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EARTHQUAKE EPICENTERS AND FAULT INTERSECTIONS IN CENTRAL AND SOUTHERN CALIFORNIA

Monem Abdel-Gawad and Joel Silverstein
North American Rockwell Science Center
1049 Camino Dos Rios (POB 1085)
Thousand Oaks, California 91360

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16. Abstract

ERTS-1 imagery provided evidence for the existence of short transverse fault segments lodged between faults of the San Andreas system in the Coast Ranges, California. They indicate that an early episode of transverse shear has affected the Coast Ranges prior to the establishment of the present San Andreas fault. The fault pattern indicates that the ancestor of San Andreas fault has been offset by transverse faults of the Transverse Ranges. It appears feasible to identify from ERTS-1 imagery geomorphic criteria of recent fault movements. Plots of historic earthquakes in the Coast Ranges and western Transverse Ranges show clusters in areas where structures are complicated by interaction of two active fault systems. A fault lineament apparently not previously mapped was identified in the Uinta Mountains, Utah. Part of the lineament shows evidence of recent faulting which corresponds to a moderate earthquake cluster.

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Preface

(a) Objective

One of the main objectives of this investigation is to assess the utility of ERTS-1 imagery in identifying significant geological structures to interpret their tectonic implications. The primary site is the southwestern part of the United States which includes by scientific necessity large areas outside the United States around the Gulf of California.

In order to accomplish the main objectives of the study we have placed our emphasis in those areas where important tectonic intersections occur. In this report we describe the work accomplished in studying a major fault intersection centered in southern California.

Before ERTS-1 imagery became available, we studied the fault pattern in parts of southern California using Apollo and Gemini photographs. This work resulted in developing a fault model which explains many of the apparent discrepancies of the San Andreas fault and shows how the complex fault pattern may have developed (Abdel-Gawad and Silverstein, 1972).

We were delighted to find that ERTS-1 imagery shows abundant evidence of old Transverse shear in the Coast Ranges supporting our fault model. For this reason we incorporated observations from one ERTS-1 scene (MSS 1037-18064) in a paper entitled "The Fault Model of Southern California - A Model for Its Development" to be submitted to the Geological Society of America Bulletin. A preprint copy of this paper is enclosed for review by NASA of ERTS-1 observations.

(b) Scope of Work

The bulk of this report describes additional observations on the Coast Ranges, the San Andreas and Transverse sets which are complementary to our previous work. ERTS-1 MSS imagery covering areas of primary importance were received late in September 1972. The report therefore represents an effective period of study of approximately two months, from the beginning of October to the end of November 1972.

One significant implication of our fault model based upon observations on the southern segment of the San Andreas fault is that the effects of Transverse shear faults predominantly noted in the Transverse Ranges should also be found in the California Coast Ranges. It was natural, therefore, when ERTS-1 imagery became available to study the Coast Ranges, the primary features we were looking for were short segments of Transverse wrench faults lodged between younger faults of the San Andreas set. The area under investigation is one of the most seismically active in the United States and includes areas of high population and industrial density.

This report includes:

(1) Observations on the fault pattern in the Coast and Transverse Ranges of profound significance to understanding the fault history.

(2) Plots of earthquake epicenters on overlays corresponding to ERTS-1 imagery and preliminary analysis of relationships to the fault pattern.

(c) Conclusions

ERTS-1 imagery is providing valuable data on active fault intersections. It appears feasible to identify geomorphic criteria of recent fault movements.

(d) Summary of Recommendations

ERTS-1 imagery of the Coast and Western Transverse Ranges of California is providing invaluable information on the relationships of active faults and the displacement patterns at their intersections. There is evidence that a major phase of transverse shear faulting has affected the Coast Ranges prior to the last phase of activity on the San Andreas system.

Many west-northwest trending segments of old wrench faults have been identified lodged between throughgoing faults of the San Andreas system. In the geological maps many of these transverse fault segments are shown incorporated with other faults which rendered their tectonic significance to be largely overlooked.

Information on the existence of these faults as a distinct system in its own right and not as a secondary or conjugate feature of the San Andreas system is consistent with our fault model which explains the development of the fault pattern in southern California.

We are working in refining a fault model for the Coast Ranges complementary to the fault model developed for southern California. When this is accomplished, the fault model is expected to shed considerable light on the very complex fragmentation pattern of the western part of California.

To state it briefly: ERTS-1 imagery is providing evidence that the San Andreas "fault" has not always been one fault as it appears today and has been offset into several segments by transverse faults during its history.

We identified from ERTS-1 imagery of the Transverse Ranges a fault lineament across the Pine Mountains (California) which seems to be quite distinct from the Ozena and Pine Mountain faults. This lineament lines up but does not seem at present to be connected with the middle segment of the San Gabriel fault.

It is speculated that the intervening unfaulted area in the vicinity of Lake Piru is a likely site for a future break. We recommend that this area be included in the network of geophysical measurements of tilt and fault creep.

Plots of earthquake epicenters from the vicinity of San Francisco to Los Angeles were completed and the patterns are under analysis. Preliminary analysis suggests clustering controlled by fault offsets at intersections.

A fault lineament was identified in the Colorado Plateau in northern Utah. Near Dragerton, Utah the lineament shows evidence of recent faulting associated with moderate seismic activity.

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Table

Introduction

The area studied in this report covers the southern part of the Coast Ranges from San Francisco to the vicinity of Los Angeles, including the western part of the Transverse Ranges (Figure 1).

ERTS-1 scenes covering this area used in this study are:

MSS 1021-18172 and 1075-18173
1021-18174
1056-18120
1037-18064 .

Observations on Fault Pattern

The significant feature we were looking for in the Coast Ranges was evidence for Transverse faults trending west-northwest lodged in blocks between faults of the San Andreas set. Examples of these and other faults are described.

San Francisco-Monterey

Reference: MSS 1021-18172; overlay Figure 2
MSS 1075-18173

In Figure 2 the major known faults are: San Andreas, Hayward, Calaveras, King City fault, and air photo lineament. In order to avoid crowding some major known faults are outlined by solid line. Observed lineaments, believed to be faults which are either not previously mapped or only partially mapped or not sufficiently emphasized in the literature, are indicated by broken lines.

(1) Fault lineament trending NNW parallel to and running approximately between Hayward-Calaveras fault zone and air photo lineament (San Jose map sheet). This lineament which cuts the Diablo Range was first recognized by Lowman (1972).

(2) Fault lineament along western side of Salinas River Valley and eastern side of Sierra de Salinas. Fault trends northwest appears to extend to Monterey Bay.

Transverse faults

Although the fault pattern here is dominated by northwest-trending

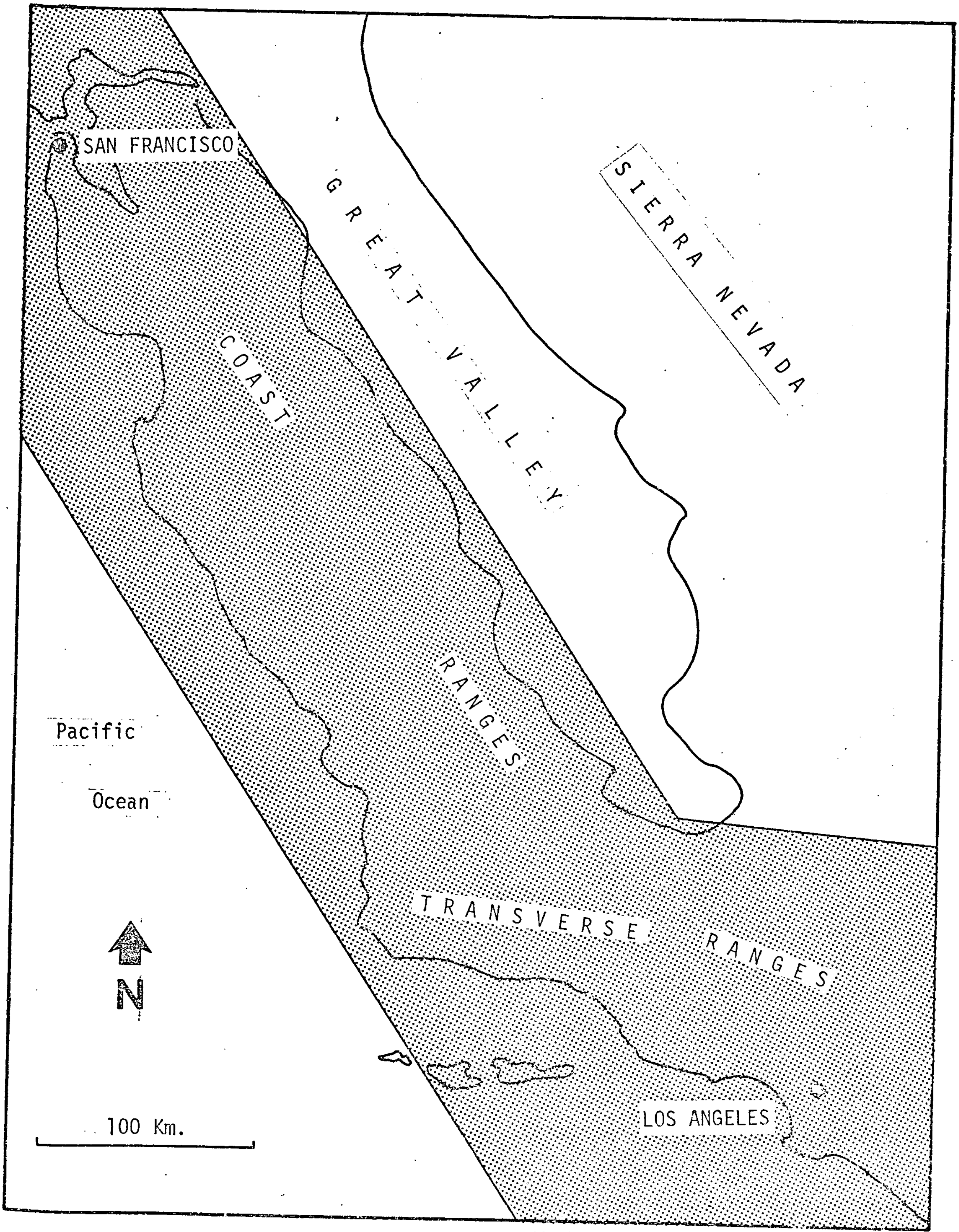


Figure 1 Area Studied

Figure 2 Fault Structures on Photograph 1021-18172

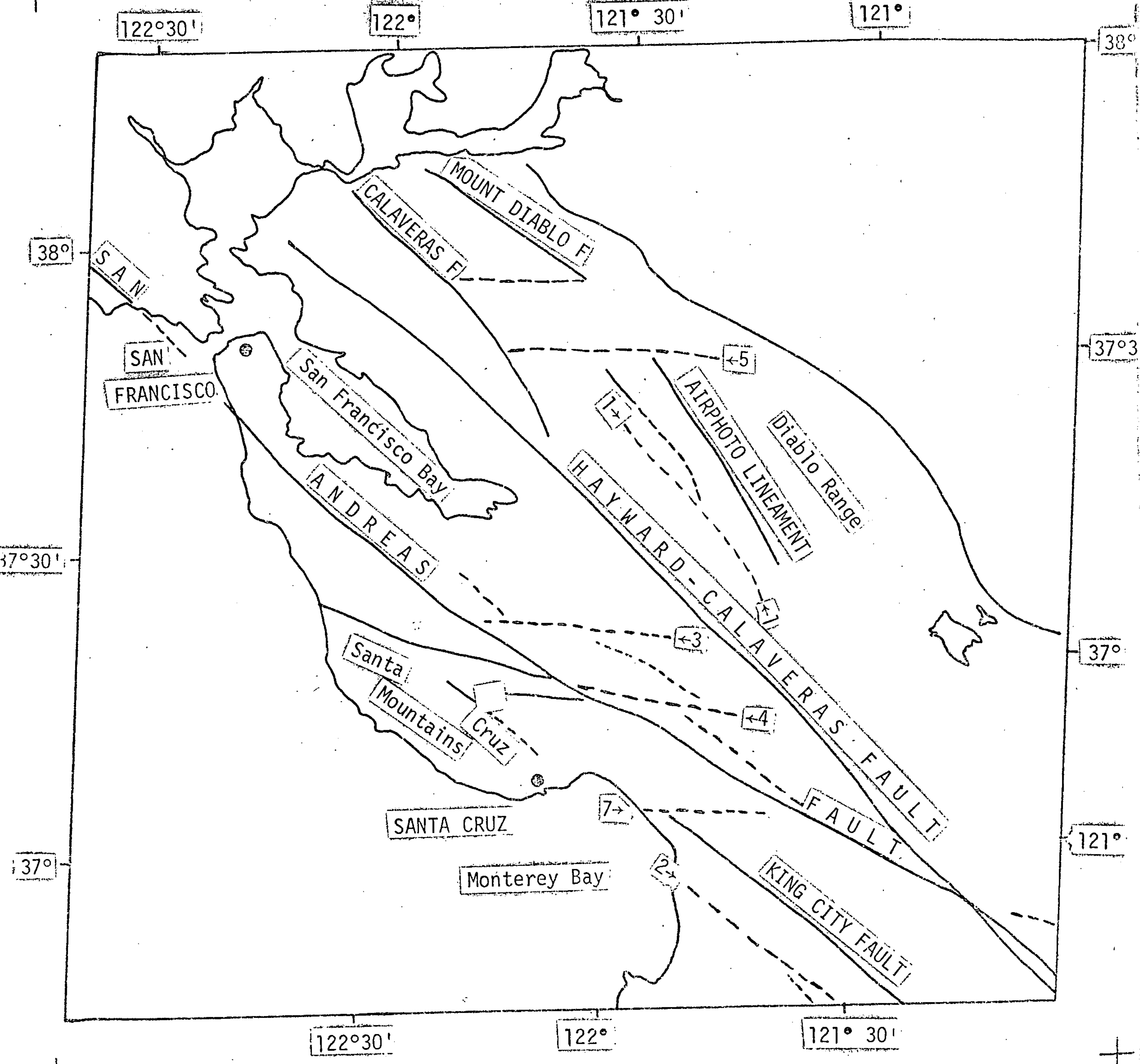
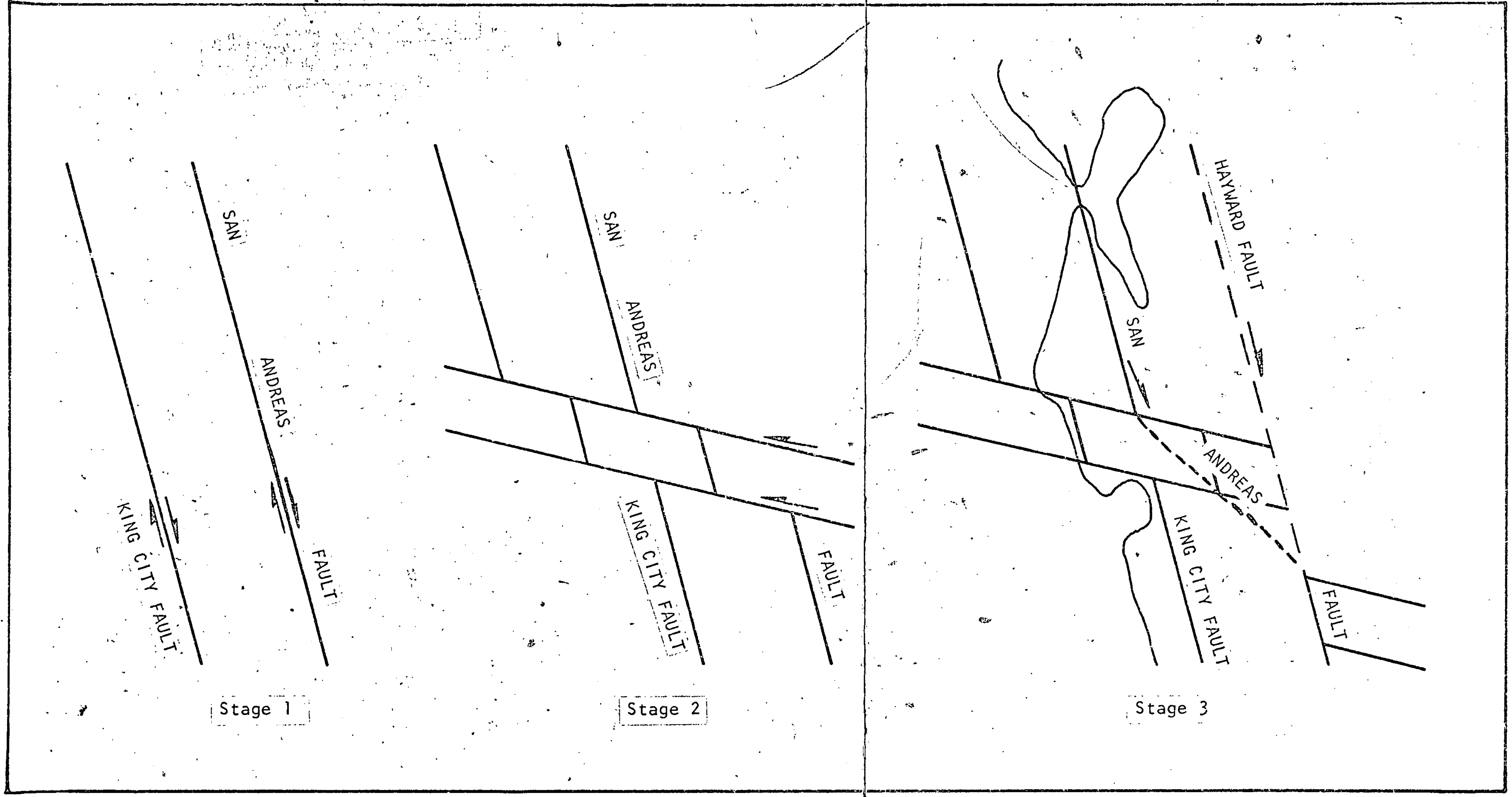


Figure 3 Proposed Development of Fault Pattern in San Francisco-Monterey Area
State 1 - Ancestors



Stage 1 - Ancestors of San Andreas and King City faults
Stage 2 - Development of left-lateral transverse faults offsetting San Andreas ancestor
Stage 3 - Propagation of faulting along Hayward and development of San Andreas short-cut near Monterey Bay

FOLDOUT FRAME 1

FOLDOUT FRAME 2

San Andreas and Hayward-Calaveras, we note the presence of another distinct system of faults trending west-northwest. These faults are relatively short and often occur lodged between throughgoing faults of the San Andreas system. Some of these transverse faults are shown in the geological maps (Atlas of California) incorporated as bends or branches in the San Andreas system. Other have not been previously mapped. But certainly they are represented as secondary features and were not given the emphasis commensurate with their immense significance in shaping the structure of the Coast Ranges. Fault lineaments 3, 4, 5, 6, and 7 are examples of the transverse faults we are referring to (Figure 2).

The effect of the transverse faults on the structure of the Coast Ranges here can be visualized if one for a moment ignores the San Andreas fault to realize that the blocks north of the transverse fault segments are consistently shifted westward relative to the blocks on their sourthern side. This suggests that the most of the lateral displacement on these faults was left-lateral and had taken place at some time prior to the establishment of the San Andreas along its present trace. The development of the fault pattern of Figure 2 is illustrated in Figure 3. Our interpretation suggests that the Hayward fault had developed by propagation to surmount a locked structure created by the offset of San Andreas ancestor by left lateral transverse faults. The segment of the San Andreas east of Monterey Bay may be considered as another short cut surmounting the locked structures.

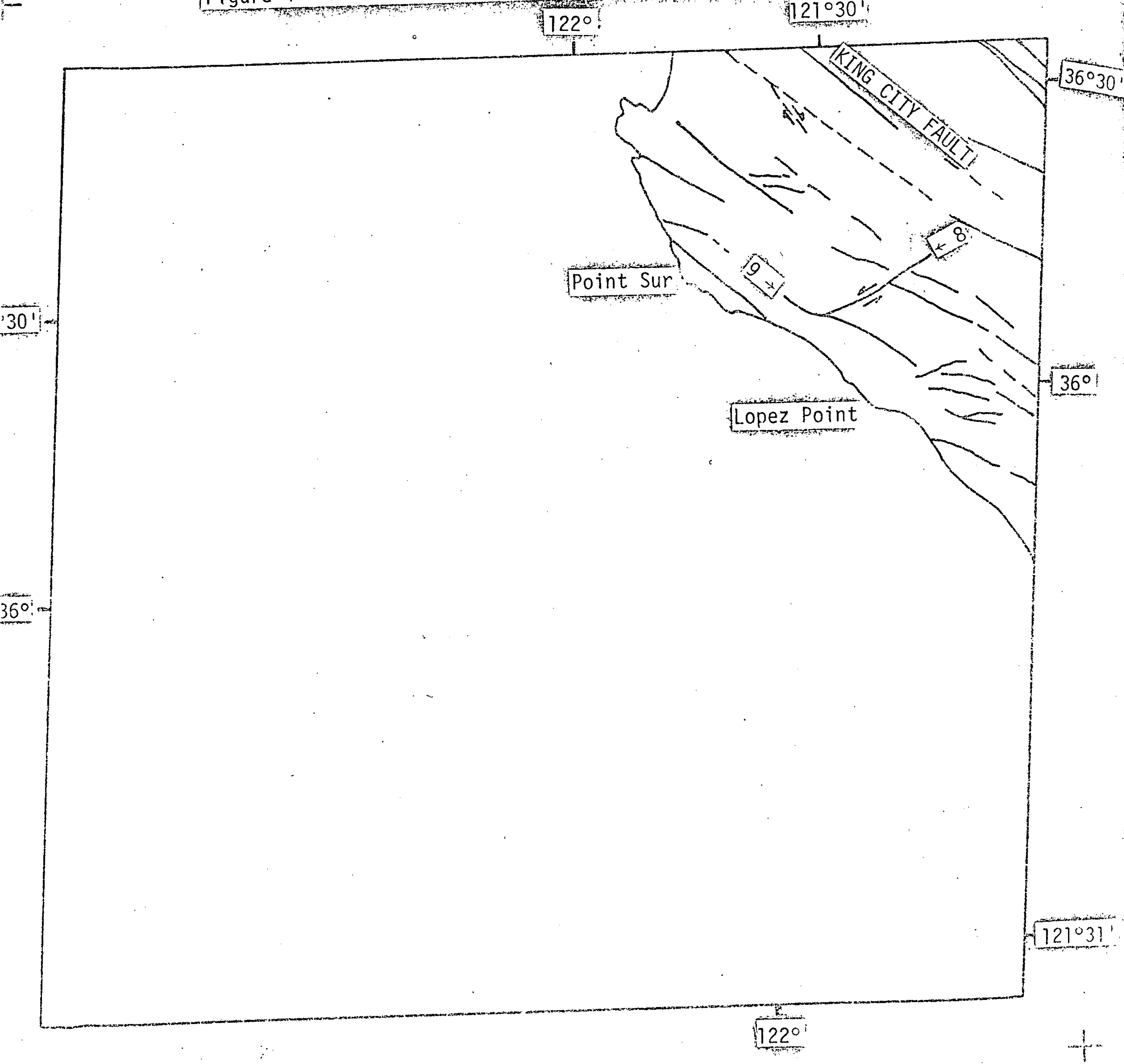
Another significant point is that despite the apparent linearity of the San Andreas fault we note that minor bends in the fault may in fact be small offsets at its intersection with the transverse faults. The resultant knickpoints are eventually broken through by fault propagation. This suggests that the tectonic forces causing the transverse shear may have continued to be active in the Quaternary. If this new interpretation is valid, the displaced extension of the King City fault which runs under the Salinas Valley be offshore of San Francisco.

Monterey-Lopez Point

Reference: MSS 1021-18174, Figure 4

The information concerning the relation of Willow Creek fault (8)

Figure 4 Fault Structures on Photograph 1021-18174



3

and Coast Ridge fault (9) is not new for it is well displayed in the Santa Cruz geologic map sheet. It is a clear case where ground truth provides strong support to our concept of fault interactions. The Willow Creek fault is a pronounced transverse fault somewhat anomalous in trend and clearly displaces the Mesozoic granites and metamorphic rocks of the northern Santa Lucia Range as well as the Miocene sedimentary rocks M some 15 km in a left-lateral sense. This proves two important points: that transverse shear has indeed taken place as far north as the Salinas block, and that this faulting took place at least late in the Miocene. The Willow Creek fault is clearly terminated (most probably offset) by the Coast Ridge fault zone (9) on the west and by Salinas Valley fault (2, Fig. 2) on the east. The orientation of the Willow Creek is intriguing since it is similar to the orientation of the Garlock fault and the eastern part of the Big Pine fault some 230 km to the southeast.

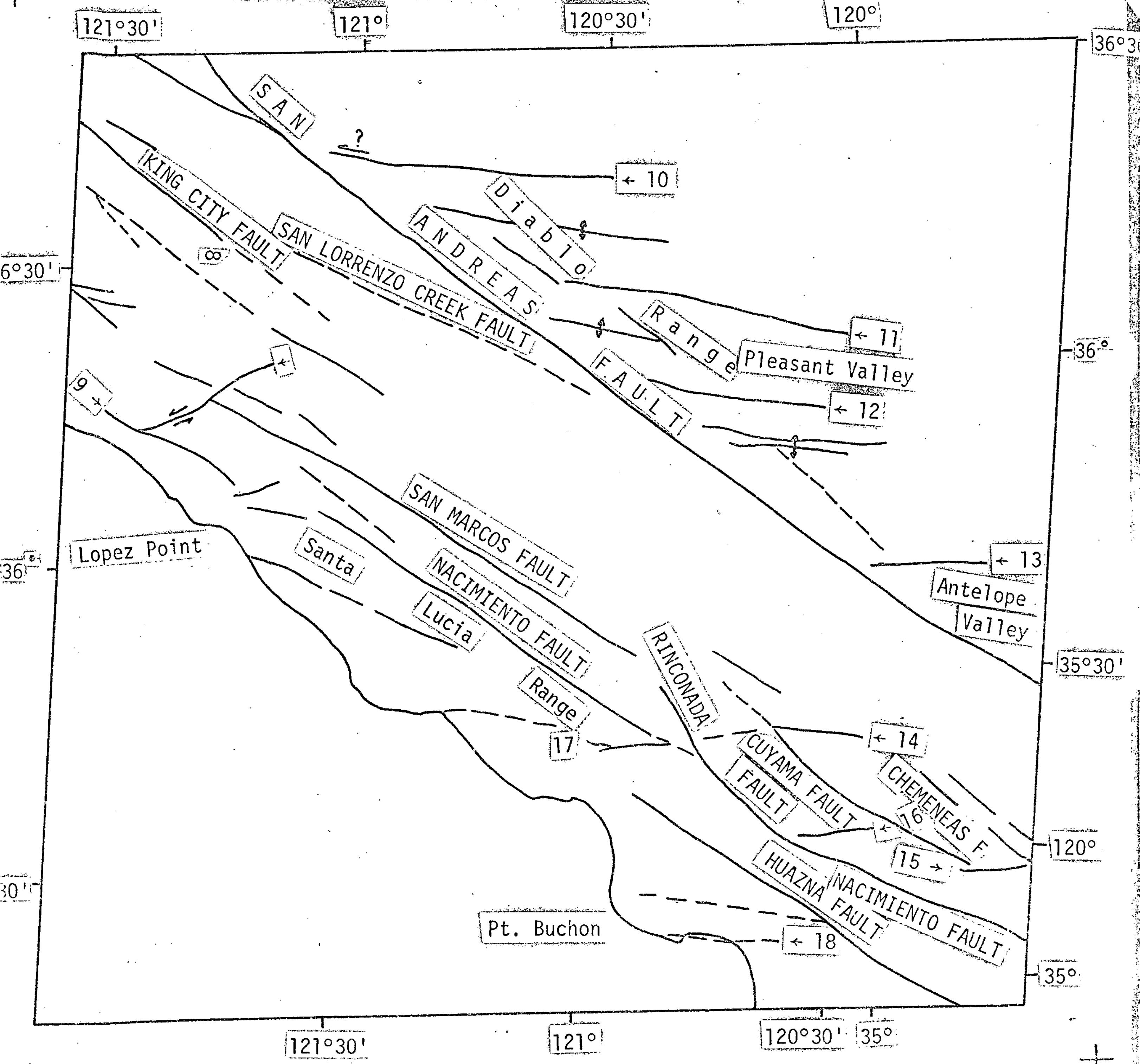
Lopez Point to Point Buchon
Reference: MSS 1056-18120, Figure 4A

This photograph which shows the southern part of the Coast Ranges (Santa Lucia Range) and the Inland Diablo Range shows that transverse faults are pervasive. In the Diablo Range several examples are noteworthy:

In Figure 4, faults 10, 11, 12, and 13 are examples. All of these lie along synclinal axes between anticlinal structures. Correlation with geological maps (Santa Cruz, San Luis Obispo sheets) shows that fault contacts occur between the Franciscan metamorphic group and the Upper Cretaceous sedimentary rocks. The Eocene and younger rocks seem to be unfaulted. This would seem to indicate that these transverse faults were active prior to the deposition of the Eocene sediments and that subsequent deformation along these structures largely took place by folding. It is significant however to note that both the Franciscan and the upper Cretaceous rocks appear to be displaced in a left-lateral fashion across these late Mesozoic breaks.

Further west in the Santa Lucia Range several transverse faults are observed lodged between Chimencas, Cuyama, Nacimiento, Huasna, and the coast line. Many of the projections of the coastline in fact appear to be

Figure 4A Fault Structures on Photograph 1056-18120



controlled by transverse faults. In the geological maps some of these structures are shown incorporated as bends in faults of the San Andreas system. We believe that reinterpretation of the significance of the transverse faults in shaping the structure of the Coast Ranges is in order. We are presently working on a fault model for the development of the fault pattern in the Coast Ranges.

Western Transverse Ranges

Reference: MSS 1037-18064 (501), Figure 5

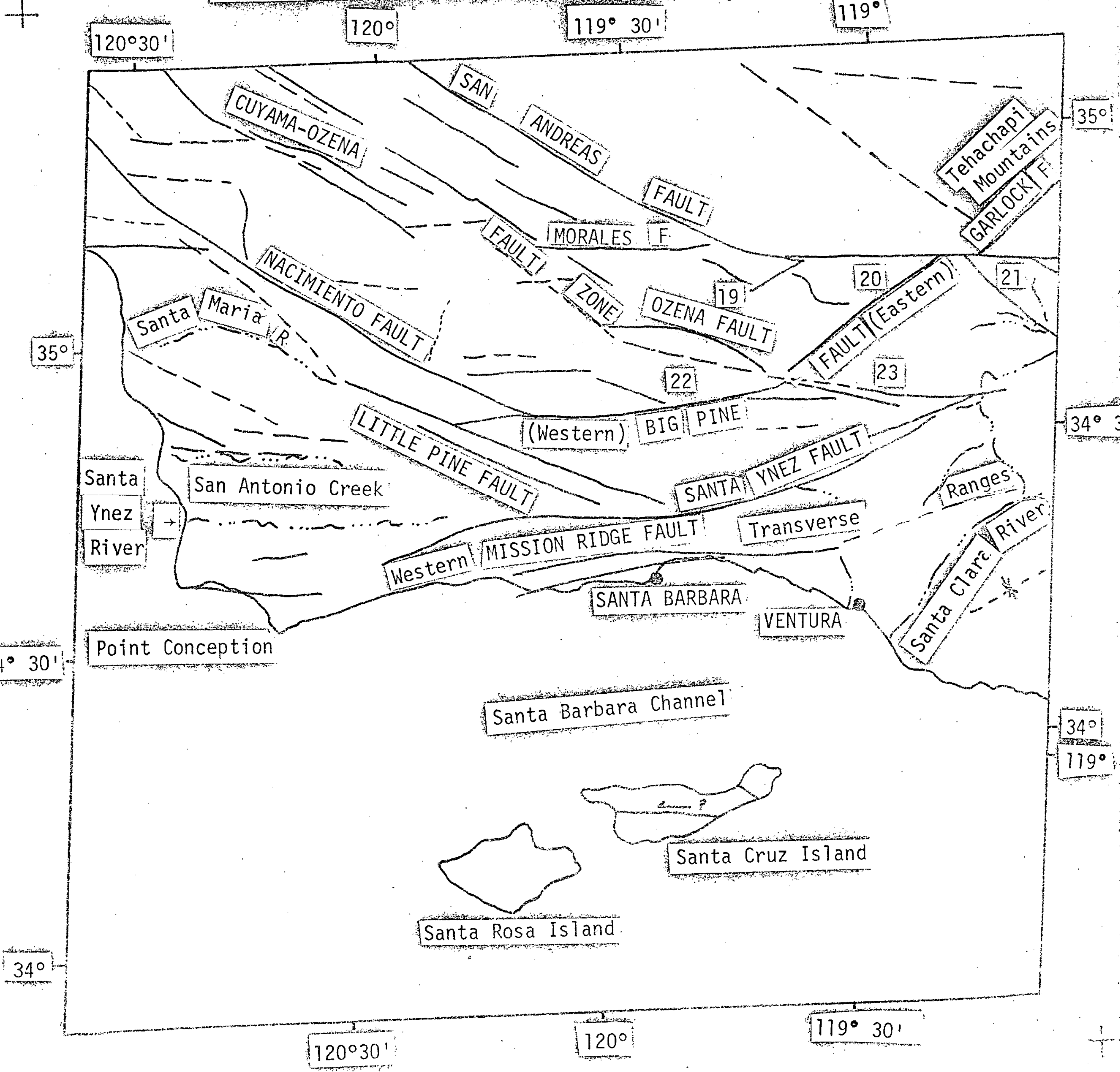
The presence of major left-lateral wrench faults in the western Transverse Ranges such as Santa Ynez, Big Pine, and Mission Ridge faults are too well known to be emphasized here. The abrupt termination of several faults of the San Andreas forming T-junctions with the Transverse faults is a problem which has been discussed (Abdel-Gawad and Silverstein, 1972). We have several observations however derived from ERTS-1 imagery which we believe are highly significant. First, the San Andreas fault along the segment between Marales and Garlock faults across the Tehachapi block appears to have an older trace which is zigzag in shape and seems to have been displaced repeatedly by east-northeast trending faults 19, 20 (Figure 5) which probably are related to the Garlock-eastern Big Pine faults.

If we ignore the Tehachapi segment of the San Andreas fault for a moment, we can visualize how the northern segment of the San Andreas may have been offset left-laterally by the Garlock-eastern Big Pine from its old route along the San Gabriel fault (21). This would suggest that the Tehachapi segment of the San Andreas is a relatively young break.

Hot Springs Lineament

The Ozena fault is shown in the Los Angeles geologic map sheet to be cut off by the Big Pine fault. We recognized from the ERTS-1 image (1037-18064) a fault lineament (22, 23, Figure 5) cutting the Eocene rocks of Sierra Madre Mountains south of Ozena fault. This fault continues across Big Pine fault, cuts across the Eocene rocks of Pine Mountain along Hot Springs Canyon and is intersected by the Santa Ynez fault. This fault lineament

Figure 5 Fault Structures on Photograph 1037-18064



is quite pronounced, has a well defined trace, and is probably an active fault. The lineament appears distinct from the Pine Mountain fault which runs approximately parallel to it and some 5-7 km to the south. Our plots of earthquake epicenters on the image show moderate seismicity in the vicinity of this lineament, particularly near its junction with the Santa Ynez fault. The occurrence of Hot Springs where this fault runs along Hot Springs Canyon supports this conclusion. The significance of this lineament goes beyond being one additional fault recognized in ERTS-1 imagery. The lineament lines up with the middle segment of the San Gabriel fault (the segment east of Newhall) and southeastward to the Sierra Madre Fault zone. To the northwest it lines up on the Cuyama fault zone. Considering this, the lineament provides a link between the Sierra Madre and the Cuyama fault zones. There appears to be an interruption of this lineament by the Santa Ynez fault. The Middle Upper Miocene rocks exposed west of Lake Piru in the White Acre Peak-Hopper Mountains do not appear to be faulted along the projection of this lineament. If we make the reasonable assumption that major faults tend to straighten their knickpoints caused by transverse offsets, propagation of faulting along this lineament would likely link it with the middle segment of the San Gabriel fault with which it lines up. The two probable routes that are candidates for breakage are along the Agua Blanca thrust and southeastward along Halsey Canyon, that is 15 km northeast of Lake Piru or along a new break in the White Acre Peak area through Lake Piru to the San Gabriel fault.

Although it is hazardous to "predict" where a given fault may break next, it seems justifiable to propose that the Piru Lake area be monitored for evidence of strain buildup.

Figure 6 is a map showing the fault relations discussed.

It is significant that the epicenter of the San Fernando earthquake (February 9, 1970) and the cluster of aftershocks is centered at a point some 40-40 km to the southeast of Piru Lake and in alignment with the Hot Springs lineament.

Earthquake Epicenters

Figures 7, 8, and 9, and 10 are copies of overlays showing computer

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Figure 7 Earthquake Epicenters on Photograph 1021-18172.

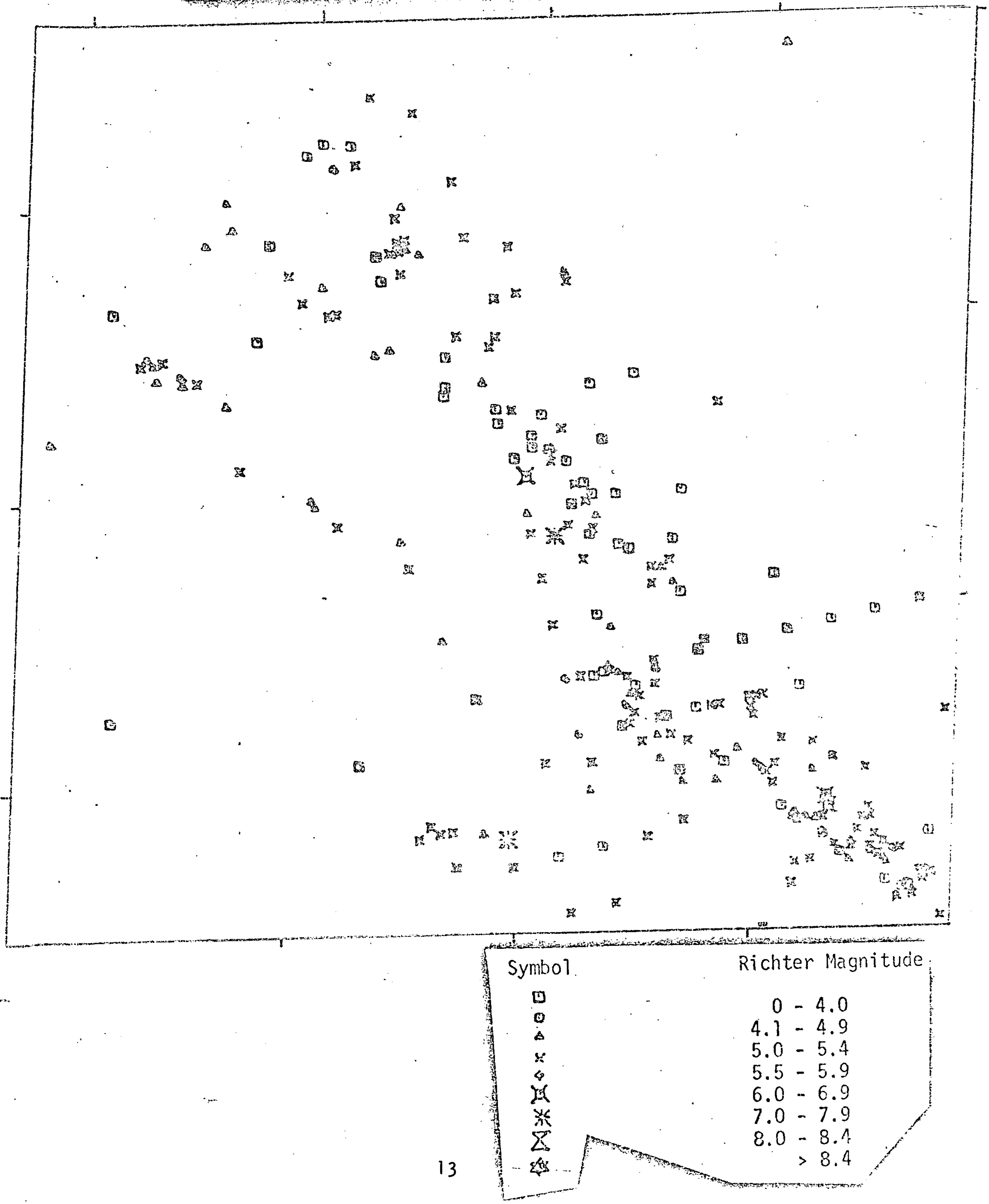


Figure 8 Earthquake Epicenters on Photograph 1021-18174

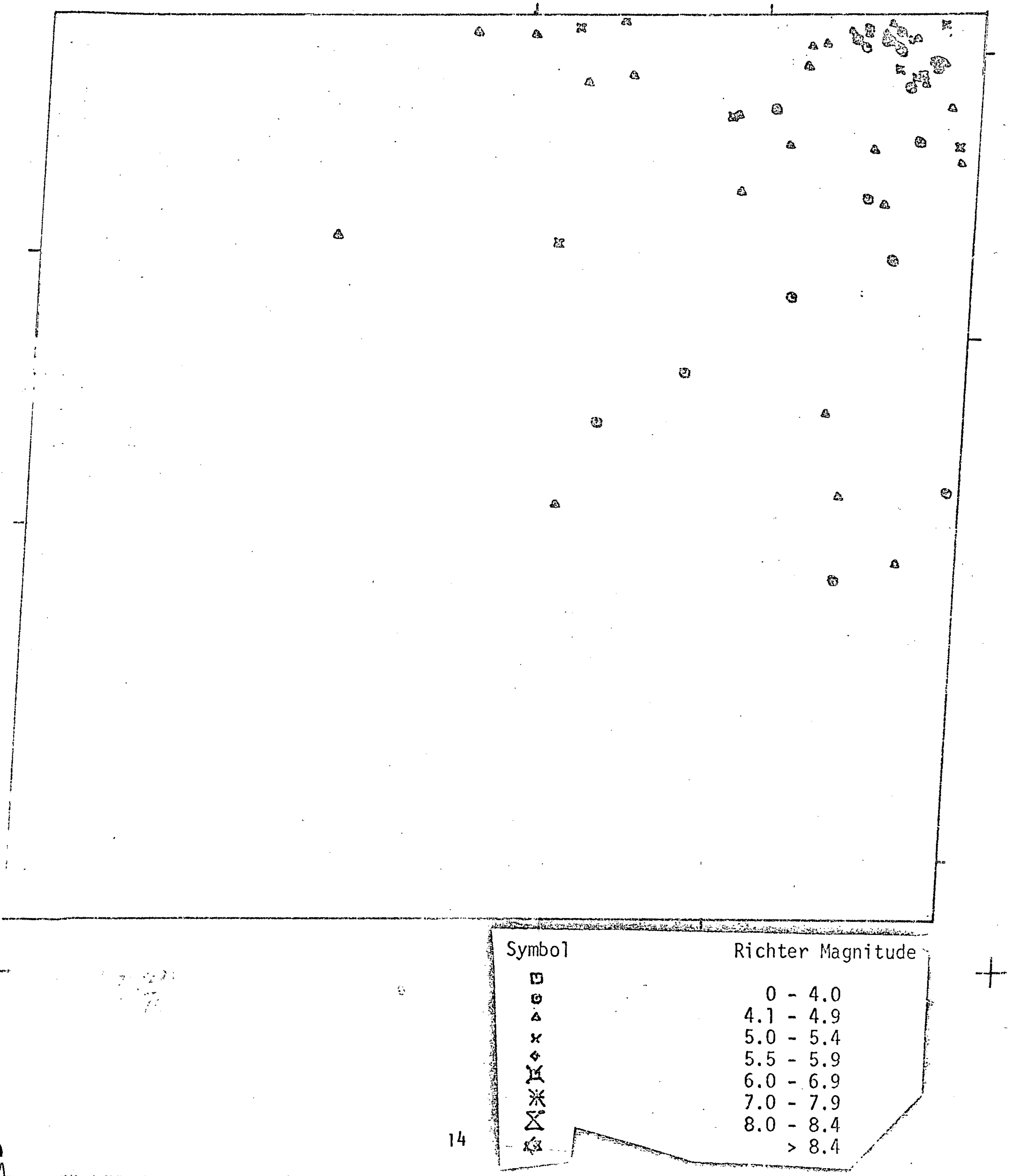
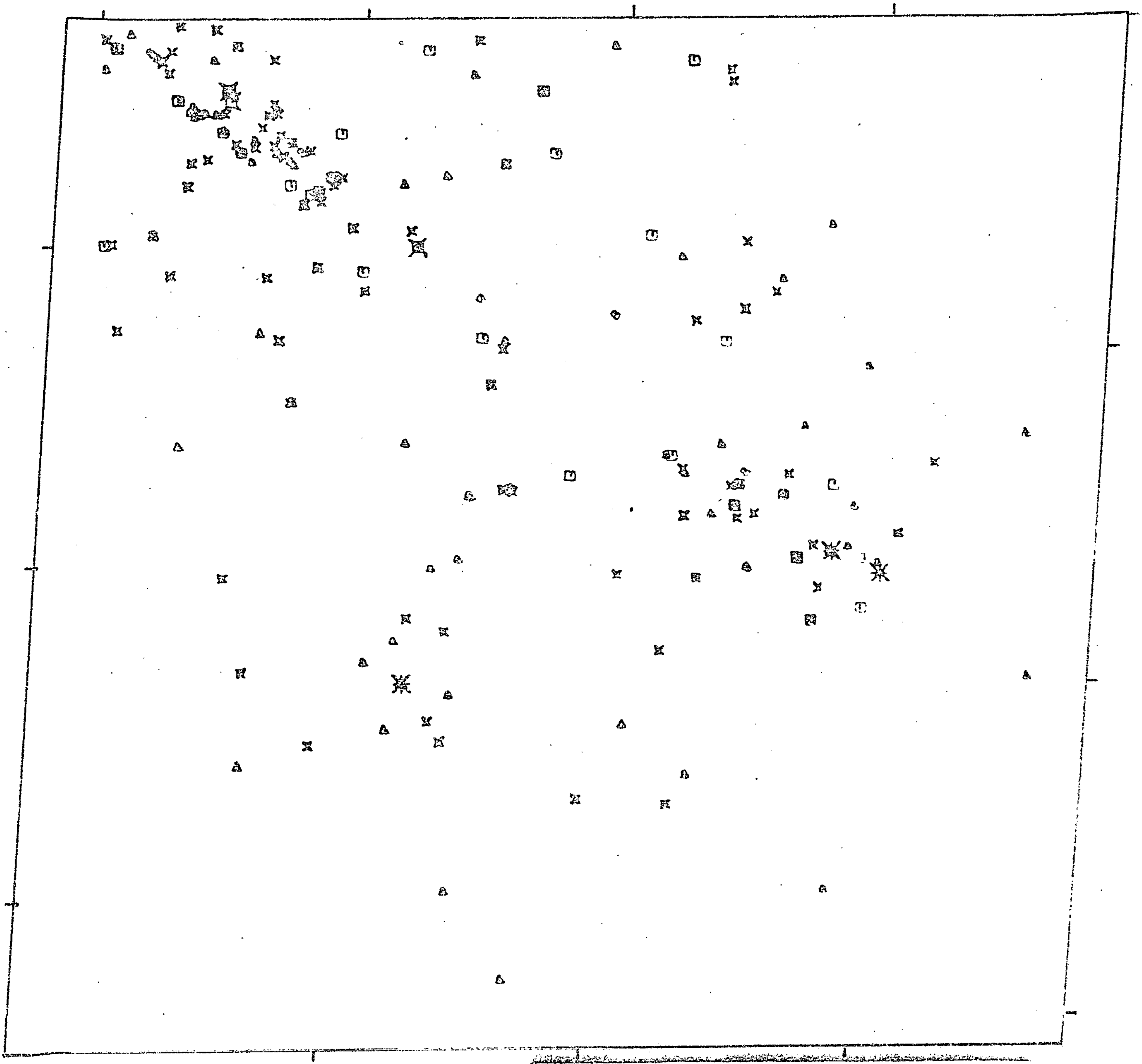
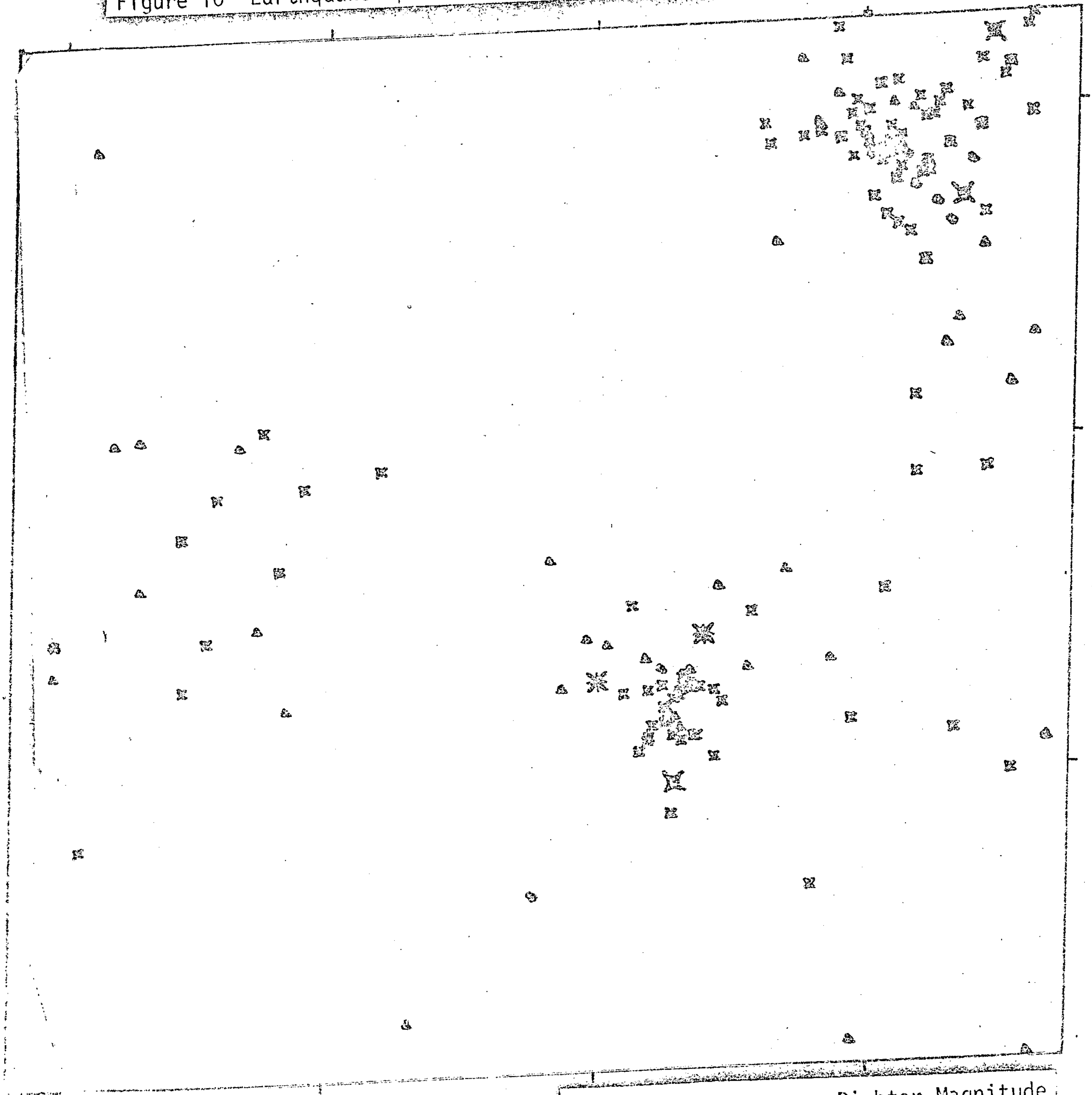


Figure 9 Earthquake Epicenters on Photograph 1056-18120



Symbol	Richter Magnitude
□	0 - 4.0
⊙	4.1 - 4.9
△	5.0 - 5.4
×	5.5 - 5.9
◇	6.0 - 6.9
⌧	7.0 - 7.9
✳	8.0 - 8.4
⧗	> 8.4

Figure 10 Earthquake Epicenters on Photograph 1037-18064



Symbol	Richter Magnitude
□	0 - 4.0
◉	4.1 - 4.9
△	5.0 - 5.4
×	5.5 - 5.9
◇	6.0 - 6.9
⌑	7.0 - 7.9
✳	8.0 - 8.4
⧗	> 8.4
✩	

plots of historic earthquake epicenters which occurred in the period 1934 through 1972 within areas covered by the ERTS-1 images listed in Table 1.

Table 1

ERTS-1 Images Used for Earthquake Epicenter Plots

MSS 1021-18172
1021-18174
1056-18120
1037-18064

Earthquake data was compiled from NOAA Geographic Hypocenter Data File (magnetic tape) January 1961 through December 1971; NOAA Hypocenter Data Cards, January 1972 through August 1972 and California Department of Water Resources Bull. 116-2 (1962).

Because the tick marks on the ERTS-1 images varied in ground accuracies up to 7 km we utilized a computer program to generate longitude and latitude grids which reduced the ground error of the grids to the order of 2 km, a value which is acceptable considering the uncertainties of epicenter determinations in the first place. Using these grids and our computer file of earthquakes (see Appendix 1) the epicenters were plotted according to the following nine categories of estimated or determined magnitudes: Unknown, 0-4.0, 4.1-4.9, 5.0-5.4, 5.5-5.9, 6.0-6.9, 7.0-7.9, 8.0-8.4, > 8.4.

The purpose for this is to obtain epicenter plots on transparent sheets which can be placed as accurately as possible on the corresponding ERTS-1 image in order to observe any significant relationship between seismic activity and structure.

Considering the importance of the San Andreas fault system as a major seismic zone, selection of this area is obviously justified. We have not yet completed this phase of the investigation. However from preliminary analysis the following tentative observations are relevant.

Preliminary Observations on Seismicity Patterns

There appears to be little or no correlation between observed evidence of recent surface breakage and the distribution of earthquake clusters.

It is quite obvious that very straight segments of the San Andreas fault showing evidence of relatively recent breakage are conspicuously quiescent. Examples are the segment between Maricopa and Colame and the segment between the Garlock intersection and Cajon Pass.

These two observations are not new and were pointed out by Ryall _et al._ (1966), Allen _et al._ (1965), and others.

There are however three significant observations which to our knowledge are not emphasized sufficiently in the literature.

First, that earthquake clusters characterize regions of complex structure where transverse faults meet or tend to distort the San Andreas system and vice versa.

Second that the earthquakes tend to cluster where propagation of a fault is likely to occur where it is offset by a crossing fault.

Third, that seismic activity and stress buildup on transverse structures and their distorting effect on the San Andreas system should receive equal attention to that given the San Andreas fault itself.

The relationship between earthquake clusters and intersections between the two fault systems is currently being analyzed.

Colorado Plateau
Reference: RBV 1013-1705

The first ERTS-1 images received on August 31, 1972 were REV prints over the central part of the Colorado Plateau. We selected from these one scene (1013-17305) showing part of the Paradox Basin and the southern flank of Uinta Basin in the area where the Green and Colorado Rivers join. Although that area was not among our high priority locations, we utilized the images to assess their quality and test our computer program for plotting earthquake epicenters.

Figure 11 shows combined overlay drawing of epicenter locations in relation to major faults. The Moab fault which lines up with Spanish and Gypsum Valley fault zones is quite conspicuous as well as the Salt Valley graben lining up with Paradox Valley through a lineament across La Sal Mountains. We were able to identify most of the major structures shown in Shoemaker's Tectonic Map (1954) reproduced in Eardley (1962, Fig. 26.7,

p. 412).

In our second bimonthly report (Abdel-Gawad, October 1972) we have reported that an important fault lineament was identified from RBV in the RBV image (1013-17305) and suggested that it may be seismically active. The location of this lineament which we referred to as the Dragerton fault zone passes in a northwest southeast direction north of the town of Dragerton, Utah through the Patmos Mountains and the southwestern side of the Tavaputs Plateau.

The Dragerton fault zone runs parallel to the Salt Valley-Paradox Valley fault zones and the Moab-Spanish Valley-Gypsum Valley fault zones.

This inferred fault is not shown on the Tectonic Map of North America (King, 1969), the Geological Map of the United States (Stose and Ljungstedt, 1960) nor in Shoemaker's (1954) Tectonic Map of the central part of the Colorado Plateau.

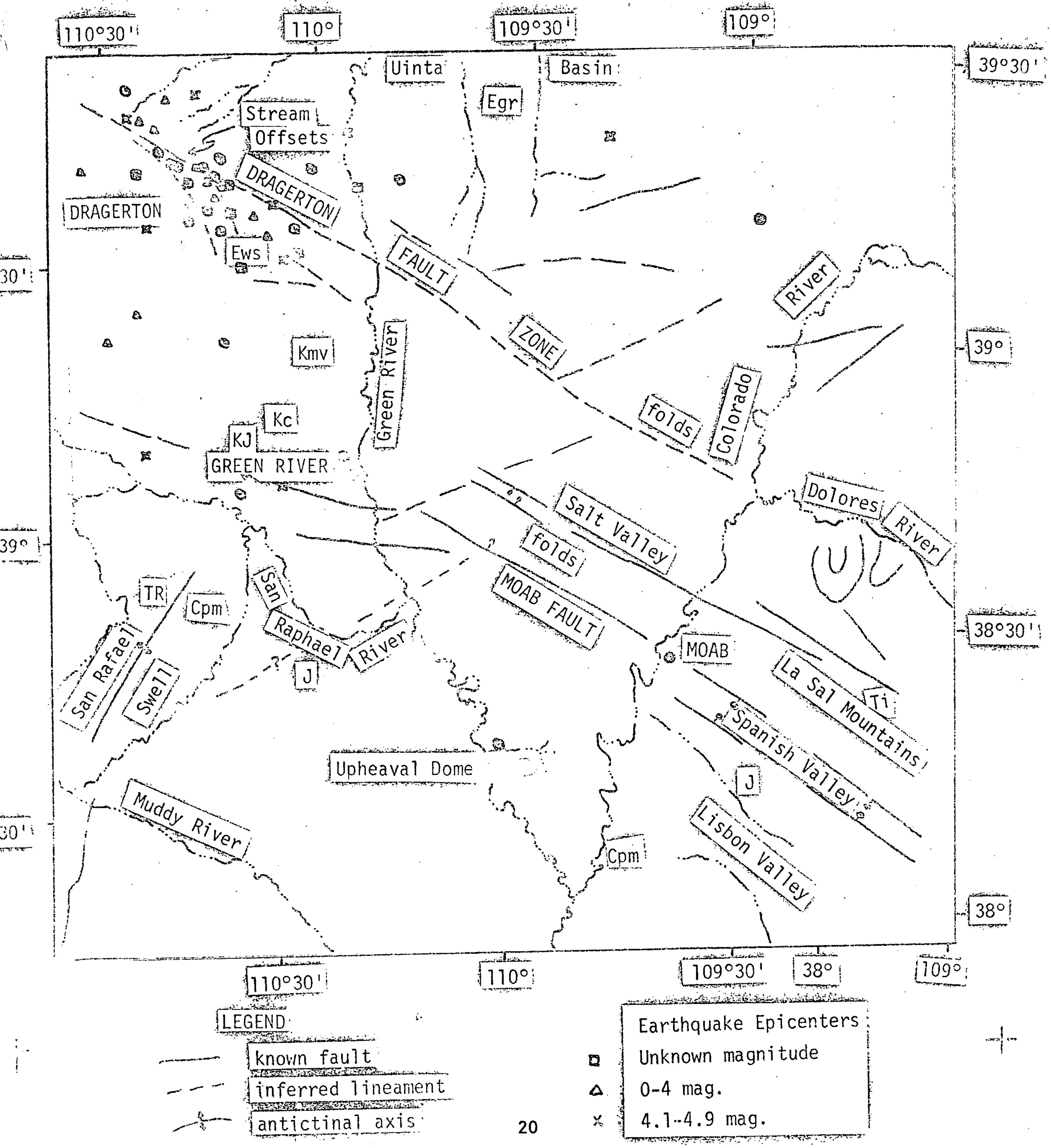
This lineament is significant for several reasons. On the southeast it projects towards the junction of the Dolores and Colorado Rivers and appears to represent a northwestward extension of a major fault lineament defining the southwestern side of the Uncompanhgre uplift as inferred from the structural contours in King's (1969) and Shoemaker's (1956) maps.

The entire tectonic line appears to project southeastward towards the Tertiary volcanic fields of San Juan Mountains, Colorado.

An earthquake cluster with shocks up to magnitude 4.9 is located in the vicinity of this lineament near latitude 39°39'N. The cluster is somewhat scattered but appears to be elongated parallel to the lineament. There, one can clearly observe many geomorphic criteria of faults trending northwest-southeast and north-south. Several faults appear to have had recent movement, perhaps right-lateral as inferred from stream offsets (Figure 11).

It is interesting to note that this moderate seismic activity is concentrated in this area which is relatively near the reentrant made by the southwestern flank of the Uinta Basin (which the lineament appears to control) with the north trending Wasatch tectonic line. The part of the lineament directly west of the Colorado River is associated with folds of the type observed associated with the Moab fault.

Figure 11 Fault Structures and Earthquake Epicenters on Photograph 1013-17305



Geologic Legend for Photograph 1013-17305

Eb	Bridger formation (Uinta formation in Uinta Basin), Upper Eocene
Egr	Green River formation, Eocene
Ews	Wasatch formation, Eocene
Efu	Fort Union formation, Eocene
El	Lance formation, Eocene
Kmv	Mesaverde formation, Cretaceous
Kc	Colorado Shale, Upper Cretaceous
KJ	Upper Jurassic-Lower Cretaceous (Dakota to Morrison formation)
J	Navajo, Kayenta, and Wingate Sandstone formations, Jurassic
TR	Triassic rocks: Chinle formation, Shinarump Conglomerate, Moenkopi formation
Cpm	Lower Permian (e.g. Kaibab Limestone, Coconino Sandstone, Hermit Shale, Supai formation)
Ti	Tertiary Intrusives

The lineament, like the Moab and other northwest trending lines in the Colorado Plateau is probably a Laramide break which may have controlled the emplacement of the Tertiary intrusives such as La Sal Mountains.

Program for Next Period

During the next reporting period our plans are:

1. extend our plotting of earthquake epicenters southward to cover the southern segment of the San Andreas fault and study its intersection with the Eastern Transverse Ranges and its extension to the head of the Gulf of California;

2. work on developing a fault model for the Coast Ranges.

Conclusions

ERTS-1 imagery is providing valuable information on continuities of active faults and their interaction with intersecting structures.

Data obtained so far indicate the feasibility of identifying geomorphic criteria of recent activity on faults.

Preliminary analysis of seismicity patterns indicate that areas showing geomorphic criteria of recent faulting are not the most seismically active. The earthquake clusters appear to characterize areas of complex structure where one fault system has displaced or otherwise distorted another. A tentative conclusion is that areas of earthquake clustering may represent locations where fault propagation is likely to occur.

Recommendations

Due to the promise found in ERTS-1 imagery in studying seismicity and fault patterns we recommend that this objective receive more emphasis during this investigation. We recommend that the objective stated in our proposal to study the relation of mineral deposits to structure be explored but as a secondary objective.

Appendix

Description of computer program to generate corrected geographic grid

A Fortran program was written which uses the basic orbital parameters of satellite latitude and longitude, elevation, and heading, along with the enlargment factor of the photograph to generate a corrected geographic grid. The program is run on a CDC 6600 computer and a Calcomp drum plotter is used to plot the results. The main problem we encountered with the grids supplied by NASA was that the grid was shifted as much as 7 or 8 mm which resulted in errors of up to 7 kms. These grids also had no internal tic marks so there was no correction for curvature and the longitude lines were drawn in straight instead of curved. There was also some ambiguity as to wich part of the tic mark the grid line should connect to. Our grids corrected for curvature and were drawn by the plotter. We positioned the grid by locating 2 or 3 parts of known coordinates on the photograph and placing the grid in its proper orientation over these known points.

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THE FAULT PATTERN OF SOUTHERN CALIFORNIA:
A MODEL FOR ITS DEVELOPMENT

M. Abdel-Gawad and J. Silverstein
North American Rockwell Science Center
Thousand Oaks, Calfiornia

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A MODEL FOR ITS DEVELOPMENT

M. Abdel-Gawad and J. Silverstein
North American Rockwell Science Center
Thousand Oaks, California

ABSTRACT

The fault pattern in southern California, dominated by two sets of wrench faults, is complex and has many conflicting features. Outstanding examples are reported discrepancies of offsets on various segments of the San Andreas fault and abrupt termination of wrench faults with large lateral displacements. Utilizing satellite photographs to study fault intersections, it was recognized that the fault pattern consists of combinations of a few simple geometric fault forms; simple intersections (x-forms), abrupt termination of wrench faults by others (T-forms), and simple and multiple furcations (h and m forms) are common. More significant is observation of short fault segments of one set between throughgoing faults of the other set (H- and ladder-forms). The fault relationships indicate that southern California has long been subject to two independent and episodically active shear systems. We shall present results of an experiment to develop a fault model based on this concept. A sequence of episodic lateral movements on two shear systems affecting a hypothetical crustal block was performed using a computer to identify geometric relationships. Progressive development of various fault forms, the overall fault pattern, and its mosaic of blocks in the model will be compared to analogs in California. The apparent offset discrepancies of the San Andreas fault will be shown to be inevitable features if the model is a valid analog of the fault's history. An important conclusion of the paper is that the two shear systems are not likely to result from a unified nor continuous stress field, but rather represent episodic and independent activities. Some implications on the tectonic history of California are discussed.

INTRODUCTION

> "Like Humpty-Dumpty, all the King's horses and all the King's men cannot put the Coast Ranges back together again."
> King, 1959, p. 171.

Geologists who have studied the San Andreas fault in detail have long been puzzled by complex and often conflicting features, many of which still post serious difficulties in understanding the true nature of the fault and its tectonic history. The problems become even more compounded when the San Andreas fault is considered in relation to the structures of the Transverse Ranges which intersect it in southern California.

That the San Andreas fault represents a major crustal break along which considerable lateral movements have probably taken place is a matter few geologists will now disagree upon. Controversy still exists, however, concerning the true nature of this break, the amount of displacement along its various segments with time, and what it really represents in terms of crustal plate interactions. The San Andreas fault, or at least certain segments, may have been active since the Cretaceous and in places its activity is demonstrable at present.

The Transverse Ranges are characterized by east trending folds and thrusts which are involved with the San Andreas system in a most complicated manner, and according to Dibblee (1966) and Crowell (1954) contain important wrench faults characterized by left-lateral shear. The Transverse Ranges were mostly developed in the Pliocene and Pleistocene (Bailey and Jahns, 1954, p. 92), but the initiation of the system may date as far back as the Mesozoic (Buwalda, 1954, p. 137). Left-lateral wrench movements on many transverse faults probably have taken place in the Quaternary and some may still be active at present. Indeed, the faulting which triggered the San Fernando earthquake of February 9, 1971 has been found to be characterized by northward thrust motion of equal magnitude to left-lateral shear along an east trending fault zone.

It seems evident that Southern California has been affected for a long time by two intersecting sets of periodically active and mutually displacive shear faults. If this concept is basically valid, then we would expect the fault pattern developed to reflect this episodic interaction.

The main objective of this paper is to show that the geometry of the fault pattern in Southern California, including many of the puzzling discrepancies is consistent with this basic concept.

Towards that objective we shall 1) describe examples from satellite photographs supported by independent field data of significant fault intersections which bring to a sharp focus the complex relationships involved;

2) Present the results of an experiment to develop a fault model based upon this concept in which we utilized the computer to perform a sequence of lateral movements on two sets of wrench faults and compare the resultant complex fault pattern to its analog in nature; and

3) Discuss some implications of this fault model on current discussions concerning the San Andreas fault and its relation to Pacific structures.

Many observations on the geometric relationship of faults and fault forms fundamental in the development of the fault model could hardly have been made without the advantage of synoptic earth photography experiments performed by NASA during Apollo, Gemini, and ERTS-1 earth-orbiting missions. Contributions on the application of satellite photographs to regional geological problems have been made by Abdel-Gawad (1969, 1970, 1971), Bannert (1972), Lowman (1969 a,b; 1972), Merifield (1972), and others.

The pictures reproduced here in black and white were selected from more than fifty color and infrared color pictures of southern California and adjacent areas taken from orbital altitudes in various perspectives.

BACKGROUND

Peculiarities of the San Andreas Fault

The great faults of California such as the San Andreas, Garlock, Nacimiento, San Gabriel, San Jacinto, and Elsinore have been described as deep-rooted and long-active wrench faults which present many problems. In the northern part, between San Francisco and its intersection with the Garlock fault, the San Andreas fault is rather straight with rift topography and shows evidence of large lateral displacement. The fault bends eastward before its junction with the Big Pine and the Garlock faults, cuts the Transverse Ranges in an east-southeast direction, and splits into two major faults, the San Andreas and San Jacinto at the northern side of the San Gabriel Mountains, becoming involved in a complex way with the east trending faults of the Transverse Ranges (Hill, 1954, p. 5).

On the south side of the San Bernardino Mountains the San Andreas fault is again involved in a very complex way with the east trending faults of the Eastern Transverse Ranges. There, the fault abruptly changes trend and is distinguished by several unusual features such as the absence of typical rift topography, stream offsets, or intense earthquakes along much of its ill-defined trace. Evidence of thrusting rather than strike-slip movement during the Quaternary is evident. As described by Hill (1954, p. 5) the interaction of the faults there is also extremely complicated, and the time relations of movements are not at all clear. The unusual features of the southern segment and the reconciliation of it with the San Andreas fault farther northwest indeed poses a most provocative structural problem.

Discrepancies in Fault Displacements

A most peculiar feature of the San Andreas fault is that the amounts of displacement along its various segments appear to differ by as much as a factor of two and perhaps more (Dickinson and Grantz, 1968). Hill (1954) has long advocated that the San Andreas fault is a zone along which some segments are several miles wide and contain several separate fault strands which were first developed in pre-cretaceous times and that the right-lateral slip has characterized the movement from its inception to the present time. The right-lateral displacement, according to Hill's estimates, amounts to at least 104 km and perhaps more than 560 km. It is also well known that not all segments of the fault are equally active. The net displacement along its various segments appear to be inconsistent with a single fault zone. Noble (1954, p. 44), for example, presented quantitative evidence for pre-upper Pleistocene right-lateral displacement of at least 48 km on a 67 km segment between the western border of the Pearland Quadrangle to Cajon Creek and noted that this 48 km displacement since late Miocene on that segment is considerably less than the estimate given by Hill and Dibblee (1953, 447-448) for movement along a northerly part of the fault during this same period. He reasoned that if one accepted the speculation offered by Hill and Dibblee (1953, p. 453) that the San Gabriel and San Jacinto faults may be ancestral portions of the San Andreas fault, it might be possible that their aggregate movements would bring those conflicting estimates more nearly in accord. Crowell (1954) has cited evidence that movement on the San Gabriel fault cannot exceed 64 km in a right-lateral sense.

Discrepancies in the total displacement on the San Andreas fault are equally puzzling. In the northern segment, from San Francisco to the latitude of Bakersfield, the total displacement has been estimated as 600 km since the Jurassic (Hill and Dibblee (1953); Hill, 1954, 4, p. 12). On the other hand correlation of basement rocks in southern California suggest no more than 275 km total displacement since the inception of faulting (Crowell, 1962). It has been suggested that a substantial part of the total displacements along the northern part of the San Andreas fault may be represented to the southeast by the displacements along the San Jacinto and Elsinore faults (Jahns, 1954; Noble, 1954). In the section south of the Garlock fault intersection the displacement on the San Jacinto fault which runs along the eastern edge of the San Gabriel Mountains is about 22 to 29 km (Noble, 1954), a figure consistent with Sharp's (1965, p. 160) estimate of the displacement on the southern part of the San Jacinto fault, which indicates that the San Jacinto fault could never have been involved with the northern segment of the San Andreas fault during its entire history.

Larger displacements have more recently been proposed. Suppe (1970, p. 3253) argued for a two-stage movement history for the northern segment of the San Andreas totaling approximately 600 km and a one stage 300 km movement on the southern segment. Anderson (1971, p. 52) conjectured that the northern segment has moved only some 480 km. In their attempts to account for these discrepancies both authors proposed essentially that the San Andreas fault may represent two different faults formed at different times in different ways and may be moving at different rates. Disagreements on displacement values aside, this concept is highly significant.

Interaction with Transverse Faults

The uplift of the Transverse Ranges and development of its folds and thrusts has taken place essentially in the Pliocene and Pleistocene although there is evidence that some transverse structures may have been initiated much earlier. The grain of Paleozoic rocks exposed in the Tehachapi Mountains trend east and northeast parallel to the Garlock fault which suggests that the easterly trend of the Transverse Ranges may have been initiated before Tertiary time. According to Allen (1957, p. 320) and Hsu (1955) the east-trending cataclastically deformed rocks along the southern margins of the San Bernardino and the San Gabriel Mountains indicate that at least some episodes of the transverse deformation may have occurred earlier than the northwest trending San Jacinto fault zone which transects them.

Yeats (1968, p. 307) suggested that a large left-lateral movement had taken place on the Channel Islands and Malibu faults. There is evidence of 16 km left lateral movement on the Big Pine fault of the western Transverse Ranges (Hill and Dibblee, 1953, Vedder and Brown, 1968, p. 242). Left-lateral movement has also been suggested along the Santa Ynez fault.

The overlap of the time span of activity of the San Andreas and Transverse fault sets is significant and should be reflected in the fault pattern. The distinctive pattern of linear subparallel faults system such as the San Andreas, San Jacinto, Elsinore faults of the Peninsular Ranges (Figure 1). At the same time the east trending faults of the western part of the Transverse Ranges (e.g. Big Pine, Santa Ynez, and Malibu-Raymond faults) appear to be offset right laterally from east-trending faults (e.g. Pinto, Blue Cut, Aqueduct) of the eastern Transverse Ranges. The Banning fault at the southern margin of the San Bernardino Mountains may be the offset continuation of the Sierra Madre fault at the southern flank of the San Gabriel Mountains (Sharp, 1965). Beside this apparent offset of the Coast Ranges relative to the Peninsular Ranges and the western relative to the eastern Transverse Ranges, simple offset features are quite often observed at the intersections of individual faults of both sets and this is evident particularly in the central part of the Transverse Ranges (San Gabriel-Pine Mountain area).

These apparent offsets are so mutual that it is difficult to ascertain which of the fault sets is older than the other. This fact has been emphasized by King (1969, p. 172). It is hard therefore to avoid the conclusion that individual faults of both sets have been episodically active over a long period of time. The general overlap of activity on both sets of faults may be responsible for the complexity of the fault pattern.

FAULT PATTERN AND GEOMETRIC FORMS

The framework of major faults in southern California has a distinctive pattern. North and south of the Transverse Ranges the faults are predominantly linear subparallel and trend northwest (Fig. 1 and 2); this geometry is predominant in the Coast Ranges as well as the Peninsular Ranges. The western and eastern parts of the Transverse Ranges are characterized by predominantly east-trending faults. In the central part of the Transverse Ranges where the two fault sets meet the structure is a complicated mosaic of rhombic blocks bounded by faults of both sets. The general fault pattern when examined in detail appears to consist of various combinations of distinctive geometric forms, which, as we shall demonstrate can be produced by a rather simple model of episodic faulting. Before doing that, it is necessary to describe some outstanding features of the fault pattern and its geometric forms using as source of data well known fault maps of California and when appropriate observations from Gemini and Apollo photographs.

In order to avoid ambiguities or misunderstanding, it is appropriate at this point to make some definitions used in this paper as clear as possible.

By fault pattern we refer to the overall geometry of the fault framework and that includes all the major faults of the San Andreas and the Transverse sets.

A fault form is the simple geometric figure made by a fault trace or by several faults at their junctions. Thus, we may refer to a straight form; a zigzag form; an x-form made by two intersecting faults; a T-form made by a fault terminating another. The total combination of fault forms made the fault pattern.

A fault segment refers to either a fault which appears now as a separate entity even though it may have been part of a larger fault or to a part of a fault which has distinctive characteristics, or behaved independently of other segments of a fault.

A fault ancestor refers to an old fault which due to subsequent tectonic movements was modified, segmented, offset, or otherwise its entity obliterated.

A fault zone refers to closely spaced subparallel faults and to several faults so nearly aligned as to be considered continuous.

A fault set refers to all faults or segments which are similar in geographic orientation. The San Andreas set refers to all faults trending northwest parallel to the San Andreas trend from San Francisco to the Garlock fault intersection. The Transverse set refers to all faults trending east. This set actually varies from east-northeast (e.g. Garlock fault) to west-northwest. The term system is avoided except when referring to the literature because the term San Andreas system has frequently been used to include faults which belong to both sets. The Garlock fault, for example, has been often included in the San Andreas system and is considered here as a member of the Transverse set. The term fault movement is used to describe the relative movement of blocks on either side of a fault. We will be mainly dealing here with right-lateral movements on the San Andreas set and left-lateral movement on the Transverse set.

The term offset will be used to describe only the displacement of two segments of a fault or any lineament or block by a movement on a cross-cutting fault.

Termination of Wrench Faults (T-Form)

Many wrench faults of the San Andreas and Transverse sets appear to terminate abruptly, often against a cross fault. Examples are the termination of the Garlock fault against the San Andreas (Fig. 1 and 2), the northern end of the Inglewood-Newport fault against the east trending

Malibu-Raymond Hills fault zone (Fig. 1 and 2).

In contrast to the San Andreas fault which bends near its junction with the Garlock fault, the Nacimiento fault, a most prominent break along the Coast Ranges and the Cuyama-Ozena fault zone come to sudden ends making T-form junctions with the Big Pine fault. The Huasna fault zone, which includes Little Pine, Suey, and Huasna faults, in the Coast Ranges terminates at the left-lateral Santa Inez fault of the western Transverse Ranges. On the other hand, the eastern end of the Santa Ynez fault appears to terminate against or near the San Gabriel fault (Fig. 1).

Figure 3 shows the western Transverse Ranges at the critical junction with the Coast Ranges of California. The red-band image (0.6-0.7 micrometers) was taken on August 29, 1972 by the multispectral scanner operating aborad the Earth Resources Technology Satellite (ERTS-1) launched by the National Aeronautics and Space Administration.

The image illustrates the complexity of the structures at the intersection of the northwest trending coast ranges with the east trending Transverse Ranges. Several observations are relevant to our discussion:

The San Andreas fault, which has been generally described as bending near its intersection with the Garlock fault can perhaps be better described as being formed of two distinct segments in this area. A rather straight northwest trending segment (1) joining a zigzag segment (2) trending west-northwest, parallel to the transverse structures. The latter segment could have been part of the transverse fault structures or has to say the least been affected by them. The three small blocks lying south of that segment (3, 4, 5) suggest that left-lateral offsets have taken place prior to the incorporation of this segment (2) by the San Andreas fault. The Garlock and Big Pine faults are both left-lateral faults which join the

the San Andreas in T form junctions. The Nacimiento fault zone, a member of the San Andreas set with right-lateral wrench movement comes to an abrupt T-form junction with the Big Pine fault (6).

As shown in the geological Atlas of California (Los Angeles sheet), the Nacimiento fault is not straight along its entire length. Near its junction with the Transverse Ranges, it is shown to bend eastward in a manner similar to the bends ascribed to the San Andreas fault which suggests that some parts of this fault may have been affected by old segments of transverse structures.

The Huasna fault zone terminates (7) or displaces the western end of the Big Pine fault, but is terminated (8) or displaced by the left-lateral Santa Ynez fault. We noted that certain parts of the Huasna fault zone are characterized by sharp geomorphologic lineaments and stream deflections which suggest recent fault movements. Examples are observed in the Middle Miocene rocks of the San Rafael Mountains along and in the vicinity of the Suey fault (9); Township R31W, T10N, Santa Maria Geologic Map Sheet.

In the eastern part of the Transverse Ranges many examples of T-form junctions are evident in satellite photographs.

Figure 4 is a Gemini 5 photograph of the area around the Salton Sea in southern California. The San Andreas fault zone runs approximately along the middle of the picture and separates the Peninsular Ranges, the Salton Sea trough and Imperial Valley depression (foreground) from the eastern Transverse Ranges and the Basin and Range Province (background). The San Andreas fault here separates two areas of radically different fault trends. In the Peninsular Ranges (foreground) throughgoing wrench faults of the San Andreas set dominate the fault pattern and trend northwest. In contrast we find that across the San Andreas fault the dominant faults in the eastern Transverse Ranges trend east. Three important faults, Pinto Mountain (1), Blue Cut (2), and Aqueduct (3) meet the San Andreas fault zone in remarkable T-form junctions (T1, T2, T3). Although the present trace of the San Andreas fault appears to terminate these faults, we observe several lineaments (e.g. 5-5, Fig. 4) parallel to the San Andreas fault which appear to be offset in a left-lateral sense by the Blue Cut Fault (2). The western edge of the block lying on the eastern side of the San Andreas fault (Chocolate, Orocopia, and Eagle Mountains) makes a zigzag form which when considered together with the T-junctions suggest that the movements which took place along the Pinto Mountain, Blue Cut, and Aqueduct faults were followed by a renewed movement on the San Andreas fault. According to T. W. Dibblee (Sharp, 1966, p. 93) the Pinto Mountain fault shows evidence of 16 km left-lateral movement since late Cretaceous and several fresh scarps in alluvial fans just east of Twenty-Nine Palms indicate Holocene activity.

It is of interest to recall that the Pinto Mountain fault was first described by R. T. Hill (1928, p. 146, named the Pinto Mountain Rift) which he considered one of the major faults of southern California, extending east to the vicinity of the Colorado River. Hill (1928) recognized an alignment with east-trending faults west of the San Andreas fault forming what he termed the Anacapa lineament extending westward beyond the Channel Islands.

The Aqueduct fault lies along the Orocopia lineament, described by Hill (1928) as showing rough-like rift features in places. The fault coincides with an east-trending low gravity anomaly (Biehler <u>et al</u>., 1964, p. 140).

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The Blue Cut fault shows evidence of left-lateral movement in late Tertiary and perhaps also in the Pleistocene.

The Pinto Mountain and Blue Cut faults, however, meet the San Andreas fault zone near the junction of its southern and middle segments where the fault undergoes a major westerly swing. This swing may be ascribed to the offsetting influence of the Transverse faults. Yet the T-form junctions indicate younger movement on the San Andreas fault. This apparent discrepancy, as we shall deomonstrate later, is a feature inherent to the concept of episodic movements on the two fault sets and should be expected. The middle segment of the San Andreas fault may have been in fact an older segment of the Transverse set and was later acquired by the San Andreas fault.

The Aqueduct fault, on the other hand, seems to come to an abrupt end in a T-form against the San Andreas fault zone. If the Aqueduct fault was once throughgoing, its segments west of the San Andreas may now be located somewhere towards the northwest, perhaps within the San Gabriel Mountains and further along the western Transverse Ranges.

The eastern end of the Pinto Mountain and Blue Cut faults project against the Sheephole fault on the western side of the Coxcomb Mountains. Sharp (1966) considered several alternatives for this apparent termination of the Blue Cut fault and conjectured that it may be offset in a right-lateral sense by the Sheephole fault which runs under the Chuckwalla Valley (Fig. 4). A fault lineament (4) of the San Andreas set terminates against the Aqueduct fault in a T-form junction (T4). It will become apparent when discussing the fault model that fault lineament 4 may be a displaced segment of a San Andreas fault ancestor or another member of the set.

We have described here only a few examples, but a careful study of the fault maps of California reveals that T-form junctions of wrench faults are quite common. It is apparent that when these junctions involve proven or suspected wrench faults with large lateral displacements, the abrupt termination of these faults is highly significant and requires explanation.

H-, Ladder-Forms

Another significant feature of the fault pattern is that many faults particularly of the Transverse set occur as short segments between throughgoing San Andreas set faults. Many make a simple H-form and in other combinations several short segments are arranged between two parallel faults like the rungs of a ladder. The short segments often terminate against the bounding faults with no apparent bends or offsets. In other cases a bend in the throughgoing fault is observed near its junction with the cross faults.

The Geological Atlas of California shows many H and ladder forms; the east trending fault segments between the San Andreas and San Gabriel faults are examples, Fig. 1. Others are observed in the satellite photographs of the Coast Ranges and the Peninsular Ranges.

In the Coast Ranges, lineaments of the Transverse trend (L, Figure 3) are observed between the San Andreas, Cuyama-Ozena, Nacimiento and Huasna fault zones. Some of these correspond in the geological maps to fold axes trending oblique to the strike of principal right-lateral faults, a common secondary feature of wrench faults as pointed out by Lowman (1972). Many others correspond to transverse-trending faults associated with no known folds. A notable example not shown in Figure 3 is the Willow Creek fault (Santa Cruz sheet), a left-lateral fault lying transversely between Nacimiento and Salinas Valley (King City fault). That the east-trending faults segments within the Coast Ranges may be offset remnants of old transverse wrench faults is worthy of consideration and will be discussed further in the text.

Figure 5 shows a part of the Peninsular Ranges Province which continue southward into Baja California. The rocks exposed in the mountainous area are mostly granitic intrusives of the great Baja-Southern California batholith of late Mesozoic age and roof pendants of Pre-Cretaceous metamorphic rocks. The picture shows the remarkable northwest-trending linear wrench faults of the San Andreas set which cut boldly across older structures. These faults contrast with the east-trending wrench faults of the eastern Transverse Ranges east of the San Andreas fault (Figure 4).

We can infer from Figures 4 and 5 many short segments (L arrows) of east trending faults between linear faults of the San Andreas set. Notable examples are observed between the San Andreas and the San Jacinto faults; others are observed between the San Jacinto fault and Agua Caliente fault and between the latter and Elsinore fault. Further west, the Santa Ana Mountain block appears to be cut by east trending fault segments lying between the Elsinore fault and the Newport-Inglewood fault.

The western side of the Peninsular Ranges appears to be marked by a lineament, passing from northern Baja California towards El Cajon and northwest towards Vista, California (5, Fig. 5). The fault zone which we will refer to as El Cajon lineament may mark an old fault segment of the San Andreas set. Because of its somewhat ill-defined and probably old age, it is not as obvious as the more prominent faults further inland

and may be offset at various places by east-trending cross faults. The continuity of the lineament north of Vista is uncertain and may be interrupted or left-laterally offset by transverse structures southeast of San Onofre. Since the Inglewood-Newport fault projects southeastward towards the vicinity of San Onofre and perhaps continues offshore towards San Diego, the fault appears to make an h-form junction with the El Cajon lineament (Figure 1). The El Cajon lineament coincides approximately with the western boundary of the Peninsular Ranges and the eastern limit of the coastal belt covered by Tertiary and Quaternary marine sedimentary rocks.

The possible existence of a large fault there has been recognized by Miller (1935, p. 1539) and even earlier by Ellis and Lee (1919) who conjectured that a great fault existed near the western boundary of the Peninsular Ranges during late Cretaceous and early Tertiary times and that the Cretaceous and Tertiary marine beds of the coastal belt were laid down on the subsiding area west of that fault. Renewed activity along this fault during Quaternary time was suggested by Miller (1935, p. 1540).

Further west a probably fault zone (6, Figure 5) runs along the Soledad Valley east of La Jolla and may be still active. Slightly west, the Rose Canyon fault (7) extends from Point La Jolla southeast, runs east of Mission Bay, and cuts the Quaternary Alluvium (Hertlein and Grant, 1954). It is conjectured that these faults may be the southward extension of the Inglewood-Newport fault zone. The El Cajon lineament may have been related to the Inglewood fault by a common ancestor. The structure of the western Peninsular Ranges between Elsinore fault and El Cajon lineament is dominated by two fault trends which profoundly influence the drainage pattern.

The east trending structures of the Transverse set product a ladder form and appear to control the courses of major rivers such as Santa Ysabel (8) and lower San Diego (9) which flow westward and across the regional grain.

The north and northeast trending structures are occupied by the upper course of the San Diego River (10), Temescal Creek (11), and Horsethief Southern Canyon (12).

Bends and Offsets in Linear Forms

Some members of the San Andreas fault set such as the San Jacinto and Elsinore faults are remarkably linear in their northern parts (2 and 3, Fig. 5) but become bent at several places in the south (7 and 11, Fig. 4). These "bends" are consistently oriented west-northwest and are particularly notable in the area west and southwest of the Salton Sea in a manner which suggests the effect of Transverse structures. This observation is substantiated when the bends observed in satellite photographs are examined together with geological maps (Santa Ana and Salton Sea sheets, Geological Atlas of California) which show swarms of east-trending faults in the vicinity of pronounced fault flextures. The distortion of active faults such as San Jacinto and Elsinore is likely to have taken place in the time period between their establishment as throughgoing breaks and the present time. It is also possible that these throughgoing faults have been invluenced by preexisting transverse structures.

It is remarkable however that the southward continuation of these active faults is difficult to establish with certainty as they extend towards the Imperial Valley depression. The apparent termination of San Jacinto, Coyote Creek, Agua Caliente, Earthquake Valley, and Elsinore faults as well as the coincidence of their bends with east-trending topographic and structural lineaments (L, Fig. 4) is highly significant. It is quite probable that the Elsinore and San Jacinto faults may have been offset or deflected left laterally from their southern segments, represented perhaps by the Imperial, Superstition, and Laguna Salada faults, Fig. 4. The zone of deflection coincides with east-trending lineaments, many of which are observed in the alluvial cover of the Imperial depression.

Whether the transverse lineaments are zones of active sinistral shear is yet to be determined and certainly require verification. The occurrence of fault furcation in the San Andreas set and localized thrusts are likely to be manifestations of strain buildup at these bends. The concept that left-lateral shear may still be active in southern California is by no means a conjecture. Evidence of sinistral shear on east-west trending structures has become abundantly clear during the 1971 San Fernando earthquake.

Furcation of Wrench Faults (h, m forms)

The San Andreas fault south of its junction with the Garlock fault branches or bifurcates. The southern segment which runs along the eastern side of the Salton Sea makes with the San Jacinto and Banning faults an h form junction, Fig. 1. Further south the San Jacinto fault joins with the Coyote Creek fault in the eastern Peninsular Ranges in a minor h-form junction. The relation between El Cajon lineament (Figure 5) and the Inglewood Newport faults and its projection towards San Diego suggests a major h-form junction as we stated before.

Repeated furcations often make m-forms such as that made by the southern segment of the San Andreas fault, the San Jacinto fault, and Elsinore in the eastern Peninsular Ranges (Fig. 1 and 4).

Another m-form is made by the San Jacinto, Elsinore, and the Inglewood faults with the Malibu-Santa Monica-Raymond fault zone, Fig. 1.

The significance of h- and m-form junctions, we believe, implies more than being simple or multiple furcations. In most cases studied in satellite photographs and fault maps furcation in the San Andreas set appears to coincide with lineaments or faults belonging to the Transverse set.

This, and the coincidence of bends, and terminations of linear wrench faults with cross structures may be related to a common cause. It is often stated in the literature that the linear faults of the San Andreas set juxtapose rocks of radically different ages and compositions. It can also be stated that many of the cross lineaments and faults of the San Andreas set juxtapose rocks of radically different ages and compositions. It can also be stated that many of the cross lineaments and faults of the Transverse set, including the short segments between long faults, either separate different rocks or at least there is evidence of lateral shift in major rock unit contacts. We believe that this observation can be substantiated by careful examination of the Santa Ana, Los Angeles, Salton Sea, and the San Diego-El Centro geological map sheets. The same observation may also apply to many short segments of east-trending faults between throughgoing faults of the California coast ranges.

General Features

An impressive mass of evidence contained in the geologic record points to a number of compelling features which should be considered together in order to understand the development of the fault pattern in southern California. These features are

1. The structure of southern California has been profoundly affected by two intersecting sets of wrench faults showing mutual offsetting relationships which suggest that both sets have been active episodically for a long period of time and have repeatedly cut and displaced one another.

2. The San Andreas fault may consist of distinct segments each apparently has had at one time or another a different history of movement independent of other segments.

3. The principle of ancestor faults may apply equally to the San Andreas and the Transverse fault sets.

4. A large displacement on one segment of a wrench fault may be distributed among several other fault segments in the set. The concept that certain faults or "branches" may be ancestral parts of an old, once throughgoing fault is probably valid. The cumulative offset of several fault segments may add up to account for the apparent discrepancy of values of offset observed another fault segment.

5. The fault pattern developed at the intersection of the two sets of wrench faults in southern California when examined in detail appears to be composed of various combinations of simple geometric forms: Linear parallel faults, rhomb-shaped blocks, T and zigzag forms, H and ladder forms, h and m forms, simple x and λ forms. All these, as well as the general complex fault pattern may represent various manifestations of the interaction of the two sets of wrench faults at their intersections.

This concept can be convincing only if it is shown that all or most of these features could be produced by a simple tectonic fault model. We believe that this can be demonstrated.

DEVELOPMENT OF FORMS AND PATTERN

Forms, Ancestral Faults and Shared Displacement

When two intersecting and episodically active wrench fault sets interact, their traces may produce a variety of geometric fault forms depending on the sequence of events involved. Figure 6 (A & B) illustrates the development of some typical forms produced by the episodic interaction of right-lateral and left-lateral wrench movements.

The total offset on a fault segment may be distributed along several true branches (Fig. 6B) or may be shared along several ancestral segments. This latter concept is illustrated in Fig. 6A. Wrench fault AA' undergoes a right-lateral movement of one unit distance (a) is then offset by a crossing wrench fault BB'. Buildup of shearing stress on AA' will encounter a locked structure due to the bend at BB'. The locked portion may become a site of a thrust fault. The projections of each segment across the cross-cutting fault become potential sites for wrench fault propagation. When this occurs the younger offset value (b) on the upper segment A will be represented on the new break A''. If fault segments AA' or AA'' are considered separate entities, one is likely to find an apparent discrepancy in the total offset observed along the northern and southern segments of the fault. The southern fault segment A' may eventually become inactive but it actually represents an ancestral part of the fault AA'. This process results in the creation of a geometric h form (Fig. 5A, Stage 4). Repetition of the process of episodic movements will produce an m fault form in which the total displacement (a+b+c) on the northern segment A is shared along three ancestral segments (A', A'', A''') and will produce localized thrusts along previous wrench fault segments. The pattern produced in Fig. 6A, Stage 6 may be analogous to the junction of the San Andreas and San Jacinto fault zones; the three thrusts may be similar to the thrusts in the southern parts of the San Bernardino Mountains where the San Andreas fault changes trend and is characterized more by thrust than wrench fault features. We can recognize several T form junctions where segments of old wrench faults end abruptly against a cross cutting fault. Figure 6A thus illustrates in a rather simplified manner the development of individual fault forms the analogies of which are frequently observed in southern California.

The important question, however, is whether these forms can all be produced and developed to make a general fault geometry similar to the natural pattern and at the same time results from a fault model that can be attributed to a plausible tectonic process. This question can be answered by an experiment in which some geometric manipulations are performed and which follow a few assumptions and rules.

We shall consider here a hypothetical portion of a crustal plate subjected to two independent sets of wrench faults, intersecting at approximately 60° along which episodic movements take place. The northwest fault set is characterized by right-lateral shear and the east-trending set by left-lateral shear.

The fault planes are assumed to be vertical and, for simplicity, the model will be considered two dimensional. Starting from this initial block, we shall break and displace the block laterally along some carefully selected, linear and throughgoing faults, which cut across the entire block from side to side. We shall not create any break which partly cuts the clock or dies out. For simplicity the block is assumed to be a rigid slab. Although folds and thrusts are important features in the Transverse Ranges, we shall consider them modifying factors which are not difficult to explain once the essential features in the wrench fault pattern are recognized.

Starting with a simple case, Figure 6A, stages 1-6 illustrates the fault pattern developed after a sequence of five episodes of lateral movements along two intersecting wrench fault sets and shows the basic types of movements allowed in the experiment. It will be noted that when an old fault segment has been offset by crossing fault it may be reactivated and the movement takes place with propagation of faulting along its continuation as a new break. As mentioned before, Fig. 6A, Stages 1-6 shows clearly that the development of various geometric forms (e.g., X, H, h, m, T) and the shared displacement on ancestral fault segments as well as the apparent discrepancies of total offset on a given fault are all inherent features of the basic fault mechanism presented in this paper.

Development of a model which resembles the natural fault pattern in southern California required trial and error experiments using a larger number of fault movements in various sequences. Because of the increasing complexity and in order to be able to identify the ancestral relationships of each fault segment and the relative position of the various fault blocks, we utilized a computer with a plotter to perform the task of a bookkeeper.

The computer was programmed to store the geometric parameters of various points in the initial block (Fig. 7a) which has been arbitrarily divided into a grid identified by a coordinate system of numerals 1-20 on the X and letters A-T in the Y directions. The computer was also programmed to store and perform the requested displacements on hypothetical faults along any desired lane in the grid and to plot at the end of each step the resultant geometric pattern, each fault is identified by a graphic symbol and the distance of offset recorded.

Fig. 7b shows the fault pattern after being offset twice: first by a left lateral east-west fault amounting to one grid unit (1-1) and second, by a right-lateral 9-unit offset along a NW-SE fault (2-2). Hypothetical bodies have been added in order to illustrate their offset geometry.

Fig. 7c depicts the block after two additional movements: fault (3-3) caused a 3-unit offset and fault (4-4) a three-unit offset, both in a right lateral sense.

Fig. 7d shows the blocks after three additional movements, all one-unit left-lateral movements in the E-W direction (5-5, 6-6, 7-7).

Fig. 7e shows the blocks after four more movements, two NW-SE right-lateral movements of two steps each (8-8, 9-9), one NW-SE right lateral movement of one unit (10-10), followed by one E-W left-lateral movement of one unit (11-11).

Fig. 7f shows the final disposition of the fault pattern after an E-W left-lateral movement of one unit (12-12). This represents rejuvenation of movement on one segment of fault no. 5.

The twelve movements performed can be generalized as follows:

One E-W left-lateral fault initiated as a new break.

Three N-S right-lateral faults initiated as new breaks.

Three E-W left-lateral faults initiated as new breaks.

Two N-S right lateral faults rejuvenated along old fault segments.

One N-S right lateral fault initiated as a new break.

Two E-W left-lateral faults rejuvenated along old fault segments.

These 12 wrench fault movements have produced by their interaction and displacement of one another a rather complicated pattern that has intrinsic features analogous to the fault pattern in southern California.

The graphic symbols along the faults in Fig. 7 identify the various segments which once were part of a common ancestor. Thus, segments carrying two symbols indicate two distinct episodes of activity.

For example, segments AB, CD, and EF (Fig. 7g) carry the same open cross symbol indicating they were involved together in a movement as parts of a single fault. Segments AB and CD carry an additional bar symbol which relates them to segment GH as three parts of another ancestral fault.

Numerals near each fault segment (Fig. 6g) show their relative displacement values. For example (3 + 2) next to segment CD indicates that the segment was involved in two fault movement episodes; the first amounted to three units of offset as part of one fault with segments AB and GH and a second episode of two unit offset with segments AB and EF.

It should be emphasized that the fault model presented in Fig. 7 is not identical with the natural fault pattern nor it is intended to be a blueprint of the fault history of southern California. The relative offset values used are arbitrary and do not represent quantitative analogs in nature. We found that changes in the sequence of fault movements and the relative offset values produce significant modifications in final pattern which are hard to predict.

However, there are several intrinsic features in the model which when examined in the context of their bearing on natural analogies will be found to be consistent with field observations and at the same time will serve to explain some apparent discrepancies.

Fault Ancestry and Offset Discrepancies

The model demonstrates that certain faults or segments may be ancestors of another fault that has since been physically detached and separated by considerable distances. For example, fault segments GH, CD, and AB (Fig. 7g) were parts of a common ancestor. Similarly, the transverse fault segments IJ, KL, MN, and OP (upper part of Fig. 7g) are similarly related. In Fig. 6e faults such as OP and IJ are related to other west-trending faults carrying the same symbol. This relationship may be a simplified analog of many transverse faults in southern California. To cite one example Allen (1957, p. 339) suggested that the Banning fault in the San Gorgonio Pass may correspond to one of the prominent east-west faults of the San Gabriel Mountains. From field work Sharp (1965) found reason to believe that the "Banning fault at the southern margin of the San Bernardino Mountains may be the offset continuation of the Sierra Madre fault zone on the southern flank of the San Gabriel Mountains." By analogy the model suggests that some faults of the western Transverse Ranges (e.g., Santa Ynez, Big Pine, Malibu) may be related with the east trending faults of the San Gabriel Mountains and of the eastern Transverse Ranges (Pinto Mountain, Blue Cut, Aqueduct faults) by common ancestors.

If we assume that segment AB (Fig. 7g) is analogous to the northern segment of the San Andreas fault, segment CD to the middle part between the Garlock fault and San Gorgonio Pass, and GH the southern part which runs along the eastern side of the Salton Sea, and assume that EF is analogous to the San Jacinto fault, the following observations are significant:

The identity of the hypothetical San Andreas fault is complex and vague between points E and G. This area may then be analogous to the San Andreas zone near Banning where it is known that the fault loses its identity, shows no rift topography and gets involved in a most complex manner with east-trending faults of the Transverse Range (Noble, 1954). If the model is valid, it shows that the ancestor of the fault between points E and G has been segmented (Z and Z') and offset left-laterally by the east trending wrench faults.

The 5 unit total offset on segments AB and CD has been distributed between segments GH and EF which show 3 and 2 offset units respectively. The analogy of this example is consistent with the relationship of the San Andreas and the San Jacinto faults suggested by Noble (1954).

Segments RS, S'T, T'U, and VW are related by common origin; some readers may recognize their analogy to Nacimiento, San Gabriel, and Elsinore faults.

Noble (1954) expressed the opinion that San Andreas fault probably was deflected eastward by the great mass of the Transverse Ranges and some of its older segments were converted into parts of the reverse faults along which the Transverse Ranges were uplifted. "The interplay of movements probably was complex in both time and space and the present San Andreas and San Jacinto fault zones almost certainly displaced many Transverse Range breaks."

The basic concept in the fault model that the two fault sets have episodically displaced one another is consistent with Noble's observations. Indeed, ancestor faults analogous to San Andreas and other faults of the Coast Ranges were developed in stages 4 and 3 (Fig. 7c) and were later offset left laterally at several places by cross cutting Transverse faults (stages 5, 6, and 7, Figure 7d). The ancestor faults were later reactivated creating new breaks which are analogous to the San Jacinto and Elsinore faults of the Peninsular Ranges. These new breaks caused considerable segmentation and offsets of the Transverse faults.

Block Shuffling

The great faults of California broke the state into a mosaic of blocks whose relationship to one another is not clear and to many geologists the pieces of the puzzle have bome to seem "more complex, disconnected and chaotic . . . some geologists have even entertained the idea that the state is really nothing but a great series of separate structural blocks, each with an independent history since some stage of the Mesozoic at least" (Reed, 1933, p. VII).

The southern part of the state in particular "is a region of sharp geomorphic and geologic contrasts resulting from the juxtaposition of blocks, commonly separated by faults, that are made up of dissimilar rock types, sedimentary sections, and structures that have unlike geologic histories (Hill, 1954, IV, p. 5).

This apparently chaotic and complicated mosaic of blocks shuffled or redistributed by fault movements does not in our opinion imply <u>a priori</u> that the tectonic process which brought it about was necessarily chaotic nor haphazard. A complicated mosaic of shuffled blocks can indeed result from the interaction of two independent wrench fault systems along which simple but episodic lateral movements take place. Some examples may serve to illustrate this point.

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San Gabriel and San Bernardino Mountains: Many geologists have long recognized that the San Gabriel and San Bernardino Mountains are similar and perhaps were once adjacent before their displacement by the San Andreas fault. Old thrust faults of probable Mesozoic age such as the Vincent fault in the San Gabriel Mountains may correspond to similar thrusts in the San Bernardino Mountains (Bailey and Jahns, 1954, 11, p. 85). This similarity is also consistent with the correlation of basement rocks (Crowell, 1962) and marine Eocene sequences (Crowell and Susuki, 1959; Chipping, 1972, p. 491).

If we consider that the San Gabriel and San Bernardino Mountains were initially formed as one block represented in the model (Fig. 7a) by an area defined as block 1, we find in the final stage (Fig. 7f) that the two mountain blocks are differentiated in a manner consistent with their present locations.

For example, the Pelona Schist of the San Gabriel Mountains and the northwest end of the Orocopia Schist near the Salton Sea which are separated by some 250 km. bear many striking petrographic similarities which suggest that they may have been once adjacent (Hill, 1954; Chapter 4, p. 5-13).

In the model the initial pre-movement locations are described by coordinates J-12 and J-14 in Fig. 7a. The two adjacent points were later separated by a cumulative movement of 5 units right-lateral and 4 units of left-lateral offsets.

Triassic Rocks in Santa Monica and Santa Ana Mountains: The Santa Monica

Mountains contain in their eastern part a large area containing the Santa Monica slate, a distinctive rock type of slatey siltstone, graywacke, fine grained sandstone of Triassic age which are mildly metamorphased but with preserved clastic textures and are correlative to the Bedford Canyon formation.

The nearest occurrences of strikingly similar rocks of known Triassic age occur in the Santa Ana Mountains, east of the city of Santa Ana. These rocks consist of mildly metamorphased slate and argillite with minor quartzite and thin lenses of limestone (Popenoe, 1954, 111, p. 15).

The Santa Monica slate and the Triassic rocks of the Santa Ana Mountains are fundamentally different in composition from mildly metamorphased argillaceous rocks that crop out in the Palos Verdes Hills and on Catalina Island to the south (Bailey and Jahns, 1954, 11, p. 87).

The problem of the structural relation between these two Triassic occurrences has long been recognized by geologists familiar with the stratigraphy of southern California. Woodford et al. (1954, 11, p. 65-81) considered various possibilities to explain this relationship, reconciling it to the fact that on the southwestern side of the Newport-Inglewood fault Triassic rocks are absent, and the pre-Cretaceous "basement" consists rather of Precambrian or Paleozoic metamorphic rocks of the glaucophane schist facies. Strike-slip faulting was considered as a possible reason for the separation of the Triassic rocks and the contrast on the "basement" rocks across the Newport-Inglewood fault. However, such mechanism seemed difficult because "the western curve that would be needed in the Newport-Inglewood fault zone to extend it around the west end of the Santa Monica Mountains makes improbable a simple strike-slip displacement of the San

Andreas type.: The fault model described here illustrates that this difficulty may be more apparent than real. A right-lateral movement on the Newport-Inglewood fault ancestor may indeed have caused the separation of the Triassic rocks. The westward curve which Woodford et al. consider necessary for their interpretation can be explained by an offset of the ancestor Newport-Inglewood fault left-laterally due to later movement on the Malibu fault. Figures 7a and 7c illustrate the feasibility of this interpretation and at the same time explain why the Newport-Inglewood wrench fault comes to an abrupt end against the Santa Monica Mountains. All occurrences of Triassic rocks in the Santa Ana Mountains are found east of the Inglewood fault and on both sides of Elsinore fault (see Santa Ana sheet, Geologic Atlas of California). This distribution is symbolized by stippled areas of Figure 7c. Reconstruction of the blocks according to the fault model shows that the detached occurrences were once adjacent and formed a more cohesive block before the fault movements (Block 2, Fig. 7a).

San Onofre Breccia: The origin of the San Onofre Breccia is another example of profound significance to the tectonic history of southern California. The San Onofre breccia occurs interbedded with Middle Miocene marine shales and is composed of fragments of glaucophane schist which reach large boulder size, up to 10 feet in diameter (Reed and Hollister, 1936, p. 120; Woodford et al., 1954, 11, p. 71; Durham, 1954, p. 27).

This unusual breccia occurs in several places in the coastal areas of Los Angeles: Palos Verdes Hills, San Joaquin Hills between Laguna and Oceanside and in two places along the coastal stretch of the western Santa Monica Mountains.

According to Woodford (1925, p. 160) the very coarse and angular slabs and boulders of schistose rocks have most probably been derived from a highland area which may have existed during the Middle Miocene a short distance to the west of the present Los Angeles shoreline.

The detritus of the San Onofre breccia is likely to have been derived from a highland composed of source rocks equivalent to the Catalina metamorphic facies (Franciscan group). Because similar material underlies the shelf region south and southwest of the Los Angeles district but not in any other region near enough to furnish coarse detritus to this district, Woodford (1925) concluded that an uplift (Catalina uplift) must have been emergent in the offshore area during the Middle Miocene. More recently, however, stratigraphic data on the geology of the sea floor off southern California (Emery, 1960, p. 68 and Fig. 62, p. 69) clearly show that marine Miocene sedimentary rocks are widespread and overlie the Franciscan rocks of the continental shelf area, occurring on nearly all topographic highs. These sedimentary rocks consist of Early, Middle, and Late Miocene shale, chert, and limestone and are associated with Middle Miocene volcanic rocks. In addition, Pre-Miocene (Jurassic?, Cretaceous, and Eocene) rocks are also found.

The widespread presence of relatively deep water marine Middle Miocene sedimentary rocks in particular casts considerable doubt that the crustal block lying off southern California now could have been the same crustal block which made the highland source of the San Onofre breccia. It is readily apparent that if the present offshore block was a highland with sufficient elevation to provide boulder sized breccia fragments, the same block could not have been the site of deep marine sedimentation at the same time. The closest other source for the San Onofre breccia is the Franciscan rocks of the Coast Ranges and offshore area now exposed some 190 km to the northwest. This suggestion is by no means implausible. Suppe (1970) and later Anderson (1971) in his review of the origin of the ancestral San Andreas fault suggested that the block now represented by the central Coast Ranges may have been situated off the coast of Southern California sometime during the Miocene. Considering this possibility in terms of our fault model a mechanism for the northward migration of the ancestral Coast Ranges block relative to Southern California becomes readily feasible.

This could be accomplished by assuming a right lateral movement along a major fault (Fault 2-2, Fig. 7b) which took place prior to the episode of major activity along the Transverse wrench faults (Figure 7d). According to the model this old hypothetical fault has been later offset left-laterally in various segments which lie in an area analogous to the continental shelf off central California.

The relationship between the source rock, Franciscan Group of Coast Ranges, as a likely source rock and the San Onofre breccia localities are consistent with our fault model. The initial position of the breccia localities and their source rock are represented in Figure 7a by Block 3. Prior to the fault movement (2-2, Fig. 7a) which displaced the Coast Ranges block, the breccia localities lay directly east of the former position of the Coast Ranges. An offset of the Coast Ranges 9 units to the northwest and 5 units to the west (faults 5, 6, 7, 11, and 12, Fig. 7d, e, and f) would place the Coast Ranges and its shelf area in a position analogous to its present location.

This mechanism is appealing not only because it provides a likely solution to the source of the San Onofre breccia but also explains how the Coast Ranges could have migrated north, a movement which if one looks at the present map of California may find difficult to visualize because of the apparent barrier posed by the present mass of the Transverse Ranges.

If the concept of the fault model proves to be basically valid, development of the old fault and the northward migration of the Coast Ranges could have taken place prior to the final development of the Transverse Ranges in the Pliocene and Pleistocene. In Suppe's model (1970) this fault is considered the ancestor of the San Andreas fault. In our model it is most likely a different fault, the segments of which may be among faults in the offshore area of California.

The main point we wish to emphasize by citing these examples is that in order to understand the relationship between individual blocks in the California mosaic it appears necessary not only to take into account large lateral displacements on the San Andreas and related faults but also the effects of lateral displacements on transverse faults. The effects of the transverse structures should not only be considered within the Transverse Ranges where they are most prominent, but also in correlating fault blocks in the Peninsular and Coast Ranges. The implications of this statement will become more apparent when we consider the displacement patterns of linear structures.

Displacement Patterns of Linear Structures

Geological structures characterized by considerable length and limited width such as ancient faults or old deformation zones, narrow sedimentary belts, or linear geological boundary lines will be fragmented and displaced in various patterns, depending upon their orientation and positions of intersection by wrench faults which offset them. We shall consider here several hypothetical examples of linear structures assumed to be older than the initiation of fault movements in our model. The fragmentation patterns are informative and may stimulate new insights into some geological problems in California.

Fig. 8a shows the initial disposition of four hypothetical lineaments trending NE-SW, WNW-ESE, E-W, and north-south.

Lineament 1 extends NE-SW diagonally across the initial unfaulted block (Fig. 8a) from coordinate 4T to 20-D. The final disposition of its fragmentation into twelve segments (α-μ) are identified before and after fragmentation. This example illustrates the complicated pattern produced and shows that an analogous lineament in nature may be very difficult to recognize.

If the lineament has outstanding geological characteristics, the relationship between segments α, β, γ, and δ may be recognized as four segments offset by a system of left-lateral wrench faults. Segments ε and γ may however be considered two separate and parallel features left-laterally displaced from segments ϕ and δ. The relationship of segments μ, ι, ζ, λ, η, and θ to each other and to the rest of the lineament may even be more confusing. Segment μ may appear in relation to ι and ζ as a continuous lineament which may be mistakenly considered as a refutation of any other evidence of the right lateral displacement on the wrench faults which cross them. This apparent continuation is more incidental than real.

Segment μ must be correlated to its continuation along λ, ι, θ, η, and ζ -- in that order. If encountered in nature segments μ, ι, and ζ may not be perfectly aligned and others show smaller apparent offsets which can be mistakenly considered as an evidence against a larger displacement found elsewhere along the fault.

Some readers may be willing to exercise some imagination to relate the geometry of Figure 11 to that of southern California. Lineament 1 is now fragmented into twelve elements which could be traced to blocks corresponding to the eastern Mojave Desert, the eastern Transverse Ranges, the northern Peninsular Ranges into the central part of the Transverse Ranges. Other lineaments of the same trend but of different position will have segments scattered in a large area and in different geologic provinces.

The fragmentation pattern of a lineament trending WNW-ESE (no. 2, Figure 8a) is shown in Fig. 8b. The right-lateral offsets of segments π and Δ, Δ and Ξ, and the left-lateral offset of Ξ and Σ may not be hard to recognize in the field. However, the large separation of segments Σ and Ω and the absence of the lineament (and the host block) in the intervening area is likely to obscure the identity of the lineament.

In order to make the implications of these hypothetical examples as clear in the context of possible natural analogies, the trace of the fault which in our model is assumed to represent the main trace of the San Andreas fault and major physiographic provinces are indicated.

The fragmentation pattern of east-trending lineaments (such as no. 3, Figure 8a) will generally be similar to the displacement of the transverse faults in the model. If the lineament is ancient and has undergone no rejuvenation, the observed offsets will amount to the maximum cumulative values.

North-trending lineaments such as no. 4 (Fig. 8) may be fragmented in a most complicated manner. While segment A and B are offset a large distance, the disposition of segments D and B may be considered an indication of a much smaller amount of offset. The apparent continuity of F and K or the minor offset K and J may erroneously be taken as an evidence against any strike-slip displacement. The north and northeast trending faults, ancient shear zones in the Peninsular Ranges (Figure 5) may be good examples of future analysis based upon these concepts.

The main point we wish to emphasize is that the fragmentation patterns discussed here may well apply to many correlation problems of old sedimentary, metamorphic, and intrusive belts in California. It ic clearly demonstrated that if analogous lineaments are encountered in nature, their various fragments would most certainly be a rich subject of various interpretations and controversy.

Tectonic Implications

The sequence of faulting episodes upon which our model is based have the following main features:

1) An early episode of left-lateral shear on east trending faults symbolized by fault 1 (Figure 7b)

2) An early episode of right-lateral movements on northwest-trending wrench faults of the San Andreas set, represented by faults 2, 3, and 4 (Figure 7c).

3) A second episode of left-lateral movements on east trending faults of the Transverse set (faults 5, 6, and 7, Figure 7d).

4) A final episode characterized by reactivation of wrench movements on certain ancestral fault segments belonging to both sets.

If we assume that the proposed model is basically valid, the early episodes represent the establishment of many ancestors of the San Andreas and Transverse fault sets. The idea that the San Andreas fault may in fact represent not a single fault but two or more segments or ancestors with different histories has been conjectured for various reasons as stated previously by Noble (1954), Jahns (1969), and others. A two stage movement on the fault has been proposed by Suppe (1970) and Atwater (1970).

The model further suggests that a genetic relationship may exist between the linear faults of the Coast Ranges (e.g., Nacimiento, etc.) and the linear faults of the Peninsular Ranges (e.g. San Jacinto, Elsinore, Inglewood-Newport faults, etc.). The intermediate segments of these ancestral faults should be found among the northwest-trending faults within the Transverse Ranges. In Suppe's (1970) model the "proto San Andreas" fault is conjectured to have run along the Inglewood-Newport fault. In ours the southern segment of San Andreas ancestor may be located further east, in the Colorado River Desert or even further south in Sonora. The great fault which carried the Coast Ranges (Salina block) northward probably lies in segments along the California coastal area. However, the concept that various ancestral segments of the San Andreas set are probably located now across the present day Transverse Ranges is similar to Suppe's ideas; the difference is regarding which ancestor faults are involved.

Our fault model is also consistent with the concept that the differential movement between the North American and the adjacent Pacific plate and the strain as a whole was dispersed over a wide region, rather than being concentrated entirely along a single San Andreas fault zone (Dickinson, Cowan, and Schweickert, 1972, p. 380).

The two main episodes of activity along San Andreas-set faults are separated in our model by a major episode of east-west trending lateral shear. The orientation and timing of these episodes may be related to the effect of one or more of the fracture zones or transform faults of the Pacific as they interact with the edge of the continent.

Some interpretations of plate tectonics consider the San Andreas as a transform fault affecting the edge of the continent but the east-trending fracture zones of the Pacific did not and are not supposed to cross it.

Our model suggests that both San Andreas and Transverse set faults have both crossed and deformed the edge of the continent.

Another important point which our model suggests is that the fault pattern in general and the fact that faults belonging to both sets offset one another can be explained better as the result of episodic rather than continuous movements. The significance of this point to the tectonic history of western North American has been the subject discussion by Hill (1972, p. 374; 384), Matthews (1972, p. 371), and Dickensen _et al_. (1972, p. 379), and others.

The episodic stresses required for producing the San Andreas set can be produced as a result of the interaction of more than one spreading center with the edge of the continent when ridges of the East Pacific Rise system come in contact with the continent at different times. The episodic shearing stresses required for creating the Transverse set can conceivably be related to the contact of one or more of the Pacific fracture zones with the continent and to transform faults related to the spreading of a portion of a Pacific rise under the Basin and Range province as suggested by Hamilton and Myers (1968). Other likely sources which account for the episodic nature may be related to the spreading of the Atlantic or left-lateral movements on the Texas lineament (Hill, 1902; Schmitt, 1966).

SUMMARY AND CONCLUSIONS

In this paper we emphasize that the role of transverse shear in the development of the fault pattern in southern California is a major one extending beyond the Transverse Ranges into the coast and Peninsular Ranges. It is also emphasized that episodic rather than continuous shearing deformation has more likely taken place on the two intersecting fault systems. The paper presents a highly simplified model of fault development which provides explanations for many apparent discrepancies in the San Andreas fault displacements and illustrates the concept of fault ancestors. The model suggests that in problems concerning geological correlations within the complex mosaic of fault blocks in California the effect of lateral shift of blocks on transverse faults should be considered as important as the effects of right lateral shift on the San Andreas system. The fragmentation and block shuffling patterns illustrated may provide useful insights into many problems of the tectonic history of California.

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CAPTIONS

Figure 1	Index map showing major faults in southern California (modified after Hill, 1954 and Chipping, 1972)
Figure 2	Apollo-7 photograph showing main physiographic features of southern California. NASA Photo number AS 7-11-2022.
Figure 3	ERTS-1 multispectral scanner image of western Transverse Ranges, California. NASA Photo number 1037-18064-501, near infrared band.
Figure 4	Gemini 5 photograph showing southern segment of San Andreas fault, California. Arrows point to features discussed in text. NASA photo number S-65-45748.
Figure 5	Apollo-9 photograph of Peninsular Ranges, California. Arrows point to features discussed in text. NASA photo number AS 9-26-3798.
Figure 6	Examples of geometric forms developed by wrench faults. (a) illustrates development of fault pattern by interaction of two intersecting wrench faults. Alternating movements on the two faults can produce multiple furcations, distribution of displacement on ancestral fault segments and development of localized thrusts. (b) distribution of fault displacements by simple branching.
Figure 7	Model of fault pattern developed by episodic movements on two wrench systems. Computer aided experiment shows

(a) hypothetical area with landmark features to be displaced by twelve wrench movements on two intersecting fault sets. Stage b illustrates pattern after left-lateral fault (1) is followed by displacement on right-lateral fault (2). Stage c shows pattern after dextral faults 3 and 4 developed. In stage d pattern is complicated by left-lateral movements on faults 5, 6, and 7. Stage f shows final pattern after 12 fault movements. Patterned blocks illustrate reshuffling of fault block mosaic. Graphic symbols along fault segments help identify common segments of fault ancestors. Numerals next to fault segments in Fig. 7g indicate relative displacements in arbitrary length units.

All stages were redrawn from computer plotted data. Computer was merely used as a bookkeeper which keeps track of complex geometric relationships developed by fault movements. Text explains relevance of experiment to fault pattern development in southern California.

Figure 8 Fragmentation patterns of linear structures

(a) Initial disposition of four hypothetical geological lineaments

(b) Distribution of various segments of old lineaments at end of 12 wrench fault movements. Redrawn from computer plotted data.

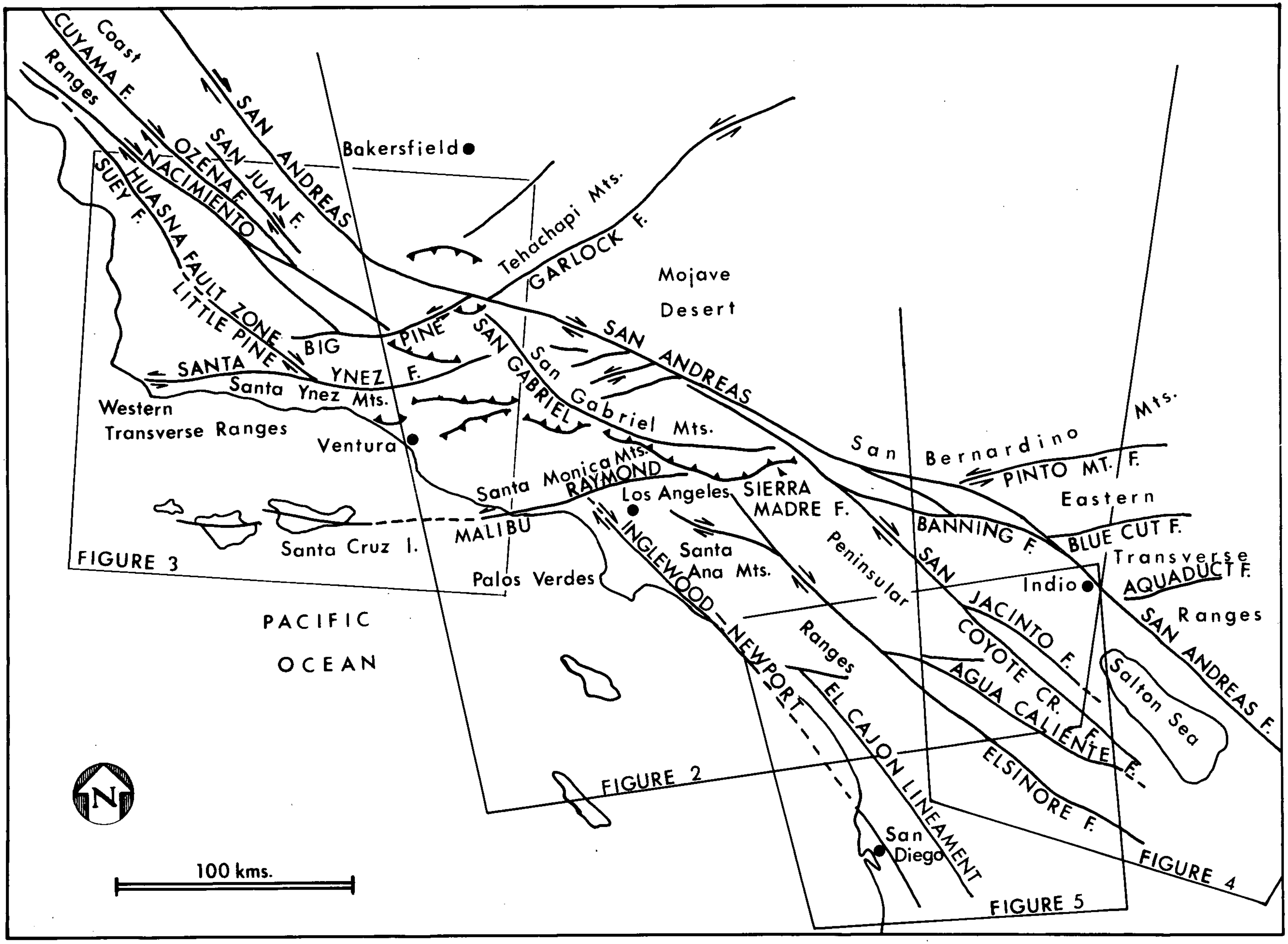
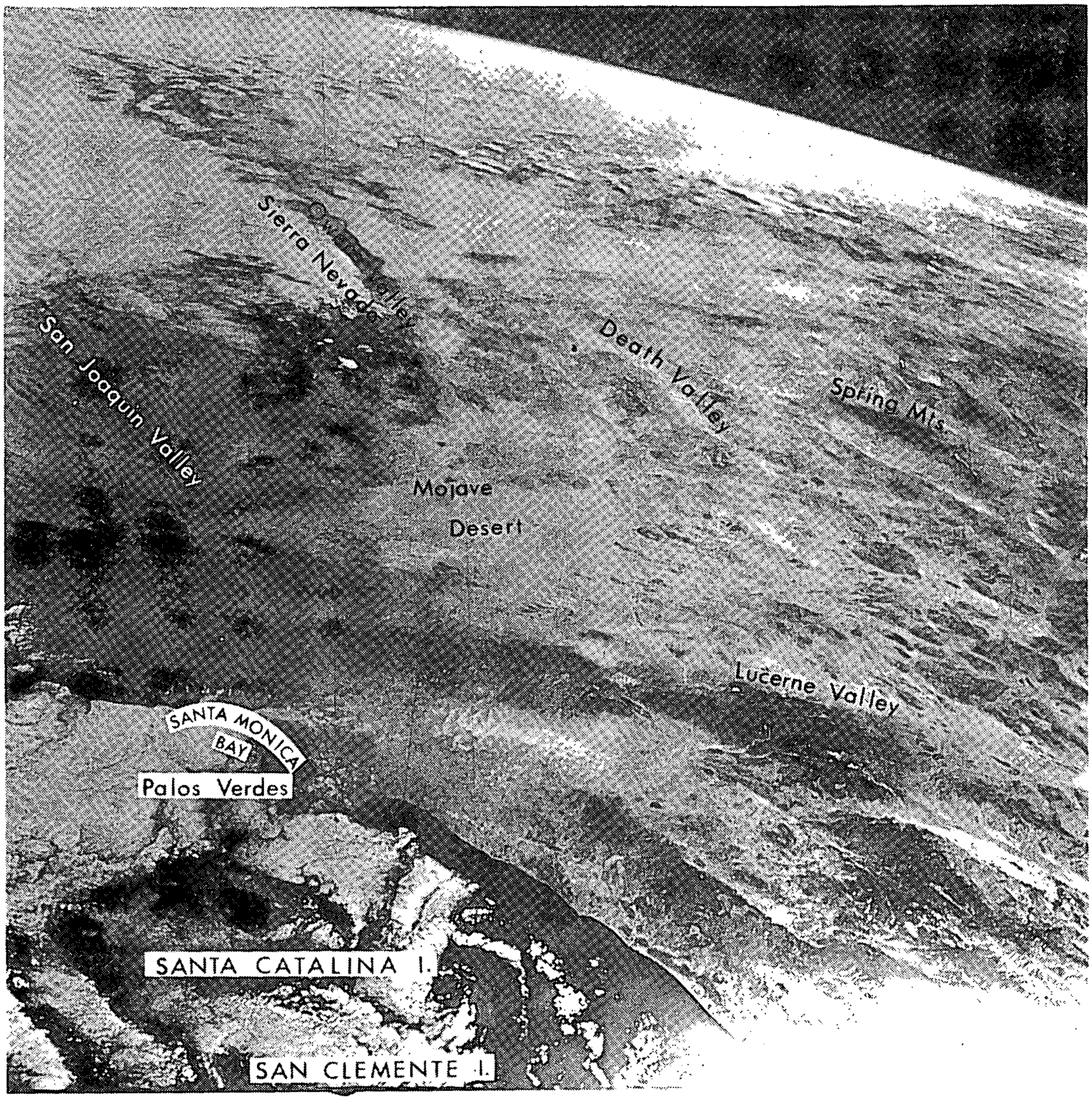

Coast
CUYAMA F.
Ranges
SAN ANDREAS
SAN JUAN F.
OZENA F.
NACIMIENTO
SUEY F.
HUASNA FAULT ZONE
LITTLE PINE
SANTA
YNEZ F.
BIG
PINE
Santa Ynez Mts.
Western
Transverse Ranges
Ventura
Bakersfield
Tehachapi Mts.
GARLOCK F.
Mojave
Desert
SAN ANDREAS
SAN GABRIEL
San Gabriel Mts.
Santa Monica Mts.
RAYMOND
MALIBU
Santa Cruz I.
Palos Verdes
Los Angeles
SIERRA
MADRE F.
Santa
Ana Mts.
INGLEWOOD—NEWPORT
Peninsular
Ranges
EL CAJON LINEAMENT
San Diego
San Bernardino Mts.
PINTO MT. F.
Eastern
Transverse
Ranges
BLUE CUT F.
AQUADUCT F.
BANNING F.
SAN JACINTO F.
COYOTE CR. F.
AGUA CALIENTE F.
ELSINORE F.
Indio
Salton Sea
SAN ANDREAS F.
PACIFIC
OCEAN
FIGURE 2
FIGURE 3
FIGURE 4
FIGURE 5
N
100 kms.

Figure 1



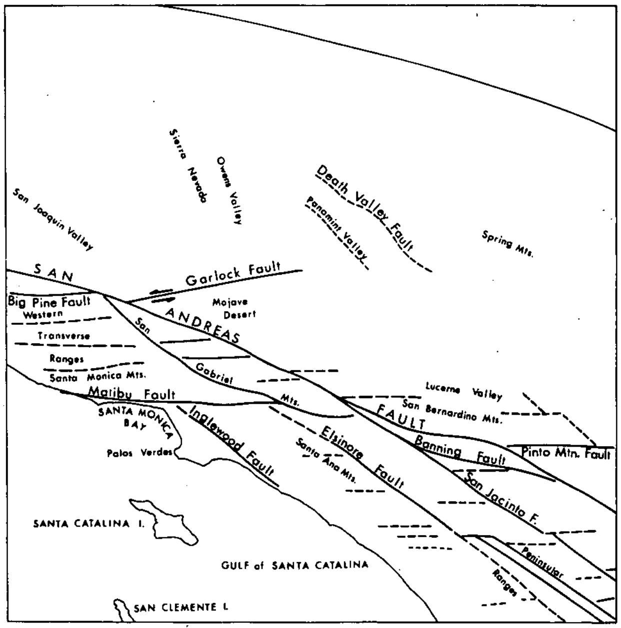


Figure 2

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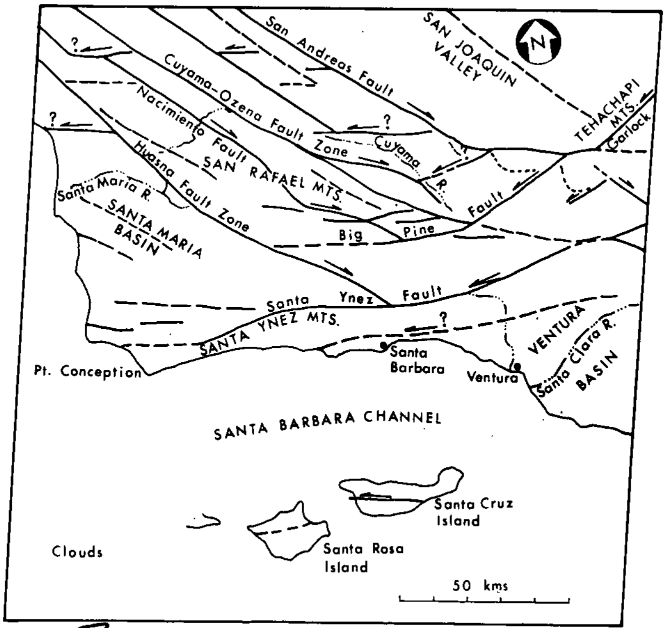

fig 3

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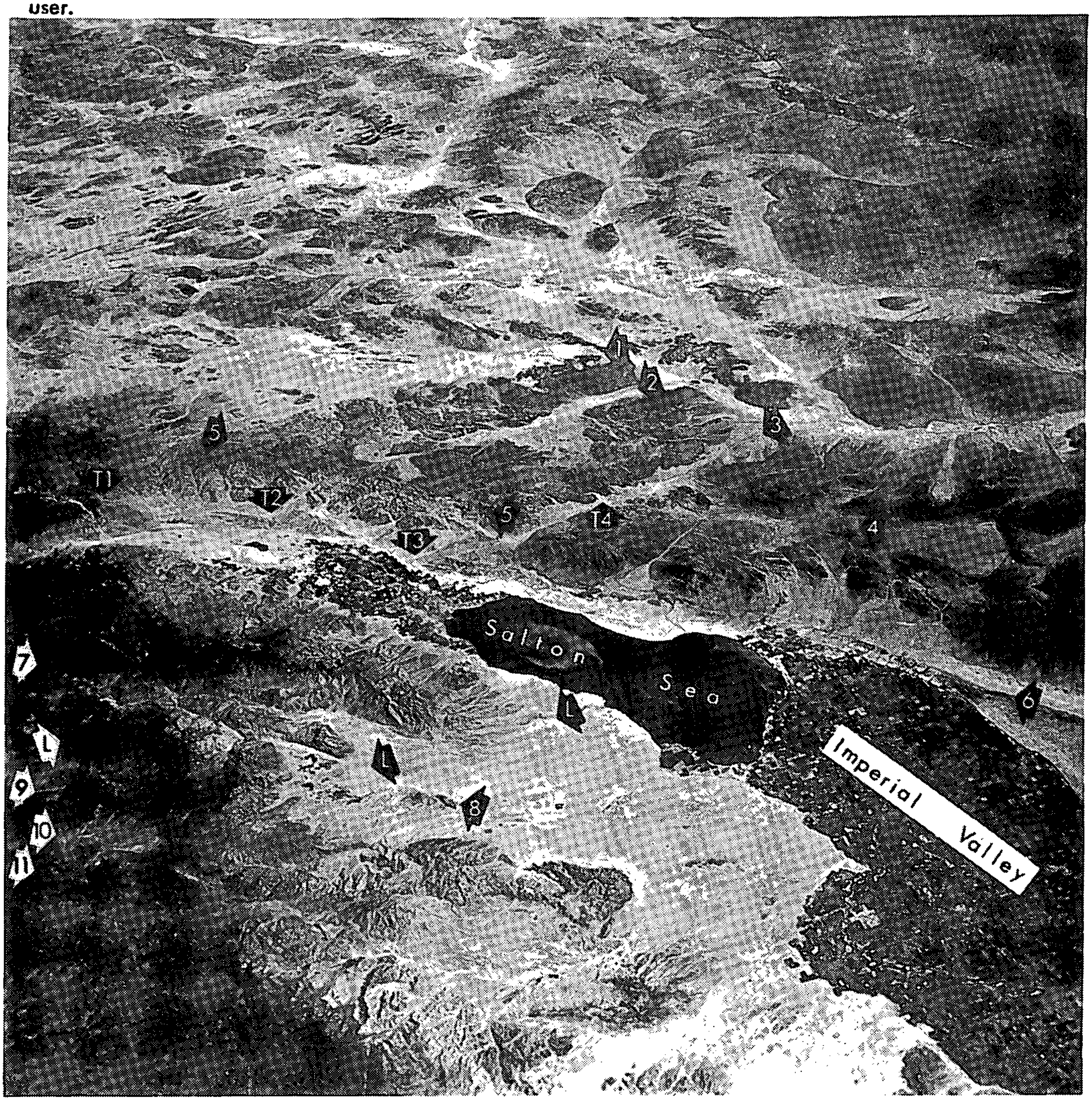

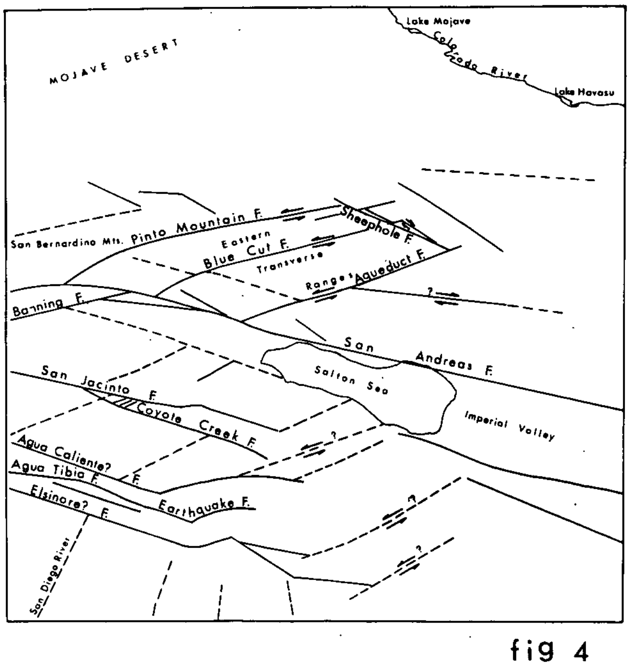

fig 4

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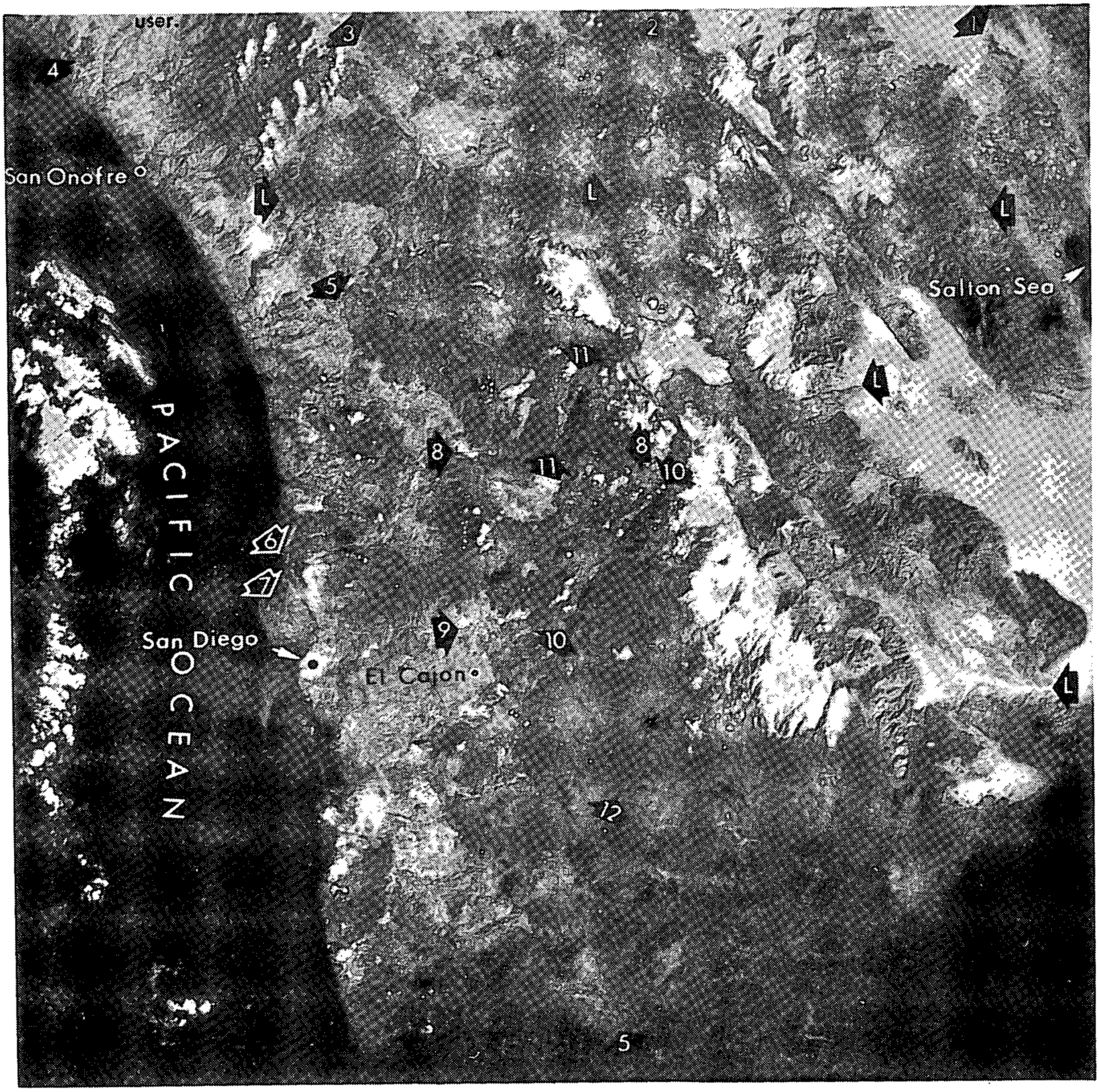


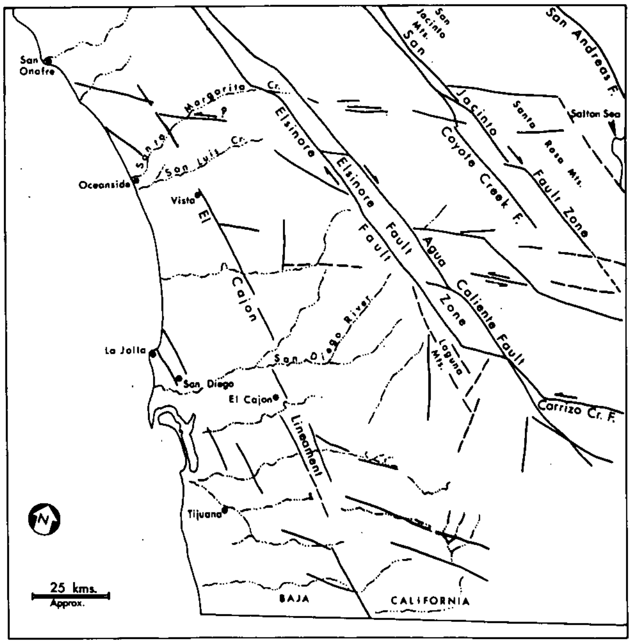
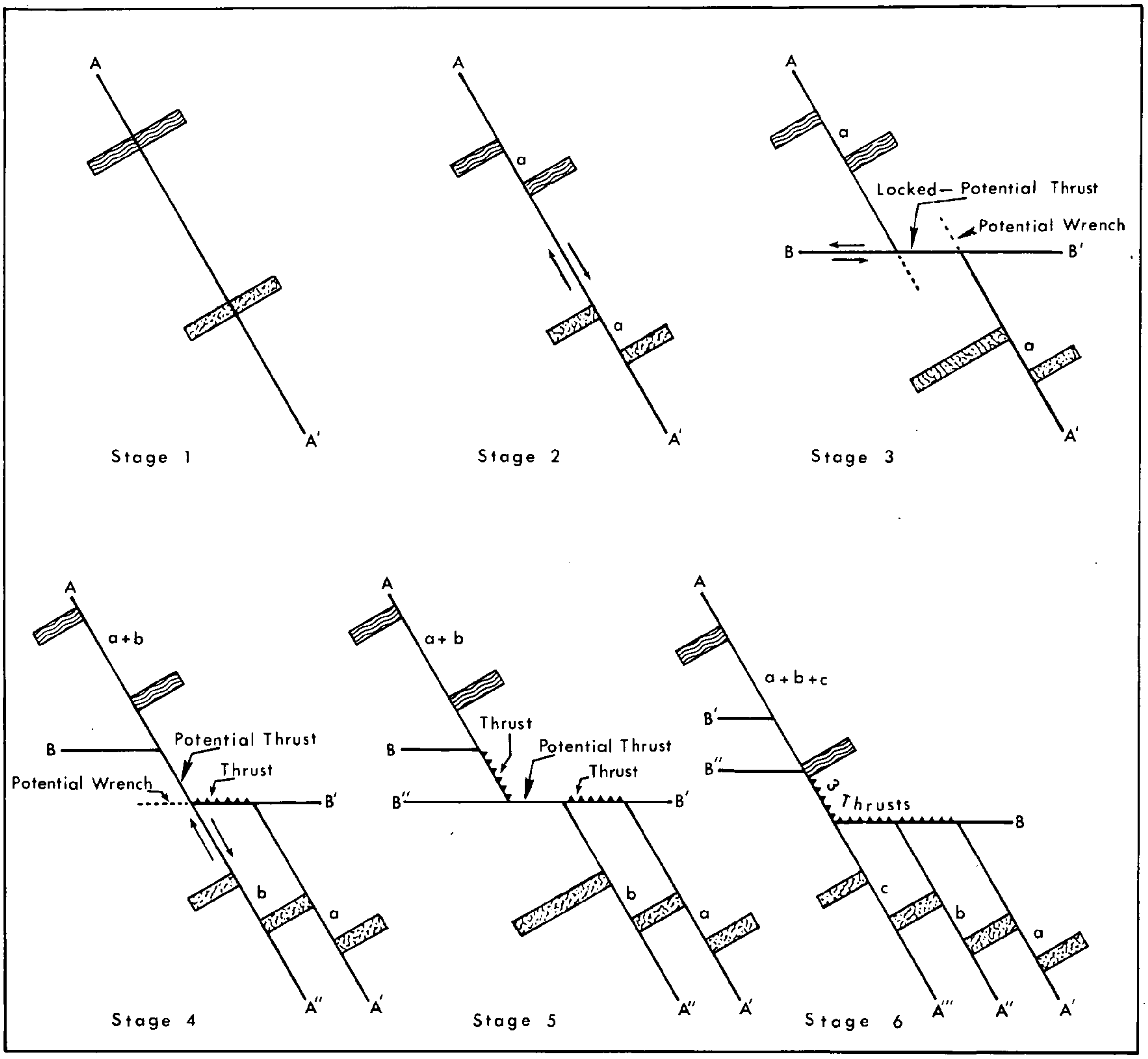
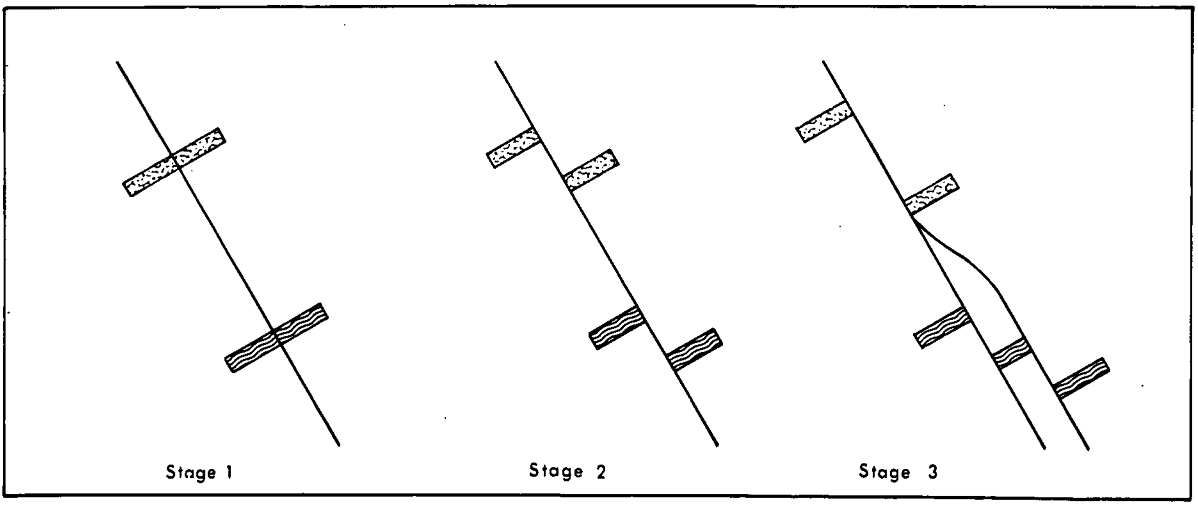


Figure 5


A
A'
Stage 1
A
a
a
A'
Stage 2
A
a
Locked— Potential Thrust
Potential Wrench
B
B'
a
A'
Stage 3
A
a+b
B
Potential Thrust
Potential Wrench
Thrust
B'
b
a
A''
A'
Stage 4
A
a+ b
Thrust
B
Potential Thrust
Thrust
B''
B'
b
a
A''
A'
Stage 5
A
a+b+c
B'
B''
3 Thrusts
B
c
b
a
A'''
A''
A'
Stage 6

(a)


Stage 1
Stage 2
Stage 3

(b)

Figure 6

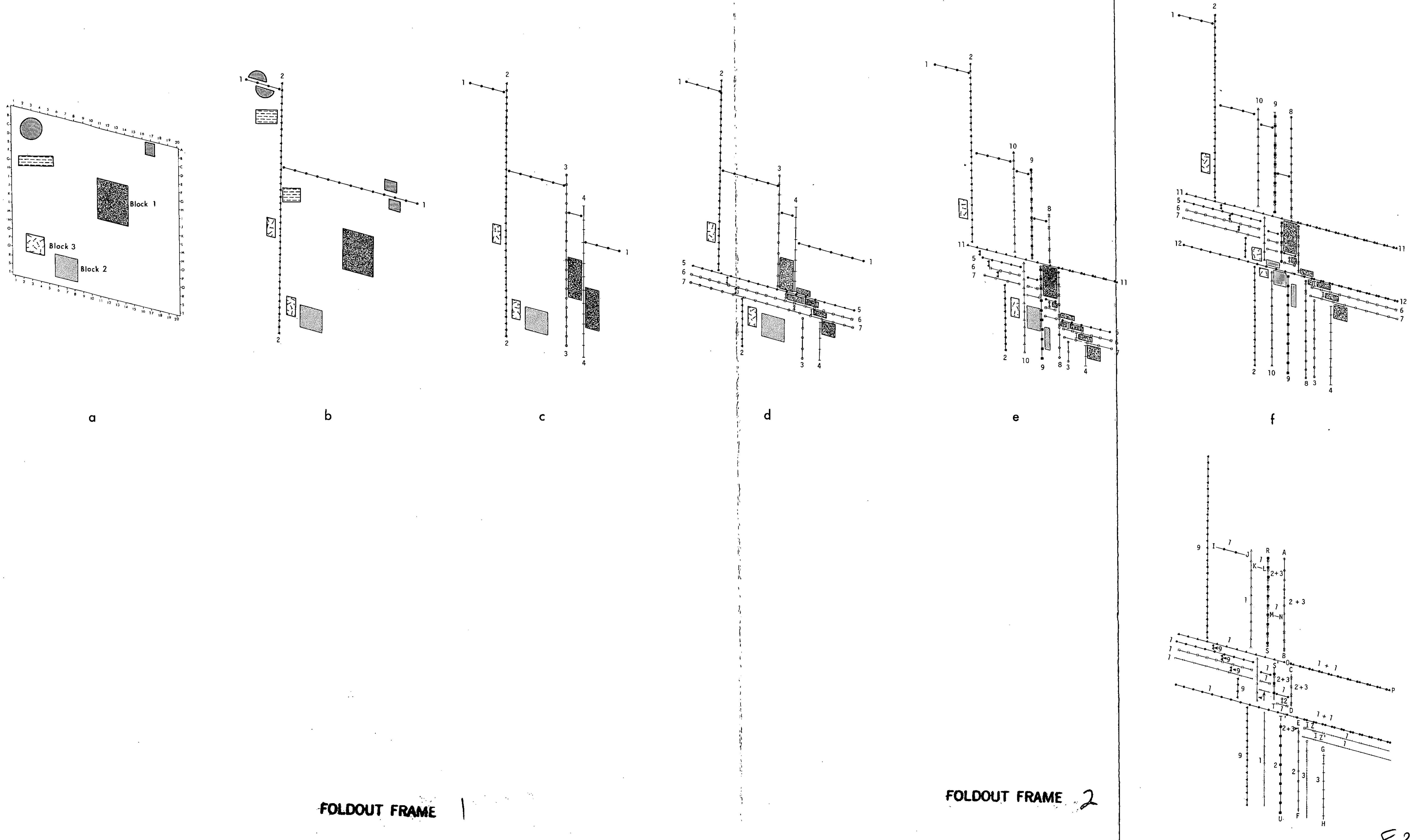
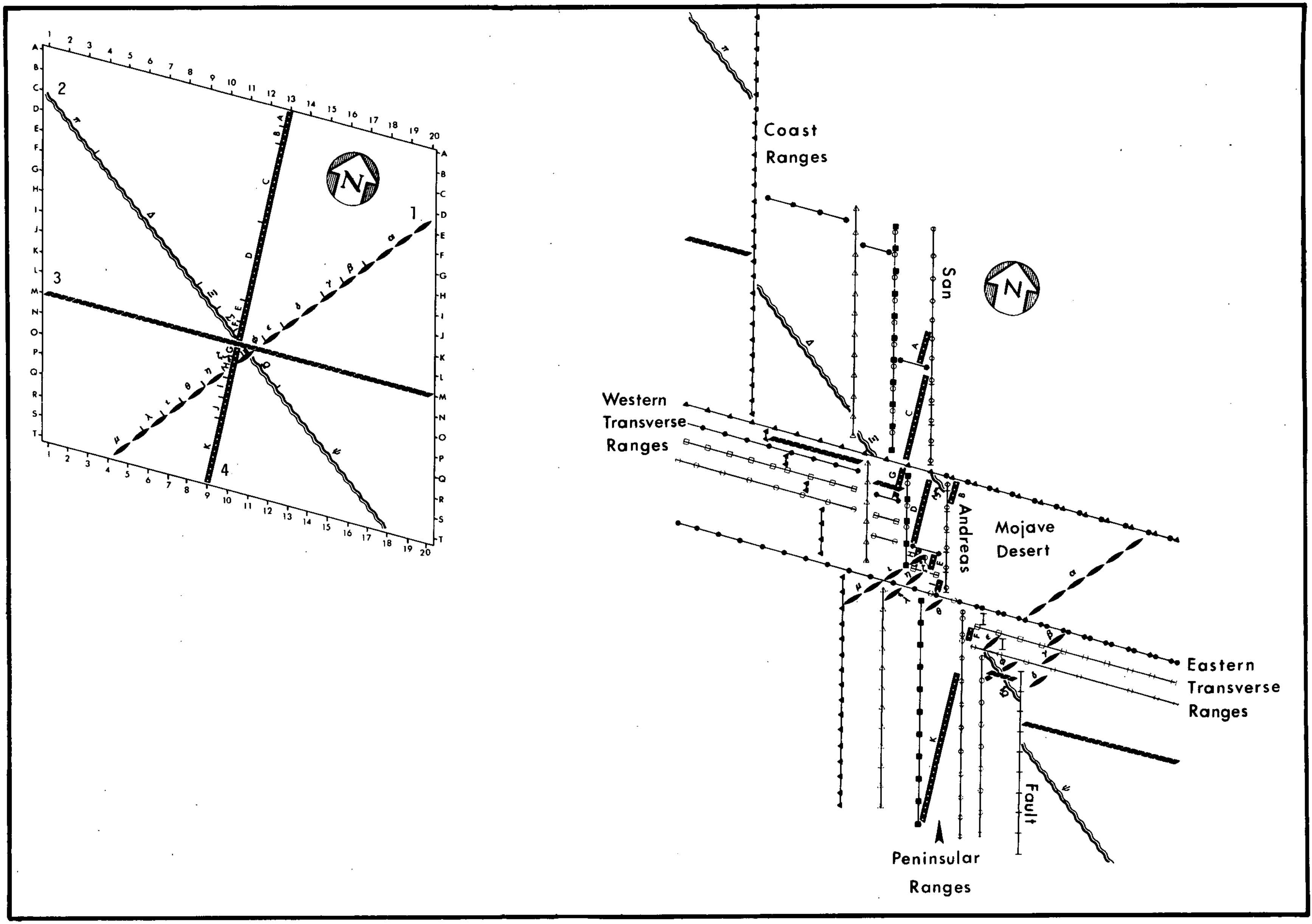


Figure 7

FOLDOUT FRAME 1

FOLDOUT FRAME 2


N
1
2
3
4
Coast Ranges
San
Andreas
Mojave Desert
Western Transverse Ranges
Eastern Transverse Ranges
Fault
Peninsular Ranges

(a) (b)

Figure 8

ERTS IMAGE DESCRIPTOR FORM

(See Instructions on Back)

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ID ______

DATE December 14, 1972

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PRODUCT ID (INCLUDE BAND AND PRODUCT)	FREQUENTLY USED DESCRIPTORS*			DESCRIPTORS
	Fault	Lineament	River	
1053-17545-6	x	x		Basin and Range
1032-17384-4	x	x	x	Lava
1070-17502-5	x	x		Coastline
1056-18120-4	x	x		Sag pond, Coastline
1033-17435-5	x	x	x	Lake, Basin and Range
1033-17444-5	x	x	x	Delta, Stream Effluent
1032-17382-6	x	x	x	Meander, Lake, Basin,Range
1049-17324-5	x	x	x	Lake, Open Pit Mine
1049-17331-6	x	x	x	
1049-17333-4	x	x	x	Coastline
1030-17265-4	x	x	x	Stream Offset
1048-17284-5	x	x		Drainage, Island, Coastline
1043-17011-5	x	x	x	Stream Effluent
1027-17120-6			x	Baymouth Bar
1064-17180-6				Baymouth Bar
1031-17343-5	x	x	x	Lagoon, Baymouth Bar
1028-17171-5	x	x	x	Trellis Drainage, Baymouth Bar
1066-17281-5	x	x	x	Lagoon
1027-17120-5	x	x		Trellis Drainage, Bay
1028-17183-5	x	x		
1078-16563-6	x	x		Lake, Drainage
1078-16560-6	x	x		Lake, Drainage
1030-17283-5	x	x		Gulf
1021-18172-4	x	x		Bay, Sag Pond
1021-18174-5		x		Coastline
1056-18120-5	x	x		Sag Pond
1037-18064-5	x	x		Fault Intersection, Island
1054-18010-5	x	x		Playa
1053-17551-5	x	x	x	Basin and Range
1070-17495-5	x	x		Lake, Basin, and Range
1053-17554-5	x	x	x	Sag Pond, Bay
1024-17220-5	x	x	x	
1024-17213-4	x	x	x	Playa
1030-17274-4	x	x	x	Open-Pit Mine

*FOR DESCRIPTORS WHICH WILL OCCUR FREQUENTLY, WRITE THE DESCRIPTOR TERMS IN THESE COLUMN HEADING SPACES NOW AND USE A CHECK (✓) MARK IN THE APPROPRIATE PRODUCT ID LINES. (FOR OTHER DESCRIPTORS, WRITE THE TERM UNDER THE DESCRIPTORS COLUMN).

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ORGANIZATION North American Rockwell Science Center

PRODUCT ID (INCLUDE BAND AND PRODUCT)	FREQUENTLY USED DESCRIPTORS*			DESCRIPTORS
	Fault	Lineament	River	
1030-17271-4	x	x	x	Playa, Open Pit Mine
1055-18053-5	x	x	x	Lake, Lava
1055-18055-5	x	x	x	Lava, Lake, Valley
1038-18111-5	x	x	x	Mountain, Lake, Valley
1020-18110-5	x	x	x	Lake, Island, Lava

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