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ERTS APPLICATIONS IN EARTHQUAKE RESEARCH AND MINERAL EXPLORATION IN CALIFORNIA

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Abstract

We shall demonstrate with examples that ERTS imagery can be effectively utilized to identify, locate, and map faults which show geomorphic evidence of geologically recent breakage. Several important faults not previously known have been identified. By plotting epicenters of historic earthquakes in parts of California, Sonora, Mexico, Arizona, and Nevada, we found that areas known for historic seismicity are often characterized by abundant evidence of recent fault and crustal movements. We also found that the opposite is not necessarily true: There are many examples of seismically quiet areas where outstanding evidence of recent fault movements is observed. One application is clear: ERTS-1 imagery could be effectively utilized to delineate areas susceptible to earthquake recurrence which, on the basis of seismic data alone, may be misleadingly considered safe. ERTS data can also be utilized in planning new sites in the geophysical network of fault movement monitoring and strain and tilt measurements. ERTS data on transverse faults and their interaction with the San Andreas system in west central California are providing significant scientific insights into the geological history of the state. In addition, an apparent correlation was observed between the distribution of mercury deposits in the California Coast Ranges Province and transverse fault zones trending west-northwest oblique to the trend of the San Andreas system. The significance of this correlation in mineral exploration will be discussed.

In this brief paper we describe significant observations derived from our study of the fault pattern revealed in ERTS-1 imagery of the central part of the Pacific mountain system of California. The practical applications of this work relate directly to problems of earthquake hazards and mineral exploration. Space limitations do not allow but a few illustrative examples.

ACTIVE FAULTS AND SEISMICITY PATTERNS

In California the most salient geologic hazard problem is the effect of earthquake damage to areas of high population density and industrial and life-supporting facilities. Activity on the San Andreas fault system has long been recognized as a major source of earthquakes. However, when we plotted the distribution of earthquake epicenters on ERTS-1 imagery we found that the seismicity pattern alone is inadequate in defining areas susceptible to earthquakes. The recent San Fernando and Oxnard earthquakes occurred in areas which if judged by seismic history alone would be considered relatively safe. On the other hand large segments of the San Andreas fault which are known from geologic evidence to have been recently active are now seismically quiet. Since our records of historic earthquakes span a relatively short time interval and the seismicity pattern appears to shift with time it becomes apparent that we are in need of another effective means to identify faults showing evidence of recent geologic activity and to regard such evidence as a more reliable basis for assessing the potential earthquake hazard.

Our approach to assess the application of ERTS-1 imagery to this problem is to plot the epicenters of historic earthquakes using a computer-stored list on overlays corresponding to the geometry of ERTS imagery and correlate the seismicity pattern with our observations on fault continuities, intersections, and inferred evidence of recent breakage.

Figures 1 and 2 are only examples of this approach which we applied so far to a vastly larger area of California, Utah, and Nevada.

Figure 1 is MSS image #1037-18064 showing the western part of the Transverse Ranges in California. Some of the major known faults are indicated by solid lines in the corresponding map. Several observations derived from this scene are significant. First that many bends of the San Andreas fault and other members of the system shown in the geological maps (Atlas of California) correspond to a distinct system of transverse faults trending west-northwest, oblique to the San Andreas system, which have acted to bend, offset, and otherwise distort these breaks.

The occurrence of major east-west faults in the Transverse Ranges is very well known; many of these are characterized by left-lateral shear. ERTS imagery has contributed to show that this system is not confined to the Transverse Ranges but is pervasive throughout the Coast Ranges. We suspect some of these may be major crustal breaks extending under the San Joaquin Valley and may be responsible for flextures in the configuration of the western side of the Sierra Nevada block and the Great Valley. Other transverse faults occur as distinct short segments lodged between throughgoing faults of the San Andreas system. We suspect those to be remnants of an old transverse shear fault system now largely intersected, offset, and in places incorporated within the San Andreas fault system. The geological maps of California show some of these transverse faults as conjugate or branching secondary features of the San Andreas system. ERTS-1 imagery on the other hand reveals that they belong to a separate and distinct fault system.

We are placing emphasis on this observation for profound scientific and practical considerations. The scientific significance will be subject to a more detailed treatment elsewhere (Abdel-Gawad and Silverstein, 1972). It may be useful, however, to suggest here that the immense complexity of the fault block mosaic of the crust in California and the Pacific Cordillera at large may be due to repeated and episodic interaction of two rather than one primary shear systems, which have cut and displaced one another and the process appears to be continuing at present.

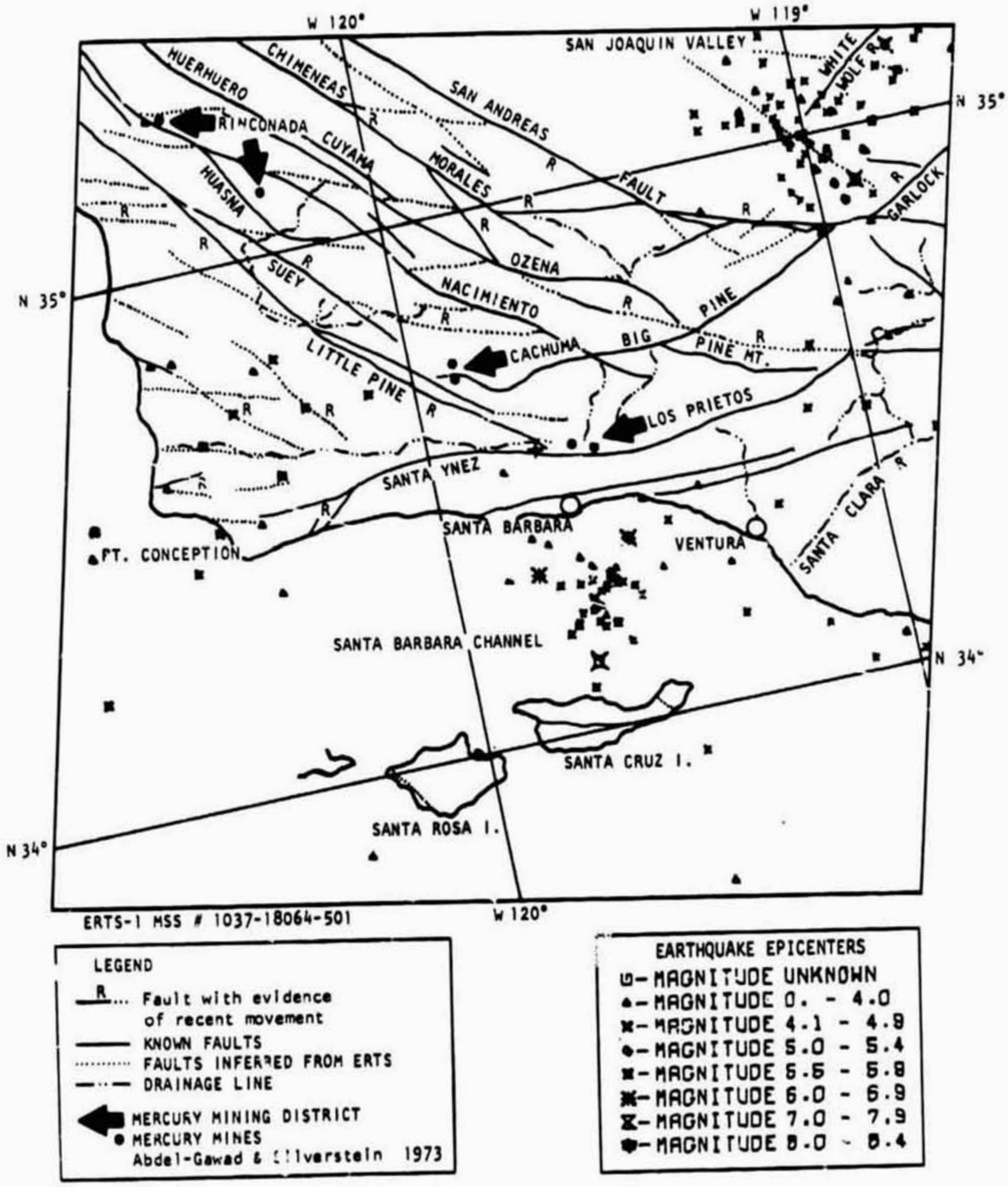
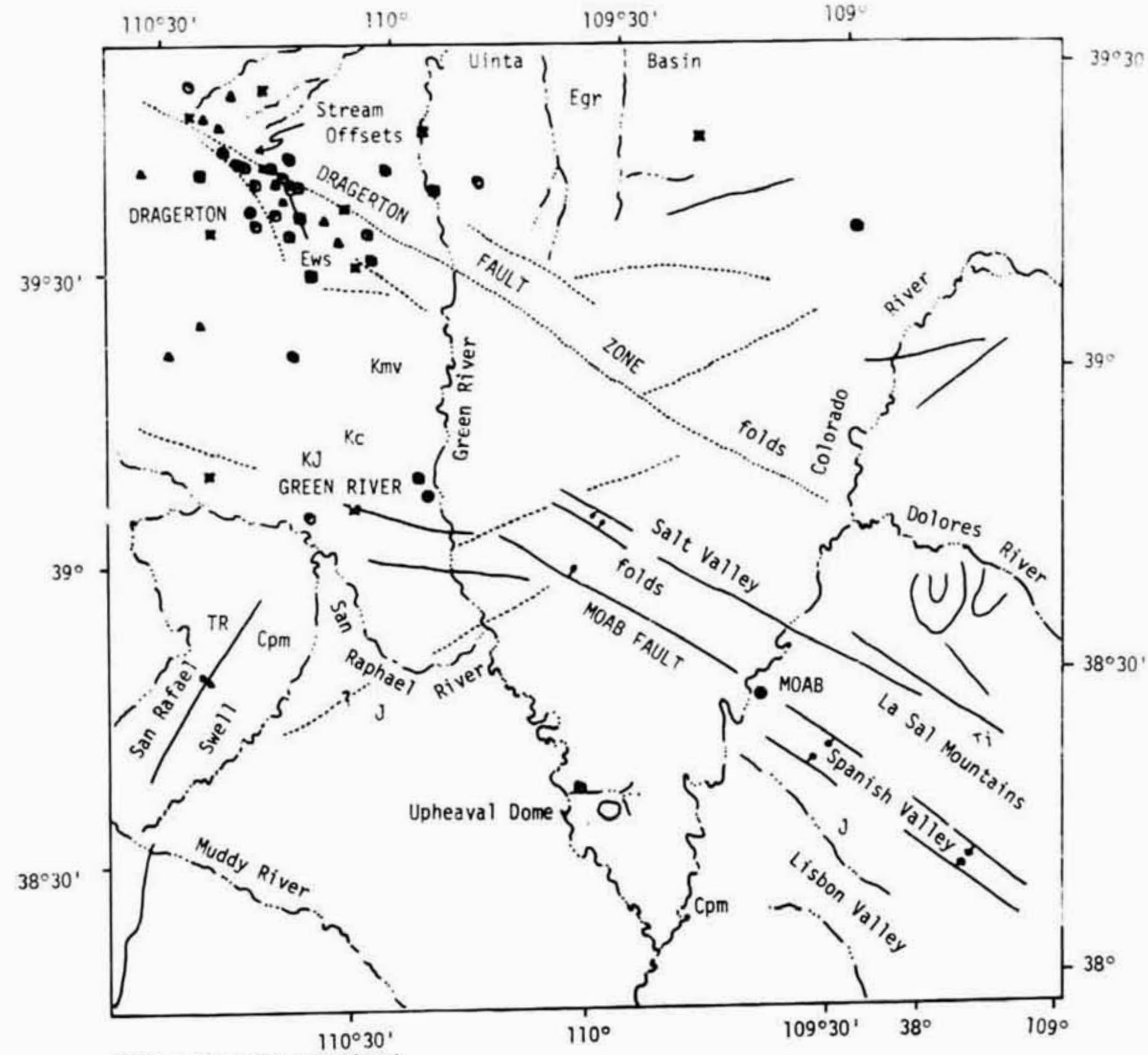

W 120°
W 119°
SAN JOAQUIN VALLEY
N 35°
HUERHUERO
CHIMENEAS
SAN ANDREAS
WHITE
WOLF R.
RINCONADA
CUYAMA
MORALES
FAULT
GARLOCK
HUASNA
OZENA
SUEY
NACIMIENTO
PINE
N 35°
LITTLE PINE
CACHUMA
BIG
PINE MT.
LOS PRIETOS
SANTA YNEZ
SANTA BARBARA
VENTURA
SANTA CLARA
PT. CONCEPTION
SANTA BARBARA CHANNEL
N 34°
SANTA CRUZ I.
SANTA ROSA I.
N 34°
W 120°
ERTS-1 MSS # 1037-18064-501
LEGEND
R.... Fault with evidence of recent movement
KNOWN FAULTS
FAULTS INFERRED FROM ERTS
DRAINAGE LINE
MERCURY MINING DISTRICT
MERCURY MINES
Abdel-Gawad & Silverstein 1973
EARTHQUAKE EPICENTERS
MAGNITUDE UNKNOWN
MAGNITUDE 0. - 4.0
MAGNITUDE 4.1 - 4.9
MAGNITUDE 5.0 - 5.4
MAGNITUDE 5.5 - 5.9
MAGNITUDE 6.0 - 6.9
MAGNITUDE 7.0 - 7.9
MAGNITUDE 8.0 - 8.4

Figure 1

Figure 1a



ERTS-1 RBV 1013-1/305(201)

LEGEND

- KNOWN FAULT
- FAULT INFERRED FROM ERTS
- DRAINAGE LINE
- ANTICLINAL AXIS

Earthquake Epicenters

- Unknown magnitude
- 0-4 mag.
- 4.1-4.9 mag.

Figure 2

Figure 2a

In Figures 1 & 4 we have identified by the symbol (R) examples of areas where we have inferred from the ERTS imagery evidence of Holocene (recent) activity on fault traces. Noting that in many places evidence of recent activity on transverse faults is almost as pervasive as that noted on the San Andreas fault system, it is rather difficult to escape the conclusion that transverse stresses are acting to distort, bend, and offset the San Andreas fault system, a process which inevitably lead to locked structures on which tectonic stresses are built and subsequently released by sudden breakage. Such a complex interaction between two episodically active fault systems may explain the tendency of earthquakes to cluster near fault intersections, an observation which has been known for some time (Allen et al., 1965).

The interaction of the two active fault systems suggests that in planning the geophysical networks for fault monitoring, more attention should be paid to active transverse faults than they are receiving at present.

Figure 1 shows many fault lineaments inferred from ERTS-1 imagery which were either not previously mapped or shown on maps incorporated with other faults. One particular example of interest is a fault lineament representing the southeastern extension of the Cuyama-Ozena fault, running along Hot Springs Canyon across Big Pine fault. This lineament is aligned with the middle segment of the San Gabriel fault. The intervening area in the vicinity of Lake Peru is likely to be subject to fault propagation.

Considering the relation of seismicity to the fault pattern, study of ERTS-1 imagery shows that in most areas where earthquake clusters occur, there is usually ample evidence of recent faulting. The opposite, however, is not necessarily true: there are many areas and even major fault segments characterized by geomorphic features indicating recent faulting, such as stream offsets and sharp lineaments in the alluvium, which are seismically quiet. This indicates as mentioned before, that characterization of earthquake hazardour areas largely on the basis of the present distribution of earthquake occurrences can be quite misleading and may result in unpleasant surprises. Based on our analysis of ERTS data over large areas in California, Nevada, Utah, and Sonora, it appears feasible to utilize ERTS imagery to identify many more potentially active faults than is presently known. Maps showing the location of potentially active faults could be prepared and in our opinion would be far superior to available maps and certainly will contribute to a more reliable earthquake safety planning program.

On the other hand our method of plotting the epicenters of historic earthquakes on ERTS imagery has been found to be useful in identifying previously unknown faults.

An example is shown in Figure 2, an RBV image showing the northern part of the Colorado Plateau, Utah. When historic earthquakes were plotted on an overlay a cluster was noted in the northwestern part of the image. The earthquake cluster drew attention to a northwest trending fault zone passing near the town of Dragerton through the Patmos Mountains and the southwestern side of the Tavaputs Plateau. This Dragerton fault zone runs parallel to the Salt Valley-Pardox valley fault zone and the Moab-Spanish Valley-Gypsum

Valley fault zones. The 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 Central 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 be a northwestward extension of a major fault lineament defining the southwestern side of the Uncompahgre uplight projecting towards the Tertiary volcanic center of San Joan Mountains, Colorado.

RELATION OF MERCURY DEPOSITS TO TRANSVERSE FAULTS

There are some 100 mercury deposits in California clustered in 21 districts. Most deposits occur in the California Coast Ranges from Lake County to the north to Santa Barbara County to the south (Davis, 1966).

Mercury ore has long been known to be deposited in epithermal (low temperature hydrothermal) conditions and is often associated with Tertiary and Quaternary volcanic regions. In California Coast Ranges mercury deposits occur in host rock conditions which are generally similar but the individual deposits have often been described an erratic, with marked differences in character, size, grade, and local structural conditions.

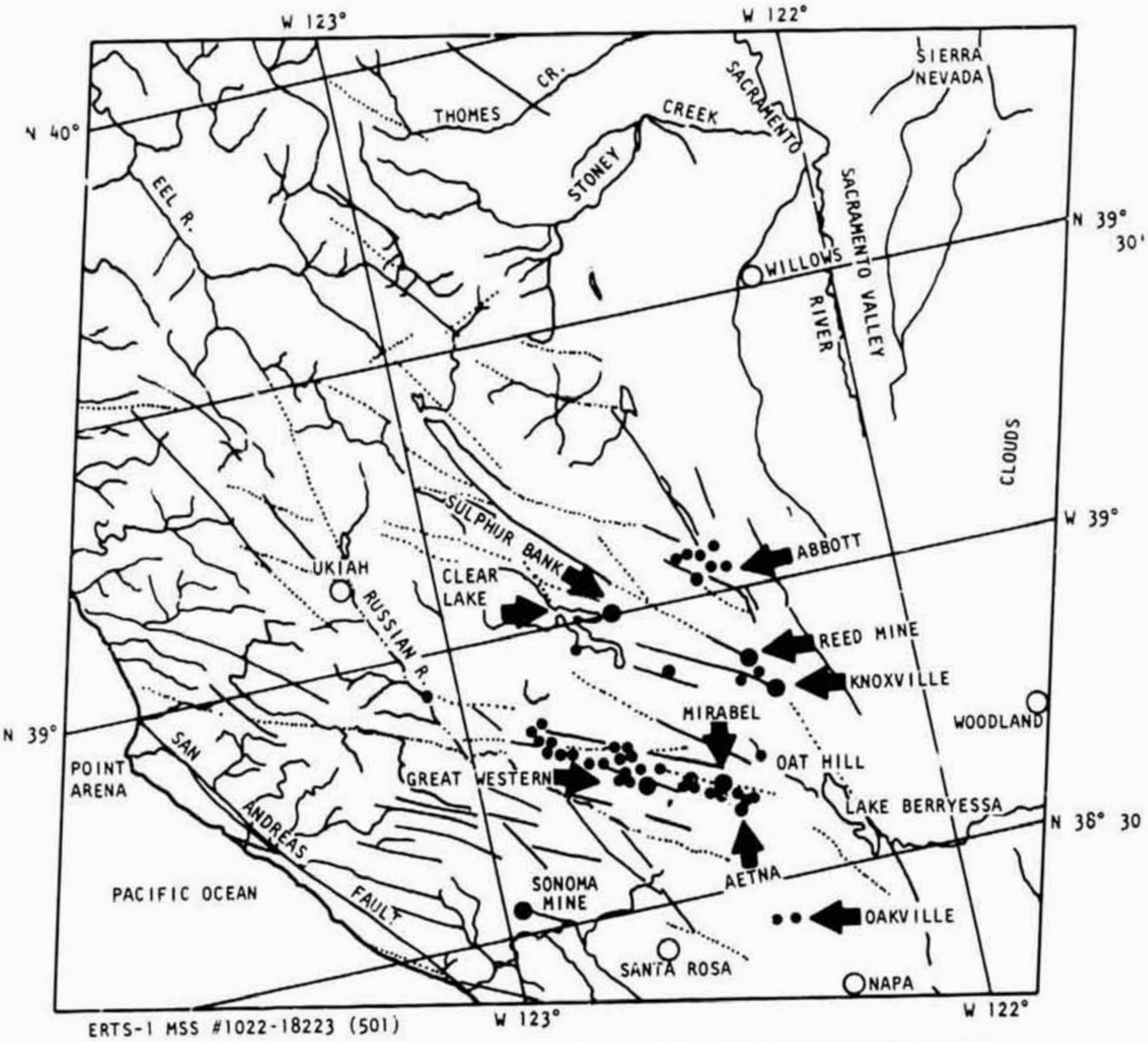
The carbonate-silica rock, an alteration product of serpentine often associated with mercury deposits, is so much more widespread than the ore itself as to be alsmost useless as an ore guide. In northern California mercury ore is found in the Clear Lake volcanic area (Figure 3). The Sulphur Bank Mine is a major hot spring-quicksilver deposit (White and Roberson, 1962).

Regionally, there has been little known regarding any specific tectonic or structural element which could be related to the regional distribution of mercury deposits even though many mines are known to occur in highly faulted, sheared, and deformed host rocks of the Franciscan Group and the overlying Upper Cretaceous strata.

That transverse faults constitute a distinct tectonic element in the deformation history of the Pacific mountain system of California appears to be economically important in addition to its profound scientific value.

Taken as an example the distribution of known mercury deposits in the California Coast and Transverse Ranges when plotted on ERTS-1 imagery shows a striking correlation with west-northwest trending shear zones, oblique to the prevalent trend of the San Andreas system.

The most striking correlation is noted in northern California in the Clear Lake and the Great Western mercury districts. Figure 3 shows an overlay map corresponding to ERTS-1 multispectral scanner scene no. 1022-18223. On this map we have plotted identifiable known faults as well as others inferred from ERTS imagery. We have also plotted as approximately as practical the most significant mercury mines as compiled by Bailey (1962). They are identified by the name of the district and some of the larger mines. The cluster of mercury mines in the Great Western, Aetna, Mirabel, and Oat Hill is the most striking in that it forms a distinct belt trending west-northwest which coincides with a zone of transverse faults. Many of these faults appear



RELATION OF MERCURY DEPOSITS TO TRANSVERSE FAULTS

COAST RANGES CALIFORNIA

LEGEND

—— KNOWN FAULTS

······ FAULTS INFERRED FROM ERTS

—·— DRAINAGE LINE

MERCURY MINING DISTRICT

●●● MERCURY MINES

Abdel-Gawad & Silverstein 1973

Figure 3

Figure 3a

on the Santa Rosa Geological Map Sheet, Atlas of California. In this specific case the relationship between mercury deposits and the transverse fault zone is rather evident from the fault pattern on the geological map. This relation, however, is not evident from the geological maps elsewhere in the Coast Ranges, because most of the known transverse faults are incorporated as bends in the northwest-trending faults of the San Andreas set and, therefore, do not stand out as a separate and significant entity. Besides, many transverse fault structures became evident from ERTS-1 imagery.

The relation between mercury mines and transverse fault zones is consequently much less apparent from the geological maps than from ERTS-1 imagery farther south in the Coast Ranges. In Figure 4 we have plotted known mercury occurrences together with transverse fault zones inferred from ERTS-1 scene 1075-18173. In this area of the Coast Ranges there are six mercury mining districts including the New Almaden, the first quicksilver mine discovered in North America and one of two most productive in California since 1846.

The New Almaden mine is typical of mercury ore associated with silica-carbonate rock underlain by graywacke, shale, greenstone, and serpentine of the Franciscan Formation. The mine is located on a "northwest trending anticline whose southwest limb is sheared and cinnabar was introduced along narrow northeast trending fractures" (Davis, 1966). Although some transverse faults are shown in the geological map (San Jose sheet) mostly as flextures in the San Andreas fault system, the position of the New Almaden, Guadalupe, and other deposits in distinct relation to transverse fault zones became readily apparent from correlation with ERTS imagery. In the Diablo Range, east of the Hayward fault four mercury districts, Vallejo, Mount Diablo, Phoenix, and Stayton are located on or near transverse fault zones identified from ERTS-1 imagery.

Figure 5 (MSS scene 1074-18121) shows the spatial relation between six mercury districts and transverse structures in the southern part of the Coast Ranges. The New Idria Mining district in San Benito County stands out as including the most productive mercury mine in the United States, which together with the New Almaden mine produced more than half a million flasks of mercury since its discovery in 1853. The New Idria cluster occurs associated with a serpentine mass which intruded through a sequence of shales and sandstones of the Upper Cretaceous Panoche formation and overlying Tertiary sedimentary rocks. Mercury ore has been described (Eckel and Myres, 1946; Davis, 1966; Linn, 1968) as localized under the New Idria thrust fault in altered Upper Cretaceous Panoche formation. A large ore shoot lies at the intersection of the New Idria thrust with a tear fault. We find it significant that the New Idria thrust has a definite transverse trend and may in fact be the surface expression of a transverse shear fault in depth. When we examine the transverse faults in this part of the Coast Ranges, particularly those which cut across the Diablo Range, east of the San Andreas fault and correlate them with the geological maps we find that they are often associated with known folds. Those have been widely regarded as drag folds and secondary faults resulting from primary right-lateral shear on the San Andreas fault. Most of the transverse faults shown on the geological maps cut the Mesozoic Franciscan formation and the overlying Upper Cretaceous sedimentary rocks, with only a few cutting rocks younger than Eocene. ERTS-1 imagery, however,

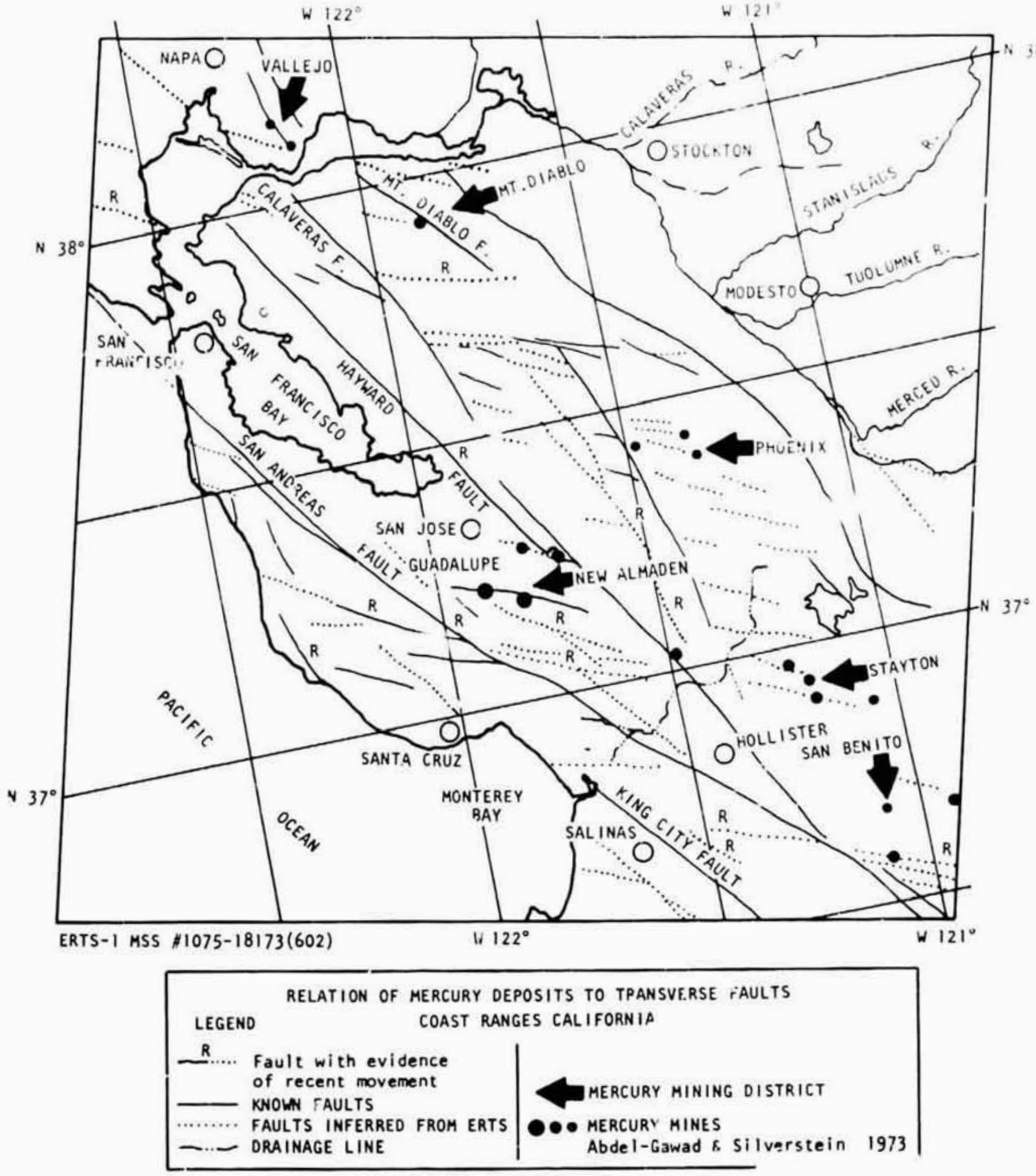

W 122°
W 121°
N 38°
N 37°
NAPA
VALLEJO
CALAVERAS R.
STOCKTON
STANISLAUS R.
MT. DIABLO
MT. DIABLO F.
CALAVERAS F.
MODESTO
TUOLUMNE R.
SAN FRANCISCO
SAN FRANCISCO BAY
HAYWARD FAULT
MERCED R.
PHOENIX
SAN ANDREAS FAULT
SAN JOSE
GUADALUPE
NEW ALMADEN
STAYTON
PACIFIC OCEAN
HOLLISTER
SAN BENITO
SANTA CRUZ
MONTEREY BAY
SALINAS
KING CITY FAULT
R
ERTS-1 MSS #1075-18173(602)
RELATION OF MERCURY DEPOSITS TO TRANSVERSE FAULTS
COAST RANGES CALIFORNIA
LEGEND
Fault with evidence of recent movement
KNOWN FAULTS
FAULTS INFERRED FROM ERTS
DRAINAGE LINE
MERCURY MINING DISTRICT
MERCURY MINES
Abdel-Gawad & Silverstein 1973

Figure 4

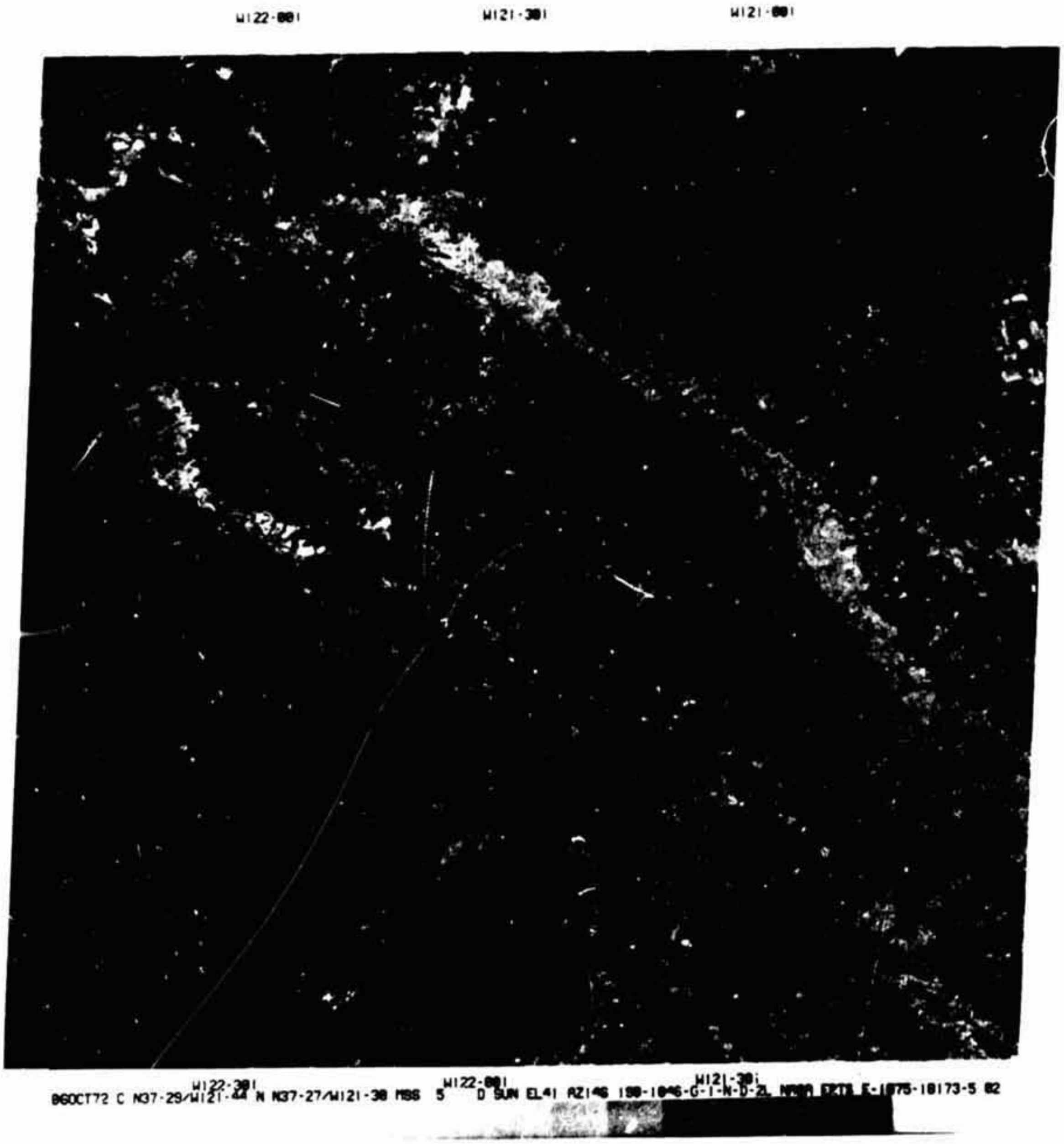
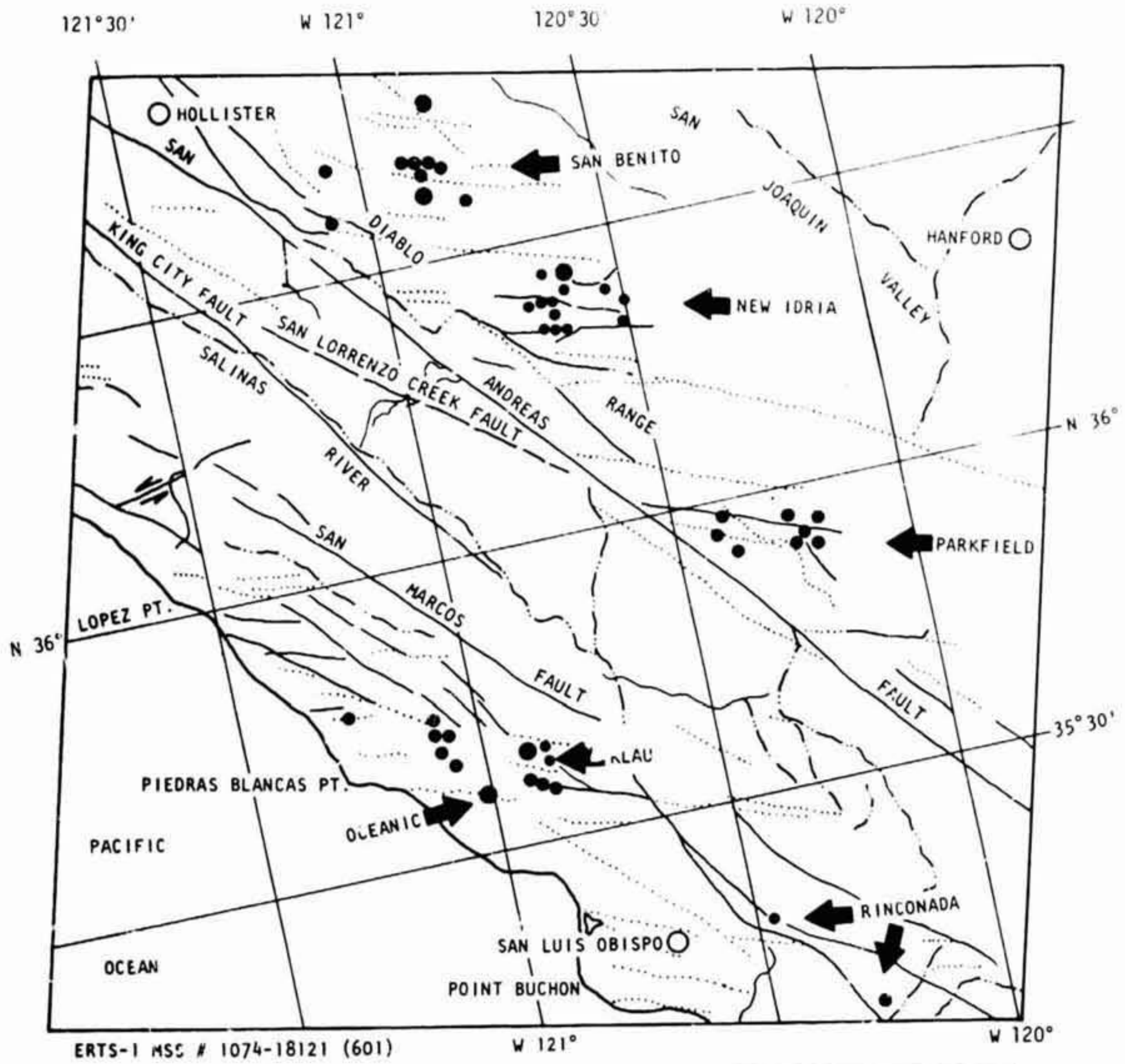

W122-001
W121-301
W121-001
W122-301
W122-001
W121-301
C N37-29/W121-44 N N37-27/W121-38 MSS 5 D SUN EL41 AZ146

Figure 4a



RELATION OF MERCURY DEPOSITS TO TRANSVERSE FAULTS
COAST RANGES CALIFORNIA

LEGEND

- KNOWN FAULTS
- FAULTS INFERRED FROM ERTS
- DRAINAGE LINE
- MERCURY MINING DISTRICT
- MERCURY MINES

Abdel-Gawad & Silverstein 1973

Figure 5

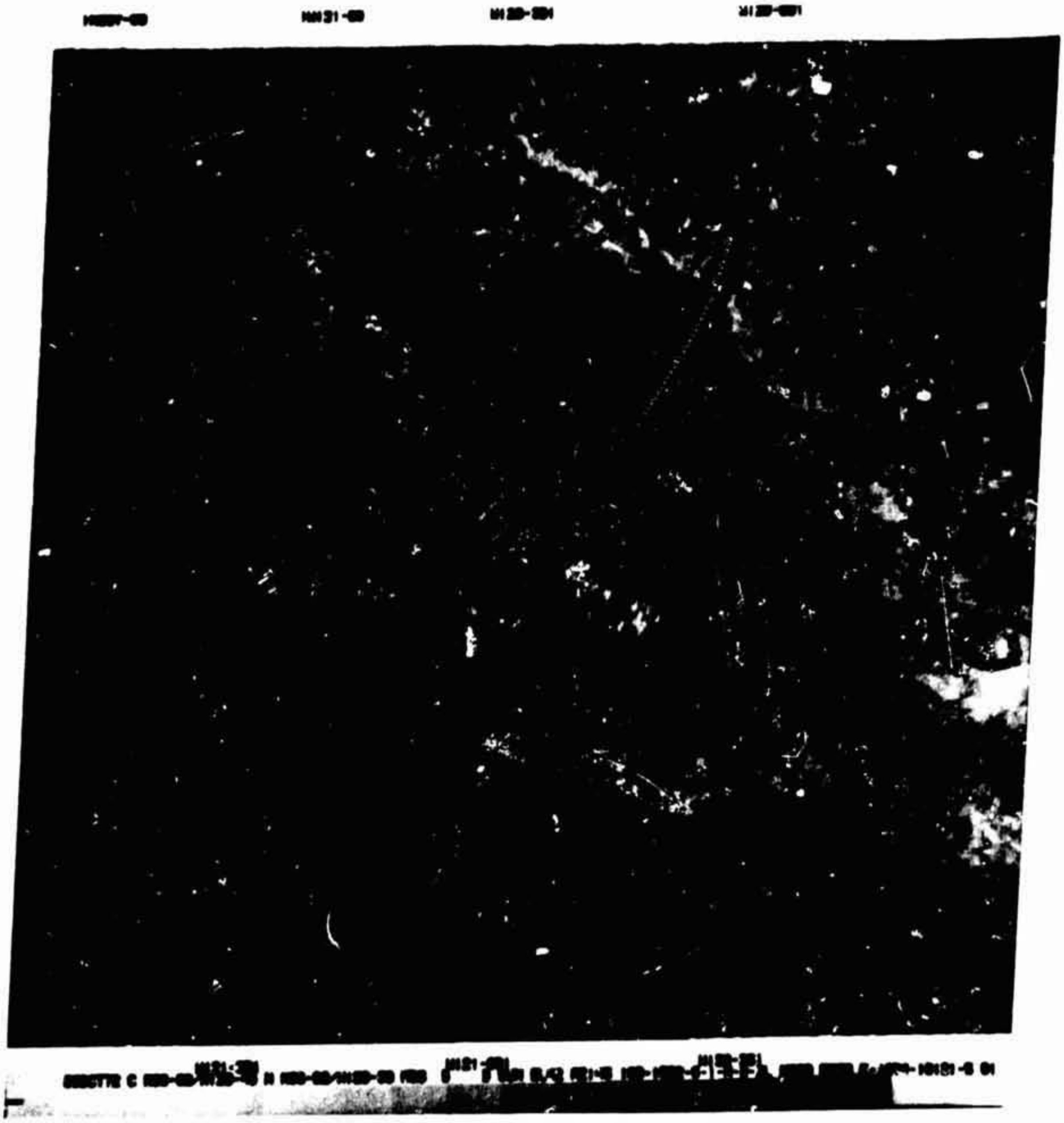


Figure 5a

show that a significant number of transverse faults, particularly those occurring along fold flexures on the eastern side of the Diablo Range, persist as distinct lineaments across Tertiary and Quaternary sedimentary rocks of the Great Valley. While the tectonic stresses which produced the transverse shear structures may have been initiated in pre-Tertiary times, the observation of fault lineaments across the blanket of younger rocks in the San Joaquin Valley suggests that transverse shear persisted during the deposition of Tertiary and Quaternary rocks and may very likely be still active.

Figure 1 corresponds to ERTS-1 scene 1037-18064 and shows the complex interaction of the Transverse Ranges and characteristic left-lateral wrench faults with the Coast Ranges and the San Andreas fault set. The three mercury districts, Rinconada, Cachuma, and Los Prietos indicate a relation to transverse structures. Although the Sunbird open pit mine (Los Prietos district) in Santa Barbara County has become among the large producers in the late 1960's (Mitko, F. C., 1968), it may appear surprising the mercury deposits were not found in greater abundance within the Transverse Ranges. The widespread presence of a thick blanket of Tertiary marine sedimentary rocks in this province probably accounts for the apparent scarcity of mercury deposits on the surface but there is no reason to discount the likelihood of more extensive occurrences in depth.

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FIGURE CAPTIONS

Figure 1. Fault pattern, seismicity, and mercury deposits in western Transverse Ranges California.

Figure 2. Fault pattern and seismicity, northern Colorado Plateau, Utah.

Figure 3. Relation of mercury deposits and transverse faults, Coast Ranges, northern California.

Figure 4. Mercury deposits and transverse faults, Coast Ranges, central California.

Figure 5. Mercury mines and transverse faults in southern Coast Ranges, California.