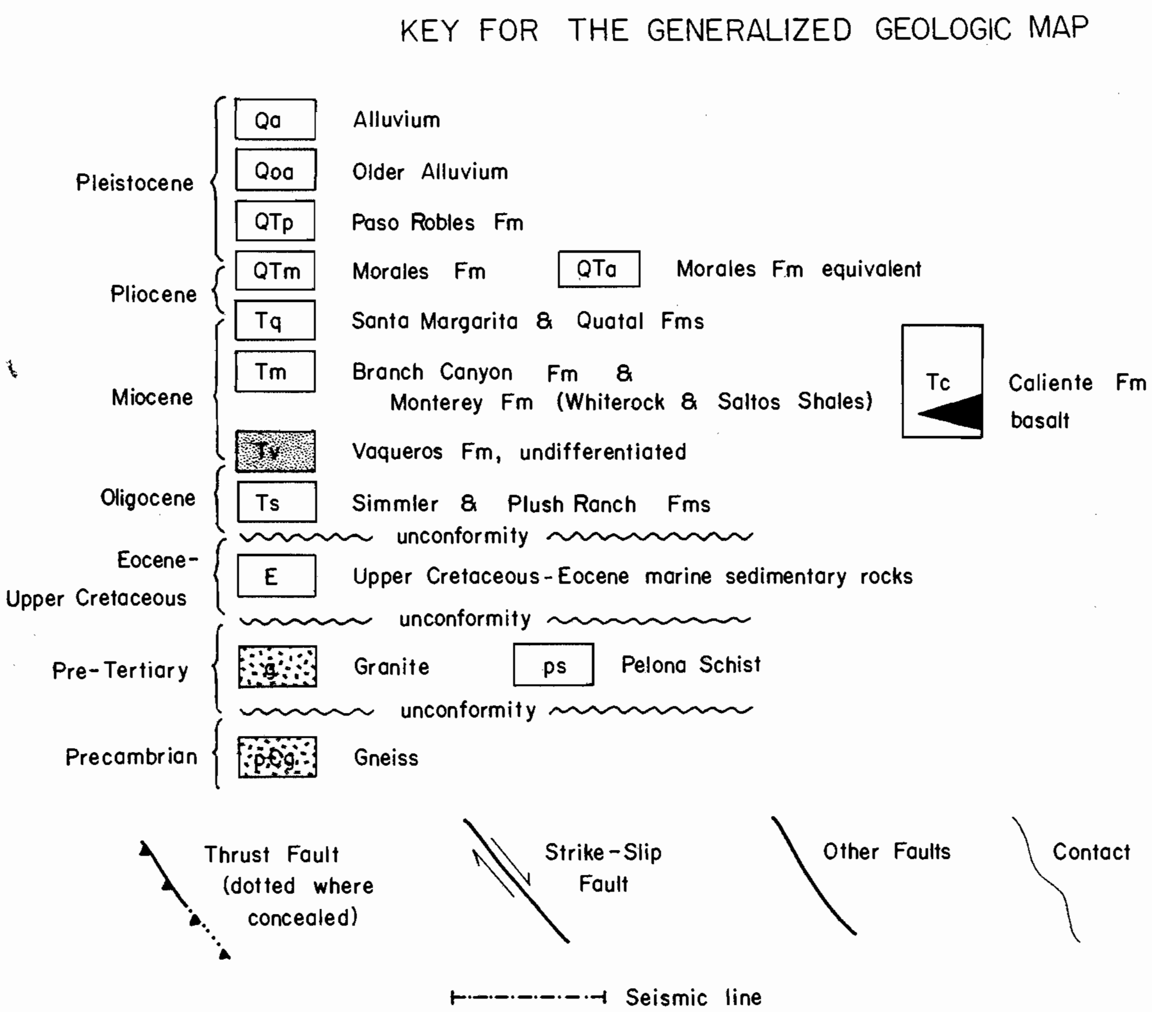


Figure 3-3a. Key for generalized geologic map.

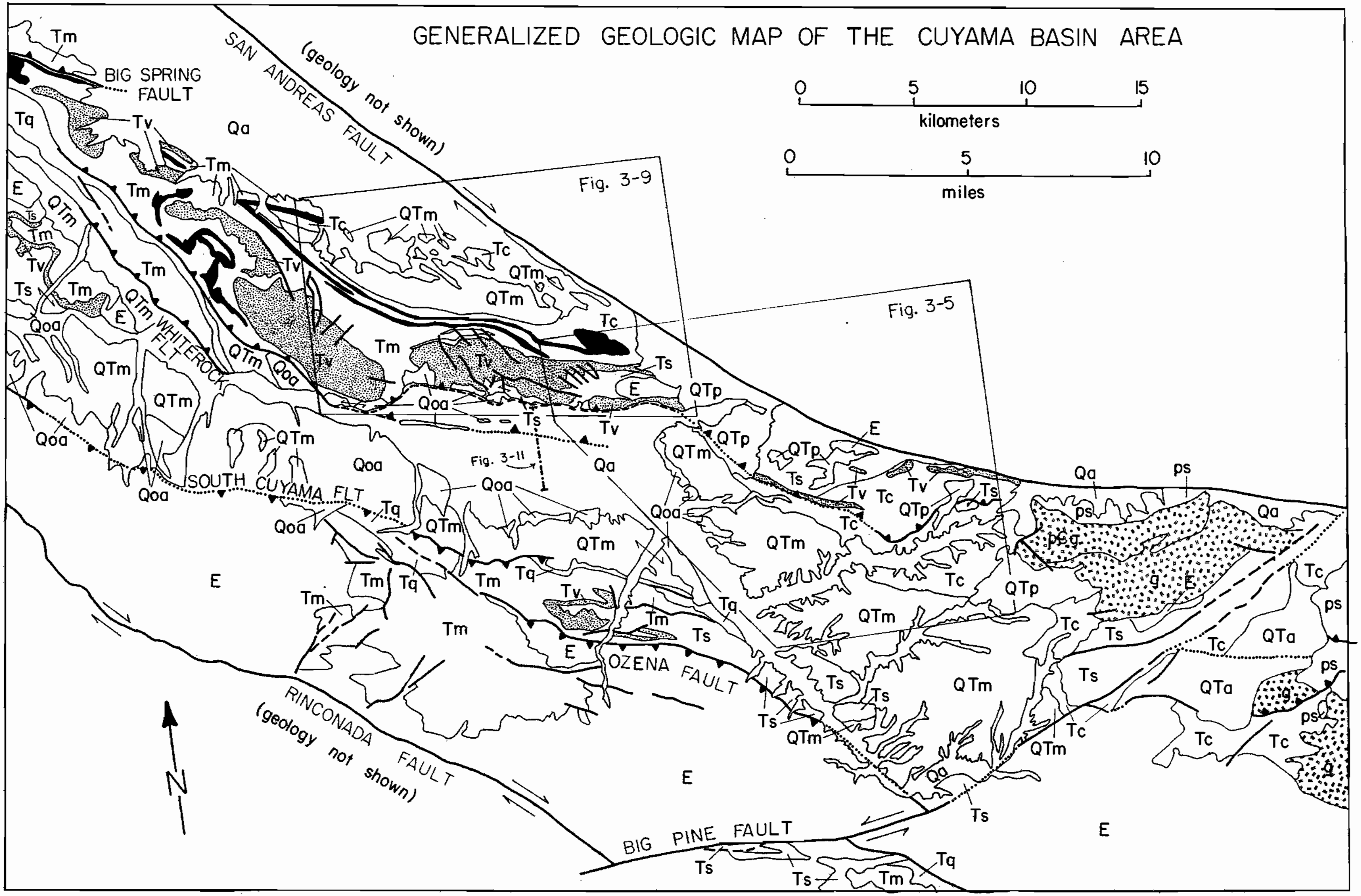


Figure 3-3b. Generalized geologic map of the Cuyama basin and surrounding areas. Modified from Jennings and Strand (1969), Smith (1965), and Dibblee (1971a, 1971b and 1971c) and Barker (1972).

Cuyama basin, the pre-Oligocene strata were identified as Cretaceous in age by Hill et al. (1958), based on microfaunal evidence. Cretaceous strata are exposed in the La Panza Range, where the base rests on crystalline basement. Later work by Gower et al. (1966) and Vedder et al. (1967) has shown that these rocks range in age from late Cretaceous through middle Eocene in age. In the Sierra Madre, the base of this sequence is not exposed. The thick marine sequence in the Sierra Madre was dated as early-middle Eocene by Chipping (1972).

In the Caliente Range, well data show that pre-Oligocene strata overlie the crystalline rocks and dip south (Yeats et al., 1988, 1989). These strata are similar to the upper Cretaceous-Eocene strata at Barrett Ridge and the La Panza Range (Yeats et al., 1988, 1989).

The Paleocene Pattiway Formation crops out in the southeastern Caliente Range and northern Cuyama Badlands (Dibblee 1971a and c; Vedder and Repenning, 1965, 1975; Vedder, 1970). The relationship of the Pattiway Formation to the Cretaceous-Eocene rocks of the Sierra Madre and Cuyama Valley is unclear.

Oligocene Continental Strata

A major unconformity separates the continental Oligocene-early Miocene Simmler Formation from the underlying marine strata and crystalline basement of the Salinian block. The Simmler consists of non-marine redbeds and rare interbedded basalts (Bartow, 1974). The Simmler Formation was deposited in local basins bounded by normal faults, and commonly has a coarse conglomeratic facies adjacent to, and on the downthrown side of, these normal faults (Fig. 3-4a and b). Normal faults that were active in the Cuyama basin during Simmler deposition include the La Panza, the Nacimiento (Ballance et al., 1983; Vedder, 1968), Ozena (Blake, 1981, 1982), and Blue Rock (Bohannon, 1975; Dibblee, 1982) faults.

Figure 3-4a. Map showing the relationship of the Simmler Formation to faults with an early Tertiary extentional history. Faults are shown in their present location. The map is modified from Bartow (1978). Areas adjacent to the Blue Rock and Big Pine faults are based on Bohannon (1976). The area adjacent to the Ozena fault is based on Blake (1981).

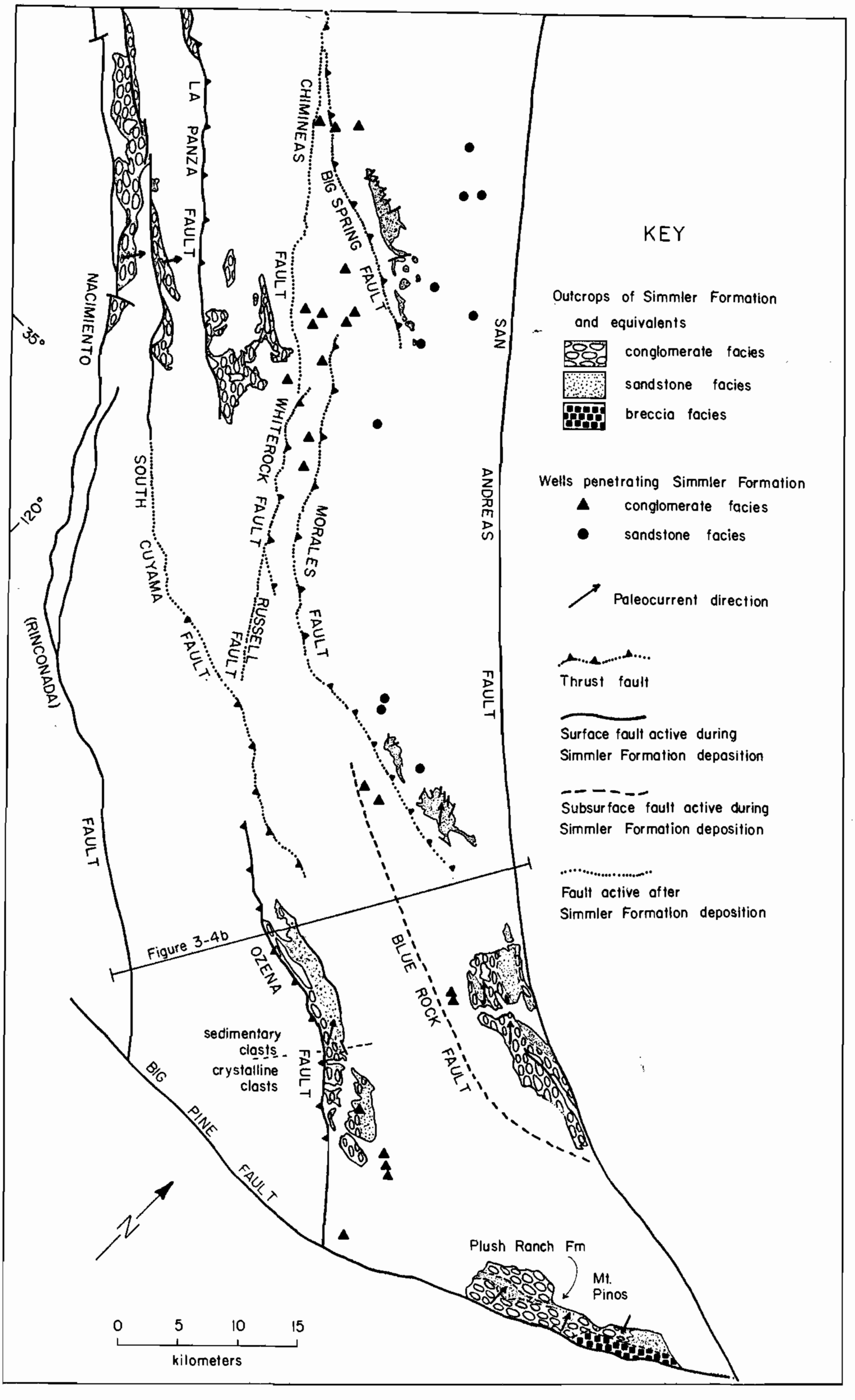

LA PANZA FAULT
CHIMINEAS FAULT
BIG SPRING FAULT
NACIMIENTO
35°
SAN ANDREAS FAULT
KEY
Outcrops of Simmler Formation and equivalents
conglomerate facies
sandstone facies
breccia facies
Wells penetrating Simmler Formation
conglomerate facies
sandstone facies
Paleocurrent direction
Thrust fault
Surface fault active during Simmler Formation deposition
Subsurface fault active during Simmler Formation deposition
Fault active after Simmler Formation deposition
SOUTH CUYAMA FAULT
WHITEROCK FAULT
MORALES FAULT
RUSSELL FAULT
120°
(RINCONADA)
FAULT
Figure 3-4b
OZENA FAULT
BLUE ROCK FAULT
sedimentary clasts
crystalline clasts
BIG PINE FAULT
N
Plush Ranch Fm
Mt. Pinos
0 5 10 15
kilometers

Figure 3-4a

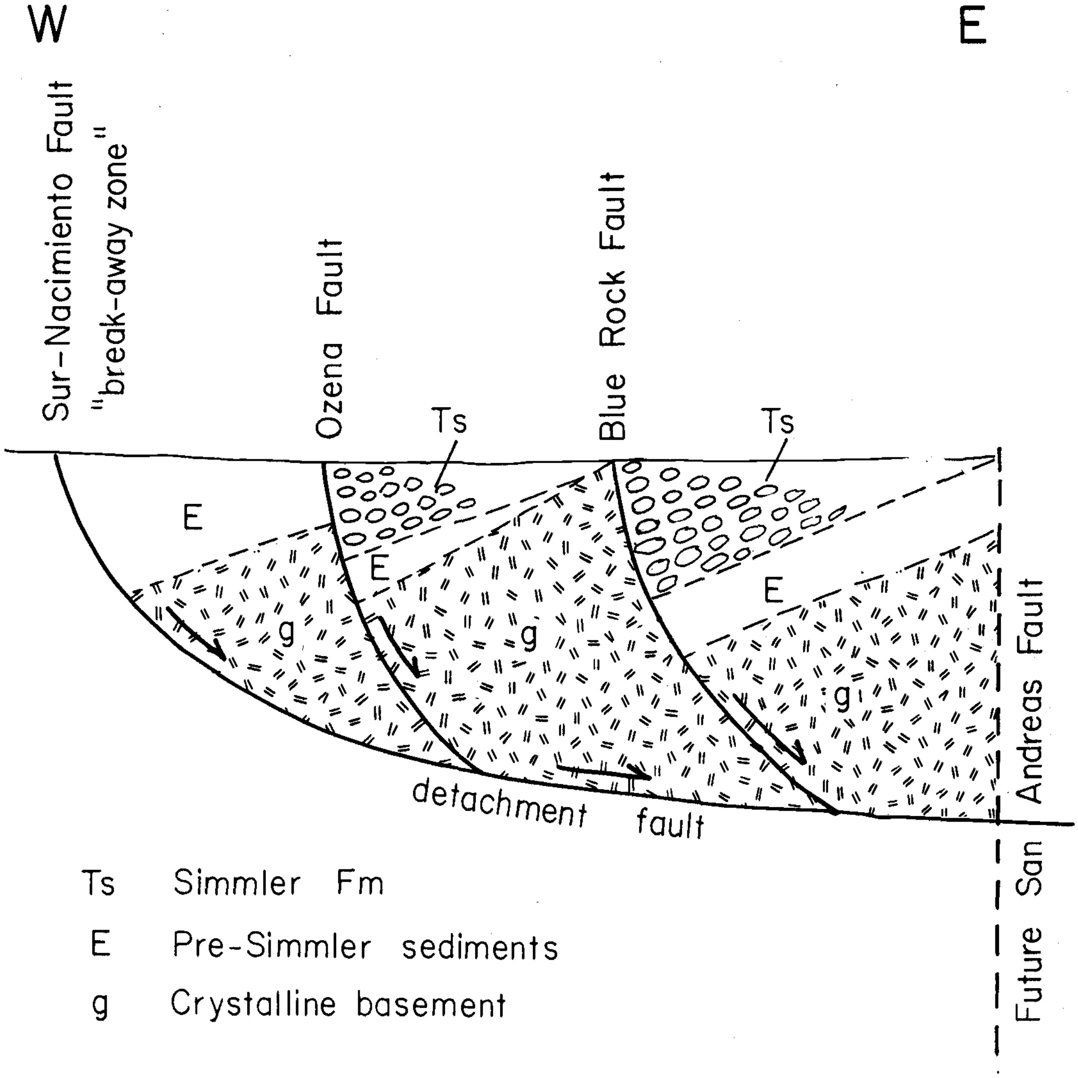


Figure 3-4b. Diagrammatic cross-section across the Nacimiento, Ozena and Blue Rock faults illustrating how the normal faults merge with a low-angle detachment fault.

Mid-Tertiary Transgressive-Regressive Sedimentary Cycles

Following the deposition of the Simmler Formation, two transgressive-regressive cycles occurred (Fritsche, 1988). The first transgression began with the deposition of the shallow-water Quail Canyon Sandstone Member of the Vaqueros Formation, and marks the beginning of the Tertiary Cuyama depositional basin (Fritsche, 1988; Yeats et al., 1988, 1989). The middle member of the Vaqueros Formation is the deep-water Soda Lake Shale (Lagoe, 1988), followed by the regressive shallow-water Painted Rock Sandstone Member, which marks the end of the first cycle. The Vaqueros Formation grades eastward into the non-marine Caliente Formation that was deposited on the eastern margin of the basin (Clifton, 1981).

The second transgressive cycle started with an abrupt deepening of the Cuyama basin and the deposition of the Saltos Shale Member of the Monterey Formation. The Saltos Shale was followed by the regressive Whiterock Bluff Shale Member. To the east, the Monterey Formation interfingers with the Branch Canyon Sandstone, a near-shore, shallow marine sandstone which prograded from east to west (Perri and Fritsche, 1988). The Branch Canyon Formation, in turn, grades eastward into the non-marine Caliente Formation.

The shallow-marine Santa Margarita Sandstone overlies both the Branch Canyon and Monterey Formations. Both the Branch Canyon and Santa Margarita Formations are shallow-water sandstones, and they may be hard to distinguish, especially in the subsurface. In general, the Branch Canyon is dominantly a resistant sandstone with abundant echinoid fossils, whereas the Santa Margarita has alternating sandstone and shale layers with oyster and scallop fossils (Nevins, 1983). These two formations mark the end of marine deposition in the Cuyama basin.

Pliocene-Pleistocene Continental Deposition

In the eastern part of the Cuyama basin, the Caliente and Branch Canyon Formations are overlain by the Quatal Formation. Locally in the Cuyama

Badlands, the Quatal Formation overlies the Caliente with a 20° angular unconformity. In the Badlands, the Quatal Formation is composed primarily of a bentonitic clay (Dibblee, 1987). A massive gypsum bed as thick as 9 m is found at the base of the Quatal Formation. On the northern flank of the Sierra Madre, the clay interfingers with sandstone. On the north side of the Caliente Range, the Quatal Formation is composed primarily of clay.

The overlying Morales Formation is a fluvial deposit that is found throughout the Cuyama basin. Fossils are rare, although Vedder (1970; pers. comm., 1990) found a Blancan age fossil in the middle of the Morales Formation on the north side of the Caliente Range. Based on magnetostratigraphy, Ellis et al. (1993) dated the Morales Formation as possibly as old as the late Gilbert paleomagnetic chron (~3.8 Ma), and it may be as young as the late Matuyama chron (~0.7 Ma).

Dibblee (1971a) mapped the nearly horizontal alluvial gravels that overlie the older folded formations in the northern Cuyama Badlands as part of the Paso Robles Formation. The gravels, composed of clasts of hornblende gabbro, hornfels, marble and Miocene grey-black shale, are derived almost entirely from the San Emigdio Mountains on the other side of the San Andreas fault. The gravels have been moved approximately 32 km (20 miles) from their source. The Paso Robles Formation overlies all of the older strata, including the Morales Formation, with an angular unconformity (Dibblee, 1987).

A formation identified as "older Quaternary alluvium" (Qoa) by Dibblee (1971a, 1971b, 1971c), Vedder (1970) and Vedder and Repenning (1975) occurs around the edges of the Cuyama Valley. On the western edge of the Cuyama Badlands, it is distinguishable from the underlying Morales Formation because it overlies the Morales Formation with a 10° -20° unconformity. On the south side of the Caliente Range, it has been uplifted as a terrace deposit above the Morales fault scarp.

MIDDLE TERTIARY EXTENSIONAL PHASE

An early phase of extensional faulting in the southern Basin and Range Province took place during the Oligocene through early Miocene. This extensional faulting also involved areas west of the San Andreas fault (Tennyson, 1989), including the Cuyama basin. Several faults within the Cuyama basin show evidence of normal faulting, including the Nacimiento/Rinconada and La Panza (Ballance et al, 1983; Bartow, 1974, 1978; Vedder, 1968), Blue Rock (Dibblee, 1982; Bohannon, 1975), Ozena (Blake, 1981; 1982), Big Pine (Bohannon, 1975), and a possible normal fault below the Caliente Range (Davis et al., 1988). These faults have a present-day west to northwest trend and separate crystalline basement and Eocene sedimentary rocks on the southwest from Simmler Formation breccias and conglomerates on their northeastern, downthrown side (Fig. 3-4a and b).

Nacimiento and La Panza Faults

In the western part of the Cuyama Basin, the Simmler Formation was deposited in half grabens north of the La Panza and Nacimiento faults (Fig. 3-4). In both areas, the Simmler has northeast-flowing paleocurrent indicators, and pebble size becomes smaller to the northeast. The faults are both downthrown to the northeast. The Simmler is over 1200 m thick adjacent to the Nacimiento fault, and was derived from Cretaceous-Eocene strata southwest of the fault. Dip slip on the Nacimiento fault is assumed to be at least 1200 m, the thickness of the syndepositional Simmler Formation on the downthrown side. The La Panza fault is downthrown a few hundred meters to the northeast, based on the same criteria (Ballance, et al., 1983). Well data show that the Simmler Formation conglomerate facies is present east of the Chimineas fault. This area is also east of the Russell fault. If 26-29 km of right-lateral slip is removed from the Russell fault (Yeats et al., 1988, 1989), these conglomerates would have been deposited east of the Russell, South Cuyama and Ozena faults. The Ozena normal fault scarp is a likely source for these conglomerates.

Big Pine Fault

The Plush Ranch Formation, which correlates to the Simmler Formation (Bohannon, 1976), was deposited along the northern edge of the Big Pine fault south of Mt. Pinos (Fig. 3-4). Bohannon (1976) mapped a breccia member that occurs in a long, narrow band adjacent to the fault. Clasts are largest near the fault, and breccia beds decrease in thickness and pinch out to the north. Paleocurrent indicators adjacent to the Big Pine fault show transport direction to the north. Sediment was also shed from the Mt. Pinos granitic area into the Plush Ranch basin. Bohannon (1976) concluded that the breccia member of the Plush Ranch Formation is a steep alluvial fan that was deposited in a rapidly subsiding basin adjacent to an active fault scarp.

The breccia member contains clasts of augen gneiss and quartz monzonite similar to outcrops on Frazier Mountain, and is offset ~14 km in a left-lateral sense from this source (Crowell, 1968; Bohannon 1976). The large size of clasts and abrupt northward fining suggest the breccia was deposited closer to its source, probably no more than 2 km away (Bohannon, 1976). Crowell (1968) and Bohannon (1976), among others, have suggested the Big Pine fault has a two-stage history: normal movement during deposition of the Plush Ranch Formation, followed by left-lateral slip after deposition of the Plush Ranch Formation.

Ozena Normal Fault

Simmler Formation conglomerates were deposited along the north edge of the Ozena fault. Paleocurrent directions based on linear features (flute casts, etc) show a northwest direction of transport (Fig. 3-4a). The conglomerate clast composition changes from dominantly crystalline rocks to dominantly sedimentary rocks from southeast to northwest along the Ozena fault (Blake, 1981). If 14 km of left-lateral slip along the Big Pine fault is removed (Crowell, 1968; Bohannon, 1976), the area along the southeastern part of the Ozena fault may have been adjacent to the crystalline rocks on the south side of the Big Pine fault (Blake, 1981). This reconstruction would have placed the Simmler Formation along the Ozena fault directly across from the crystalline rocks on the other side of the Big Pine fault, and provide a source terrane for the crystalline clasts east of the Ozena fault. It would also restore the crystalline basement in the southeast corner of the Cuyama basin with the crystalline basement south of the Big Pine fault (Fig. 3-5).

Blue Rock Fault

The Blue Rock fault is inferred to be in the subsurface of the Cuyama Badlands (Dibblee, 1982; Bohannon, 1975). South of upper Quatal Canyon (Fig. 3-2) east of the Vaqueros Formation outcrops, the Miocene Caliente Formation rests directly on granitic basement rocks. North of the canyon, Caliente Formation rests on the Vaqueros Formation, which itself rests on Oligocene Simmler strata (Dibblee, 1982) (Figs. 3-3b, 3-6). Scattered outcrops of granitic and gneissic basement are located in an east-west trending zone in Quatal Canyon. Wells in the Cuyama Badlands also reach the basement (Fig. 3-7). The Blue Rock fault is inferred to be just north of these outcrops and wells.

Based on well data, the trace of the Blue Rock fault is interpreted to extend from the Cuyama Badlands across the Cuyama Valley to the Caliente Range (Fig. 3-7). Both the Drake Federal Well and the Arco Caliente Unit (CU) Well encountered granite directly below the Vaqueros Formation in the lower plate of the Morales thrust. To the east of these wells, the Richfield Russell well encountered granitic conglomerate below the Vaqueros Formation, and the Natural Gas Corporation Koch-Russell well encountered conglomerate of unknown clast composition. These conglomerates are interpreted be derived from the granitic basement and Eocene sedimentary strata on the southwestern, upthrown side of the Blue Rock fault. The Blue Rock fault trace is interpreted to continue from the Badlands between the wells encountering granitic basement to the west and those encountering conglomerate to the east.

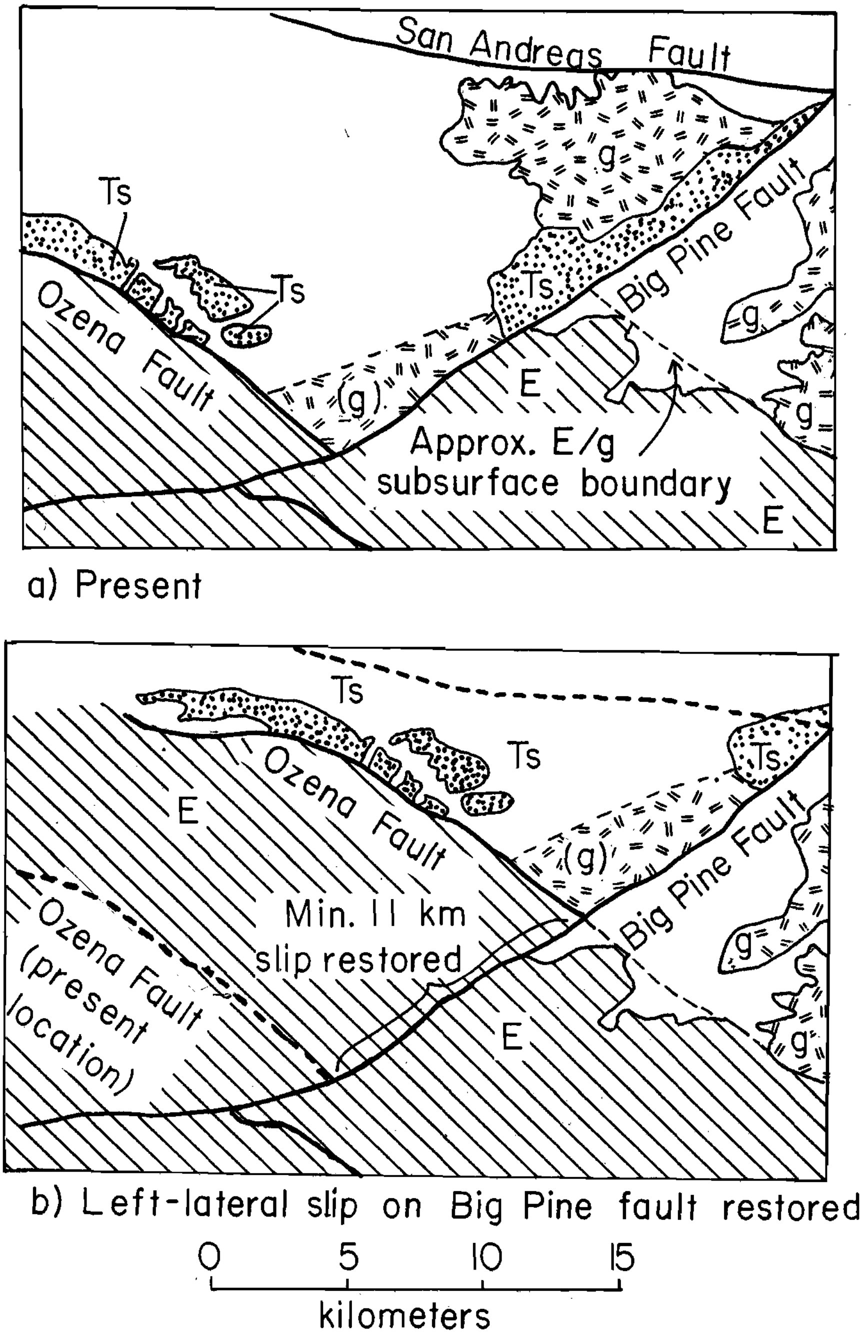


Figure 3-5. Restoration of a minimum of 11 km of left-slip along the Big Pine fault. The Eocene sediments-granitic basement contact is used as a piercing point along the Big Pine fault. Eleven kilometers is a minimum slip because the location of the Eocene sediments-granite boundary south of the fault is approximate, and the Ozena fault, which has had more recent compression, is used as the current Eocene sediments-granite boundary north of the fault.

Figure 3-6. Detailed geologic map of the Cuyama Badlands fold belt. Modified from Dibblee (1971a) and Barker (1972). Lines A-A' and B-B' mark the location of cross-sections shown on Figure 3-15.

Numbered well locations:

1. Shell Chambers Federal, total depth = 15,293 feet
2. Humble K.E. Norris
3. Mobil Ballinger, total depth = 11,981 feet
4. Bolsa Chica Hickey #1, total depth = 6819 feet
5. Texaco Blue Diamond, total depth 5675 feet

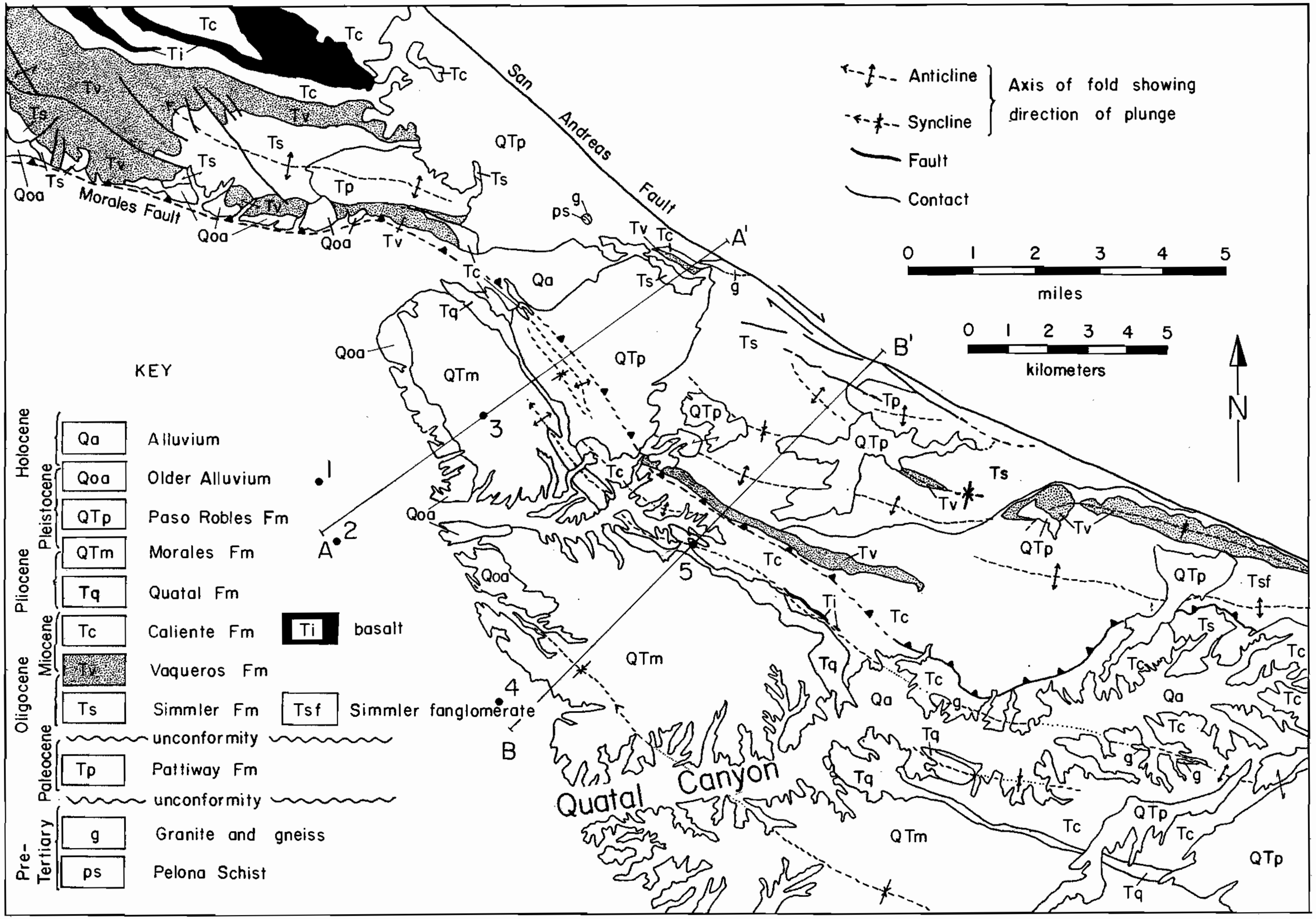

San Andreas Fault
Morales Fault
Quatal Canyon
Anticline
Syncline
Axis of fold showing direction of plunge
Fault
Contact
0 1 2 3 4 5
miles
0 1 2 3 4 5
kilometers
N
KEY
Holocene
Pleistocene
Pliocene
Miocene
Oligocene
Paleocene
Pre-Tertiary
Qa Alluvium
Qoa Older Alluvium
QTp Paso Robles Fm
QTm Morales Fm
Tq Quatal Fm
Tc Caliente Fm
Ti basalt
Tv Vaqueros Fm
Ts Simmler Fm
Tsf Simmler fanglomerate
unconformity
Tp Pattiway Fm
unconformity
g Granite and gneiss
ps Pelona Schist
A
A'
B
B'
1
2
3
4
5

Figure 3-6.

Figure 3-7. Subcrop map below the Vaqueros Formation. The Blue Rock fault is projected from the Badlands northwest to the Cox fault, based on well data. The Blue Rock fault is assumed to separate granite and Cretaceous-early Tertiary marine sediments to the south from conglomerates to the north. The Russell fault is assumed to connect with the Blue Rock fault. See text for explanation. All outcrops north of the Blue Rock fault are in the hanging wall of the Morales thrust, all well control points are in the footwall block. To restore the paleogeography, dip slip on the Morales thrust must be removed. Dip slip on the Morales thrust has been estimated to be as much as 14 km (Davis et al., 1988; and more commonly to be under 10 km (e.g. Nevins, 1983). Because of the uncertainty regarding the amount of slip on the Morales thrust, outcrops in the hanging wall of the Morales thrust were shown in their present position.

Numbered wells:
1. Arco Federal Caliente Units (CU), total depth = 11,962 feet.
2. Arco Drake Federal, total depth = 17,193 feet
3. Richfield Russell, total depth = 12,981 feet.
4. Natural Gas Corporation Koch-Russell, total depth = 12,764 feet.
5. P.G. & E. Koch-Russell, total depth = 12,970 feet.
6. Shell Chambers Federal, total depth = 15,293 feet.
7. Mobil Ballinger, total depth = 11,981 feet.
8. Texaco Blue Diamond, total depth = 5675 feet.
9. Bolsa-Chica Hickey #1, total depth = 6819 feet.

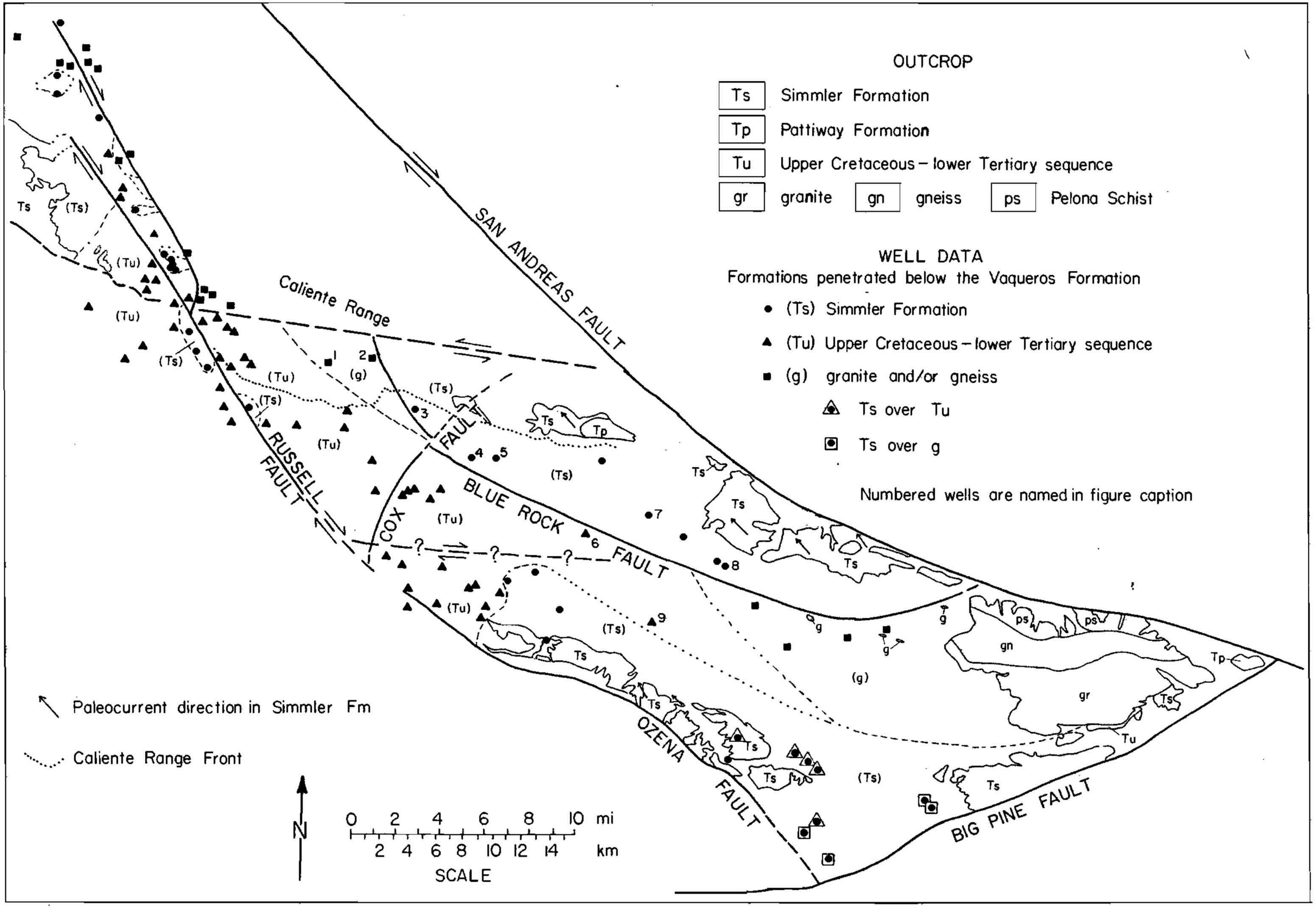

OUTCROP
Ts Simmler Formation
Tp Pattiway Formation
Tu Upper Cretaceous – lower Tertiary sequence
gr granite
gn gneiss
ps Pelona Schist
WELL DATA
Formations penetrated below the Vaqueros Formation
(Ts) Simmler Formation
(Tu) Upper Cretaceous – lower Tertiary sequence
(g) granite and/or gneiss
Ts over Tu
Ts over g
Numbered wells are named in figure caption
SAN ANDREAS FAULT
Caliente Range
RUSSELL FAULT
COX FAULT
BLUE ROCK FAULT
OZENA FAULT
BIG PINE FAULT
Paleocurrent direction in Simmler Fm
Caliente Range Front
N
0 2 4 6 8 10 mi
2 4 6 8 10 12 14 km
SCALE

Figure 3-7

In the Cuyama Badlands, the overlying Caliente Formation is not cut by the Blue Rock fault. Based on vertebrate fossils, the Caliente Formation is dated as middle Hemingfordian to Clarendonian (20 Ma to 10-8 Ma) (Kelley and Lander, 1988; T.S. Kelley, pers. comm., 1988). Therefore, the Blue Rock fault was active prior to the late early Miocene.

Normal fault below the Caliente Range

Davis et al. (1988) suggest that a normal fault underlies the Caliente Range, based on seismic evidence. Reflectors below the Morales thrust fault abruptly terminate against crystalline basement that was encountered in the Arco Drake Federal Well (Davis et al., 1988, their Figure 8). According to their interpretation of the seismic line, the fault has Simmler on the northern, downthrown side, and was active during deposition of the lower part of the Vaqueros Formation. The upper surface of the Vaqueros Formation is not cut by the fault, implying the fault had ceased movement before the end of Vaqueros deposition. This fault may be the continuation of the Blue Rock fault (Fig. 3-7), as described above.

Discussion of Extensional Faulting in Cuyama Basin

During the early Miocene, the Cuyama area was part of the extensional terrain of southeastern California and Arizona. Several lines of evidence suggest the Cuyama area was adjacent to the Orocopia Mountains that are approximately 320 km southeast of the Cuyama basin on the eastern side of the San Andreas fault.

The Simmler Formation shares several characteristics with the Diligencia Formation in the Orocopia Mountains. Both formations are nonmarine sedimentary rocks interbedded with basalt. The basalt flows in the Simmler Formation have a K/Ar date of 22.9 $\pm$ 0.7 Ma and 23.4 $\pm$ 0.8 Ma (Ballance et al., 1983), which is similar to the K/Ar dates of 19.1 $\pm$ 1.9 Ma (Spittler 1974a and b) to 22.9 $\pm$ 2.9 Ma (Crowell, 1973) for the basalts in the Diligencia

Formation. (Both dates for the Diligencia basalts have been corrected for new constants defined by Dalrymple (1979), in Squires and Advocate, (1982)).

Both the Simmler and Diligencia Formations were deposited directly on both Eocene marine strata and crystalline basement (Bohannon, 1975; Spittler and Arthur, 1982), and both have conglomerates deposited in alluvial fans near the base of the formations. The Diligencia Formation was deposited in an east-trending basin that was bounded by normal faults to the north and south (Spittler and Arthur, 1982).

Crowell (1975) correlated the Diligencia Formation to the Vasquez Formation in the Soledad basin. Bohannon (1975) agreed with Crowell's correlation and continued it across the San Gabriel fault to the Cuyama valley. He correlated the Pelona Schist of Abel Mountain (Fig. 3-1) to the Pelona Schist of the Sierra Pelona Ridge in the San Gabriel block, then to the Orocopia Schist in the Orocopia Mountains. Sierra Pelona Ridge is located just south of and adjacent to the San Francisquito fault (Fig. 3-1). The Pelona anticline is matched with the Orocopia anticline. The Blue Rock fault is correlated with the San Francisquito fault in the San Gabriel block, which is linked to the Clemens Well fault in the Orocopia Mountains. The Simmler Formation that was deposited north of the Blue Rock fault is correlated with the Vasquez Formation in Charlie Canyon north of the San Francisquito fault.

Powell (1993, p. 9) correlates the Frazier Mountain-Mt. Pinos crystalline highlands with the Orocopia Mountains east of the San Andreas fault in the southeast California desert. Nearby in southern Arizona, extension began after 25 Ma, peaked between 22 and 19 Ma, and decreased between 19 and 15 Ma (Reynolds et al., 1986; Davis et al., 1987; Howard and John, 1987: Sherrod et al., 1987; Davis and Lister, 1988; Dokka et al., 1988). The Simmler Formation is late Oligocene (30-24 Ma), and locally possibly early Miocene (24-16 Ma) (Bartow, 1974), so the extensional faulting in the Cuyama basin is of similar age to that in the rest of the southern Basin and Range province.

Crouch and Suppe (1993) suggest an extensional model for the Santa Maria-Cuyama area that is similar the model for the core complexes of the Basin and Range province. In their model, the Cuyama area was a graben, or series of grabens in the hanging wall of an east-dipping detachment fault. The break-away zone for the detachment fault is identified as the Sur-Nacimiento fault zone. In fact, the area was a series of half-grabens, or fault blocks tilted to the southwest and downthrown to the northeast (present-day orientation), with the conglomerate facies of the Simmler Formation deposited on the downthrown side (Fig. 3-4a and b). A series of tilted blocks implies that the dip of the master detachment fault decreases with depth.

STRIKE-SLIP PHASE

The San Andreas system has evolved from a complex and varied set of structures to a more simplified, through-going fault trace (Weldon et al., 1993). Right and left-lateral fault strands and extensional and compressional features would have been active in what Atwater (1970) termed a "soft shear zone" between the Pacific and North American plates.

The early phase of strike-slip faulting south of the western Transverse Ranges overlaps in time and space with extension. Powell (1993, p. 77) suggests that an early belt of dextral shear, along with oblique extension, occurred before a through-going strike-slip fault was established. This early dextral shear and accompanying extension were distributed in a northwest-trending belt of normal fault basins filled with syndepositional sedimentary deposits and volcanics. Coeval extension and strike-slip faulting does not preclude the possibility that extension in the Cuyama basin was taking place along a detachment fault as Crouch and Suppe (1993) suggest. Most of the volcanics are dated at 26-25 to 23-22 Ma, with some ages in the range of 32-26 Ma and 26-22 Ma. In the Cuyama basin, extensional faulting may have overlapped in time with strike-slip faulting as it did south of the Transverse Ranges, if the Simmler Formation is as young as early Miocene (24-16 Ma) in some areas, as Bartow (1974) suggests. This belt of dextral shear became the location of the future Clemens Well-Fenner-San Francisquito fault. The Clemens Well-Fenner-San Francisquito fault was active by 17 Ma, and possibly as early as 22 Ma (Powell, 1993, p. 32, his Figure 8).

Powell (1993, p. 33) infers that an early strand of the San Andreas fault was active north of Tejon Pass and connected with the Clemens Well-Fenner-San Francisquito fault. This fault was the active strand of the San Andreas in southern California during the late early and early middle Miocene. The San Andreas fault system may have become active in the vicinity of the Cuyama basin as early as 22 Ma according to Powell (1993, p. 32, his Figure 8). The Cuyama basin was cut off from a distinctive volcanic clast source in southern

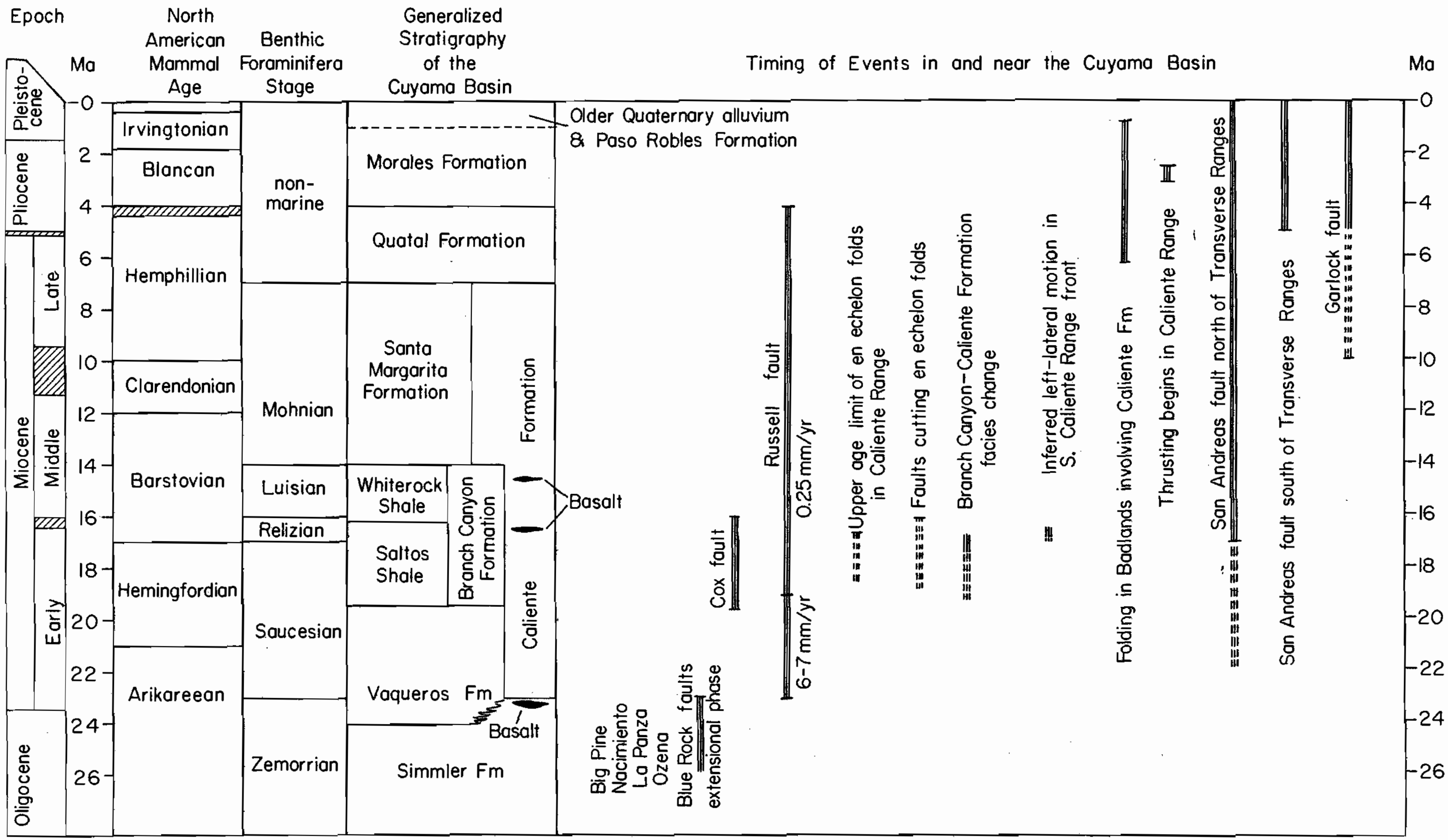
California between 16 and 12 Ma (Ehlert, 1982), implying that the San Andreas fault was active at that time near the Cuyama basin (Fig 3-8).

The Russell Fault

The oldest documented right-lateral fault in the Cuyama Valley is the Russell fault. It is overlain by the Pliocene-Pleistocene Morales Formation and Quaternary alluvium of the Cuyama Valley, and is being overridden by the Whiterock thrust to the north. The Russell fault was studied in detail by Nevins (1983), Schwing (1982, 1984) and Calhoun (1985, 1988), and its history was synthesized by Yeats et al. (1989). The Russell fault was active from 23 to 4 Ma, with the majority of movement occurring during the deposition of the Vaqueros Formation, approximately 23-19 Ma. There are three lines of evidence for right-lateral motion on the Russell fault: 1) offset contacts between formations below the Vaqueros Formation, 2) offset isopach lines of the Vaqueros Formation, and 3) offset of the facies boundary between the Monterey and Branch Canyon Formations. The pre-Vaqueros strata are offset 26-29 km, while the Vaqueros isopachs are only offset 3.7 km. The Russell fault is thought to be an early strand of the San Andreas fault system.

What happens to the Russell fault and its 26-29 km of right-lateral strike-slip south of the Big Pine fault is unclear. Yeats et al., (1988, 1989) suggested that the Ozena normal fault may have been reactivated as a strike-slip fault to become a continuation of the Russell fault to the south. However, Powell (1993, p. 51) was unable to trace the 26-29 km of displacement south of the Big Pine fault, and therefore he questioned whether strike-slip movement took place on the Ozena fault. Crouch and Suppe (1993) accept the Ozena as a continuation of the Russell fault, and they suggest that it might have continued to the south of the western Transverse Ranges as the East Santa Cruz Basin fault, which is south of Catalina Island. However, the chance to correlate these two faults directly has since been obliterated by the Neogene clockwise rotation of the western Transverse Ranges.

Figure 3-8. Stratigraphy of the Cuyama basin and timing of tectonic events. See text for stratigraphy references. Other references include: timing of the Nacimiento and other normal faults based on Bartow (1978), Bohannon (1975), and Blake (1981); timing of the Cox fault based on Spitz (1985), timing of the Russell fault based on Yeats et al. (1988, 1989), timing of the San Andreas fault north of the Transverse Ranges based on Powell (1993); timing of the Garlock fault based on Burbank and Whistler (1987).



Epoch
Ma
North American Mammal Age
Benthic Foraminifera Stage
Generalized Stratigraphy of the Cuyama Basin
Timing of Events in and near the Cuyama Basin
Ma
Pleisto-cene
Pliocene
Miocene
Late
Middle
Early
Oligocene
0
2
4
6
8
10
12
14
16
18
20
22
24
26
Irvingtonian
Blancan
Hemphillian
Clarendonian
Barstovian
Hemingfordian
Arikareean
non-marine
Mohnian
Luisian
Relizian
Saucesian
Zemorrian
Morales Formation
Quatal Formation
Santa Margarita Formation
Whiterock Shale
Saltos Shale
Branch Canyon Formation
Caliente Formation
Vaqueros Fm
Simmler Fm
Basalt
Basalt
Older Quaternary alluvium & Paso Robles Formation
Big Pine
Nacimiento
La Panza
Ozena
Blue Rock faults
extensional phase
Cox fault
Russell fault
0.25 mm/yr
6-7 mm/yr
Upper age limit of en echelon folds in Caliente Range
Faults cutting en echelon folds
Branch Canyon-Caliente Formation facies change
Inferred left-lateral motion in S. Caliente Range front
Folding in Badlands involving Caliente Fm
Thrusting begins in Caliente Range
San Andreas fault north of Transverse Ranges
San Andreas fault south of Transverse Ranges
Garlock fault

Figure 3-8.

A possible path to continue the 29 km of dextral slip south of the Cuyama Valley might be to link the Russell fault to the Blue Rock fault (Fig. 3-7, Fig. 3-9). Smith (1977) also suggested the Blue Rock fault might have some right-lateral slip; however, he correlated the San Juan-Chimineas fault to the Blue Rock via hypothetical right-slip on the Morales fault. In Powell's (1993, p. 28) reconstruction of fault paths, he states that in tracing the Clemens Well-Fenner-San Francisquito fault to the north of the Big Pine fault, it must lie between the modern trace of the San Andreas on the east and the Red Hills-San Juan-Chimeneas-Russell fault zone to the west, or within one of those fault zones. However, he argues against correlating the Blue Rock fault to the Clemens Well-Fenner-San Francisquito fault. The crystalline clasts in the Simmler Formation on the north side of the Blue Rock fault, which are similar to the lithology in the Mt. Pinos area, suggests the Blue Rock fault has insufficient lateral displacement. He prefers to correlate the Clemens Well-Fenner-San Francisquito fault to the modern trace of the San Andreas fault. However, the crystalline clasts in the Simmler conglomerate do not preclude lateral displacement. If Powell's reconstruction is correct, the Mt. Pinos crystalline basement was adjacent to the Orocopia Mountains area at 20 Ma (Powell, 1993, his figure 8, p. 14) which has similar lithologies. The Simmler Formation of the Cuyama Badlands would align with the Diligencia Formation. The Simmler Formation of the Badlands would have been closer to the Frazier Mountain area which is composed predominantly of augen gneiss and granitic orthogneiss. Moving the area north of the Blue Rock fault east by 30 km would place the Simmler conglomerates across the Blue Rock-Fenner-San Francisquito fault from the Frazier Mountain area.

The greatest uncertainty lies in tracing the Russell fault from the western part of the Cuyama basin where it was mapped in detail in the subsurface (Spitz, 1985) into the Cuyama Badlands where it could join with the Blue Rock fault. The trace of the Russell fault in the western Cuyama basin that has been mapped to the south toward the Ozena fault could be a splay that dies out to the south, while another splay of the Russell turns toward the east. This eastern splay would have to be south of the subsurface folds in the Vaqueros Formation mapped by Spitz (1985) and Nevins (1983), and would probably be south of the Cox fault, which has good well control constraining its location (Fig. 3-7). Also, the grid of seismic lines in the Cuyama Valley shows no definitive evidence of a strike-slip fault going through the area they cover.

The Soda Lake Shale, the deep-water facies of the Vaqueros Formation, provides evidence for right-lateral slip along a proposed Russell-Blue Rock fault strand (Fig. 3-9). In the northern Cuyama Badlands, surface sections of the Soda Lake Shale are 50 m (163 feet) thick at Santiago Canyon and 40 m (130 feet) thick at Cerro Noroeste (Fig 3-8). In the western part of Ballinger Canyon, the Soda Lake Shale is 118 m (384 feet) thick and gradually thins and disappears to the east in upper Ballinger Canyon (Freitag, 1989). In the central part of the valley, north of the hypothesized Russell fault trace, the Soda Lake Shale is approximately 215 m (700 feet) thick. In the southern Cuyama Valley, subsurface thicknesses of the Soda Lake Shale were measured from well logs (Spitz, 1985). North of the proposed Russell-Blue Rock fault trace, the Soda Lake Shale is ~12 m (40 feet) thick in the Shell-Chambers well. To the west and north of the fault trace, it is ~215 m (700 feet) thick. South of the Rusell-Blue rock fault trace, the Soda Lake Shale is not present in the 4 eastern wells, and thickens to the west. Right-lateral displacement between the zero isopach of the Soda Lake Shale in the southern Cuyama Valley and Ballinger Canyon is approximately 10 km. There may be right-stepping en echelon folds south of the Rusell-Blue Rock fault trace, based on the alternating thicker and thinner sections of the Soda Lake Shale. Another right-lateral fault strand may separate the thin section of Soda Lake Shale in Ballinger Canyon from the thick section of Soda Lake Shale in Santiago Canyon. Minimum offset would be 10 km. Together, these two fault strand would account for 20-22 km of the 29 km of slip Yeats et al. (1989) documented for the Russell fault. The Soda Lake Shale offset would probably not record all of the slip on the Russell fault, as much of the movement

Figure 3-9. Thickness of the Soda Lake Shale offset across the hypothesized Russell-Blue Rock fault strand. Thickness measurements north of the Blue Rock fault from measured outcrop sections (Freitag, 1989). Thickness measures south of the Blue Rock fault from well data (Spitz, 1985).

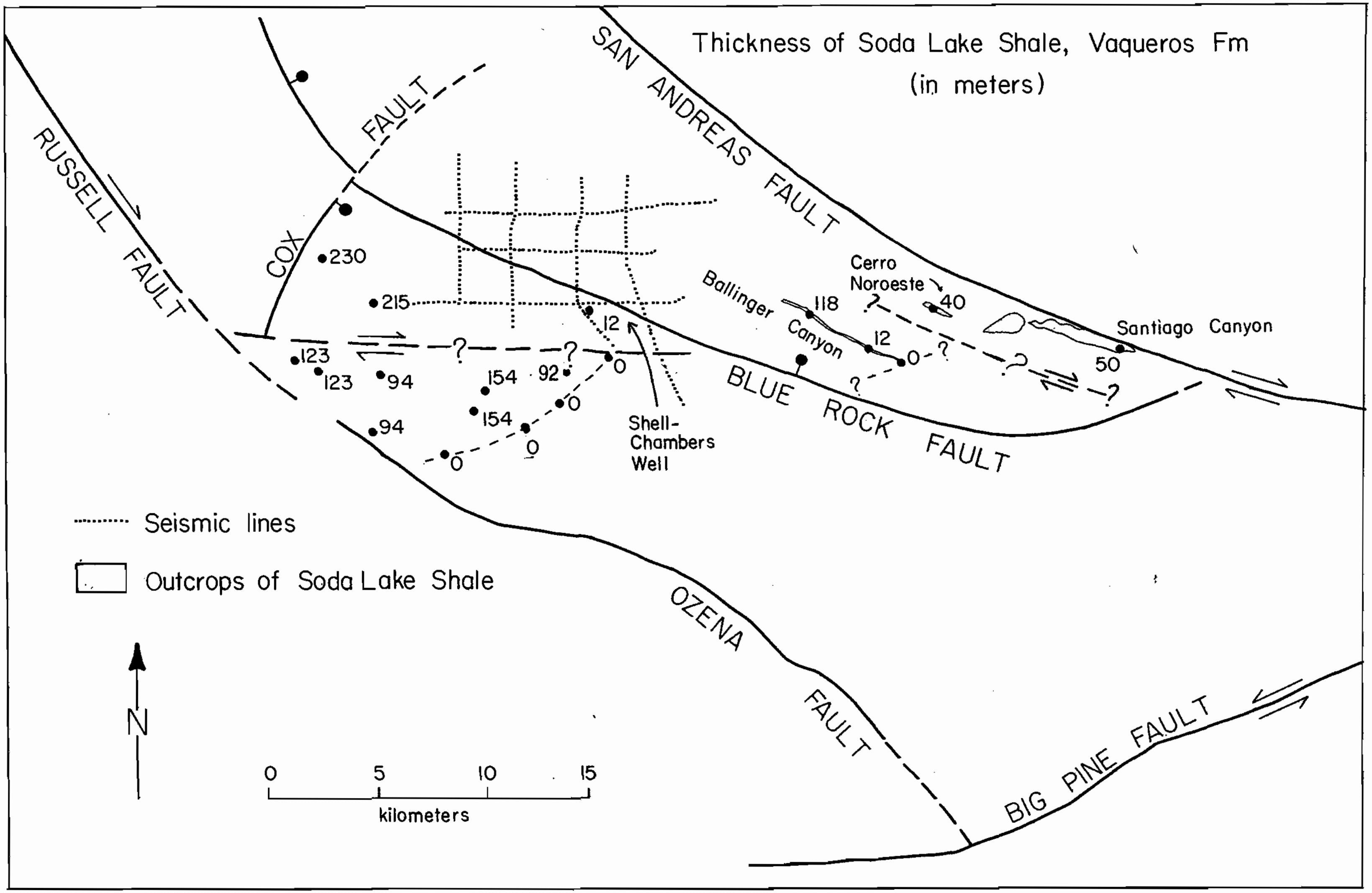

Thickness of Soda Lake Shale, Vaqueros Fm
(in meters)
SAN ANDREAS FAULT
RUSSELL FAULT
COX FAULT
BLUE ROCK FAULT
OZENA FAULT
BIG PINE FAULT
230
215
123
123
94
94
154
154
92
12
0
0
0
0
0
118
12
0
40
50
Cerro Noroeste
Ballinger Canyon
Santiago Canyon
Shell-Chambers Well
Seismic lines
Outcrops of Soda Lake Shale
N
0
5
10
15
kilometers

Figure 3-9.

on the Russell fault may have occurred by the end of Soda Lake shale deposition. Thus, the Russell-Blue Rock fault could have the full 28-29 km of strike-slip recorded to the west by Yeats et al. (1988, 1989), but there are no piercing points older than the Soda Lake shale that would show it.

In spite of the problem with tracing the Russell fault to the south, 26-29 km of right lateral movement is well documented in the northern part of the Cuyama Valley and could not die out abruptly. A strand of the early Russell fault may follow the Ozena fault, as Yeats et al. (1989) suggested, but there is no direct evidence for this along the Ozena fault itself.

Possible Left-Lateral Fault below the Caliente Range

A left-lateral fault may have existed in the vicinity of the southern edge of the Caliente Range as a conjugate to the right-lateral Russell fault. It may also have been a conjugate to an early San Andreas fault, if Powell (1993, p. 32, his figure 8) and Sims (1989) are correct about the age of the beginning of the San Andreas in this area. The left-lateral fault zone would trend approximately east-west and would be located north of the Drake Federal well in the footwall block of the younger Morales fault (Fig. 3-7).

Evidence for a left-lateral fault includes the following:

1. A set of left-stepping, en echelon folds exist in the southeast part of the Caliente Range (Fig. 3-10). Strata from the Paleocene Pattiway Formation through the Miocene Monterey Formation are folded; however, the overlying Caliente Formation and Triple Basalts of Eaton (1939) are not involved in the en echelon folds. Turner (1970) dated the lower basalt layer at 16.5 Ma ± 1.3 Ma and the upper layer at 14.7 ± 0.7 Ma using K/Ar methods. The fold axes have a trend of approximately N45°W, implying left-lateral movement on a west-trending fault.

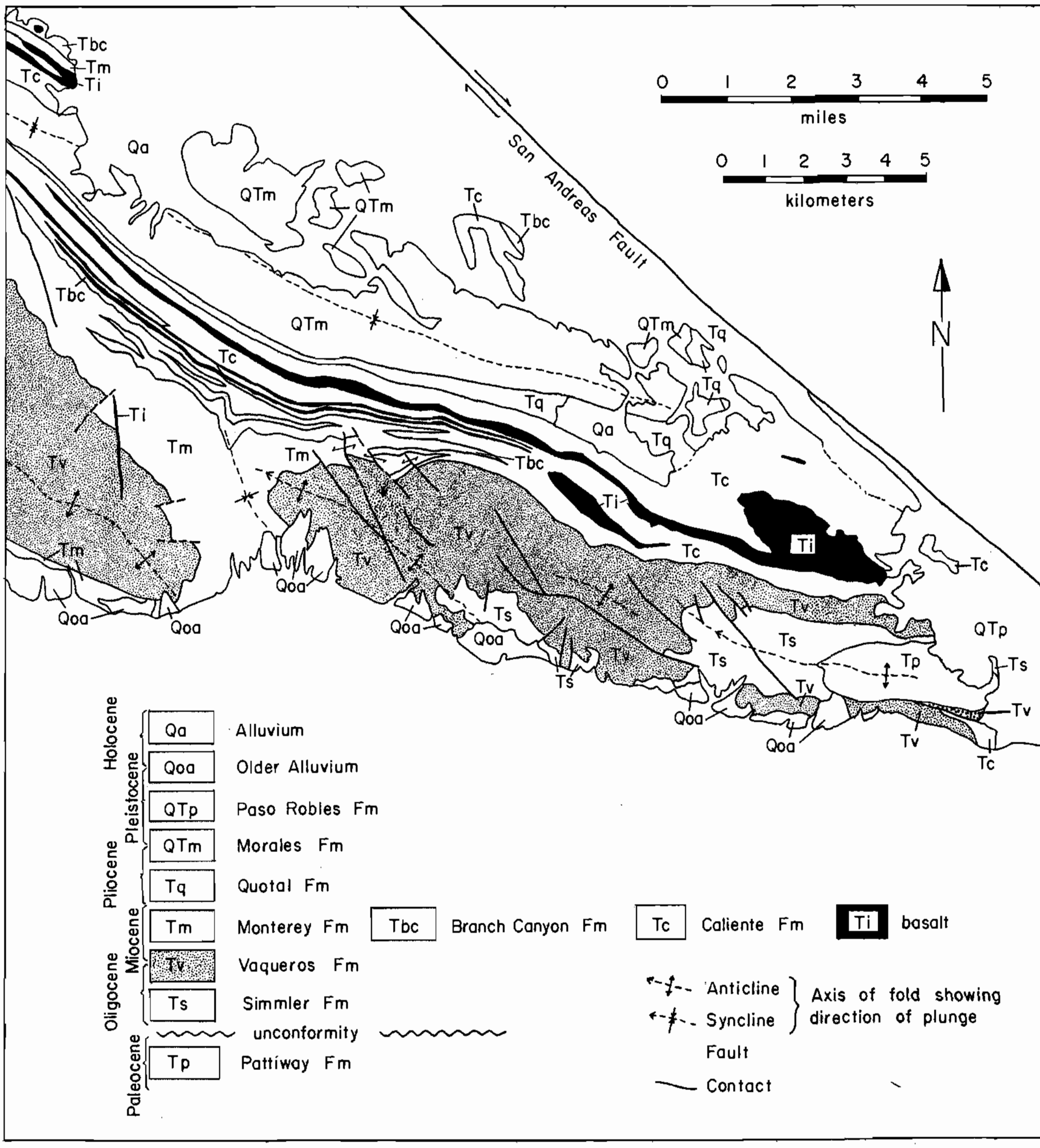


Figure 3-10. Detailed geologic map of the southeastern Caliente Range. The Monterey Formation and older strata are involved in left-stepping, en echelon folds. These folds are overlain by the basalt layers and younger strata. The southern range front is close to the surface trace of the Morales thrust. Map modified from Dibblee (1971c) and Vedder and Repenning (1975).

2. A series of faults with a predominant trend of N30-40°W cut the folds, but do not displace the Triple Basalts. Some of these faults have right-lateral map separation, and may be antithetic strike-slip faults (R' shears).

3. Isopach maps of the Vaqueros Formation, based on seismic lines and well data, show an unusually thick deposit of the Vaqueros Formation in the northeastern part of the Cuyama Valley (Figs. 3-11 and 3-12). The Vaqueros is more than 4000 feet (1230 m) thick here, as opposed to a range of 600-1800 feet (185-554 m) in the rest of the valley. In the Caliente Range, the Arco Drake Federal well encountered 4090 feet (1260 m) of Vaqueros Formation above the Morales thrust fault, but only 1130 feet (348 m) of Vaqueros Formation below the thrust. If these two areas of similar thicknesses of Vaqueros were adjacent,they are now separated by approximately 8 km of apparent left-lateral displacement.

4. The facies boundary between the marine Branch Canyon Formation and the non-marine Caliente Formation was first identified in the Caliente Range by Clifton (1981). Lagoe (1984, 1985) found the same facies boundary in the subsurface of the Cuyama Valley. The facies boundary in the Caliente Range is offset by approximately 9 km in a left-lateral sense from the valley.

Davis et al. (1988) suggest the 9 km of separation of the Branch Canyon-Caliente facies boundary can be explained by 13.7 km of reverse dip slip along a N10°E vector. Part of the 9 km of separation could be due to left-lateral slip on an older fault zone. Pure dip slip does not explain the presence of the older, left-stepping en echelon folds below the Triple Basalts. Also, Davis et al. (1988) claim that the N10°E direction of slip is perpendicular to the regional strike of bedding, fold axes and the surface trace of the Morales thrust. However, to the west where the Morales and Whiterock thrusts are exposed in the Caliente Range, the dip slip direction perpendicular to the fault traces and related folds

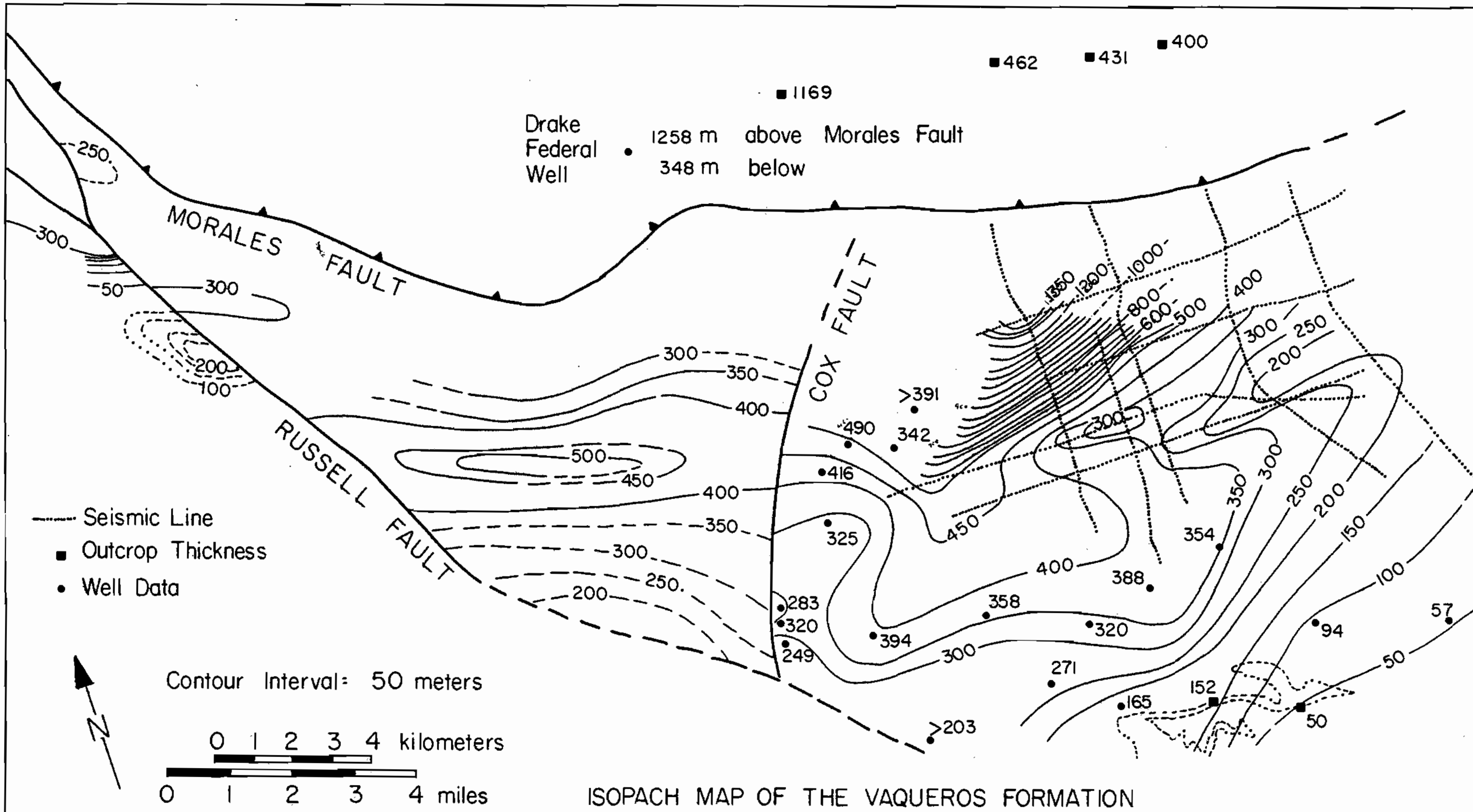


Figure 3-11. Isopach map of the Vaqueros Formation. Seismic lines show that the Vaqueros is over 4000 feet (1354 m) thick in the north central part of the Cuyama Valley. The area west of the Cox fault is based on Nevins (1983), Spitz (1985) and Calhoun (1986). Outcrop thickness north of the Morales fault based on Vedder and Repenning (1975). Well data south of the seismic lines based on Spitz (1985).

Figure 3-12. North-south seismic line (line 7) showing the northward increase in thickness of the Vaqueros Formation. A blind thrust appears to be propagating south into the Cuyama Valley in front of the Caliente Range. this blind thrust is on strike with the ridges of older Quaternary alluvium (Qoa) in the Cuyama Valley. a) uninterpreted line. b) interpreted line.

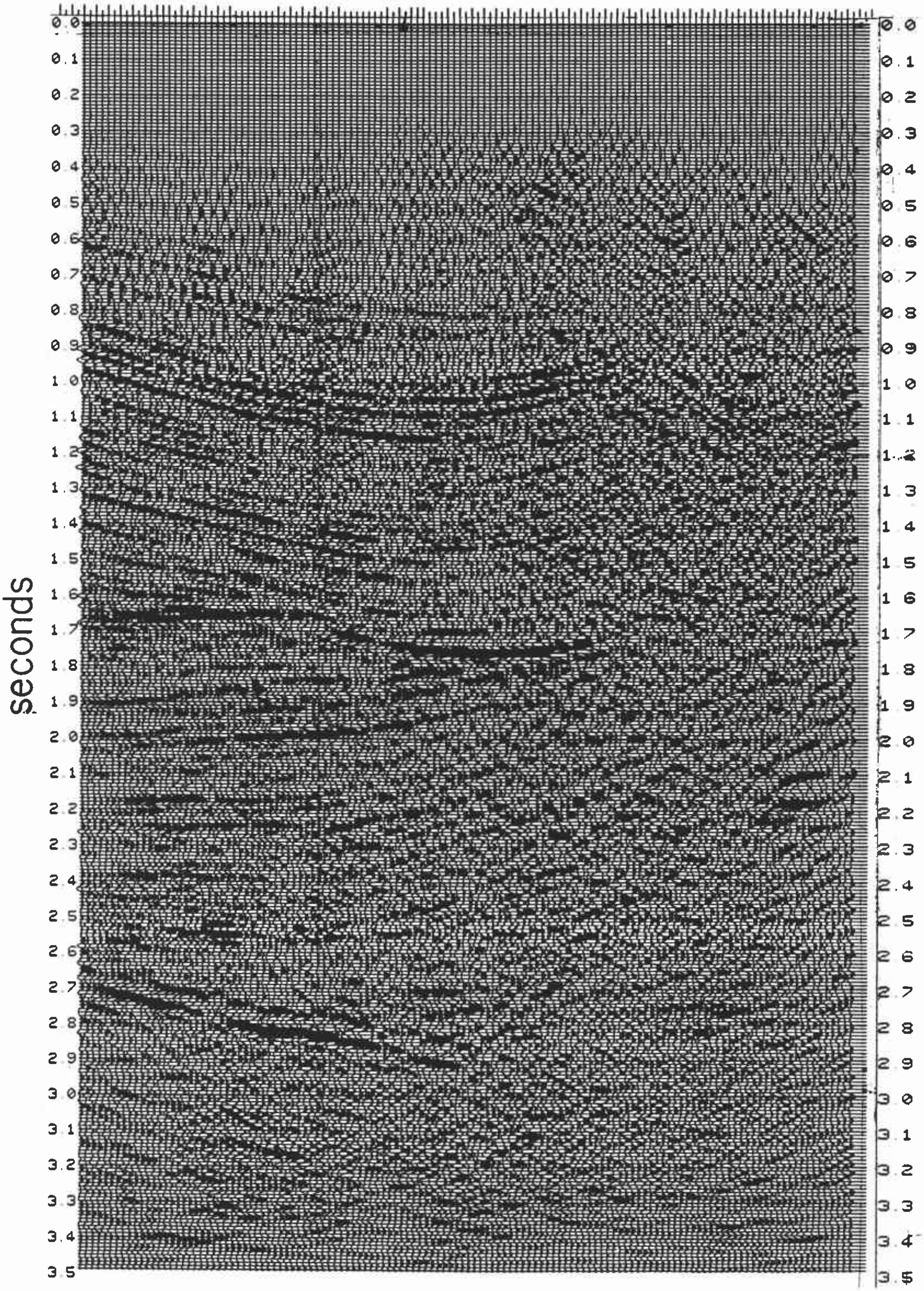

seconds
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
2.1
2.2
2.3
2.4
2.5
2.6
2.7
2.8
2.9
3.0
3.1
3.2
3.3
3.4
3.5

Figure 3-12a

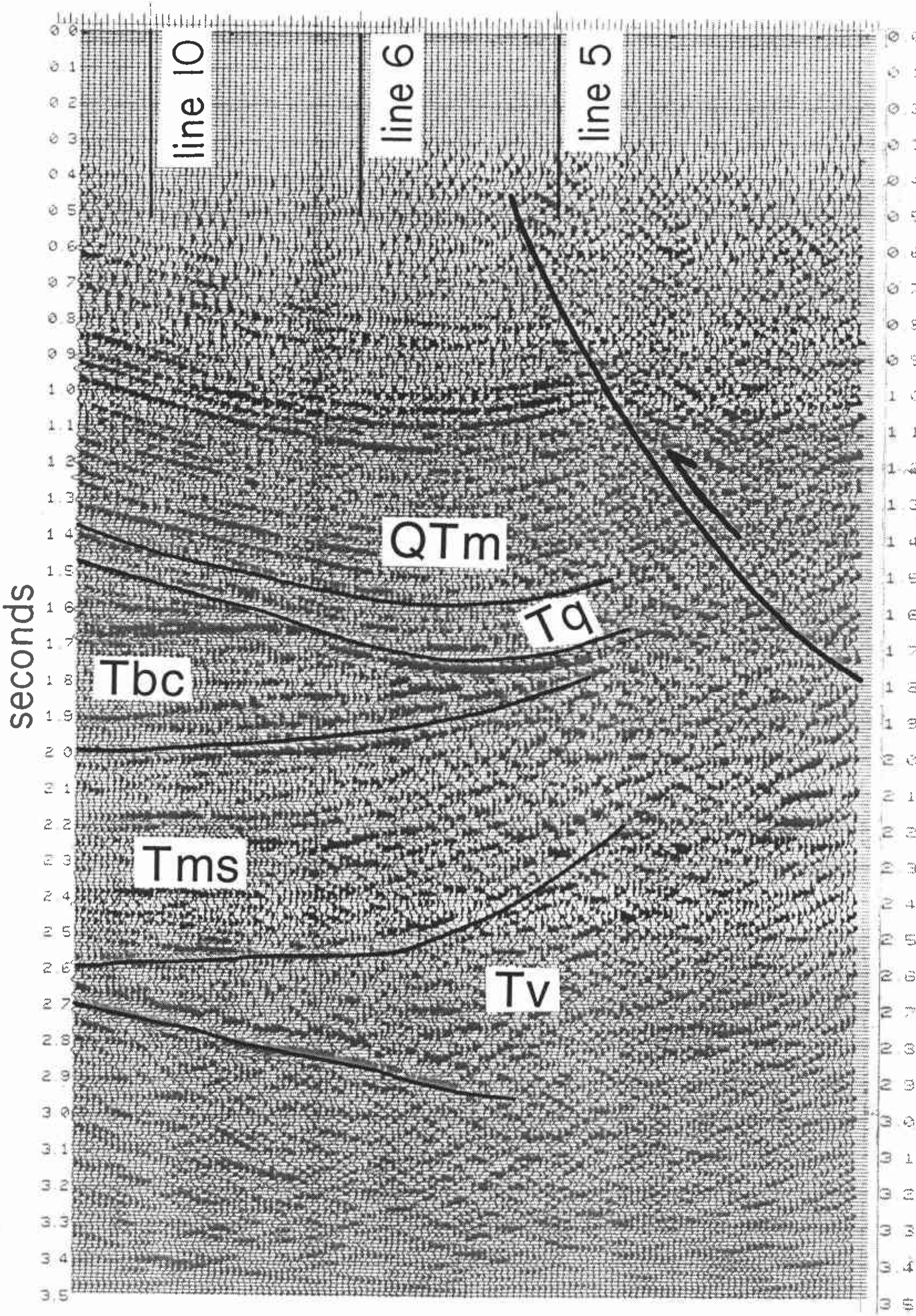


Figure 3-12b

would be N70°E. This direction is also more in keeping with borehole breakout data that records the current direction of maximum stress (Zoback et al., 1987; Mount and Suppe, 1992) as approximately perpendicular to the San Andreas fault.

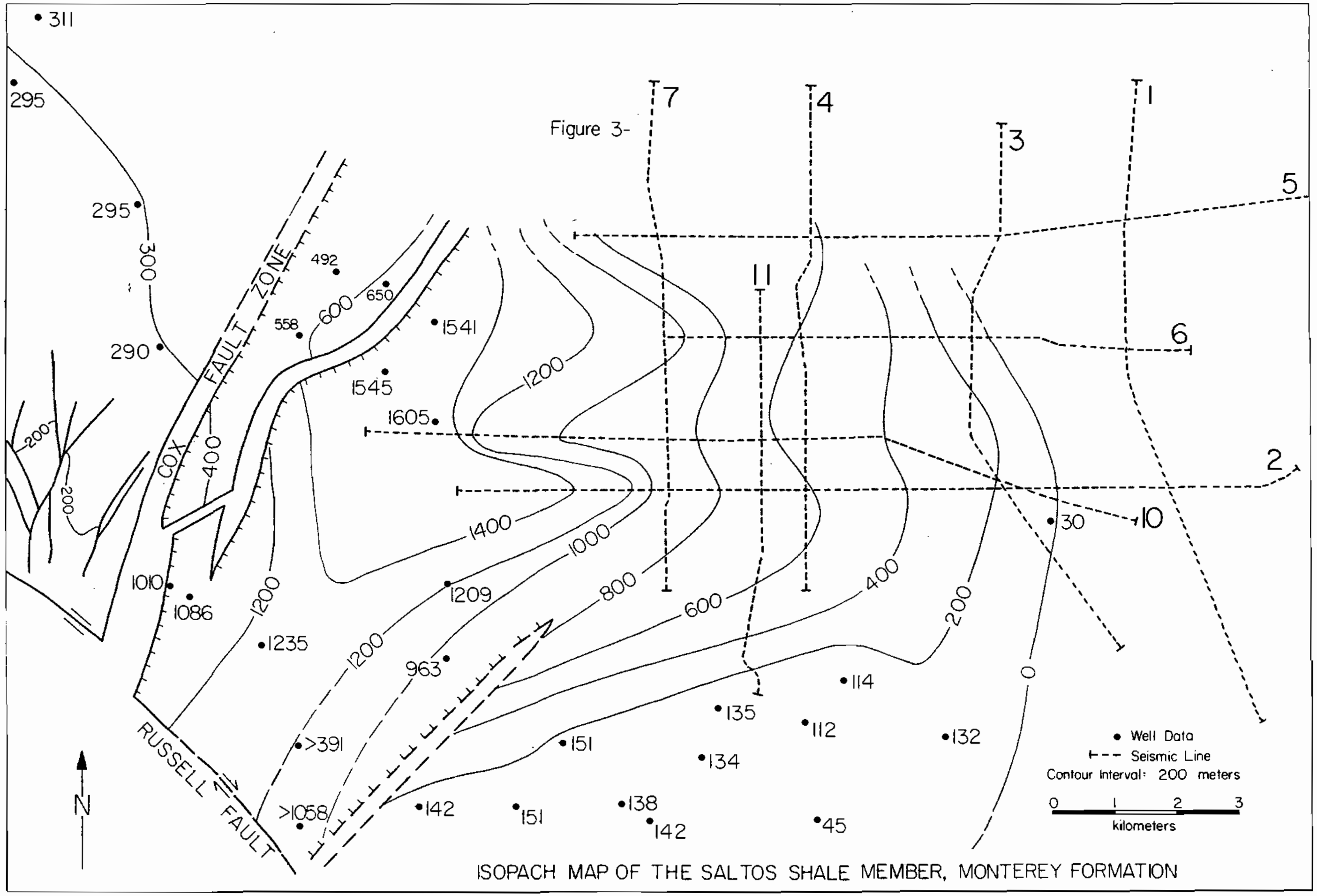
The Cox Fault

The Cox fault zone is known only from subsurface data in the Cuyama Valley. It differs from the other normal faults in the Cuyama area in two ways: 1) its present trend is north to northeast, rather than east-west, and 2) it is younger than the faults associated with late Oligocene-early Miocene extension. The Cox fault zone is a normal fault that was active during the deposition of the Saltos Shale (Spitz, 1985, 1988). Lagoe (1981) dates the Saltos Shale as latest Saucesian to Relizian. Berggren (1972) dates the Relizian as early Miocene, approximately 17-15 Ma. The Saltos Shale is 3-5 times thicker on the eastern, downthrown side of the fault (Fig. 3-13). The underlying Vaqueros Formation does not change thickness across the fault, implying the Cox fault was not active until the end of Vaqueros deposition (Spitz, 1985, 1988).

Seismic lines show there is no major, west-dipping normal fault to the east (Fig. 3-14). Instead, the Saltos Shale was deposited in a half-graben, and it becomes progressively thinner to the east where it grades into the non-marine Caliente Formation (Ellis and Spitz, 1987).

There is no correlative fault to the Cox fault in the Caliente Range that has a dramatic thickening of the Saltos Shale across. Thus, the Cox fault probably terminates against the proposed left-lateral fault, as it does to the south against the right-lateral Russell fault. As the Cox fault is younger than the Blue Rock fault, the Blue Rock may be offset across it, as shown diagrammatically in Figure 3-7, although the amount of displacement is unknown.

Figure 3-13. Isopach map of the Saltos Shale Member of the Monterey Formation. The Saltos Shale Member is 3 to 5 times thicker on the eastern, downthrown side of the Cox fault. The area west of the Cox fault is based on Spitz (1985). Seismic data were used to modify Spitz' (1985) interpretation between the Cox fault and the seismic lines. Seismic lines are numbered.



ISOPACH MAP OF THE SALTOS SHALE MEMBER, MONTEREY FORMATION
Figure 3-
COX FAULT ZONE
RUSSELL FAULT
N
Well Data
Seismic Line
Contour Interval: 200 meters
0 1 2 3
kilometers
311
295
295
290
492
650
558
1541
1545
1605
1010
1086
1235
1209
963
>391
>1058
142
151
151
138
142
135
134
112
114
132
45
30
300
600
200
400
200
1200
1400
1200
1000
800
600
400
200
0
1200
1200
7
4
3
1
5
11
6
2
10

Figure 3-13.

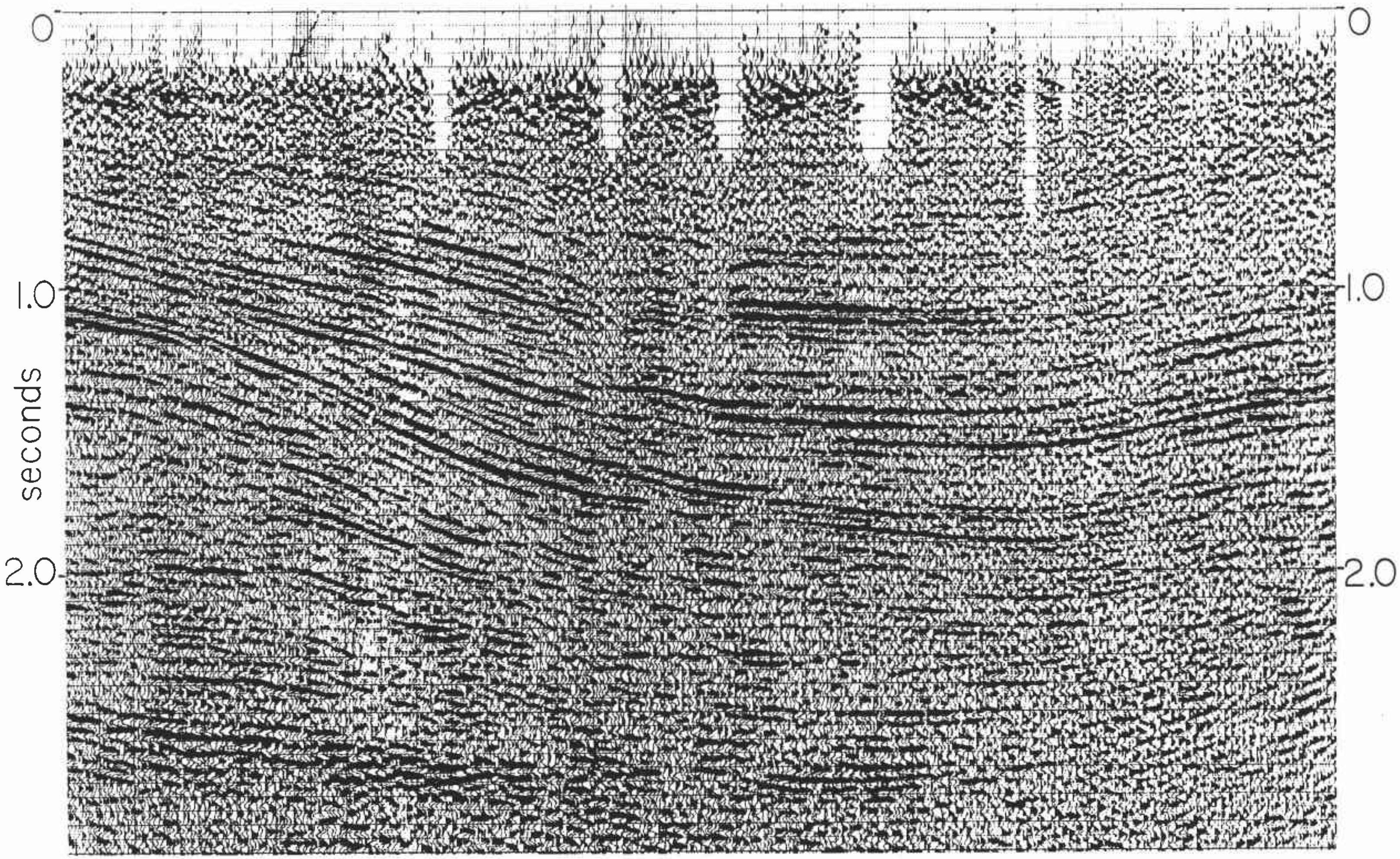


Figure 3-14a. Seismic line 10, uninterpreted. See Figure 3-12 for location of seismic line 10.

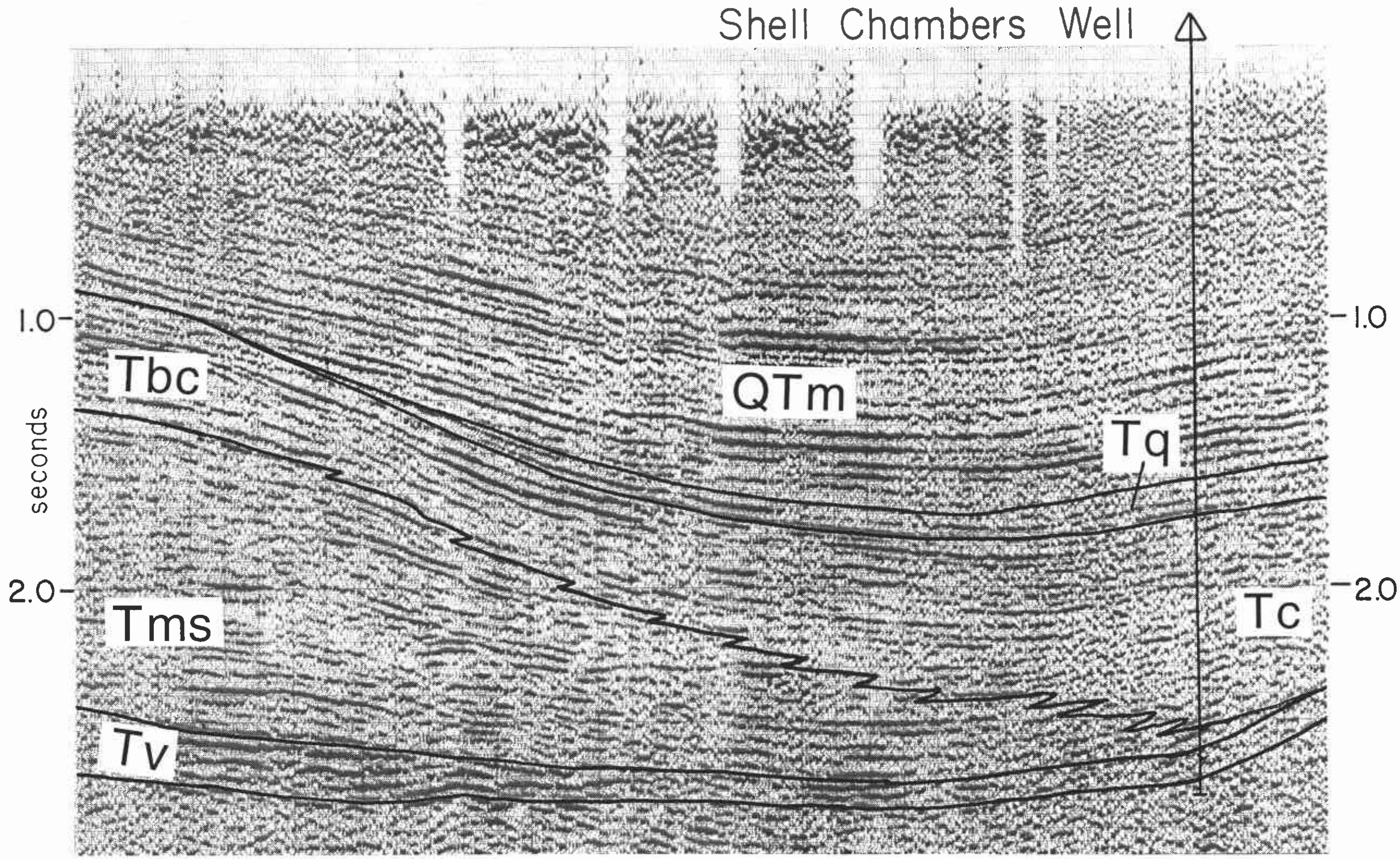


Figure 3-14b. Seismic line 10 showing eastward thinning of the Saltos Shale Member of the Monterey Formation, interpreted. QTm = Morales Formation, Tq = Quatal Formation, Tbc = Branch Canyon Formation, Tc = Caliente Formation, Tms = Saltos Shale Member of the Monterey Formation, Tv = Vaqueros Formation.

Strain and Stress Patterns

The orientation of the left-stepping en echelon folds in the Caliente Range, the right-stepping folds along the Russell fault, the Cox normal fault, and the right- and left-lateral strike-slip faults fit into an overall dextral strike-slip stress pattern (Fig. 3-15). Axes of the en echelon folds involving the Vaqueros Formation along the Russell fault and the en echelon folds in the Caliente Range are parallel, implying the maximum principal stress directions for both strike-slip faults are the same, and both formed under the same stress regime.

In experimental studies, a variety of structures form along a shear zone. The sequence of the formation of different structures depends upon materials and conditions. (Wilcox et al, 1973; Bartlett et al., 1981). In homogeneous clay models (Wilcox et al., 1973) folds and Riedel (R) shears form first, P shears form second and finally, a narrow, through-going fault zone appears, which they term the Y shear. Folds form at an oblique 55° angle to the main fault zone, and extensional faults are at a 90° angle to the fold axes. Another experimental study (Bartlett et al., 1981) used a veneer of limestone over sandstone. The order in which structures formed differed from the clay models. As would be expected with more rigid materials, no folds formed. Instead, R and P shears formed concurrently, followed by the lengthening of the existing R shears, formation of new R shears and X and R' shears. Finally, the principal displacement zone (Y shear) is formed.

To compare the Cuyama area to these strain models, the whole area could be considered part of a right-lateral strain pattern during the mid-Tertiary. The Russell fault would be the through-going Y shear, where the maximum amount of displacement occurs. The left-lateral fault zone beneath the Caliente Range would be analogous to the X shear, which forms later and has less displacement because of its orientation. At a smaller scale, the left-lateral fault has a similar, though reversed, orientation of structures. The left-lateral fault zone would be analogous to the R, P and Y shears, with the en echelon folds of the Caliente range at the expected oblique orientation. The en echelon fold axes that are

Figure 3-15. Evidence for left-lateral slip in the vicinity of the southeastern Caliente Range and the relationship of tectonic features to idealized strain patterns. Evidence for left-lateral slip includes the en echelon folds, the offset thick Vaqueros Formation between the seismic grid in the Cuyama Valley and the Drake Federal well in the Caliente Range, and the offset Branch Canyon-Caliente Formation facies boundary. The subsurface right-stepping, en echelon folds along the Russell fault are parallel to the left-stepping en echelon folds in the Caliente Range, implying that both sets of folds and related faults formed under the same stress regime. The Caliente Range front appears to have left-stepping straight segments that are parallel to the fold axes in the Caliente Range. These straight segments may be an expression of "P" shears that formed under the left-lateral shear regime and have been utilized by subsequent thrusting. The left- and right-lateral strain ellipses show an idealized model for the orientation of structures formed under strike-slip stress regimes, based on Bartlett et al. (1981) and Harding (1974).

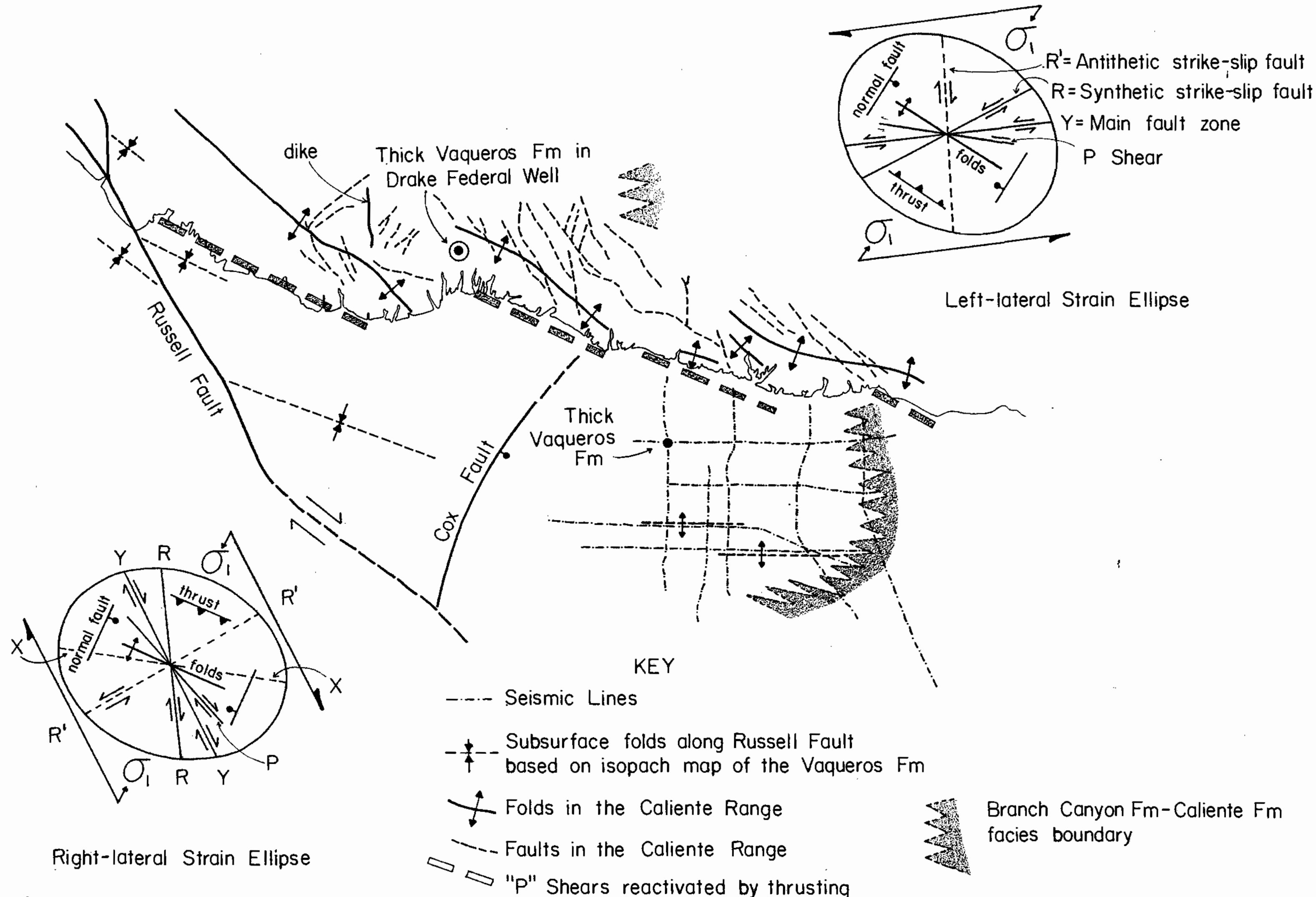

R' = Antithetic strike-slip fault
R = Synthetic strike-slip fault
Y = Main fault zone
P Shear
normal fault
folds
thrust
Left-lateral Strain Ellipse
dike
Thick Vaqueros Fm in Drake Federal Well
Russell Fault
Cox Fault
Thick Vaqueros Fm
Y
R
R'
X
P
Right-lateral Strain Ellipse
KEY
Seismic Lines
Subsurface folds along Russell Fault based on isopach map of the Vaqueros Fm
Folds in the Caliente Range
Faults in the Caliente Range
"P" Shears reactivated by thrusting
Branch Canyon Fm-Caliente Fm facies boundary

Figure 3-15.

related to the dextral Russell fault and to the sinistral fault in the Caliente Range area are parallel, and both are at the right orientation for strike-slip shear on their related faults. The Cox fault is at right angles to the fold axes, and its orientation also fits into the overall right-lateral strain pattern, with the maximum stress direction (σ_1) oriented N25°E to N35°E. The parallel, en echelon folds are the main evidence for a unified stress field.

The left-lateral fault zone may not have been a single, through-going fault, but rather may have formed as a series of en echelon "P" shears, following the terminology of Tchalenko and Ambraseys (1970) and Bartlett et al. (1981). The frontal escarpment of the Caliente Range appears to be offset in a stepped manner that is parallel to the en echelon folds (Fig. 3-15). The trace of the younger Morales thrust, which controls the uplift of the Caliente Range, may be taking advantage of these older, en echelon faults, giving the frontal escarpment of the Caliente Range its left-stepped appearance.

A comparison of the Russell/left-lateral fault relationship to idealized, experimental models is not perfect. Both the clay model and the limestone model assume a more or less homogenous medium with no pre-existing structures as a starting point. If an earlier, normal fault existed below the Caliente Range, as Davis et al. (1988) suggest, the left-lateral slip could have taken advantage of this plane of weakness. Also, the original orientation of these structures may have been obscured by subsequent compression and rotation.

Timing of Events Related to the Strike-Slip Regime

In order to show a relationship between structures in a unified stress pattern, those structures must be related temporally as well as spatially. The sequence of events that formed the Russell fault and the left-lateral fault system would have been as follows (Fig. 3-8). The Russell fault was most active from 23-19 Ma during the deposition of the Vaqueros Formation. Syndepositional folds within the Vaqueros formed and were offset in a right-lateral sense along the Russell fault. Movement on the Russell slowed down dramatically at 19 Ma, and the Cox fault zone became active during deposition of the Saltos Shale. At the same time, right-lateral slip may have begun to jump east to the modern San Andreas fault strand. Powell (1993, p. 32, his Figure 8) shows that the San Andreas fault north of the Big Pine fault was active by 17 Ma, and it may have been active as early as 23 Ma. Normal movement on the Cox fault continued into the early stages of deposition of the Branch Canyon Formation which began at approximately 16 Ma. Most of the movement on the Cox fault zone occurred during Saltos Shale deposition. It is not clear when left-lateral movement started on the ancestral Morales fault, however the en echelon folds had to form prior to the emplacement of the Triple Basalts which started at 16.5 $\pm$ 1.3 Ma (Turner, 1970) and are not involved in the en echelon folds. Left-lateral motion on this fault zone had to occur after the beginning of deposition of the facies boundary between the Branch Canyon and Caliente Formations, which began during the Saucesian (Davis, et al., 1988). The facies boundary is offset the same amount as the thick Vaqueros between the Cuyama Valley subsurface and the Drake Federal well. The en echelon folds appear to have formed first, followed by left-lateral movement on the fault zone.

This zone of left-lateral movement may not have had enough displacement to develop into a through-going, continuous fault. Instead, it may have only developed into a set of left-stepping P shears and en echelon folds. The left-lateral fault zone could only have been active a short time. the lowest basalt layer, which is not involved in the en echelon folds provides an upper age limit of 16.5 Ma for left-lateral movmenet. The offset thick Vaqueros Formation provides a lower age limit of 18-19 Ma. The 8 km of left-lateral separation of the thick Vaqueros Formation and Branch Canyon-Caliente Formation facies boundary provides a maximum slip distance, although some of the apparent separation is probably due to later dip-slip on the Morales thrust fault. A possible maximum slip rate of 2.3-5.3 mm/yr can be calculated for the left-lateral fault zone, based on the 8 km of left-lateral separation and the 18-19 to 16.5 Ma period of activity. Of course, if the total slip on this fault zone is less, the slip rate would be lower. For comparison, the slip rate on the Russell fault at this time was ~0.25 mm/yr. This left-lateral fault zone was probably active at the time right-slip was being transferred from the Russell fault to the modern trace of the San Andreas fault.

COMPRESSION AND ROTATION

The most recent strain regime in the area is compressional. The Caliente Range is moving southwest towards the Cuyama Valley on the Morales and Whiterock thrust faults, and the Sierra Madre is moving north on the South Cuyama and Ozena faults. All of these thrusts override the Pliocene-Pleistocene Morales Formation with the exception of the Ozena fault, which is not in contact with the Morales formation (Figs. 3-2 and 3-3).

Paleomagnetic stratigraphy was used to date the Morales Formation, and by inference, the beginning of uplift of the Caliente Range and the Frazier Mountain-Mt Pinos crystalline highlands (Ellis et al., 1993) (Fig 3-16). In the Caliente Range, the Morales Formation was sampled in the footwall of both the Whiterock and Morales thrusts, and in the Wells Ranch syncline on the north side of the range. It was also sampled in Quatal Canyon in the Cuyama Badlands and in Santa Barbara Canyon. In the Wells Ranch syncline section, in contrast to the other sections, the Morales Formation becomes finer-grained toward to the top, where thick clay beds accumulated. The Wells Ranch syncline section probably predates the Gauss chron (Ellis et al., 1993), which began at 3.57 Ma (McDougall et al., 1992). The fine-grained clay beds in the Wells Ranch syncline section suggest that the coarse-grained sediment source from an ancestral Cuyama River was cut off by the rising Caliente Range. The uplift and erosion of the hanging wall of the Whiterock thrust are well defined in the stratigraphic record. Approximately half way up the Morales Formation in the section below the Whiterock fault, angular shale chips suddenly appear and dominate the clast composition. Below this appearance, the clasts are almost entirely well-rounded crystalline pebbles. The shale chips were most likely shed from the Monterey Formation in the rising hanging-wall block of the Whiterock thrust. The paleomagnetic sections below the Whiterock and Morales thrusts are correlated to the Gauss chron (3.57-2.60 Ma). Uplift of the Caliente Range began during the middle to upper Gauss chron.

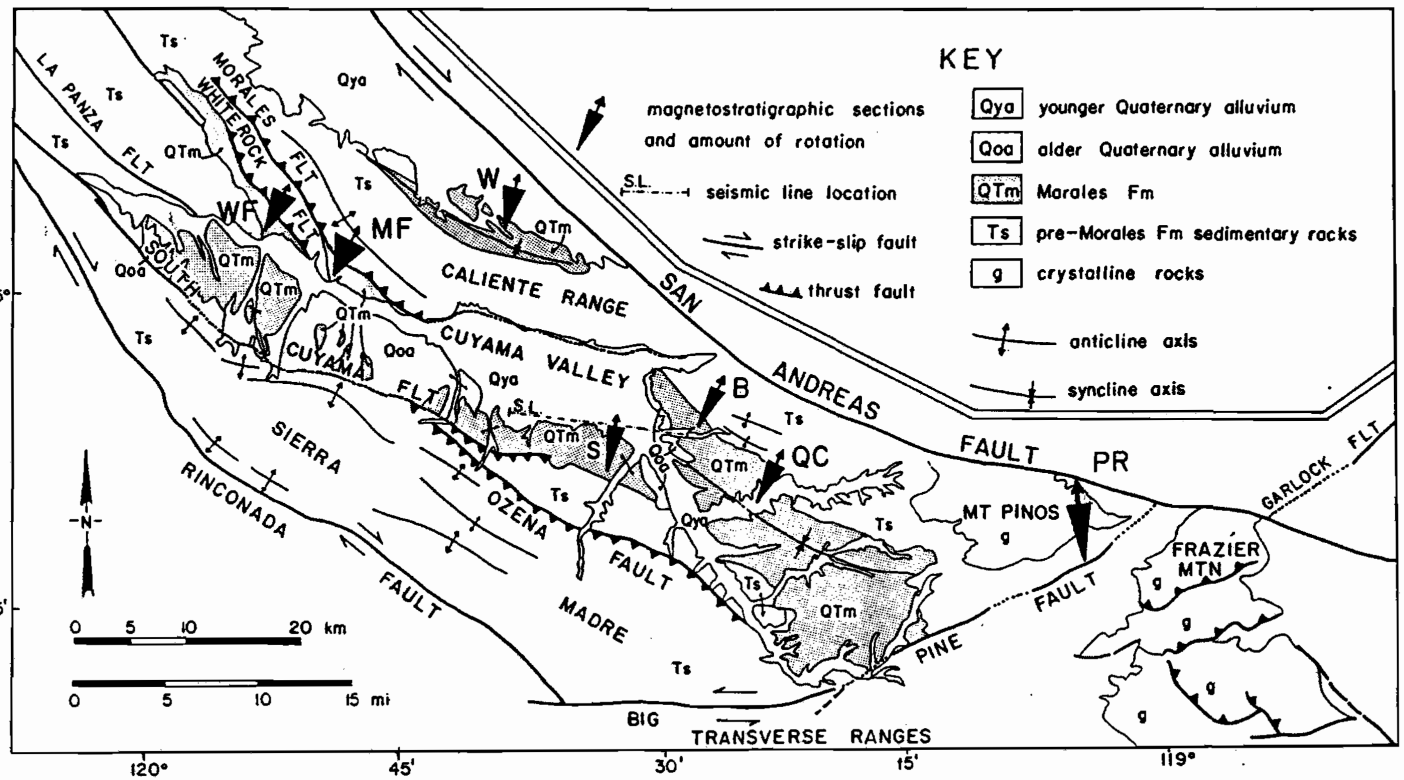


Figure 3-16. Location of paleomagnetic sections and amount of rotation (Figure 2 from Ellis et al., 1993). The Plush Ranch Formation data (PR) is from Luyendyk et al. (1985).

Stratigraphic evidence for the recent uplift of the Mt. Pinos-Frazier Mountain crystalline highlands is recorded by the presence of a boulder bed in the Morales Formation in Quatal Canyon. These boulders have the same lithology as the crystalline highlands to the east; some boulders are more than a meter in diameter. Based on the stratigraphic position of the boulder bed within the Morales Formation, and the paleomagnetic dating of the Morales Formation, uplift of the crystalline highlands began at 2.6 and 0.78 Ma (Ellis et al., 1993). Dibblee (1971b) mapped the Morales fault trace near and south of the base of the older Quaternary alluvium terraces along the southern front of the Caliente Range. Crystalline pebbles on the surface of the terraces are similar to those on the valley floor. The fault scarps of these "older Quaternary alluvium" terraces appear to be arranged in an en echelon pattern parallel to the axes of the older, left-stepping en echelon folds. The Morales thrust system may be taking advantage of an older system of left-stepping en echelon P shears related to earlier left-lateral faulting (Fig. 3-15). Others (e.g. Davis et al., 1988) have interpreted the fault to underlie ridges of "older Quaternary alluvium" in the Cuyama Valley south of the Caliente Range front. Both interpretations may be correct, in that the fault is splaying and has stepped forward to form a blind thrust below the ridges. This splay probably dies out east of the ridges of older alluvium. The north-south seismic line (Fig. 3-12) also suggests a splay of the Morales thrust may be present under the Cuyama Valley and in front of the Caliente Range.

The relationship of the eastern end of the Morales thrust to the San Andreas fault is unclear. Dibblee (1971a and b) suggests that it continues to the east, possibly ending at the San Andreas fault. An alternative idea is that it turns to become a blind thrust beneath the Cuyama Badlands (Fig. 3-1 and 3-2) This hypothesis is explored in more detail below.

The Cuyama Badlands fold belt is interpreted to continue to the northwest under the alluvium of the Cuyama Valley, based on a grid of seismic lines in the eastern Cuyama Valley. The southwestern portion of the grid has well-defined, gently dipping to horizontal reflectors. The northeast portion of the grid has poor quality data. A fairly distinct boundary separates the good from the poor quality data. This difference is interpreted to be due to the presence of more steeply dipping beds associated with the continuation of the Badlands fold belt beneath the Cuyama Valley.

In the Cuyama Badlands fold belt, an angular unconformity of 25° exists between the Caliente Formation and the Quatal Formation in Quatal Canyon, suggesting that folding began prior to deposition of the Quatal Formation. The Pleistocene(?) Paso Robles Formation, as mapped by Dibblee (1971a) overlies the Morales and older formations. In many areas, the Paso Robles is almost horizontal and overlies an erosion surface on tightly-folded older formations. In the northwest part of the Badlands near the southwestern extent of the Paso Robles and northeast of well #3 on cross-section A-A', however, the Paso Robles is folded, with dips as steep as 75° (Dibblee, 1971a) (Fig. 3-5).

The folds in the Caliente Formation and older rocks are tight and overturned and have a southwest vergence in the central part of the Cuyama Badlands fold belt. (Figs. 3-5 and 3-17). Folds in the same formations closer to the San Andreas fault verge toward the northeast. This pattern of folding in the Caliente Formation and older rocks is interpreted to result from a blind thrust that dips to the northeast under the central part of the fold belt. The tight, overturned folds suggest a fault propagation fold, although it is not clear if the adjacent syncline is a backlimb of this fold. To the east and on strike with these tight folds, Dibblee (1971a) mapped a thrust fault that places older Caliente Formation over younger Caliente, and dips 52° north. The folds on the southwest edge of the overlying Paso Robles Formation have the opposite sense of vergence from the folds in the older rocks below the Paso Robles. The folds in the Paso Robles Formation are interpreted to be due to flexural slip faulting in the underlying folds, shown diagrammatically in cross-section A-A', Figure 3-17. These flexural slip faults offset the base of the Paso Robles by one to two meters, and they are responsible for the northeast sense of vergence in the Paso Robles

KEY FOR CUYAMA BADLANDS CROSS-SECTIONS

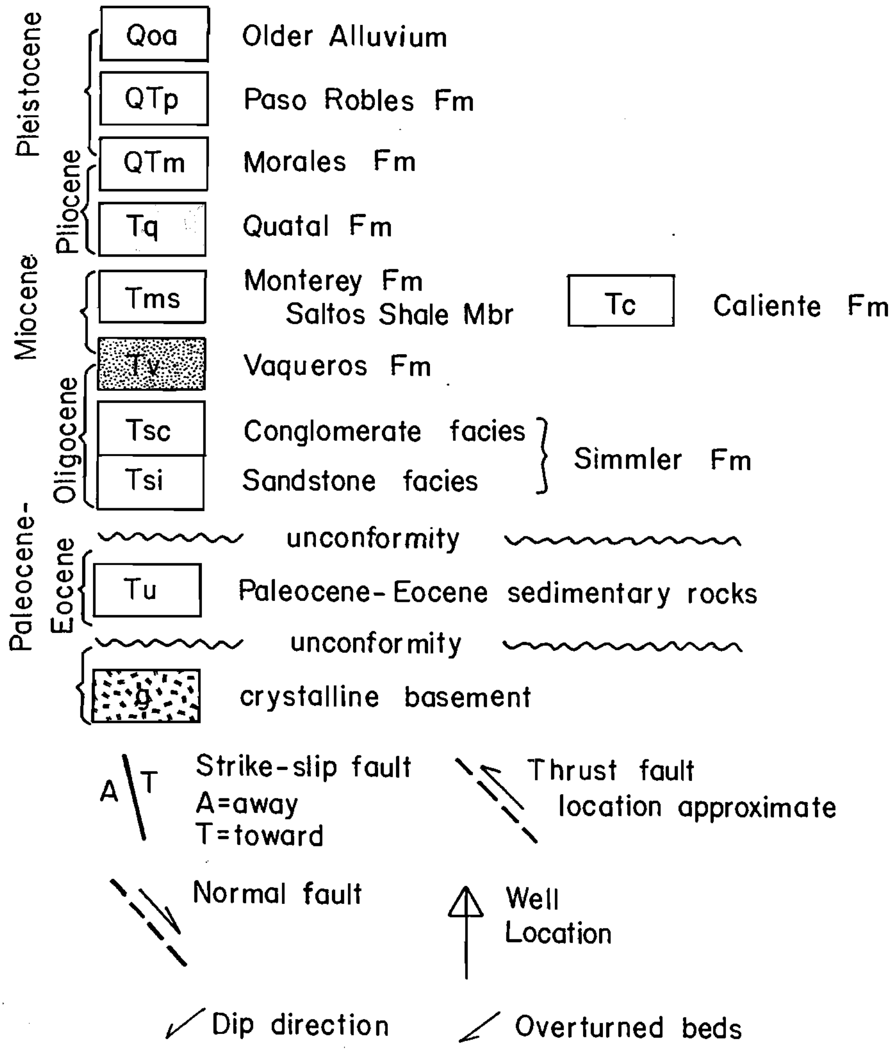


Figure 3-17a.

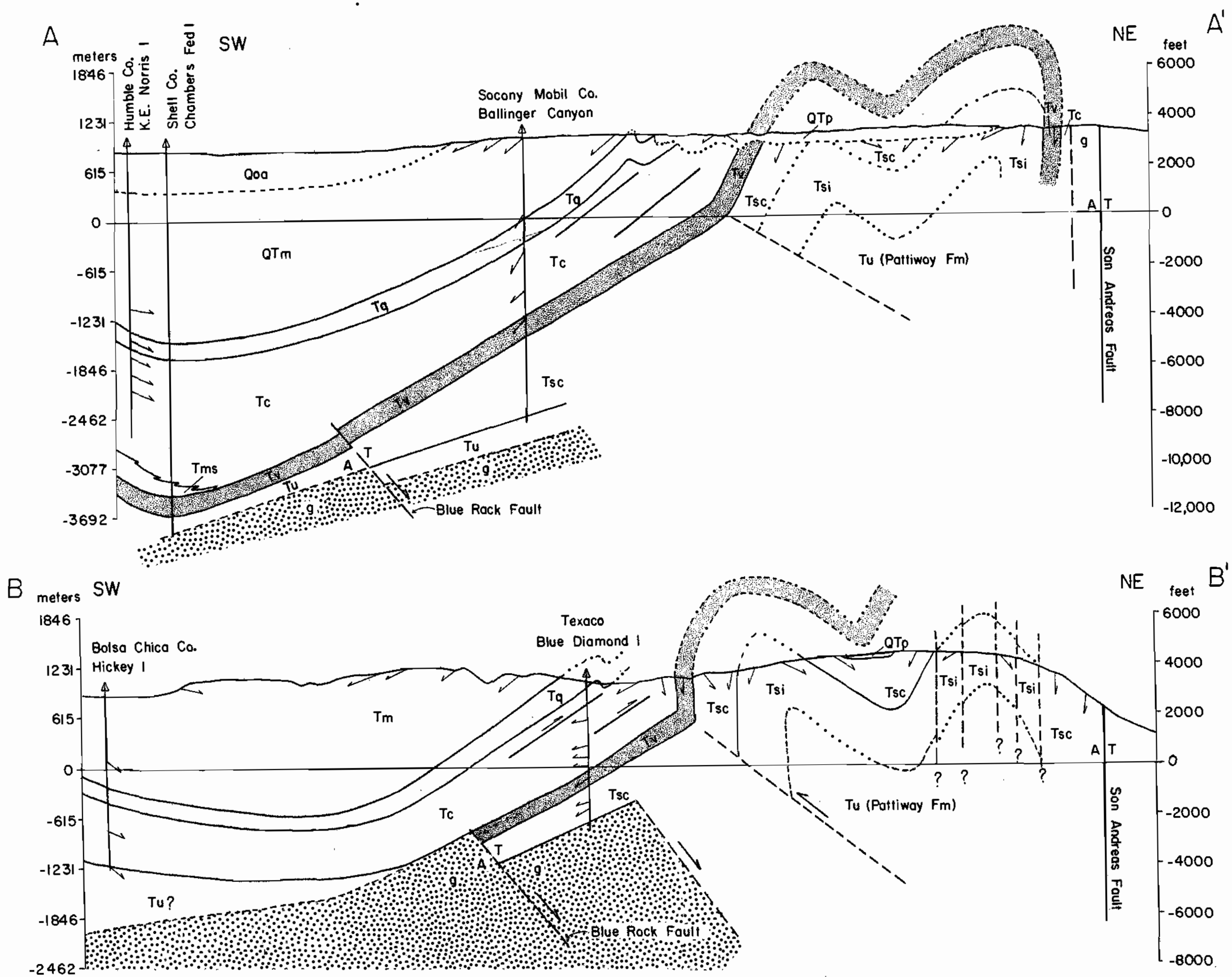


Figure 3-17b. Cross-sections of the Cuyama Badlands. The Blue Rock fault is assumed to have a right-lateral component of slip, which precludes the construction of an accurate balanced cross-section.

folds. Both the flexural slip faults that cut the base of the Paso Robles and the tight folds in the Paso Robles itself suggest that folding and compression is still active.

The Morales thrust may diverge from the Caliente Range front and become a blind thrust under the tight folds in the Badlands, based on the following evidence: 1) The stratigraphy between the southeastern Caliente Range and the northwestern part of the Badlands is similar, suggesting there is no major fault separating these two areas. In both areas, there are outcrops of Pattiway, Simmler, Vaqueros and Caliente Formations. 2) The tight, southwest verging folds in the Badlands suggest that they may be underlain by a blind thrust. 3) Seismic evidence from the Cuyama Valley suggests the Badlands fold bend continues to the northeast under the valley. Most of the young folds and thrust faults in the Cuyama area are subparallel to the San Andreas, and follow the curvature of the Big Bend. If the Morales thrust continued under the Badlands, it would fit this pattern.

Alternatively, the Morales thrust may continue along the southeastern Caliente Range front toward the San Andreas fault. The fold belt and blind thrust in the Cuyama Badlands may continue to the northwest to be overridden by the Caliente Range as it moves south on the Morales thrust. This pattern would be similar to the map pattern of the Big Spring thrust at the northern end of the Morales thrust in the central Caliente Range (Bartow, 1988; Davis et al., 1988) (See Fig. 3-1).

Evidence for continuing compression includes the uplifted terrace of older Quaternary alluvium (Qoa) on the south side of the Caliente Range and the linear ridges of Qoa approximately 2 km south of the Caliente Range front. The ridges of Qoa on the valley floor are linear and may mark the location of a blind thrust propagating out in front of the Caliente Range. The uplifted terrace is a linear feature high with a minimum of topographic dissection. Crystalline gravels, similar to those on the valley floor, are present on the surface of the terrace.

ROTATION OF THE CUYAMA BASIN

Paleomagnetic studies of the Pliocene-Pleistocene Morales Formation revealed that the Cuyama basin has undergone approximately 23° of clockwise rotation since deposition of the Morales Formation ended at approximately 2 Ma (Ellis et al., 1993). Previous studies of rotation have concentrated on areas south of the Big Pine fault, the northernmost west-trending left-lateral fault of the western Transverse Ranges (e.g. Luyendyk et al., 1980; Luyendyk et al., 1985; Terres, 1984; Terres and Luyendyk, 1985; Hornafius et al., 1986; Liddicoat, 1990). Rotation rates in the western Transverse Ranges are estimated at 5-6°/Ma (Jackson and Molnar, 1990; Luyendyk, 1991). In the Cuyama basin, however, 23° of clockwise rotation has occurred since 2 Ma, which is twice as fast as the predicted rate for areas south of the Big Pine fault.

Although simple shear due to right-lateral motion between the North American and Pacific plates may account for much of the rotation in southern California, it may not be the only mechanism, especially in the area adjacent to the Big Bend. A possible explanation is similar to Suppe's (1983) model of a fault-bend fold that develops above a ramp in a thrust fault. In this case, however, the map view of the western Big Bend of the San Andreas fault is the plane which is usually seen in a cross-sectional view of a thrust fault ramp. As right-lateral motion on the San Andreas fault takes place, crustal material to the south moves north and west around the bend, rotating as it passes the Big Bend.

Swinging around the Bend: The fault bend fold analogy model

Any model for rotation of the Cuyama Valley must take into account the following: 1) the rate of rotation is twice the predicted value for the area directly to the south; 2) fold axes are sub-parallel to the San Andreas fault, and 3) the direction of maximum stress remains nearly perpendicular to the San Andreas fault around the Big Bend. These points are discussed in detail below.

1. The rate of rotation: 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 suggest that this rate is consistent with estimates of rotation rates for the past 10 my. Luyendyk (1991) shows that theoretical models favor a lower rate of rotation when motion between tectonic plates is transtensional and a higher rotation rate when motion is transpressional. However, data on rotation rates in the western Transverse Ranges (Hornafius et al., 1986; Luyendyk, 1991) do not confirm this, and Luyendyk suggests rotation has occurred at an average rate of 5-6°/Ma since the middle Miocene in the western Transverse Ranges, based on data from the Santa Ynez Range. Using either Jackson and Molnar's (1990) or Luyendyk's (1991) estimates of rotation rates, the Cuyama basin should have rotated 10-12° clockwise since deposition of the Morales Formation ended at approximately 2 Ma. However, the Cuyama basin shows approximately 23° of post-Morales Formation clockwise rotation, almost twice the predicted value.

2. Orientation of fold axes: In models of strike-slip strain patterns (e.g. Wilcox et al., 1973; Harding, 1974), compressional folds and faults should be oblique to the San Andreas fault. However, many of the young folds and faults in central California are parallel to the main fault (Crouch et al., 1984; Zoback et al, 1987). Also, many of the young fold axes in the Cuyama area are parallel to the San Andreas fault around the curve of the Big Bend, such as the South Cuyama syncline in the Cuyama Badlands and the Wells Ranch syncline, both of which involve the Morales Formation (Fig 3-2).

3. Zoback et al. (1987) and Mount and Suppe (1992) demonstrated that the maximum horizontal stress direction, as measured by borehole elongations in wells and fault-plane focal mechanisms, is nearly perpendicular to the San

Andreas fault. Also, the direction of maximum horizontal stress remains close to perpendicular around the Big Bend (Fig. 3-18).

The change in strike of the San Andreas fault at the Big Bend is 27°, similar to the average rotation of 23° of the Cuyama valley. The Big Pine fault is also bent 25° (Fig. 3-1).

A possible explanation for the Cuyama basin's rotation involves a map model resembling Suppe's (1983) cross-sectional model of a fault-bend fold that develops above a ramp in a thrust fault (Fig. 3-19). In this model, the Big Bend of the San Andreas fault is analogous to a thrust ramp lying on its side. As right-lateral motion progresses, crustal material southeast of the Big Bend rotates as it moves northwestward around the bend. As in Suppe's (1983) model of a thrust ramp, there should be a hinge line associated with the Big Bend. Crustal material on the west side of the San Andreas would rotate as it passes the hinge. Sediments deposited to the south and east of the hinge line (in the area analogous to a thrust ramp) that have not moved past the bend should not be rotated. Sediments that were deposited south of the hinge and have moved northwest of the Big Bend's hinge should be rotated. Also, young sediments that are deposited north of the bend should not be rotated. These statements could be tested by further paleomagnetic sampling on the Morales Formation equivalents on both sides of the Big Bend.

Luyendyk et al. (1985) sampled the Plush Ranch Formation of Lockwood Valley just north of the Big Pine fault. Results indicate 6.4 + 12.5 of counterclockwise rotation. Luyendyk et al. (1985) give three possible explanations: 1) the Plush Ranch formation is not rotated, 2) it has rotated counterclockwise as it moved north into the left bend of the San Andreas fault, or 3) structural corrections are incorrect. Although they consider the data to be ambiguous, results from this locality suggest the area south of the Big Bend has not yet rotated.

If the Morales Formation rotated due to "swinging around the bend", it would have to have been deposited south and east of the hinge, analogous to

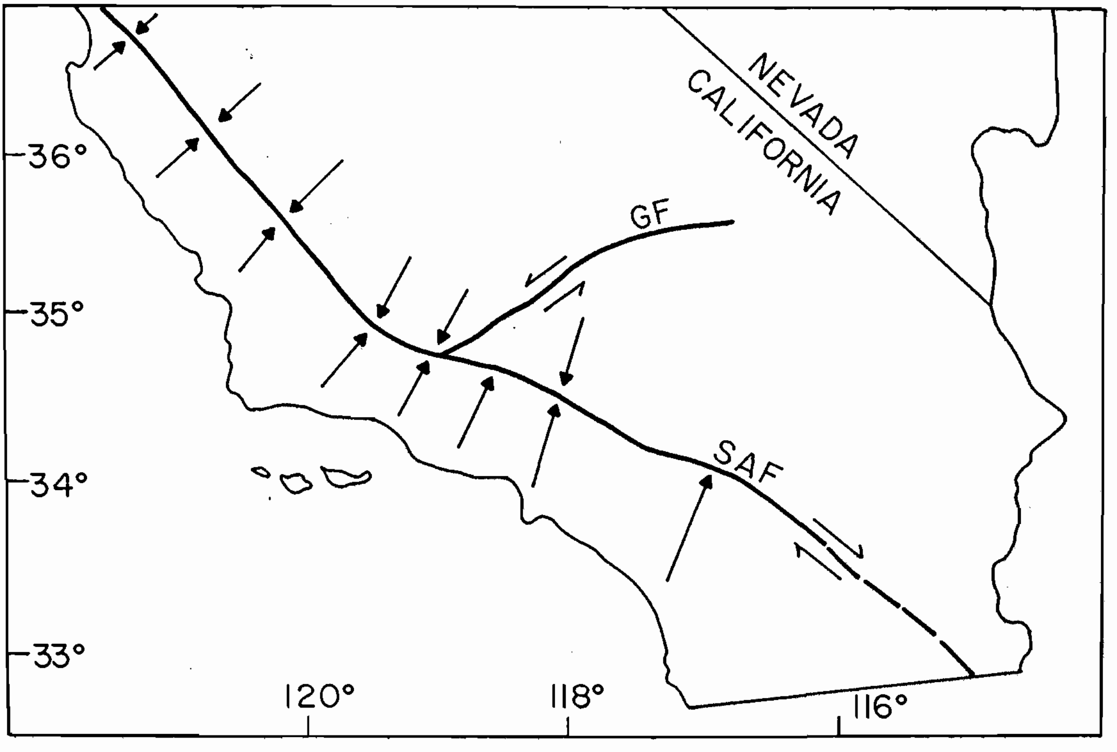
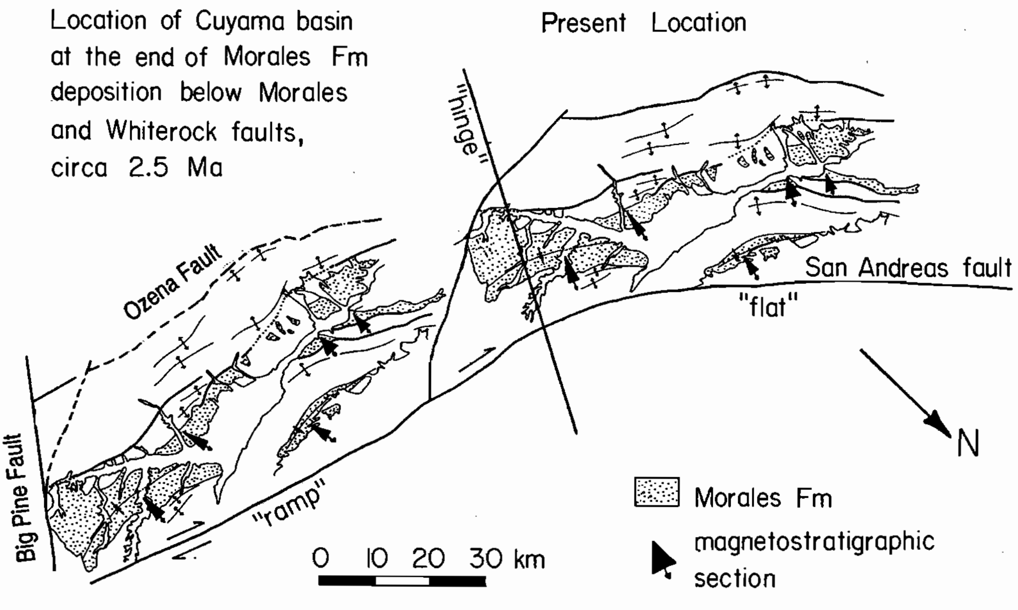


Figure 3-18. Orientation of σ_1 (maximum stress direction) in relation to the San Andreas fault. The arrows show the direction of σ_1 , based on borehole breakout data from wells (Zoback et al., 1987; Mount and Suppe, 1992).



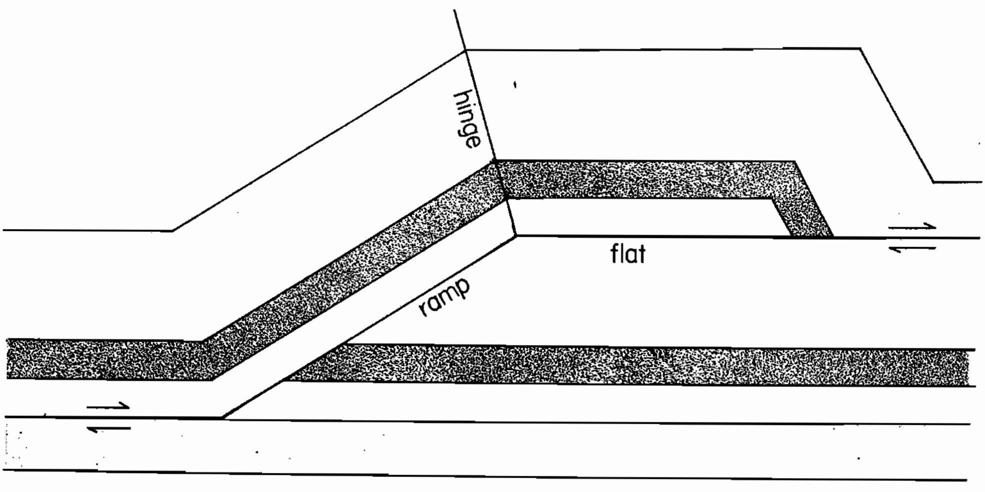


Figure 3-19. Model of rotation around the Big Bend of the San Andreas fault.
a) Map view of the location of the Cuyama basin at 2.5 Ma and at present. The arrows show the paleomagnetic vector with the 95% confidence level.
b) Cross-section view of a fault-bend fold above a thrust ramp (Suppe, 1993).

The map view of the San Andreas fault is compared to the cross-section of the thrust fault. As the Cuyama basin moves around the Big Bend, it rotates through the hinge zone in a similar fashion to the formation of a fault bend fold above the hinge between the ramp and flat in a thrust fault.

deposition occurring along the ramps of a thrust. If 33 mm/yr is used as the rate of movement along the San Andreas fault in the vicinity of the Big Bend (Sieh and Jahns, 1984; Sims, 1989) and 1.8 Ma (the beginning of the Olduvai subchron) is assumed to be the latest possible limit of deposition in the Cuyama Badlands, this section moved at least 60 km since deposition. It is now in the vicinity of the hinge of the Big Bend. If 2.5 Ma is the latest time limit on deposition of the Morales Formation in the Whiterock and Morales thrust sections of the Caliente Range, these sections moved 82.5 km in the last 2.5 m.y., and are now 40 km northwest of the hinge line of the Big Bend.

Back-rotating geologic features of the Cuyama Valley counter-clockwise by 23° gives them a trend similar to those in the western Transverse Ranges. This suggests that they formed parallel to the San Andreas fault southeast of the Big Bend, in keeping with the stress field described by Zoback et al. (1987). If 23° of clockwise rotation and 82.5 km of slip along the San Andreas fault are removed from the traces of the Morales and Whiterock faults, these thrusts would be parallel to the San Andreas fault south of the Big Bend. This implies that the faults formed parallel to the San Andreas fault and have rotated around the bend to remain parallel to the San Andreas fault.

This model implies that the Big Bend was present during the rotation of the Cuyama basin. Garfunkel (1974) and Bohannon and Howell (1982) suggested that the Big Bend formed due to extension of the Basin and Range Province north of the Garlock fault. Burbank and Whistler (1987) have suggested that motion on the Garlock fault began at approximately 10 Ma, based on paleomagnetic evidence for rotation of adjacent strata. Therefore, the Big Bend appears to have been present at the time of deposition of the Morales Formation.

The fault-bend fold analogy for the Cuyama basin rotation is meant to be a kinematic, rather than a mechanistic model. It is only intended to show how movement of the Cuyama basin around the San Andreas fault's Big Bend may account for rotation is this area.

CONCLUSIONS

The Cuyama basin has a complex tectonic history, involving extension, strike-slip, compressional faulting, and rotation. Extensional faulting in the Cuyama basin is recorded by the Simmler Formation, a continental sequence that was deposited in fault-bounded basins. The Simmler is Oligocene to early Miocene in age (30-24 Ma). Restoring the Cuyama basin to its location along the San Andreas fault during the Oligocene puts it adjacent to the Orocopia Mountains of southeastern California. Tennyson (1989) and Crouch and Suppe (1993) suggest the Cuyama basin and adjacent areas were part of the Basin and Range extensional terrain. Crouch and Suppe (1993) further suggest that the Cuyama basin was a graben (or several grabens) in the hanging wall of a major detachment fault, and the break-away zone was the Sur-Nacimiento fault.

The transitional time between extension and strike-slip faulting may have been a period of transtension. Powell (1993, p. 32, his Figure 8) dates the beginning of right-lateral movement on the Clemens Well-Fenner-San Francisquito fault at 17 Ma, and possibly as early as 23 Ma, a time that overlaps with deposition of the Simmler and Diligencia Formations. He also suggests that early right-lateral movement took place along a zone of right stepping, en echelon normal fault basins and antiforms.

As strike-slip faulting continued, the Cuyama basin acted as a part of a diffuse shear zone with complex interactions between right- and left-lateral faults, en echelon folds and normal faults. The earliest well-documented right-lateral movement in the Cuyama Basin took place along the Russell fault at 23 Ma. The Russell fault was active from 23 to 4 Ma, and slowed down at 19 Ma.

A perplexing problem concerning the Russell fault is determining its path to the south of the western Cuyama Valley. Powell (1993, p. 51) disagrees with the connecting the Russell fault to the Ozena fault (Yeats et al., 1988, 1989) because the 29 km of right-lateral slip cannot be traced south of the Big Pine fault. An alternative path to continue the 29 km of slip to the south connects the Russell fault with the Clemens Well-Fenner-San Francisquito fault via the Blue

Rock fault. The Clemens Well-Fenner-San Francisquito fault was active by 17 Ma, and possibly as early as 23 Ma. Powell (1993, p. 31) found this fault had moved approximately 110 km and suggests it joins with the modern San Andreas fault north of the Big Pine fault. Perhaps 30 km of its movement was taken up by the Blue Rock-Russell fault north of the Big Pine fault. Thus, the Cuyama basin may have had two parallel right-lateral faults active at the same time, and the majority of right-lateral movement may have been transferred from the Russell to the modern trace of the San Andreas fault at approximately 19 to 17 Ma.

As part of this "soft shear zone", I propose that a left-lateral strike-slip fault zone existed in the vicinity of the southern Caliente Range that acted as a conjugate fault to the Russell fault. Evidence for the existence of such a fault includes the following:

1. A set of left-stepping, en echelon folds in the southeastern Caliente Range that formed prior to the eruption of the lowest basalt layer at ~16.5 Ma.

2. A series of faults with a N30-40W trend cut the folds, but do not disrupt the basalt layers, although one of the faults is filled with a basalt dike.

3. Areas of similar thicknesses in the Vaqueros Formation in the Cuyama Valley and the Caliente Range are separated in an apparently left-lateral sense.

4. The Branch Canyon-Caliente Formation facies boundary is displaced in an apparent left-lateral sense between the Caliente Range and the Cuyama Valley, the same amount as the displacement of the Vaqueros Formation. This indicates that left slip began after 18(?) Ma, and was completed by 16.5 $\pm$ 1.3 Ma.

The overall pattern of right- and left-lateral faults, en echelon folds and the normal Cox fault fit a pattern of right-lateral strain.

The transition from dominantly strike-slip to compressional tectonics occurred during the deposition of the fluvial Morales Formation. The Morales Formation overlies the Russell fault without being displaced by that fault. It is folded and cut by thrust faults, and it contains sediments that were shed from the rising Caliente Range and Mt. Pinos-Frazier Mountain highlands. Based on a paleomagnetic study of the Morales Formation, the uplift of the Caliente Range along the Whiterock and Morales thrusts occurred since 3.57 Ma, the beginning of the Gauss chron. Uplift of the Mt. Pinos-Frazier Mountain crystalline highlands began after 2.6 Ma. Compressional tectonics in the Cuyama basin may have been initiated by the northward movement of this area into the restraining bend (Big Bend) of the San Andreas fault. As the Caliente Range is north of the Mt. Pinos-Frazier Mountain highlands, it would have encountered the restraining bend earlier, and therefore, the recent episode of uplift of the Caliente Range is older.

Dibblee (1971) and Vedder and Repenning (1975) have suggested that the trace of the Morales thrust is parallel to the southern front of the Caliente Range, and it possibly ends at the San Andreas fault. I propose that the Morales thrust diverges from the Caliente Range front to become a blind thrust below the Cuyama Badlands. Evidence for the existence of such a fault includes the following:

1. The stratigraphy in the southeastern Caliente Range and the northwestern Cuyama Badlands is similar and does not appear to be displaced by a fault between these two areas.

2. The folds beneath the Paso Robles Formation, which lies horizontally over the older rocks of the Cuyama Badlands for much of its extent, are tightly folded with a vertical to overturned southern limb. This fold geometry suggests it may be a fault propagation fold.

3. Seismic evidence suggests the Cuyama Badlands fold belt continues underneath the Cuyama Valley.

The paleomagnetic study of the Morales Formation also revealed that approximately 23° of clockwise rotation has occurred since the Morales Formation was deposited. No progressive rotation through time was found. A mechanism to explain the very young clockwise rotation is proposed that is a map analogue to Suppe's (1983) cross-sectional fault bend fold model for thrust faults. In this model, crustal material west of the San Andreas fault rotates as it moves northward and around the Big Bend. The 27° angle of the Big Bend is similar to the average amount of rotation, 23°, recorded in the Morales Formation.

Current maximum stress patterns, based on borehole breakout data, show that the maximum stress direction is oriented perpendicular to the San Andreas fault and remains perpendicular around the Big Bend. Other geologic features, most notably young fold axes, are parallel to, and bent around, the Big Bend. Again, this suggests that the crustal material is rotating around the Bend.

In this synthesis of the tectonic history of the Cuyama basin, five new ideas have been presented:

1. The Simmler Formation was deposited in half-grabens bound on the southwest by normal faults, and were coeval in part with initiation of strike-slip faulting in the San Andreas fault system.

2. The 28-29 km of right lateral slip on the Russell fault continues to the southeast via the Blue Rock fault, which may be a continuation of the San Francisquito-Fenner-Clemens Well fault.

3. A left-lateral fault that acted as a conjugate fault to the Russell, and possibly the San Andreas fault, existed in the vicinity of the southern Caliente Range

prior to emplacement of the lowest basalt layer at ~16.5 Ma. This fault may have been active only during the time strike-slip movement shifted from the Russell fault eastward to the San Andreas fault.

4. The Morales thrust fault diverges from the Caliente Range to become a blind thrust below the Cuyama Badlands.

5. The recent, post-Morales Formation clockwise rotation of the Cuyama basin can be explained by the movement of crustal material around the Big Bend of the San Andreas fault.

ACKNOWLEDGEMENTS

Discussions with Drs. Robert S. Yeats and Gary J. Huftile were very helpful in critiquing and framing the ideas presented here. Discussions with W.J.M.Bazeley, T.L. Davis, and T.W. Dibblee early in the project helped me focus on critical areas for detailed study. Dr. Huftile's expertise with balanced cross-sections was appreciated. Dr. Shaul Levi provided access to the paleomagnetic laboratory, and was instrumental in analyzing the resulting data. Seismic lines were provided by G.W. Charlton of COHO Resources, Ltd., and Coleman Morton. Well data were obtained from a variety of sources, including W.J.M. Bazeley of ARCO. T.W. Dibblee, Jr. made his unpublished geologic maps available. Dr. Jack Vedder provided me with the location of the Blancan fossil in the Morales Formation, and Dr. T.S. Kelley gave me the fossil locations in the Caliente Formation of the Cuyama Badlands. Grants from Arco, the Geological Society of America and the Oregon State University Dept. of Geology, the Southern California Fault Studies project and the Bureau of Land Management made this study possible. Dr. Gregg Wilkerson of the Bureau of Land Management helped secure funding, and made their data available. I would like to thank the Reyes family of the Cuyama Valley for providing me with their friendship and a place to stay during three seasons of field work. Wayne Sugai provided computer support.

BIBLIOGRAPHY

Atwater, T., 1970, Implications of plate tectonics for the Cenozoic tectonic evolution of western North America: Geol. Soc. of America Bull., v. 81, p. 3513-3536.

Ballance, P.F., Howell, D.G. and Ort, K., 1983, Late Cenozoic wrench tectonics along the Nacimiento, South Cuyama, and La Panza faults, California, indicated by depositional history of the Simmler Formation, *in* Andersen, D.W., and Rymer, M.J., eds., Tectonics and Sedimentation along Faults of the San Andreas System, Pacific Section, SEPM, p. 1-10.

Barker, J.M., 1972, Geology and petrology of the Toad Spring Breccia, Abel Mountain, California and its relation to the San Andreas fault: unpub. M.A. thesis, Univ. of California, Santa Barbara, 100 p.

Bartow, J.A., 1974, Sedimentology of the Simmler and Vaqueros Formations in the Caliente Range-Carrizo Plain area, California: U.S. Geol. Survey Open File Report 74-338, 163 p.

Bartow, J.A., 1978, Oligocene continental sedimentation in the Caliente Range area, California: J. of Sedimentary Petrology, v. 48, p. 75-98.

Bartow, J.A., 1988, Geologic map of the Northwestern Caliente Range, San Luis Obispo County, California: U.S. Geol. Survey Open-File Report 88-691, scale 1:36,000.

Bartlett, W.L., Friedman, M., and Logan, J.M., 1981, Experimental folding and faulting of rocks under continuing pressure, Part IX, Wrench faults in limestone layers: Tectonophysics, v. 79, p. 255-277.

Berggren, W.A., 1972, A Cenozoic time-scale--some implications for regional geology and paleobiogeography: Lethaia, v. 5, p. 195-215.

Blake, T.F., 1981, Depositional Environments of the Simmler Formation in Southern Cuyama Valley, Santa Barbara and Ventura Counties, California: unpub. M.S. thesis, California State Univ., Northridge, 151 p.

Blake, T.F., 1982, Depositional environments of the Simmler Formation in southern Cuyama Valley, Santa Barbara and Ventura Counties, California, *in* Ingersoll, R.V and Woodburne, M.O., eds., Cenozoic Nonmarine Deposits of California and Arizona: Pacific Section, SEPM, p. 35-50.

Bohannon, R.G., 1975, Mid-Tertiary conglomerates and their bearing on Transverse Range tectonics, southern California, *in* Crowell, J.C., ed., San Andreas fault in southern California: California Division of Mines and Geology Special Report 118, p. 75-82.

Bohannon, R.G., 1976, Mid-Tertiary non-marine rocks along the San Andreas fault in southern California: unpub. Ph.D. dissertation, Univ. of California, Santa Barbara, 311 p.

Bohannon, R.G. and Howell, D.B., 1982, Kinematic evolution of the junction of the San Andreas, Garlock and Big Pine faults, CA: Geology, v. 10, p. 358-363.

Burbank, D.W. and Whistler, D.P., 1987, Temporally constrained tectonic rotations derived from magnetostratigraphic data: implications for the initiation of the Garlock fault, California: Geology, v. 15, p. 1172-1175.

Calhoun, J.A., 1985, Structural geology of the Morales Canyon and Taylor Canyon region of the Cuyama Basin, S. Coast Ranges, California: Oregon State Univ. unpub. M.S. thesis, 80 p.

Calhoun, J.A., 1988, Structural geology of the Morales Canyon and Taylor Canyon area of the Cuyama Basin, southern California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara and Ventura Counties, California: Pacific Section SEPM, v. 59, p. 97-112.

Chipping, D.H., 1972, Early Tertiary paleogeography of central California: American Assoc. of Petroleum Geologists Bull., v. 56, p. 480-493.

Clifton H.E., 1973, Marine-nonmarine facies changes in middle Miocene rocks, southeastern Caliente Range, California, *in* Sedimentary Facies Changes in Tertiary Rocks--California Transverse Ranges and South Coast Ranges: SEPM Trip 2, p. 55-57.

Clifton, H.E., 1981, Progradational sequences in Miocene shoreline deposits, southeastern Caliente Range, California: J. of Sedimentary Petrology, v. 51, no. 1, p. 165-184.

Crouch, J.K., Bachman, S.B., and Shay, J.T., 1984, Post-Miocene Compressional tectonics along the central California margin, *in* Crouch, J.K., and Bachman, S.B., eds., Tectonics and Sedimentation along the California Margin: Pacific Section SEPM, Los Angeles, California, p. 37-54.

Crouch, J.K, and Suppe, J., 1993, Late Cenozoic tectonic evoluion of the Los Angeles Basin and Inner California Borderland: A model for core complex-like crustal extension: Geol. Soc. of America Bull. v. 105, p. 1415-1434.

Crowell, J., 1968, Movement histories of faults in the Transverse Ranges and speculations on the tectonic history of California, *in* Dickinson, W.R., and Grantz, A., eds., Proceedings of Conference on Geologic Problems of San Andreas Fault System: Stanford Univ. Publications, Geological Sciences, v. 11, p. 323-341.

Crowell, J. 1973, Problems concerning the San Andreas fault system in southern California, *in* Kovach, R.L. and Nur, A., eds., Proceedings of a Conference on Tectonic Problems of the San Andreas Fault System: Stanford Univ. Publications, Geological Sciences, v. XIII, p. 125-135.

Crowell, J., 1975, Geologic sketch of the Orocopia Mountains, southeastern California, *in* Crowell J., ed., San Andreas fault in southern California: California Division of Mines and Geology, Special Report 118, p. 99-110.

Dalrymple, G.B., 1979, Critical tables for conversion of K/Ar ages from old to new constants: Geology, v. 7, p. 558-560.

Davis, G.A. and Lister, G.S., 1988, Detachment faulting in continental extension: Perspectives from the southwestern U.S. Cordillera, *in* Clark, S.P., Jr., Burchfiel, B.C., and Suppe, J., eds., Processes in Continental Lithospheric Deformation: Geol. Soc. of America Special Paper 218, p. 133-159.

Davis, G.H., Naruk, S.J. and Thorman, C.J., 1987, Structural geology of the Rincon and Pinaleno metamorphic core complexes, southeast Arizona, *in* Davis, G.H. and Vendendolder, F.M., eds., Geologic Diversity of Arizona and Its Margins; Excursions to Choice Areas: Arizona Bureau of Geology and Mineral Technology Special Paper 5, p. 249-259.

Davis, T.L, 1983, Late Cenozoic structure and tectonic history of the western "big bend" of the San Andreas fault and adjacent San Emigdio Mountains: unpub. Ph.D. dissertation, Univ. of California, Santa Barbara, 579 p.

Davis, T.L, Lagoe, M.B., Bazeley, W.J.M., Gordon, S., McIntosh, K., and Namson, J.S., 1988, Structure of the Cuyama Valley, Caliente Range, and Carrizo Plain and its significance to the structural style of the southern Coast Ranges and Western Transverse Ranges, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara and Ventura Counties, California: Pacific Section SEPM, v. 59, p 141-158.

Dibblee, T.W. Jr., 1971a, Geologic map of the "Ventucopa" Quadrange, unpublished mapping.

Dibblee, T.W. Jr., 1971b, Geologic map of the Salisbury Canyon Quadrange, unpublished mapping.

Dibblee, T.W. Jr., 1971c, Geologic map of the "Fellows" Quadrangle, unpublished mapping.

Dibblee, T.W., Jr., 1973, Stratigraphy of the southern Coast Ranges near the San Andreas fault from Cholame to Maricopa, California: U.S. Geol. Survey Prof. Paper 764, 45 p.

Dibblee, T.W., Jr, 1982, Geology of the Alamo Mountain, Frazier Mountain, Lockwood Valley, Mount Pinos and Cuyama Badlands areas, southern California, *in* Geology and Mineral Wealth of the California Transverse Ranges: South Coast Geological Society Publication, p. 57-77.

Dibblee, T.W., Jr, 1987, Geology of the Sierra Madre and Pine Mountain Area, California, *in* Davis, T.L. and Namson, J.S., eds., Structural Evolution of the Western Transverse Ranges, Pacific Section SEPM, v. 48A, p. 43-53.

Dokka, R.K., McCurry, M., Woodburne, M.O. Frost, E.G., and Okaya, D.A., 1988, A field guide to the Cenozoic crustal structure of the Mojave Desert, *in* Weide, D., and Faber, M.L. eds., This Extended Land: Geological Journeys in the Southern Basin and Range (Geological Society of America Cordilleran Section meeting field trip guidebook): Las Vegas, Univ. of Nevada, Special Publication 2, p. 21-44.

Eaton, J.E., 1939, Geology and oil possibilities of the Caliente Range, Cuyama Valley and Carrizo plain, California: California J. of Mines and Geology, v. 35, p. 255-274.

Ehlert, K.W., 1982, Basin analysis of the Miocene Mint Canyon Formation, southern California, *in* Ingersoll, R.V., and Woodburne, M.O., eds., Cenozoic Nonmarine Deposits of California and Arizona: Los Angeles, Pacific Section SEPM, p. 51-64.

Ellis, B.J. and Spitz, H.M., 1987, Subsurface cross-section of the southeastern Cuyama basin, southern California, *in* Davis, T.L. and Namson, J.S., eds., Structural Evolution of the Western Transverse Ranges, Southern California: Pacific section SEPM, volume and guidebook no. 48A, p. 77-84.

Ellis, B.J., Levi, S. and Yeats, R.S., 1993, Magnetic stratigraphy of the Morales Formation: Late Neogene compression and clockwise rotation in the Cuyama basin, California Coast Ranges: Tectonics, v. 12, p. 1170-1179.

Fisher, R.A., 1953, Dispersion on a sphere: Proceedings Royal Soc. of London, Series A, v. 271, p. 295-305.

Frakes, L.A., 1959, The geology of the Quatal Canyon area, Kern, Ventura and Santa Barbara Counties, California: unpub. M.S. thesis, Univ. of California, Los Angeles, 92 p.

Freitag, G.A., 1989, Stratigraphic Analysis of the Vaqueros Formation, Southeastern Cuyama Valley, California: M.S. thesis, California State University, Northridge, 138 p.

Fritsche, A.e., 1969, Miocene geology of the central Sierra Madre Mountains, Santa Barbara County, California; unpub. Ph.D. dissertation, Univ. of California, Los Angeles, 385 p.

Fritsche, A.E., 1988, Origin and paleogeographic development of the Tertiary Cuyama depositional basin, southern California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara and Ventura counties, California: Pacific Section SEPM., v. 79, p. 159-162.

Garfunkel, Z., 1974, Model for the late Cenozoic tectonic history of the Mojave desert, California, and for its relation to adjacent regions: Geol. Soc. of America Bull., v. 85, p. 1931-1944.

Gower, H.D., Vedder, J.G., Clifton, H.E., and Post E.V., 1966, Mineral resources of the San Rafael primitive area, California: U.S. Geological Survey Bulletin 1230-A, p. A1-A28.

Harding, T.P., Vierbuchen, R.C, and Christie-Blick, N. 1985, Structural styles, plate-tectonics settings and hydrocarbon traps of divergent (transtensional) wrench faults, *in* Biddle, K.T. and Christie-Blick, N., eds., Strike-Slip Deformation, Basin Formation and Sedimentation, SEPM Spec. Pub. no. 37, p. 51-77.

Harding, T.P., 1974, Petroleum traps associated with wrench faults: American Assoc. of Petroleum Geologists Bull., v. 58, p. 1290-1304.

Hill, M.L., Carlson, S.A., and Dibblee, T.W., Jr., 1958, Stratigraphy of Cuyama Valley-Caliente Range area, California: American Assoc. Petroleum Geologists Bull., v. 42, p. 2973-3000.

Hornafius, S., Luyendyk, B.P., Terres, R.R, and Kamerling, M.J., 1986, Timing and extent of Neogene tectonic rotation in the western Transverse Ranges: Geol. Soc. of America Bull., v. 97, p. 1476-1487.

Howard, K.A. and John, B.E., 1987, Crustal extension along a rooted system of imbricate low-angle faults: Colorado River extensional corridor, California and Arizona, *in* Coward, M.P., Dewer J.F., and Hancock, P.L. eds., Continental Extensional Tectonics: Geol. Soc. of London Spec. Publication 28, p. 299-311.

Howell, D.G., Vedder, J.G., McLean, H., Joyce, J.M., Clarke, S.H., Jr., and Smith, G., 1977, Review of Cretaceous geology, Salinian and Nacimiento blocks, Coast Ranges of central California, *in* Howell, D.G., Vedder J.G., and McDougall, K. eds., Cretaceous Geology of the California Coast Ranges, West of the San Andreas fault: Pacific Coast Paleogeography Field Guide 2: Pacific Section SEPM, p. 1-46.

Jackson, J., and Molnar, P., 1990, Active faulting and block rotations in the western Transverse Ranges, California: J. of Geophysical Research, v. 95, no. B13, p. 22073-22087.

James, G.T., 1963, Paleontology and non-marine stratigraphy of the Cuyama Valley Badlands, California: Univ. Calif. Pubs. Geol. Sci., v. 45, 154 p.

Jennings, C.W, and Strand, R.G., 1969, Geologic Map of California, Los Angeles Sheet, 1:250,000, California Division of Mines and Geology.

Joseph, S.E., Criscione, J.J., Davis, T.E. and Ehlig, P.L., 1982, The Lowe igneous pluton, *in* Fife, D.L. and Minch, J.A., eds., Geology and Mineral Wealth of the California Transverse Ranges: Mason Hill Volume: South Coast Geological Society Publication p. 307-3093.

Kelley T.S. and Lander, B.E., 1988, Biostratigraphy and correlation of Hemingfordian and Barstovian land mammal assemblages, Caliente Formation, Cuyama Valley area, California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama basin, San Luis Obispo, Santa Barbara and Ventura Counties, California, Pacific Section SEPM, v. 59, p. 1-19.

Kistler, R.W., Peterman, Z.E., Ross, D.C. and Gottfried, D., 1973, Strontium isotopes and the San Andreas fault, *in* Kovach, R.L. and Nur, A., eds., Proceedings of the Conference on Tectonic Problems of the San Andreas Fault System: Stanford Univ. Pubs. in Geol. Sciences, v. 13, p. 339-347.

Lagoe, M.B. 1981, Subsurface facies analysis of the Saltos Shale Member, Monterey Formation (Miocene) and associated rocks, Cuyama Valley, California, *in* Carrison, R.E. and Douglas, R.G., eds., The Monterey Formation and Related Siliceous Rocks of California: Pacific Section SEPM, Los Angeles, p. 199-211.

Lagoe, M.B., 1982, Stratigraphy and paleoenvironments of the Monterey Formation and associated rocks, Cuyama basin, California: Stanford Univ., unpub. Ph.D. thesis, 216 p.

Lagoe, M.B., 1984, Paleogeography of Monterey Formation, Cuyama basin, California: American Assoc. of Petroleum Geologists Bull., v. 68, p. 610-627.

Lagoe, M.B., 1985, Depositional environments of the Monterey Formation, Cuyama basin, California: Geol. Soc. of America Bull., v. 96, p. 1296-1312.

Lagoe, M.B., 1988, An outline of foraminiferal biofacies in the Soda Lake Shale Member, Vaqueros Formation, Cuyama basin, California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama basin, San Luis Obispo, Santa Barbara and Ventura Counties, California, Pacific Section SEPM, v. 59, p. 21-27.

Liddicoat, J.C., 1990, Tectonic rotation of the Santa Ynez Range, California, recorded in the Sespe Formation: Geophys. J. International, v. 102, p. 739-745.

Lundelius, E.J. Jr., Churcher, C.S., Downs, T., Harington, C.R., Lindsay, E.H., Schultz, G.E., Semken, H.A. Webb, S.D., Zakdrzewski, R.J., 1987, The North American Quaternary sequence, *in* Woodburne, M.O. eds., Cenozoic Mammals of North America, Geochronology and Biostratigraphy, Univ. of Calif. Press, p. 211-235.

Luyendyk, B.P., Kamerling, M.J., and Terres, R.R., 1980, Geometric model for Neogene crustal rotations in southern California: Geol. Soc. of America Bull., Part 1, v. 91, p. 211-217.

Luyendyk, B.P., Kammerling, M.C., Terres, R.R. and Hornafius, J.S., 1985, Simple shear of southern California during Neogene time suggested by paleomagnetic declinations: J. of Geophysical Research, v. 90, no. B14, p. 12454-12466.

Luyendyk, B.P., 1991, A model for Neogene crustal rotations, transtention and tranpression in southern California: Geol. Soc. of America Bull. v. 103, p 1528-1536.

McDougall, I., Brown, F.H., Certling, T.E., Hillhouse, T.W., 1992, A reappraisal of the geomagnetic polarity time scale to 4 Ma using data from the Turkana Basin, East Africa: Geophys. Res. Lett. v. 19, p. 2349-2352.

McElhinny, M.W., 1963, Statistical significance of the fold test in paleomagnetism, Geophys. Journal Royal Astronomical Society, v. 8, p. 338-340.

McKenzie D.P. and Jackson, J.A., 1986, A block model of distributed deformation by faulting: Geol. Soc. of London J., v. 143, p, 349-363.

Mount, V.S., and Suppe, J. 1992, Present day stress orientations adjacent to active strike-slip faults: California and Sumatra: J. of Geophysical Research, v. 97, no. B8, p. 11995-12013.

Nevins, B.B., 1983, Structural evolution of the Russell Ranch oil field and vicinity, southern Coast Ranges, California: Oregon State Univ., unpub. M.S. thesis, 69 p.

Pelka, G.J., 1971, Paleocurrents of the Punchbowl Formation and their interpretation: Geol. Soc. of America Abstract with Programs, v. 3, p. 176.

Perri, M.L. and Fritsche, A.E., 1988, Stratigraphy and depositional environments of the Miocene Branch Canyon Formation in the Sierra Madre, Caliente Range and Sepse Creek Areas, California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara and Ventura Counties, California: Pacific Section SEPM., v. 59, p. 87-96.

Powell, R.E., 1993, Balanced palinspastic reconstruction of pre-late Cenozoic paleogeology, southern California: geologic and kinematic constraints on evolution of the San Andreas fault system, *in* Powell, R.E., Weldon R.J. II, and Matti, J.C., eds., The San Andreas Fault System: Displacement, Palinspastic Reconstruction and Geologic Evolution, Geol. Soc. of America Memoir 178, p. 1-106.

Reynolds, S.J., Shafiqullah, M., Damon, P.E., and DeWitt, E., 1986, Early Miocene mylonitization and detachment faulting, South Mountains, central Arizona: Geology, v. 14, p. 283-286.

Ross, D.C., 1972, Petrographic and chemical reconnaissance study of some granitic and gneissic rocks near the San Andreas fault from Bodega head to Cajon Pass, California: U.S. Geol. Survey Professional Paper 698, 92 p.

Ross, D.C., 1974, Map showing basement geology and location of wells drilled to basement, Salinian Block, central and southern Coast Ranges, California: U.S. Geol. Survey Misc. Field Studies, Map MF-588, 2 sheets.

Ross, D.C., 1978, The Salinian block - a Mesozoic granitic orphan in the California Coast Ranges, *in* Howell, D.G. and McDougall, K.A., eds., Mesozoic Paleogeography of the Western United States, Pacific Coast Paleogeography Symposium 2: Pacific Section SEPM, p. 509-522.

Sauber, J., 1989, Geodetic measurement of deformation in California: Ph.D. thesis, Mass. Inst. of Technol., Cambridge.

Schwing, H.G., 1982, Interaction between the Transverse Ranges and Salinian block in the South Cuyama oil field, Cuyama Valley, California, *in* Geology and Mineral Wealth of the California Transverse Ranges: South Coast Geological Society Publication, p. 395-402.

Schwing, H.G., 1984, Subsurface geology of the South Cuyama Oil Field and adjacent areas, southern Coast Ranges, California: Oregon State Univ., unpub. M.S. thesis, 71 p.

Sherrod, D.R., Pickthorn, L.G., Tosdal, R.M., Grubensky, M.J., and Koch, R.D., 1987, Major early Miocene extensional deformation in southwestern Arizona and southeastern California: Geol. Soc. of America Abstracts with Programs, v. 19, p. 841.

Sieh, K.E., and Jahns, R.H., 1984, Holocene activity of the San Andreas at Wallace Creek, California: Geol. Soc. of America Bull., v. 93, p. 883-896.

Sims, J.D., 1989, Chronology of displacement on the San Andreas fault in central California: Evidence from reversed positions of exotic rock bodies near Parkfield, Calfornia: U.S. Geol. Survey Open-File Report 89-571, 40 p.

Smith, A.R., 1965, Geologic Map of California, Bakersfield Sheet, 1:250,000, California Division of Mines and Geology.

Smith, D.P., 1977, San Juan-St. Francis fault - hypothesized major middle Tertiary right-lateral fault in central and southern California: California Division of Mines and Geology Special Report 129, p, 41-50.

Spittler, T.E., 1974a, Volcanic petrology and stratigraphy of nonmarine strata, Orocopia Mountains; their bearing on Neogene slip on the San Andreas fault, southern California: unpub. M.S. thesis, Univ. of California, Riverside, 115 p.

Spittler, T.E., 1974b, Tertiary basaltic volcanism of the Orocopia Mountains: Geol. Soc. of America Abstracts with Programs, v. 6, p. 260.

Spittler, T.E., and Arthur, M.A., 1982, The lower Miocene Diligencia Formation of the Orocopia Mtns., southern California: stratigraphy, petrology, sedimentology and structure, *in* Ingersoll, R.V., and Woodburne, M.O., eds., Cenozoic Nonmarine Deposits of California and Arizona, Pacific Section SEPM, p. 83-100.

Spitz, H.M. 1985, Subsurface geology of the southeastern Cuyama Valley, southern Coast Ranges, California: Oregon State Univ., unpub. M.S. thesis, 83 p.

Spitz, H.M., 1988, Structure of the Cox Trough, southeastern Cuyama Valley, southern California, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara, and Ventura Counties, California: Pacific Section SEPM, v. 59, p.113-126.

Squires, R.L., and Advocate, D.M., 1982, Sedimentary facies of the nonmarine lower Miocene Diligencia Formation, Canyon Spring area, Orocopia Mountains, southern California, *in* Ingersoll, R.V., and Woodburne, M.O., eds., Cenozoic Nonmarine Deposits of California and Arizona, Pacific Section SEPM, p. 101-106.

Suppe, J., 1983, Geometry and kinematics of fault bend folding: American J. of Science, v. 283, p. 684-721.

Tchalenko, J.S. and Amraseys, N.N., 1970, Structural analysis of the Dasht-e Bayaz (Iran) earthquake fractures: Geol. Soc. of American Bull. v. 81, p. 41-60.

Tennyson, M.E., 1989, Pre-transform early Miocene extension in western California: Geology, v. 17, p. 792-796.

Terres, R.R., 1984, Paleomagnetism and tectonics of the central and eastern Transverse Ranges, southern California, Ph.D. dissertation, Univ. of Calif., Santa Barbara.

Terres R.R. and Luyendyk, B.P., 1985, Neogene tectonic rotation of the San Gabriel region, California, suggested by paleomagnetic vectors: J. of Geophys. Res. v.90, no. B14, p. 12467-12484.

Turner, D.L., 1970, Potassium-argon dating of Pacific Coast Miocene foraminiferal stages, *in* Bandy, O.L., ed., Radiometric Dating and Paleotonological Zonation: Geol. Soc. of America Special Paper 124, p. 91-129.

Vedder, J.G., 1968, Geologic map of the Fox Mountain quadrangle, Santa Barbara County, California: U.S. Geol. Survey Map I-547.

Vedder, J.G., Gower, H.D., Clifton, H.E., and Durham, D.L., 1967, Reconnaissance map of the central San Rafael Mountains and vicintiy, Santa Barbara County, California: U.S. Geol. Survey Misc. Geol. Investigations Map I-487, scale 1:48,000.

Vedder, J.G., 1970, Geologic map of the Wells Ranch and Elkhorn Hills quadrangles, San Luis Obispo and Kern Counties, California: U.S. Geol. Survey Map I-585.

Vedder, J.G. and Repenning, C.A., 1965, Geologic map of the southeastern Caliente Range, San Luis Obispo County, California: U.S. Geol. Survey Map OM-217.

Vedder, J.G. and Repenning, C.A., 1975, Geologic map of the Cuyama and New Cuyama quadrangles, San Luis Obispo and Santa Barbara Counties, California: U.S. Geol. Survey Map I-876.

Vedder, J.G., compiler, 1977, Preliminary list of Late Cretaceous mollusks from the Pozo district, San Luis Obispo County, California, *in* Howell, D.G., Vedder J.G., and McDougall, K. eds., Cretaceous Geology of the California Coast Ranges, West of the San Andreas fault: Pacific Coast Paleogeography Field Guide 2: Pacific Section SEPM, p. 107-109.

Weldon, R.J. II, Meisling, K.E., and Alexander, J., 1993, A speculative history of the San Andreas fault in the central Transverse Ranges, California, *in* Powell, R.E., Weldon R.J. II, and Matti, J.C., eds., The San Andreas Fault System: Displacement, Palinspastic Reconstruction and Geologic Evolution, Geol. Soc. of America Memoir 178, p. 161-198.

Wilcox, R.E., Harding, T.P., and Seeley, D.R., 1973, Basic wrench tectonics: American Assoc. of Petroleum Geologists Bull., v. 57, p. 74-96.

Yeats, R.S., Calhoun, J.A., Nevins, B.B., Swing, H.F., and Spitz, H.M., 1988, The Russell fault: An early strike-slip fault of the California Coast Ranges, *in* Bazeley, W.J.M., ed., Tertiary Tectonics and Sedimentation in the Cuyama Basin, San Luis Obispo, Santa Barbara and Ventura Counties, California: Pacific Section SEPM, v. 59, p. 129-139.

Yeats, R.S., Calhoun, J.A., Nevins, B.B., Schwing, H.F., and Spitz, H.M., 1989, Russell fault: early strike-slip fault of California Coast Ranges: American Assoc. of Petroleum Geologists Bull., v. 73, p. 1089-1102.

Zoback, M.D., Zoback, M.L., Mount, V.S., Suppe, J., Eaton, J.P., Healy, J.H., Oppenheimer, D., Reasenberg, P., Jones, L., Raleigh, C.B., Wong, I.G., Scotti, O., Wentworth, C., 1987, New evidence on the state of stress of the San Andreas fault system: Science, v. 238, p. 1105-1111.