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"Skylab Explores the Earth"

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Geological Features of Southwestern North America

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THE SKYLAB 4 crewmen conducted visual observations of seven designated geological target areas and other targets of opportunity in parts of southwestern United States and northwestern Mexico. The experiments were designed to determine how effectively geologic features could be observed from orbit and what research information could be obtained from the observations when supported by ground studies. For the limited preparation they received, the crewmen demonstrated exceptional observational ability and produced outstanding photographic studies. They also formulated cogent opinions on how to improve future observational and photodocumentation techniques.

Significant research contributions to ongoing field investigations were obtained from the photographs and observations. These contributions were integrated into other aspects of the ground investigations to (1) identify and evaluate zones of major faulting in southeastern California, Baja California, and northwestern Sonora; (2) develop a new key to the regional stratigraphy of the prebatholithic rocks of northern Baja California; (3) discover the most southwesterly known occurrence of Precambrian crystalline rocks in North America; (4) discover a previously unmapped section of Mesozoic (?) volcanic rocks in southeastern California; and (5) contribute important overview perspectives to many regional geologic problems.

The experimental data and the demonstrated crew capabilities justify planning future geology visual observation experiments for manned Earth-orbiting programs such as the Space Shuttle. Both professional scientist-observers and astronaut-observers can make contributions if properly prepared and equipped. The experiments should be closely coordinated with active surface research investigations. The emphasis should be on selecting important problems and objectives and integrating orbital observations and ground studies, not on prospecting for isolated spectacular discoveries.

INTRODUCTION

Man's role as a direct and discriminating observer of geologic features on the Earth's surface as seen from the vantage point of an orbiting platform was tested formally for the first time during the third manned visit to Skylab. The great value of unmanned Earth-orbital photographic and other remote-sensing techniques in Earth science studies had been clearly established before the Skylab missions. However, the potential of man in real-time, dedicated, terrestrial geological observation activities had not been previously investigated. With the obvious future requirement for a better geological understanding of the Earth, man's capability to meet these needs in various space-flight applications deserves thorough consideration and evaluation.

To provide relevance, there are two general conceptual areas in which the objectives and implementation

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of the Skylab geology observation experiments should be considered.

1. What are man's inherent capabilities as a geological observer from a satellite? What orbital conditions, equipment, and techniques and what ground-based activities can provide the most effective use of these capabilities?

2. What are the types of geologic problems and scientific questions to which man in orbit can make superior or unique observational contributions? Are the problems and his contributions of sufficient scientific value to justify the use of man in this space activity as compared to other functions he can perform? As compared to other approaches to the same problems?

The Skylab visual observations experiments provided useful data and experience pertaining to these questions. In addition, photographic and visual observations data that are valuable to geological research in a number of areas in southwestern North America were obtained.

Approximately a month before the Skylab 4 mission, the senior author participated in the preparation of a visual observations program in which the crewmen would examine and photograph selected geological areas in southwestern North America (fig. 4-1). A series of seven operational exercises and study areas in the southwestern United States and northwestern Mexico was discussed during a 1-hour briefing for the astronauts. For each exercise, a photograph from Apollo or earlier Skylab missions illustrated the feature to be studied. These photographs were included in the onboard data package for use by the astronauts.

During the mission, the crew made extensive visual observations in almost all the geological study areas of southwestern North America and collected a comprehensive photographic record of their observational opportunities. The results of these efforts are contained in table 4-I and figure 4-2.

On March 12, 1974, the crew participated in a 4-hour geology debriefing conducted by the principal investigators of the geology experiments. Included in the debriefing were a brief review of the available handheld-camera photographs and discussions of the observational opportunities, conditions, and equipment and of the construction of the exercises. The transcript of this debriefing was used in the preparation of this report. Photographic transparencies and a limited number of photographs of the experiment sites and nearby areas were analyzed. Field studies to verify the photogeologic interpretations were carried out from April to December 1974. Field work and photointerpretation were done by the various authors: Arizona, C. M. Conway and L. T. Silver; southern California, R. E. Powell and L. T. Silver, Baja California, J. D. Murray and L. T. Silver; and Sonora, Mexico, T. H. Anderson and L. T. Silver. Dayna Salter assisted in the study of structural lineaments in southern California.

PLANNED GEOLOGY VISUAL OBSERVATION EXPERIMENTS

The geology experiments were designed with dual objectives: to determine how effective an orbiting observer could be in the context of the Skylab flightpath, flight time, and facilities and to determine the type of scientific yield that could be obtained from analysis of the crewmen's observations and photographic products when supported by ground studies.

The assigned exercises are shown in figure 4-1. Because of time constraints, the preflight briefing was minimal, and the crewmen's understanding of the experiment objectives was obtained only from discussions with the senior author. The general orbital tracks shown in figure 4-1 show the types of northeast and southeast passes during which the crewmen made their observations.

Each exercise was designed around a geological problem or group of problems with which the senior author and his colleagues were concerned. In each area, extended field work had been carried out before the Skylab 4 mission and considerable familiarity with ground truth had been established. Therefore, some questions were designed to test the crewmen's observations of known phenomena. Nevertheless, substantial scientific questions remained in each area for which it was hoped that the astronauts' observations would make significant contributions. Further ground-verification activities were intended to be a part of these studies.

DATA PRODUCED BY THE EXPERIMENTS

The direct results of the observational experiments take three forms.

1. The in-flight verbal commentary by crewmembers as they conducted their observations was recorded and subsequently transcribed.

2. Crewmembers used a handheld Hasselblad 70-mm camera with a 100-mm lens and a Nikon 35-mm

camera with 55- and 300-mm lenses to photograph sites and features. Both cameras were used for all sites designated for this study under a variety of observing positions and lighting conditions. Also photographed were "targets of opportunity" (i.e., geological features that the astronauts believed to be noteworthy but that had not been included in the assigned exercise). A total of more than 400 photographs was taken during the mission as part of these experiments. A tabulation of the photographs according to geographical area is given in table 4-I. A geographical map index showing photographic coverage and photographic orientation is presented in figure 4-2.

3. Postmission crew debriefing and individual crew-

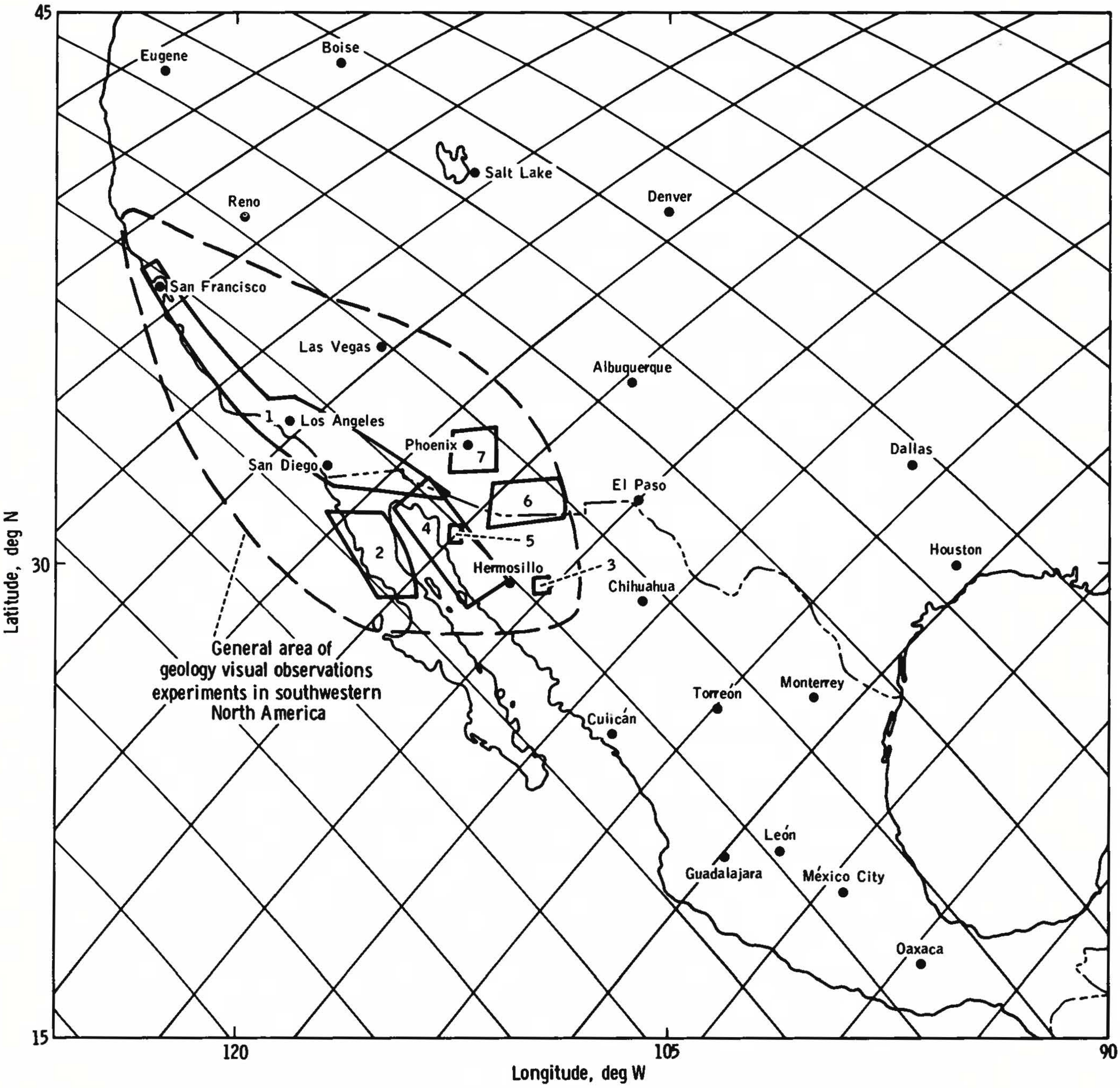


FIGURE 4-1.—Skylab 4 orbital track map showing the general region and the seven study areas involved in this experiment.

TABLE 4-I.— Index of Skylab 4 Handheld-Camera Photographs of Southwestern North America

Area	Photograph no.	
	Nikon 35-mm camera	*Hasselblad 70-mm camera*
Baja California and Gulf of California	SL4-152-5186 SL4-156-5294 and 5295 SL4-191-7036 to 7040 SL4-193-7187 to 7190 SL4-194-7234, 7235, and 7238 SL4-195-7325 SL4-196-7371 and 7372 SL4-197-7426, 7428, and 7429 SL4-199-7552 and 7553 SL4-202-7718, 7725, and 7732 SL4-203-7807 to 7813 and 7816 to 7819 SL4-204-7870 and 7882 to 7885 SL4-206-7967 and 7970	SL4-136-3385, 3409, 3410, 3437 to 3439, and 3479 to 3481 SL4-137-3727 SL4-138-3807 to 3810, 3827 to 3829, 3860, 3861, 3880, and 3881 SL4-140-4126 to 4140, 4154 to 4156, 4197, and 4198 SL4-142-4486 to 4489, 4544 to 4550, 4552 to 4554, 4562 to 4565, and 4581 SL4-143-4603 to 4607
Sonora, Mexico	SL4-156-5294 and 5295 SL4-193-7154 and 7155 SL4-194-7236, 7237, 7239, and 7240 SL4-196-7355, 7356, 7363, 7371, and 7372 SL4-197-7429 to 7431 SL4-199-7558 to 7580 SL4-200-7619 to 7622 SL4-202-7725 to 7745 SL4-203-7807 to 7825 SL4-204-7870 SL4-206-7970 and 7989 SL4-207-8034 to 8056 SL4-209-8199 to 8201	SL4-136-3409 and 3410 SL4-139-3983 and 4062 to 4064 SL4-140-4130 to 4141, 4154 to 4156, 4186 to 4188, 4197, and 4198 SL4-141-4390 to 4401 SL4-142-4547 to 4554 SL4-143-4603 to 4607 and 4616 to 4622
Arizona	SL4-156-5294 to 5297 SL4-191-7008, 7009, and 7019 SL4-193-7192 SL4-194-7216 and 7217 SL4-196-7371 SL4-197-7429 SL4-199-7552 to 7557 SL4-202-7719 to 7724, 7726, and 7730 SL4-203-7800, 7806, 7812 to 7815, and 7820	SL4-138-3808 to 3812, 3860, 3861, and 3881 SL4-139-4034 to 4037 SL4-140-4132, 4134, 4135, 4137 to 4141, 4157, and 4185 SL4-141-4385, 4386, 4390, and 4391 SL4-142-4435 to 4440, 4474, 4477, 4564, 4565, 4580, and 4581
San Andreas and related faults	SL4-156-5294 and 5295 SL4-193-7191 SL4-194-7212 to 7214 SL4-196-7354, 7361, and 7362 SL4-197-7426 to 7431 SL4-199-7552 to 7557 SL4-203-7784 to 7825 SL4-204-7879 to 7885 SL4-206-7961 to 7972 and 8009 to 8019 SL4-207-8026 to 8033 and 8086 SL4-208-8116 to 8120 and 8123 to 8126 SL4-209-8192 to 8196	SL4-136-3406 to 3408 and 3437 to 3439 SL4-138-3807 to 3810, 3828, 3829, 3843, 3860, and 3861 SL4-139-4033 SL4-140-4130 to 4141 SL4-141-4377, 4378, 4381 to 4384, and 4387 to 4389 SL4-142-4482 to 4487, 4520 to 4523, 4530 to 4547, 4551, and 4558 to 4565 SL4-143-4615
California, Nevada, Utah, Colorado, and New Mexico	SL4-156-5296 and 5297 SL4-191-7004 and 7019 SL4-192-7091 SL4-193-7151 and 7197 SL4-199-7552 to 7557 SL4-202-7716 to 7726 SL4-204-7870 SL4-206-7961 to 7969, 7972, and 8009 to 8019 SL4-207-8081 and 8082	SL4-138-3811, 3812, 3844, 3845, 3875, and 3881 SL4-139-4034 to 4040 and 4047 to 4049 SL4-140-4086, 4157 to 4159, 4167, 4168, 4185, 4211, 4231, and 4232 SL4-141-4258, 4259, 4371 to 4376, and 4379 to 4386 SL4-142-4430 to 4437, 4580, and 4581

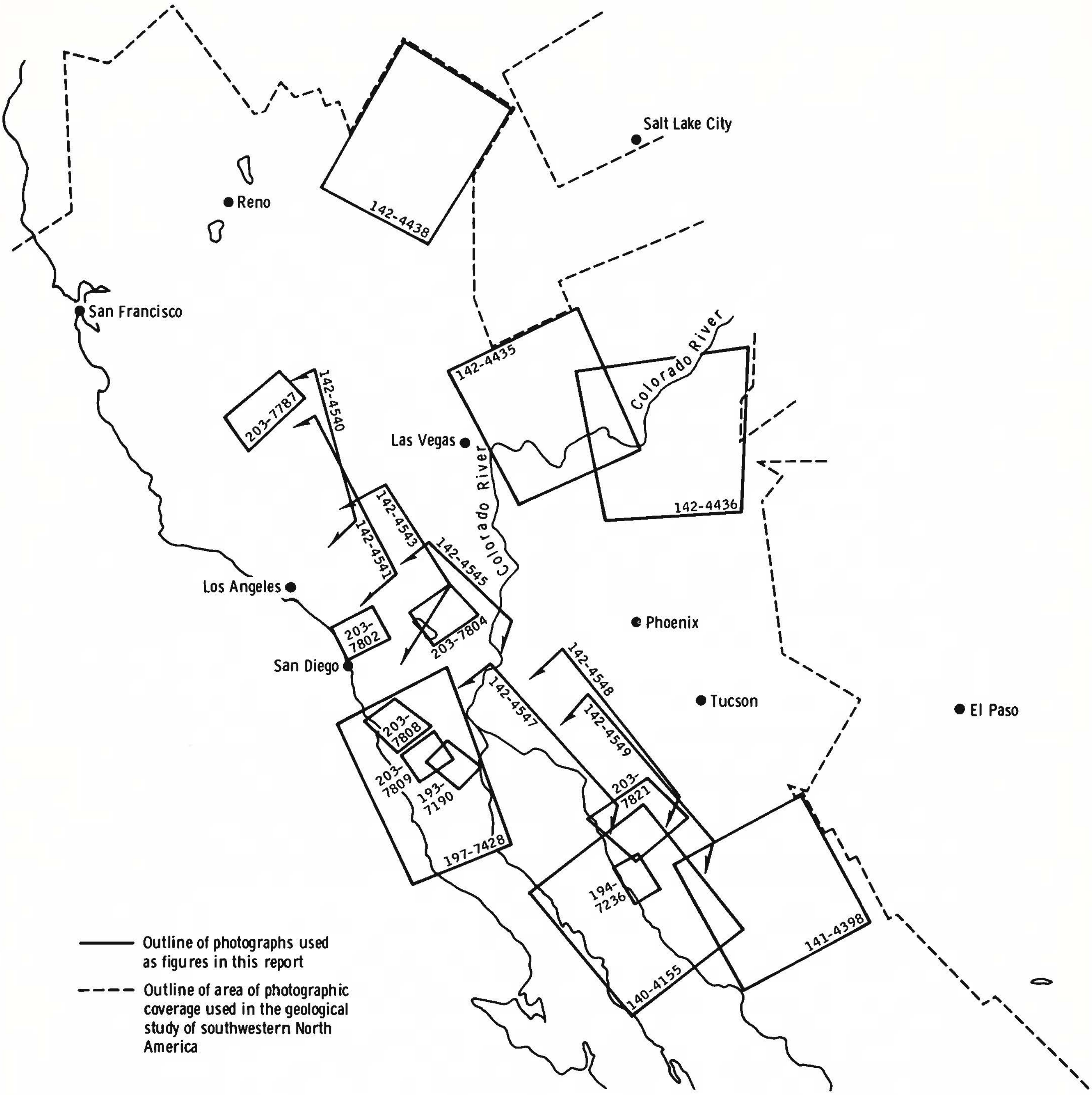


FIGURE 4-2.—Geographical map index showing selected photographic coverage and photographic orientation used in this report.

man communications provided opportunities for the crewmen to synthesize and summarize their impressions of the actual observing conditions, of the art of observation, and of the scientific subjects explored by them and to offer their recommendations for future improvements. The discussions with the Skylab 4 crew have been useful in completing this report.

CREW EFFECTIVENESS

Our preliminary assessment of crew effectiveness in conducting geology experiments from space (ref. 4-1) has been reinforced during the completion of the report. The effectiveness of a visual observations program depends on many key factors, such as the interest, scientific training, observational powers, and preflight preparation of the personnel involved. The Skylab 4 crew demonstrated a high degree of interest in the general visual observations program and in the specific geologic questions that concerned the related sites. This interest and an obvious enjoyment of Earth observation were manifested both during and after the mission. The scientific background of the crewmen indicated that they clearly understood the nature of observational techniques and the associated inductive logic. The crewmen did not receive extensive familiarization with geologic phenomena, and they recognized that a longer geological training program would have been beneficial.

The observational powers of the crewmen were exceptional. Combined with their interest and enthusiasm, these capabilities have produced some outstanding photographs of geologic phenomena. The contribution of the verbal commentary is subordinate to these photographs because of the general tendency of the crew to depend on their photographic documentation. This tendency may reflect a lack of confidence in their command of the diverse scientific subject matter. The fact that the crewmembers quickly recognized and identified the geological features in the designated sites reinforces the belief that more extensive preflight preparation would have enhanced the total scientific yield of the visual observations.

The crew developed many new and significant impressions of visual observation and photographic techniques. For example, they have stressed one important factor: no photograph can match the effectiveness of the human eye in perception of color, texture, and form of surface phenomena. During the debriefing session, the commander made the following comment:

> I think there is one fallacy we fell to, and that was the tendency to depend on the photographs. We've gotten back and we've looked at this photography now. It doesn't capture everything that's there and I think you guys understand that. I don't think we understood it as well as we should have before we left. Some of the stuff we have looked at just does not hold a candle to what you can really see with the old MK-VIII eyeball. And this is something we are going to have to do in future programs, and that is either to get better photography or start training a little bit more towards being able to get verbal descriptions of what you're looking at, because these pictures just don't have all of it at all.

In summary, the observational performance of the crew was outstanding. On the basis of the photographic documentation and results from discussions with them, we believe that they have made a convincing argument for future geological visual observations experiments from Earth orbit. Such experiments should continue to test and compare the effectiveness of manned visual observations with other approaches. They should be designed, however, as part of ongoing research programs with the orbiting observer (astronaut or scientist) as an active participant in the research. The criteria for effectiveness should include measures of steady research contribution as well as the opportunities for unexpected discovery.

DISCUSSION

The observations made by the astronauts, particularly their photographic record, were deliberately directed to areas where regional research investigations were being actively pursued by various members of this team. Our studies have shown that the selective photography is a rich reservoir of new information and insight.

Totally new, unsuspected major geologic features have rarely been found although there are innumerable new data points. Invariably, it has been found that space photography has given a new perspective to each research problem in which the geography and geometry of the diverse geologic elements of a region hundreds of kilometers in dimension fall into obvious spatial relation. This is not simply a result of having a new horizontal map base; it demonstrates that space photographs help to establish the color, texture, structure, and form of surface features on a scale and with an orientation that was not previously available.

From previous work and postmission field studies, we have learned to be cautious of oversimplifying the significance of many apparent photographic relations. At the same time, several large-scale relationships that were suspect but that had not been properly integrated into the regional framework because of the lack of a documented overview have been confirmed.

For a region as geologically well known as southern California, the photographs from the Skylab 4 handheld camera appear to make their greatest research contribution when used in conjunction with other diverse approaches in developing a more complete understanding of large-scale features. In this application, the usefulness of the photographs is more steady and pervasive if less spectacular.

In more unfamiliar regions such as northwestern Mexico, there is a greater potential for exciting discoveries, and it is believed that some of the results from the Skylab 4 experiments will help achieve this result. However, it is in precisely this type of situation that premature generalization without adequate ground studies for confirmation can obscure the potential. The extent of our efforts has not been such as to provide thorough testing of most of the important possibilities inferred from the studies of the Skylab photographs and crew commentary.

This section contains some of the many promising (and sometimes enigmatic) research results that have been derived and will continue to be derived from the visual observation efforts of the Skylab 4 crew.

San Andreas Fault System and the Architecture of Southern California

The remarkable control exerted by the San Andreas Fault system on the topographic character of southern California was explicitly documented by the Skylab 4 astronauts. From a striking series of oblique handheld-camera photographs, a photomosaic (fig. 4-3(a)) has been constructed that captures the continuity and the relationship of the principal active faults of this system and the Gulf of California. The principal elements of this fault system are identified in figure 4-3(b).

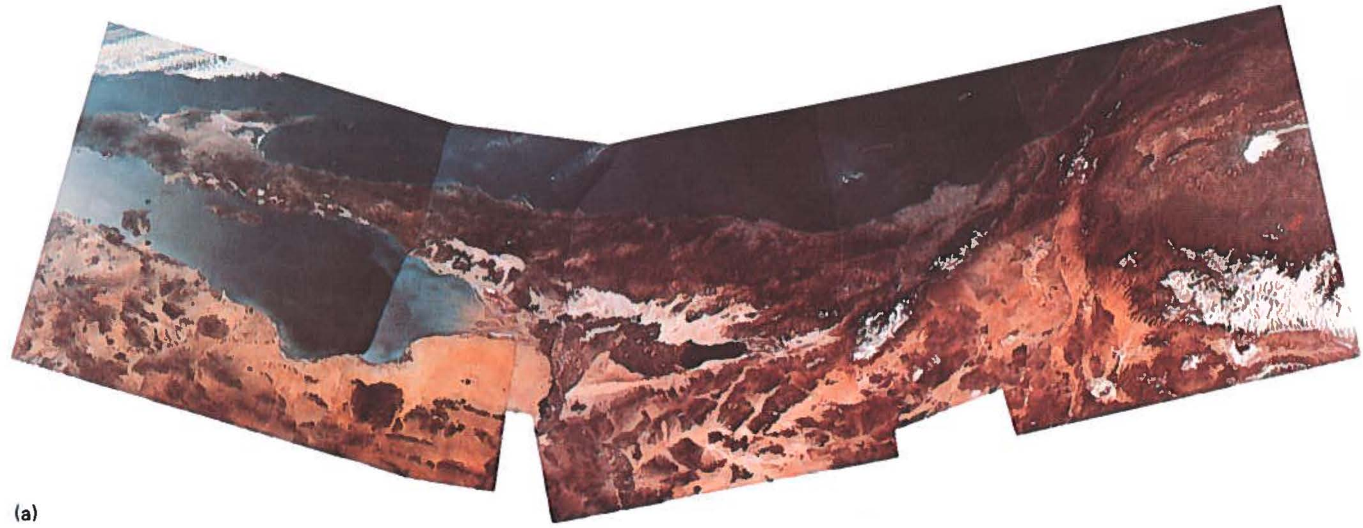
Most of the fault structures are well known and have been intensively studied. The crew's attention was directed to them as perhaps the best examples of fault-line features from which they could establish their observational criteria for fault recognition. The Skylab 4 photographic record has provided, in turn, an unparalleled overview of the fault system. From a significant number of relevant applications to southern California geology, three diverse examples that illustrate the great potential of the Skylab 4 handheld-camera photographs are presented.

East-west lineaments.—A profound geologic and physiographic break in the general northwest-southeast trends of California and Baja California is formed by the east-west structural grain of the Transverse Ranges. The tectonic significance of this unique transverse province in western North America is not fully understood in terms of the timing of structural events and the definition of structural elements. Skylab 4 handheld-camera photographs have provided an excellent overview of the Transverse Ranges province (fig. 4-3) and an opportunity to further delineate some of its structural elements.

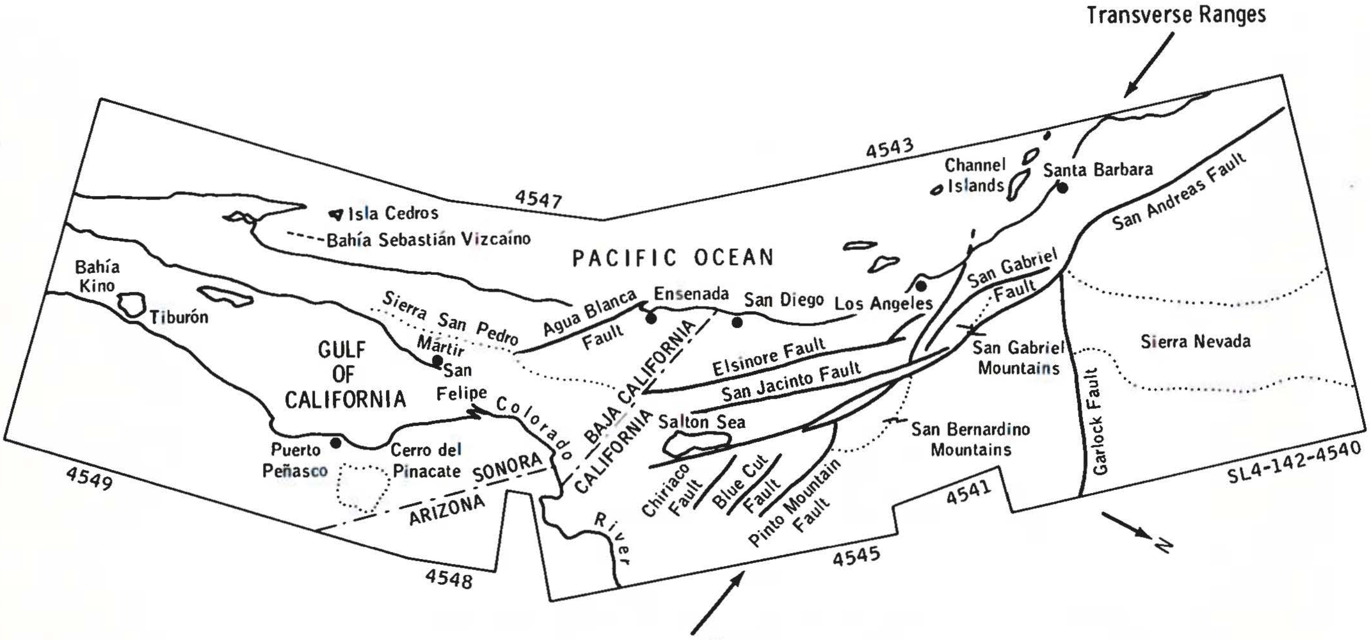
The eastern Transverse Ranges are distinguished by several east-west faults along which left-lateral displacement has been documented (refs. 4-2 and 4-3). These faults, including the Pinto Mountain, Blue Cut, and Chiriaco Faults (fig. 4-4), define prominent linears on Skylab 4 handheld-camera photographs. The Pinto Mountain, Blue Cut, and a few smaller faults were known to have left-lateral displacement before the Skylab 4 mission.

Based on ground verification of the in-flight observations of the Skylab 4 crewmen, 11.3 km of left-lateral movement has been demonstrated along the eastern half of the Chiriaco Fault (fig. 4-5(b) and ref. 4-4). The offset lithologic units cannot be resolved on the Hasselblad photographs, but areas for comparison and possible correlation are suggested and are detectable on the Nikon 300-mm photograph (fig. 4-5(a)).

The study of Skylab 4 handheld-camera photographs has resulted in the recognition of additional east-west linears south of the Chiriaco Fault. Left-lateral displacement has been established on two of these linears. An important goal for continued research is to determine whether the remaining linears are controlled by left-lateral faults. Recognition of the distribution of east-west linears on Skylab 4 photographs, followed by documentation of fault control and timing of fault motion, will increase understanding of the mechanical evolution of the Transverse Ranges structural province.



(a)



(b)

FIGURE 4-3.—Overview of major fault systems in southern California and northwestern Mexico. (a) Photomosaic. (b) Sketch map.

FIGURE 4-4.—Major linear features in southern California. (a) Photograph (SL4-142-4545). (b) Sketch map showing major east-west and northwest-southeast linears. Arrows indicate the direction of relative motion on opposite sides of faults. (c) Prominent conjugate linears in the northern Peninsular Ranges.

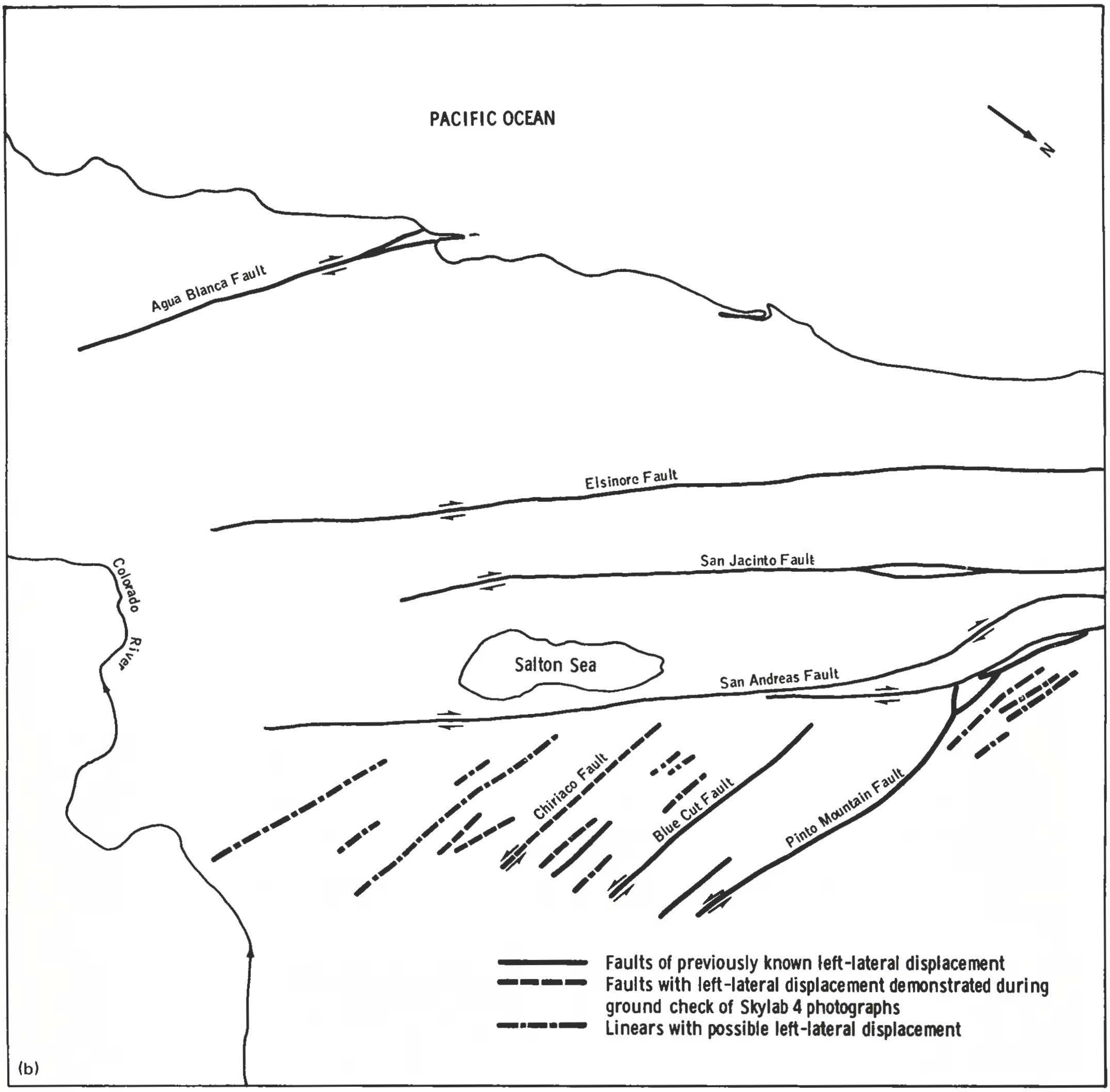


FIGURE 4-4.—Continued.

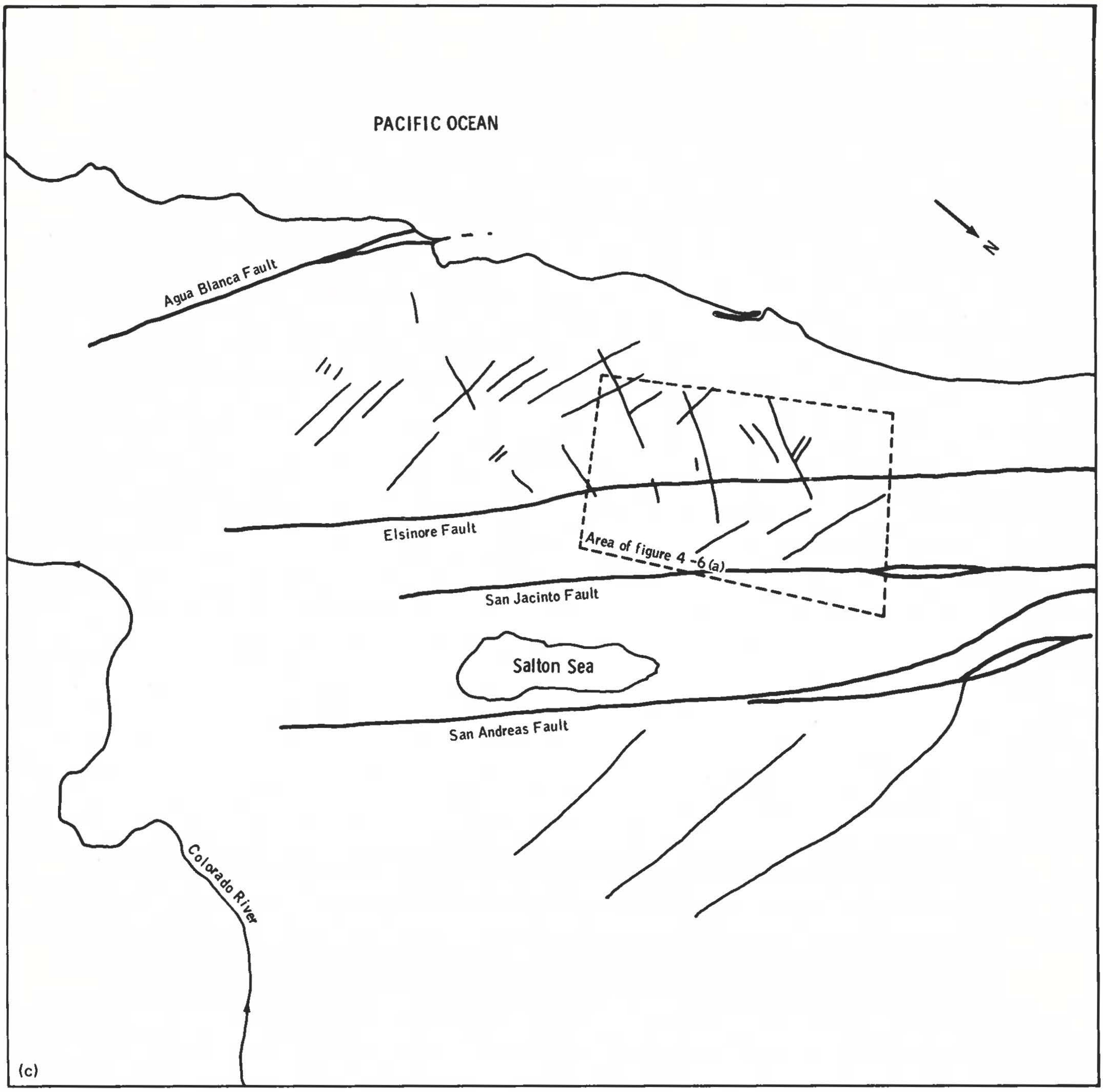


FIGURE 4-4.—Concluded.

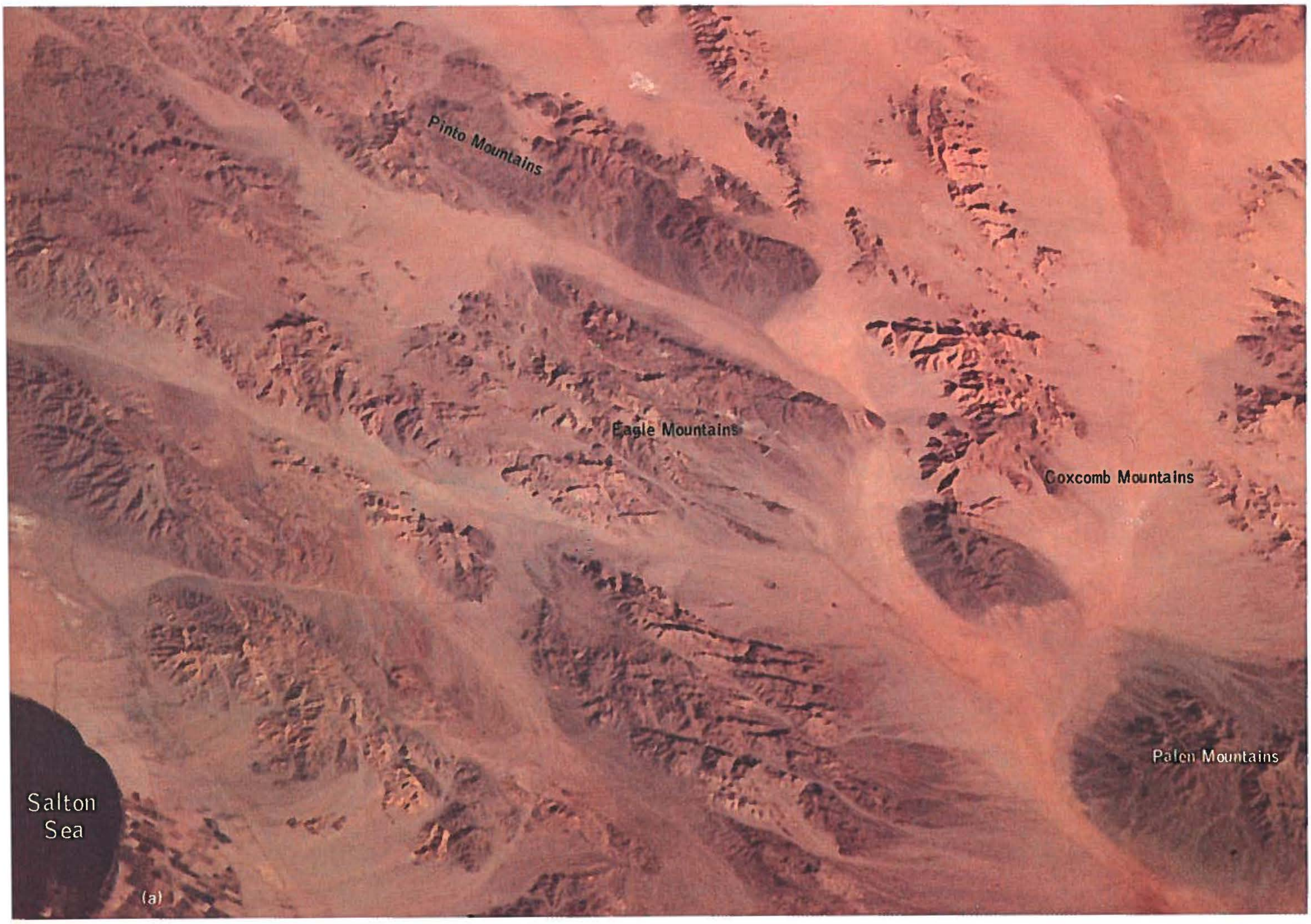


FIGURE 4-5.—The area northeast of the Salton Sea. (a) Photograph (SL4-203-7804). (b) Sketch map showing prominent east-west linears northeast of the Salton Sea. Distance from A to A′ indicates 11.3 km left-lateral displacement on the Chiriaco Fault. (c) Geologic map based on combined photointerpretation and field reconnaissance. Regions indicated as alluvium contain clastic debris derived from the bedrock units shown.

Conjugate fracture systems in the Peninsular Ranges.— Two prominent sets of linears are recognized in the Peninsular Ranges of southern California and Baja California in the Skylab 4 handheld-camera photographs. Southwest of the Elsinore Fault, these sets strike N 15° to 35° E and N 70° to 80° W (figs. 4-4(a), 4-4(c), and 4-6). Northeast of the Elsinore Fault, the linear sets strike N 20° to 30° E and N 60° to 70° E. The geometric pattern of the linears suggests that they may be conjugate fracture sets that have been superimposed on the batholithic terrane, transgressing but not confined to individual plutons. The fractures have been identified throughout the length of the Peninsular Ranges covered by the Skylab 4 photographs (see section entitled "Northern Baja California"). Other structural linears are present but are considered as separate phenomena.

If the conjugate fracture system is interpreted as a conjugate shear system, then the axis of maximum principal (compressional) stress is oriented approximately N 65° E or roughly perpendicular to the main structural, petrologic, geochemical, and geophysical

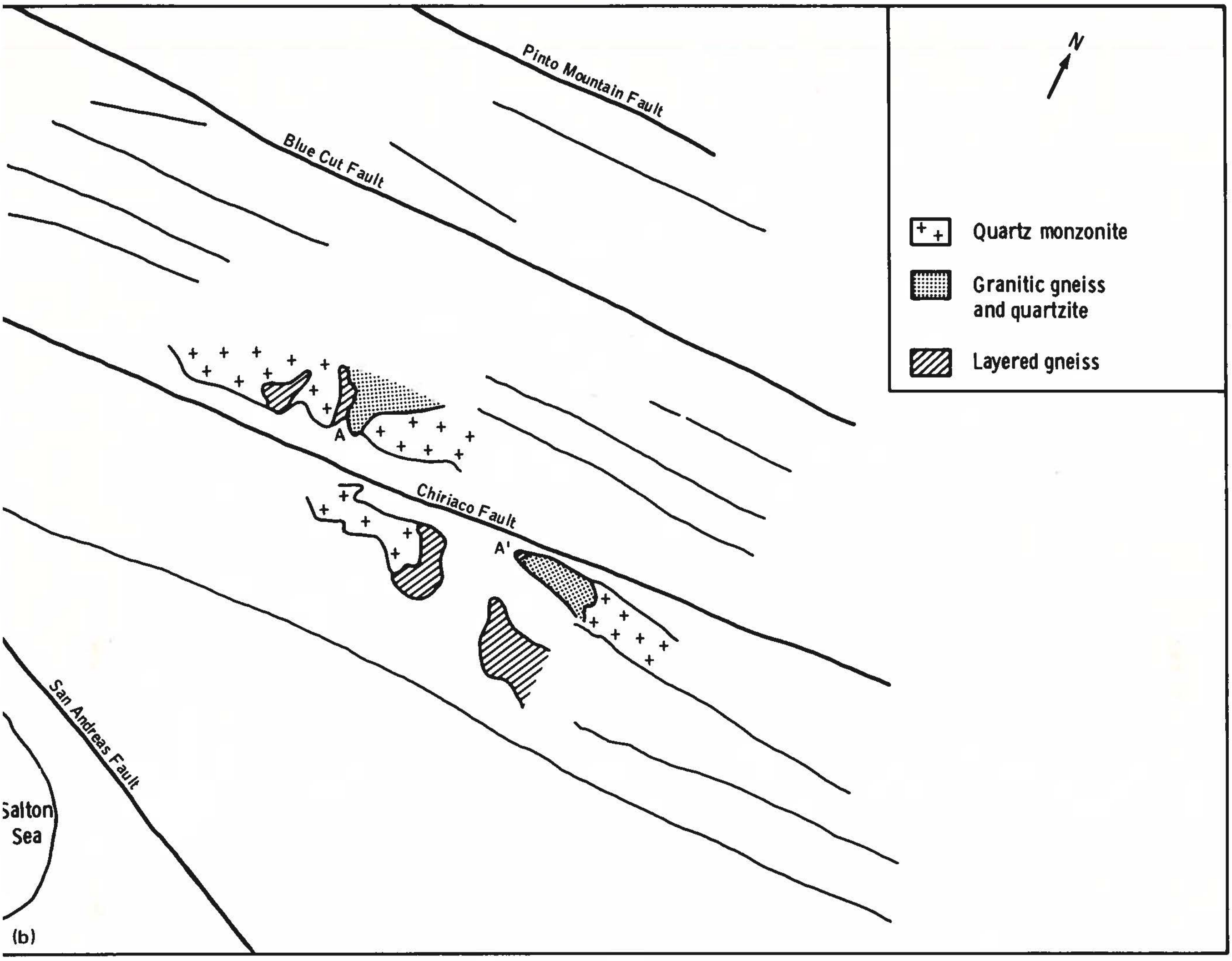


FIGURE 4-5.—Continued.

trends of southern California and Baja California. The slightly different orientation of the fracture pattern northeast of the Elsinore Fault may reflect a variation in local stress field across one of the major faults of the Peninsular Ranges or a superimposed rotational effect produced by later movements on the Elsinore and San Jacinto Faults. The conjugate fracture pattern may represent a response of the peninsula to compressional stresses imposed on the peninsular block during the opening of the Gulf of California or to regional stresses developed on a more extensive area of southwestern North America shortly before the rifting of the Gulf. It does not appear to be related directly to the San Andreas stress system. A similar pattern of fracturing appears to be present in the southern Sierra Nevada, as shown faintly in figure 4-3(a) and very distinctly in figure 4-7, centered on Lake Isabella, California.

The overview of these regional fracture patterns provided by the Skylab photographs suggests the possibility of an integrated crustal response to tectonic strain on a scale that has not previously been observed and appreciated. It appears that within the inventory of Skylab mapping and handheld-camera photographs are the resources for an extended investigation of these phenomena and their broad geologic implications.

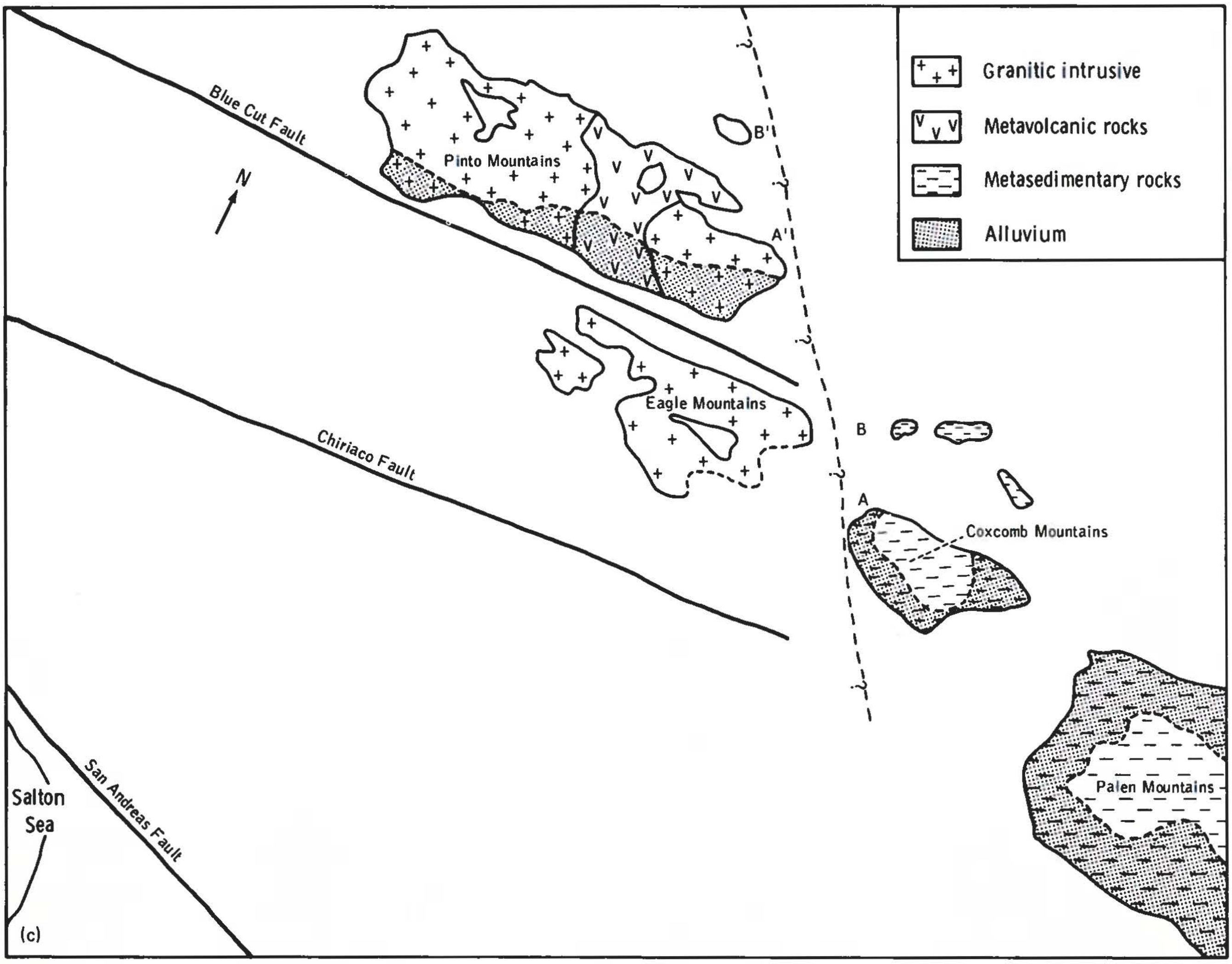


FIGURE 4-5.—Concluded.

A test of color values for lithologic correlations.—The value of Skylab handheld-camera color photographs for identifying and correlating lithologic units on a regional scale is potentially great, although reliable use requires a thorough understanding of color values and the factors that influence them. Color differences between rock types of varying lithologic composition are modified by such parameters as Sun angle, desert varnish, surface texture of bedrock and debris, and vegetation. Ambiguity in photointerpretation arises when some or all of these factors combine to give different lithologies similar color values. Resolution of the ambiguity requires an interplay of photointerpretation and field work. A cross-check of this type was conducted in an area northeast of the Salton Sea (figs. 4-5(a) and 4-5(c)).

Existing field and photointerpretive maps represent the eastern Eagle and Pinto Mountains as granitic intrusive rocks and the southern Coxcomb and Palen Mountains as volcanic-derived metasedimentary rocks. However, the color values of the eastern Pinto, southern Coxcomb, and Palen Mountains in figure 4-5(a) are very nearly the same, which suggests the possibility that existing maps are inaccurate and that the dark color values are reflected from equivalent lithologies. On the basis of these color values, a possible right-lateral offset of approximately 32 km along the dashed line in figure 4-5(c) was postulated. This line represents the eastern physiographic limit of the Transverse Ranges as well as a consistent local geologic discontinuity. In the use of Skylab 4 handheld-camera photographs for photogeologic interpretation, a correlation of dark-color-valued units intersecting the queried line at points A and B with those at A' and B' was postulated. Field reconnaissance has indicated that there is in fact a significant area of unmapped volcanic rocks in the eastern Pinto Mountains, although it is subordinate to the granite intrusives (fig. 4-5(c)). However, the dark color values do not represent equivalent lithologic units, so the suspected fault displacement was not confirmed. The dark units in the eastern Pinto Mountains are metavolcanic and granitic intrusive rocks, whereas volcanic-derived metasedimentary rocks comprise the southern Coxcomb and Palen Mountains.

There are several points to note in figure 4-5(a) with respect to photointerpretation of the dark color values. First, this particular granitic rock in the Pinto and Eagle Mountains is deeply colored by desert varnish; thus, its color value in the eastern Pinto Mountains is difficult to distinguish from that of the lithologically darker metasedimentary and metavolcanic rocks. Second, the texture and the color of the alluvial material derived from the granitic unit are distinct from those derived from the sedimentary and volcanic units. In particular, the freshly broken stream material is lighter colored in granitic-derived fans than in fans derived from metavolcanic or metasedimentary rocks. This contrast probably reflects primary lithologic color differences unbiased by desert varnish. Third, metasedimentary and metavolcanic rocks are indistinguishable on the basis of color value. Fourth, the texture and the color of the alluvium derived from metasedimentary and metavolcanic sources are indistinguishable.

The geologic usefulness of the Skylab photographs of southeastern California is constrained by the overlap of color value contributed by lithology and that contributed by desert varnish. The usefulness may, however, be enhanced by coordinating photointerpretation and field study. Comparison of photographs taken of a single area with visible and infrared film and at different Sun angles might further help to distinguish lithologic units.

Northern Baja California

Northern Baja California was divided into five specific sites (fig. 4-8(b)) and objectives, and the detail of photography, visual observations, and commentary varied greatly among these sites. The crew focused particularly on the Agua Blanca Fault zone (site 3) but also addressed themselves directly to the other sites. A total of 58 Hasselblad and 44 Nikon 55- or 300-mm photographs of the test area was obtained.

The geology of Baja California has not been studied in great detail, and the potential yield from satellite-based observations and photographs in terms of geologic reconnaissance is therefore high. The overall objective of the experiment was to identify (1) major patterns in the folded strata, (2) the occurrence of granite plutons, and (3) the location of major faults and conspicuous recent geological features. The photographs provide an overview of large areas of the peninsula that cannot be obtained from conventional aerial photographs; they are therefore especially useful for observation and integration of large-scale structural patterns.

The results are discussed under four major topics: (1) observation and interpretation of the significance of a 200-km-long light-colored stripe (site 1) and associated linear features, (2) recognition and mapping of igneous intrusive bodies (plutons), (3) observations of the Agua Blanca Fault zone and related features, and (4) photogeologic mapping of major fracture patterns in the northern part of the peninsula. The crewmen also photographed and discussed the young volcanic features at San Quintín and farther south (site 5). Apparently, the cinder cones were more clearly visible to the naked eye than they are in the photographs. Little detail of the volcanic construction is visible in the photographs, despite the fact that the photographs are of as good quality as any of the others.

The light-colored stripe and associated linear features.—The objectives of the Skylab 4 crewmen for sites 1 and 4 were to photograph and trace the extension of two major linear features (A and B in figs. 4-8(a) and 4-8(b)). The goal was to map these features, to identify patterns or differences in the rocks or vegetation on either side of these features, and to search for evidence relating to their geologic nature.

Numerous photographs show both features clearly, especially the light-colored stripe (A). The crewmen were able to recognize this stripe for a distance of approximately 45 km southward from a point just south of the San José pluton. In figure 4-8(a), the stripe can be traced much farther, for a distance of nearly 100 km southeastward from Arroyo Calentura. North of the San José pluton, the stripe is less well defined than it is farther south, and it may, in fact, consist of two subparallel stripes that possibly combine near the northern end of the pluton. Near B in figure 4-8(b), the light-colored stripe merges with a region of arcuate patterns. Because it is generally exposed on westward- or southward-facing slopes, the stripe is most clearly visible when illuminated by midday or afternoon Sun.

Field studies at four localities (fig. 4-8(b)) indicate that the light-colored stripe is principally the expression of a specific stratigraphic zone in the prebatholithic section, at least along a 15-km-long segment north and east of the San José pluton. The light color is due to (1) the paucity of brush and the smoothness of the ground surface underlain by this unit, (2) the light color (tan) of the rock and its derivative soil, and (3) the fissile (platy and chippy) nature of the rock that partially covers the

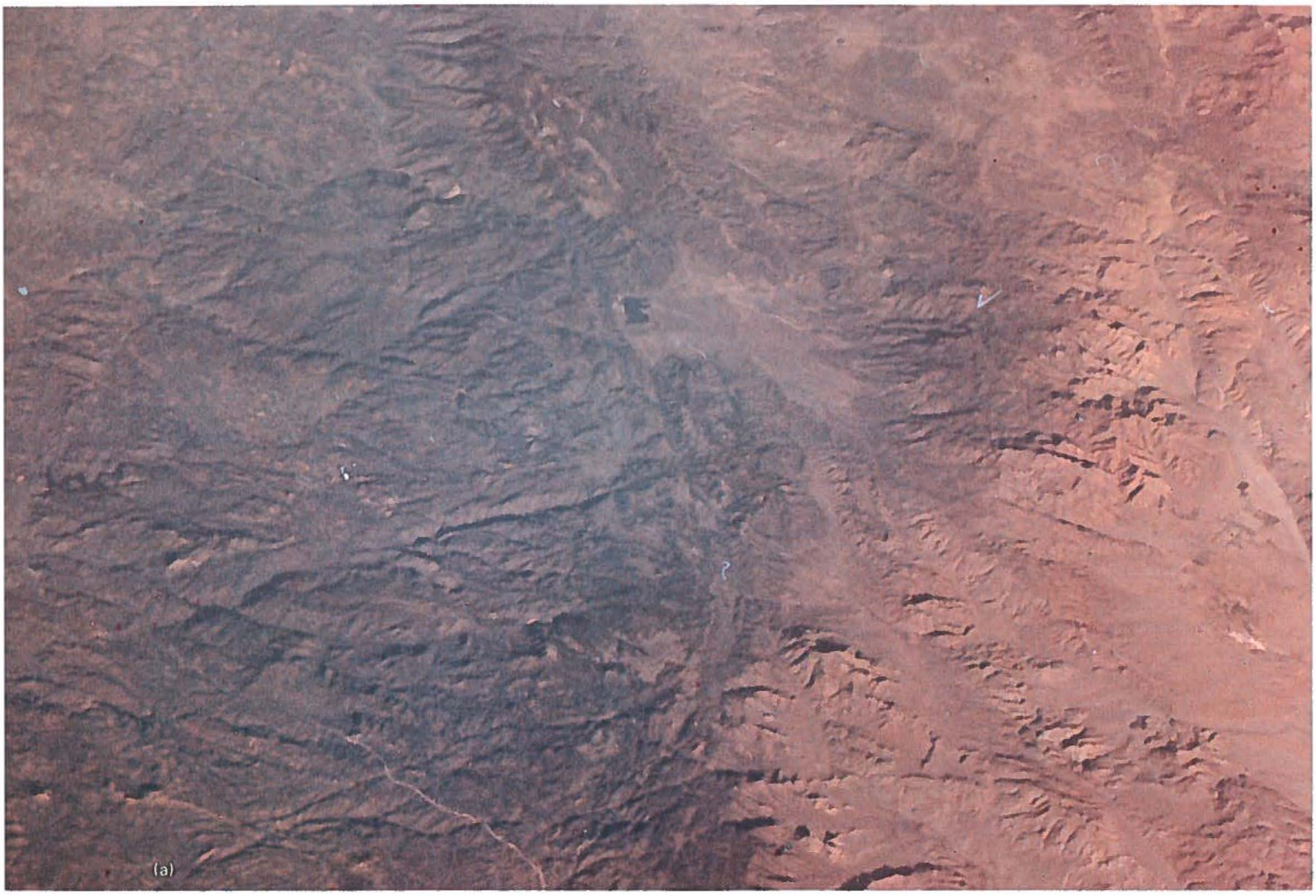


FIGURE 4-6.—Conjugate linear fractures in the north-central Peninsular Ranges. (a) Photograph (SL4-203-7802). (b) Sketch map.

slope with small reflective platy chips lying parallel to the ground surface. However, for a 2-km distance between the two northernmost field sites, the stripe coincides with a steep southward-facing reflective slope in the southern margin of a light-colored granitic (tonalite) pluton. Farther south, a 15-km portion of the stripe (near A on fig. 4-8(b)) appears on the photographs to coincide with the western escarpment of the Sierra San Pedro Mártir. In the latter area, the light-colored stripe may be a manifestation of the same stratigraphic zone, or it may be due to reflection off a steep westward-facing slope that possibly coincides with the western margin of a large mass of granitic rock underlying much of the sierra (the largest stippled area in fig. 4-8(d)). Thus, although evidence suggests that the light-colored stripe defines the distribution of a single stratigraphic zone, it is not known that this condition exists along its entire length. Field studies at additional localities along the stripe are required to resolve this question.

The recognition that the stripe is related to a stratigraphic unit provides new and extremely valuable information on the regional stratigraphy and structure

in the prebatholithic rocks. For the first time, it appears that a single stratigraphic zone can be traced from a region west and northwest of the San José pluton, where the age and general structural characteristics are fairly well known, into a little-explored area southeast of the pluton. Northwest of the pluton, the light-colored stripe is part of a section known from the work of Silver et al. (ref. 4-5) to be part of the Alisitos formation of upper Lower Cretaceous age. In reference 4-5, it was shown that this section can be traced from the Pacific coast just south of the Agua Blanca Fault zone southeastward for 110 km to the San José pluton. Little information exists for the area southeast of this point. The trace of the light-colored stripe now suggests that, east

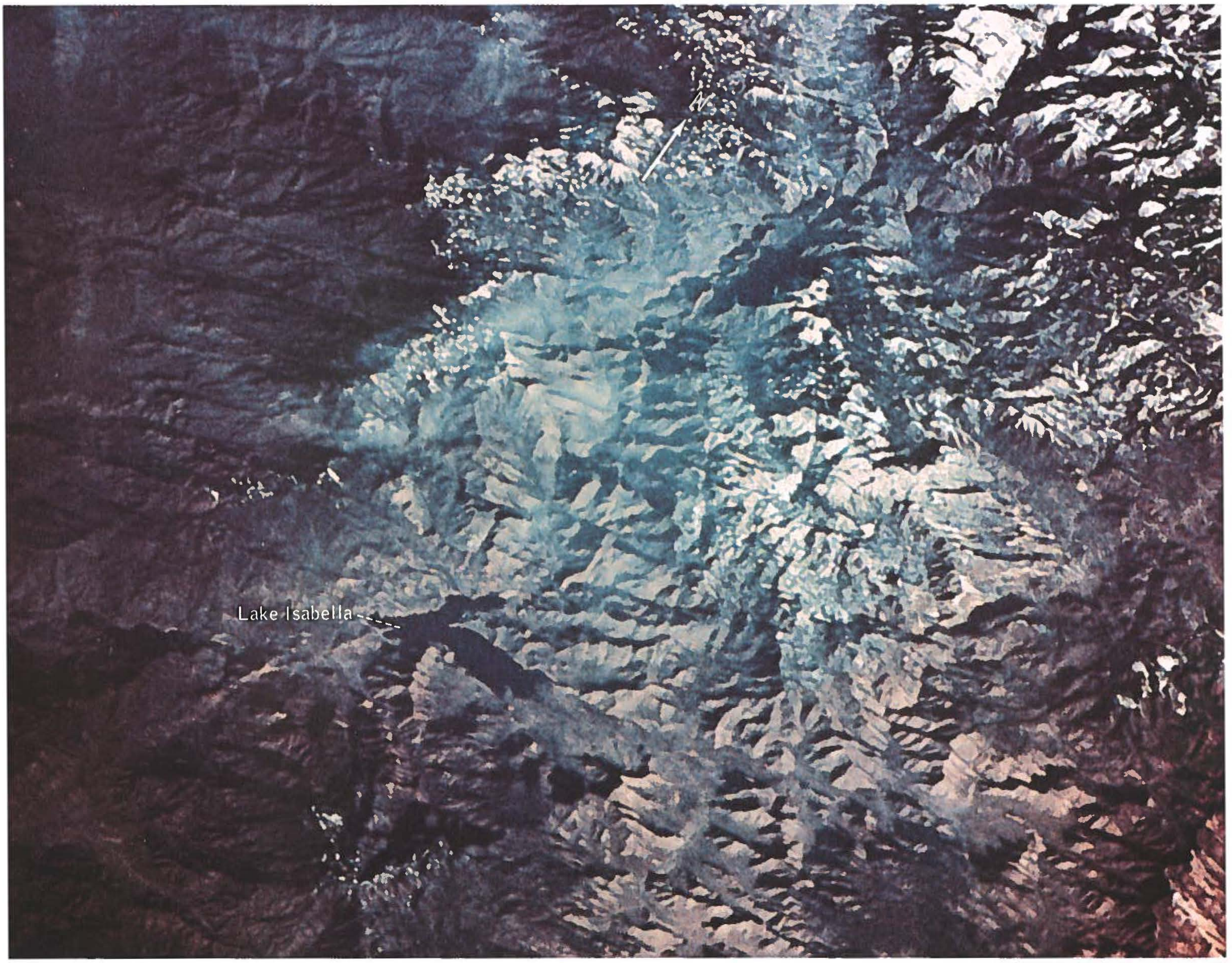


FIGURE 4-7.—Fracture patterns in the granitic rocks of southern Sierra Nevada around Lake Isabella (SL4-203-7787).

FIGURE 4-8.—Northern Baja California. (a) Photograph (SL4-197-7428). (b) Trace of linear features A (light-colored stripe) and B and the intervening region of arcuate patterns. Small X's denote locations of ground study. (c) Overview of the Agua Blanca Fault zone and associated fractures. (d) Principal sharp linear features and several prominent plutons (stippled). Lines are dashed where defined only by vague color change or where continuity is probable but uncertain.

and southeast of the pluton, the Alisitos formation swings abruptly to a more southerly trend and can be projected with reasonable confidence for another 55 to 60 km parallel to the trend of the Sierra San Pedro Mártir. This projection, however, should be tested by more extensive ground observations, particularly concerning the validity of the identification of the light-colored stripe as the trace of a single stratigraphic zone.

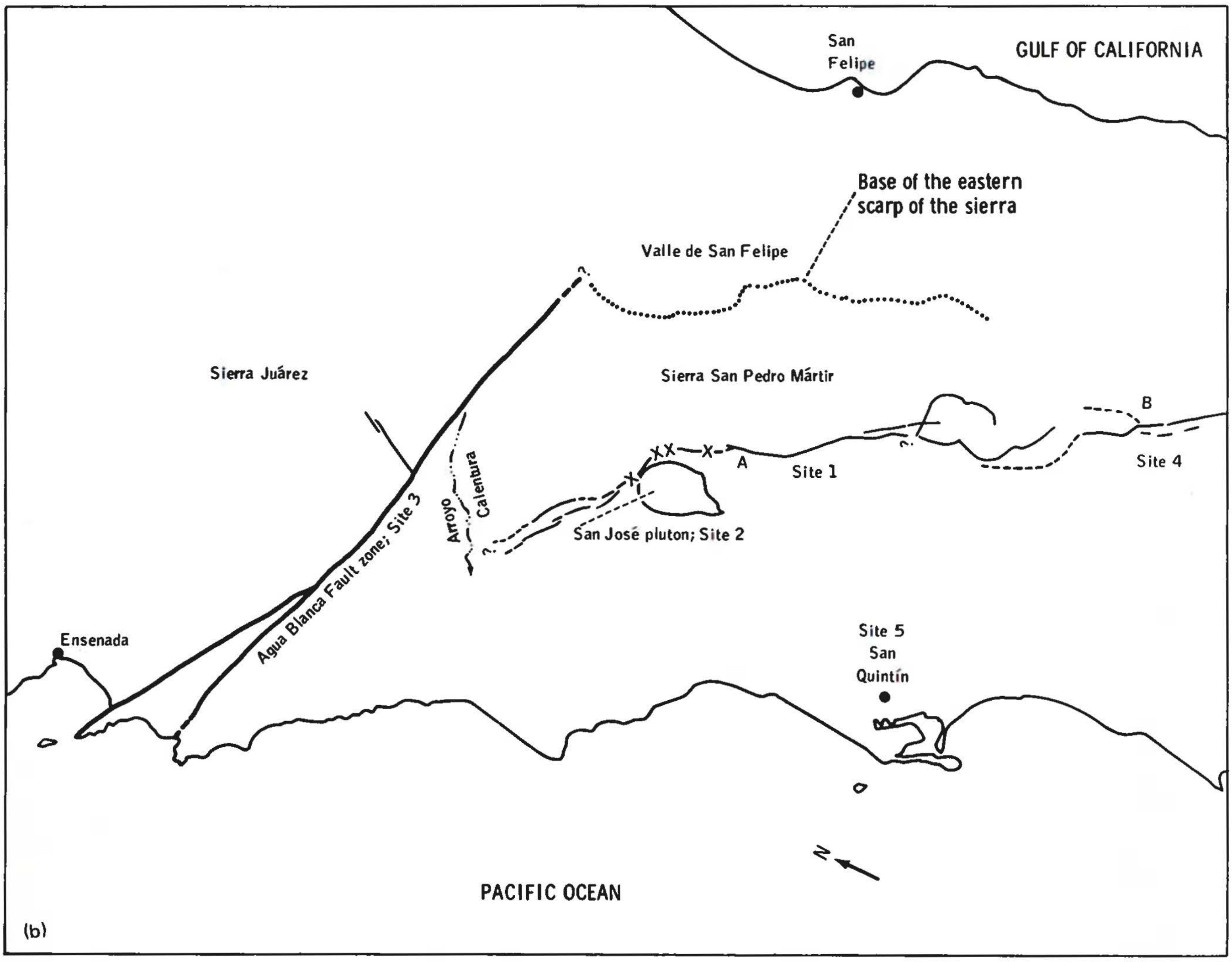


FIGURE 4-8.—Continued.

Near the San José pluton and in much of the area to the west and northwest, the Alisitos strata are known to be tightly folded, but the structure of this region has not been mapped. Near Arroyo Calentura, the occurrence of two light-colored stripes may be a manifestation of this folding. Folding may also account for the apparent discontinuity of the stripe east of the San José pluton. Recognition of the stripe has thus provided a geologic feature that can be mapped and used to decipher the complex structures of the region.

At feature B on figure 4-8(b) is the northernmost and least well defined portion of a major linear feature. Although the trend of this linear is parallel to and along the projected extension of the light-colored stripe (A), it is separated from the stripe by a 25-km-long area dominated by complex arcuate rather than linear patterns. The photographic coverage of the linear feature at B did not result in new information on the nature or the structural or stratigraphic relationship of the feature to the light-colored stripe.

Recognition and mapping of igneous intrusive bodies.—The crewmen were asked to describe and photograph igneous intrusive masses (plutons) with particular emphasis on their size and distribution and their relationship to layering in the surrounding rocks. The San José pluton (figs. 4-8(a), 4-8(b), and 4-8(d)) served as a

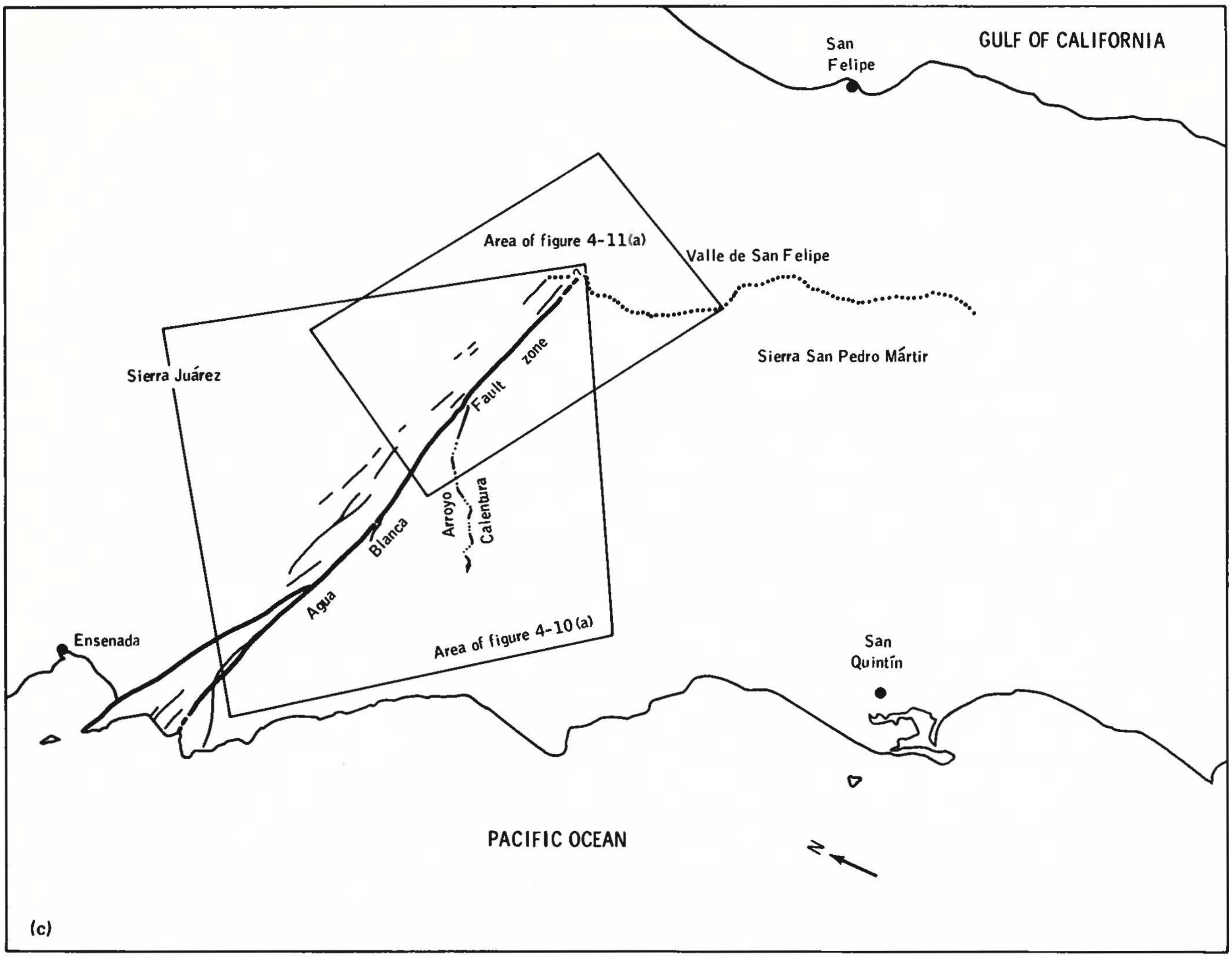


FIGURE 4-8.—Continued.

readily visible and identifiable reference. Other plutons are also visible on many photographs, yet comparatively few of the plutons known to exist are actually recognizable. However, the crewmembers have emphasized that the plutons, especially the San José pluton, were much more clearly visible to the naked eye than they are in the photographs.

The identification of plutons on Skylab photographs appears to be dependent on Sun angle, density of vegetative cover, and atmospheric clarity. An oblique view of an area also may aid or hinder the identification of plutons. Arcuate patterns associated with known or possible plutons are shown in figure 4-9(a), a Nikon 300-mm oblique photograph taken in the early morning. These patterns have been traced on the sketch map in figure 4-9(b). The plutons are revealed principally by their topographic expression enhanced by the low Sun angle. The color and the albedo contrast between the plutons and their surrounding rocks are subdued, partly because illumination is not uniform at a low Sun angle and partly because, under these lighting and viewing conditions, vegetation is especially effective in masking color variations.

Contrast figure 4-9(a) with figure 4-8(a), which is a near-vertical Nikon 55-mm photograph taken at a high Sun angle (about 11:30 a.m. local time). Color and

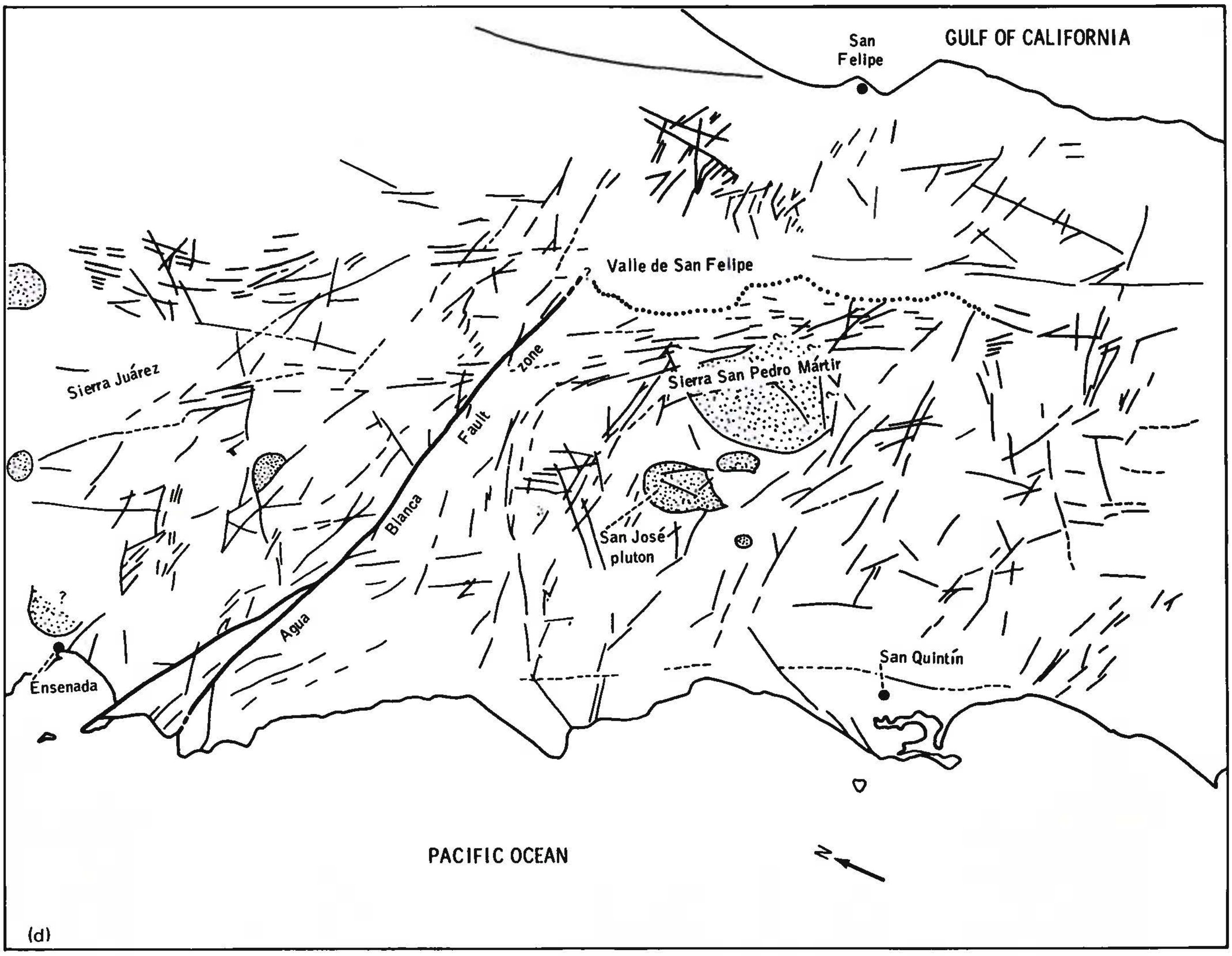


FIGURE 4-8.—Concluded.

albedo contrast are enhanced in the latter photograph, but topographic expression is less pronounced. Several prominent plutons recognized in figure 4-8(a) have been outlined in figure 4-8(d). The San José pluton and a smaller pluton several kilometers to the southeast are strikingly visible in figure 4-8(a), principally because of their high albedo. Unlike the plutons visible in figure 4-9(a), these two bodies become less visible (although still distinct) at low Sun angles. Thus, the ideal Sun angle for satellite observation and photography of plutonic bodies varies, depending on whether the bodies are best distinguished by their topographic expression or by their color and albedo contrast with adjacent rocks.

Many more plutons are known to exist in the area shown in figure 4-8(a) than are indicated on figure 4-8(d). Some can be distinguished vaguely on the photograph, but many cannot. Although the effect of vegetation is minimized by the high Sun angle and the near-vertical view, vegetation still is an important factor in masking color and albedo contrast between the plutons and their adjacent rocks. In addition, atmospheric haze has probably reduced both spatial resolution and color and albedo contrasts. In the absence of clouds, the effects of haze are not obvious. The ability of the crewmembers to see plutons more clearly than they appear on the photographs is due to an observer's ability to mentally compensate to some degree for obscuring effects such as haze and shadows.

Despite the difficulties in recognizing many plutons on the Skylab 4 photographs, it is clear from figures 4-8(a), 4-8(d), 4-9(a), and 4-9(b) that a combination of low- and high-Sun-angle photographs and visual observations could contribute significantly to reconnaissance geological mapping in unexplored areas, particularly where conventional aerial photographic coverage is not available. For problems requiring maximum color and albedo contrast, high-Sun-angle vertical-view photographs are essential.

Agua Blanca Fault zone and associated fractures.— The greatest part of the crew's effort in northern Baja California was directed toward the Agua Blanca Fault zone (site 3). In addition to general observation and photography of the fault zone, the investigation of the site involved two principal questions. How far east can the fault be traced? Can offset streams or other features indicative of the relative motion on opposite sides of the fault be recognized by the crew or on photographs? The astronauts' verbal commentary concentrated on (1) the striking physiographic expression of the fault — especially the appearance of a "k" shape defined by the intersection of Arroyo Calentura with a canyon from the north and a canyon along the fault trace (figs. 4-8(a) and 4-10(a)); (2) the eastern limit of the fault zone— whether or not it crosses Valle de San Felipe and reaches the Gulf; and (3) suggestions of offset along the fault zone. Twenty photographs with the fault as the principal target were obtained by the crewmen.

In figures 4-8(c), 4-10(b), and 4-11(b), the known trace of the fault breaks as mapped by Allen et al. (ref. 4-6) has been drawn, together with some of the more prominent subparallel lineaments. The correspondence between the fault trace and the topography is obvious.

The astronauts looked repeatedly but saw no evidence that the fault zone crosses the Valle de San Felipe to the Gulf of California. Several excellent photographs (e.g., fig. 4-11(a)) reveal only faint lineaments east of the end of the mapped trace of the fault zone, and most of these lineaments stop at the western edge of the valley. Physiographic evidence of a major fault appears to terminate at the end of the mapped trace of the fault zone. Thus, the photographs and crew observations offer no contradiction to the ground-based interpretation that the fault zone ends west of the Valle de San Felipe. The objectives of this aspect of the site 3 study were very successfully completed.

An important goal at site 3 was to determine whether or not small-scale fault features such as offset streams could be recognized from Skylab. The commander (at 18:46:07 GMT, Dec. 7, 1973) interpreted the "k" pattern as a "cross-fault" offset in a left-lateral sense by movement on the Agua Blanca Fault zone (fig. 4-10). He also inferred (02:31:24 GMT, Jan. 20, 1974) a left-lateral offset of a stream crossing the fault zone just west of the "k." However, detailed ground studies of this region by Allen et al. (ref. 4-6) have shown that the direction of relative motion on the fault zone is right-lateral. The suggested left-lateral stream offset described by the commander is indicated in the rectangular area outlined in figure 4-10(b). In figure 4-10(a), a drainage (A, fig. 4-10(b)) enters the fault zone from the northeast, appears to be diverted approximately 4 km southeastward along the fault zone (B), and then turns abruptly southwestward away from the fault. Field data have shown that the drainage is actually diverted approximately 6 km northwestward (C) along the fault zone (fig. 4-10(b)). A low drainage divide (not distinguishable on the photograph) would not permit the drainage from northeast of the fault to connect with the drainage that intersects this fault at B on figure 4-10(b).

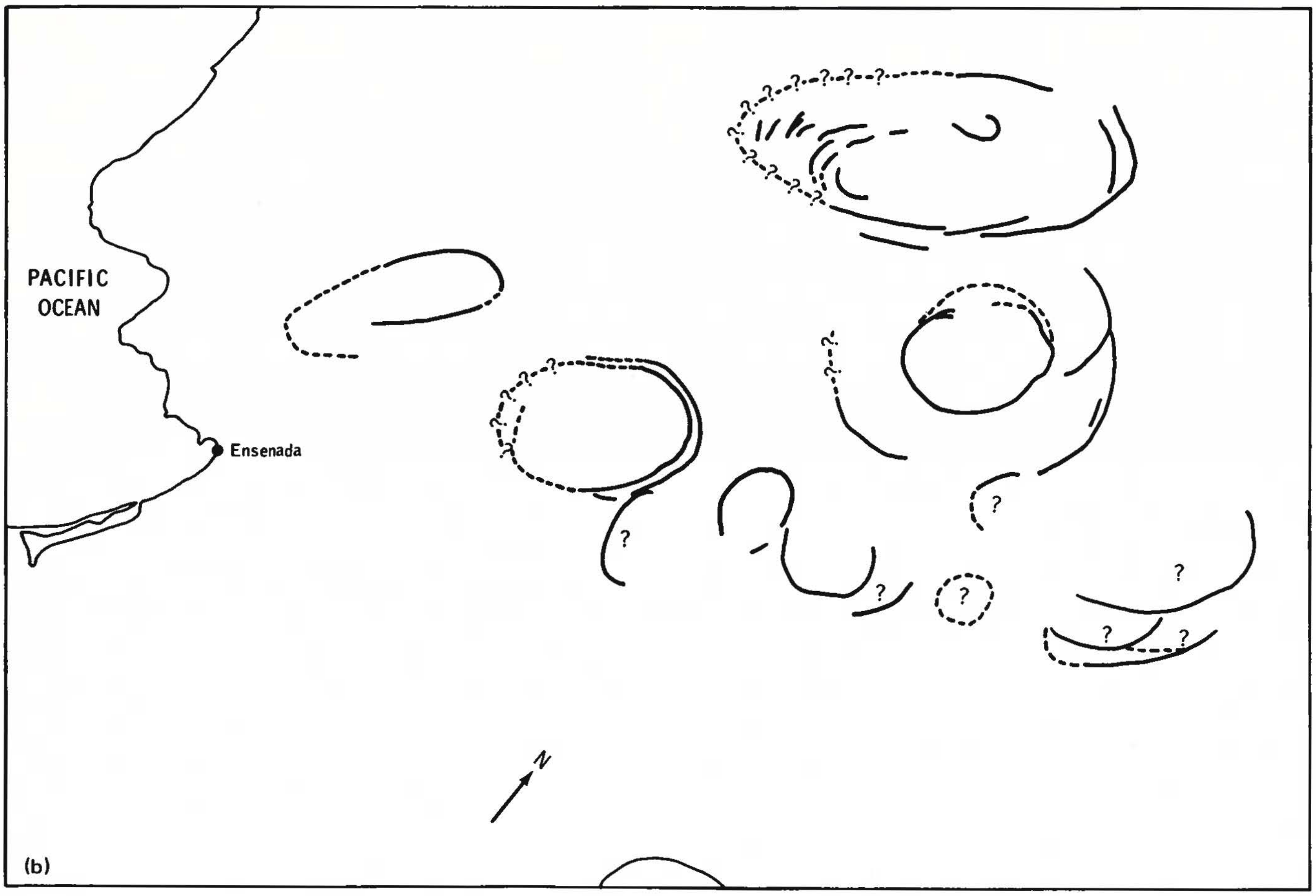
Two points should be emphasized concerning the use of offset streams as evidence of fault motion. First, such offsets are generally small-scale features. Second, reliable interpretation of relative motion from such offsets requires observation of numerous offsets with consistent direction. Sharp jogs in drainage traces may result from processes other than fault motion and may even be in the direction opposite that of the true relative motion. The true relative fault movement is indicated only when there is a pattern of many consistent offsets. Allen et al. (ref. 4-6) observed numerous right-lateral stream offsets along much of the length of the Agua Blanca Fault zone, but the offsets are generally on the order of tens to hundreds of meters. One offset identified by Allen et al. can be seen, although in a distorted and unconvincing view, in figures 4-10(a) and 4-10(b) (the feature labeled "O.S."). Fault offsets of the magnitude of the Agua Blanca Fault zone can be identified by crewmen and in satellite-based photographs. The crew emphasized that the details along this fault zone

FIGURE 4-9.—Arcuate features associated with known or possible granitic intrusive bodies in northern Baja California. (a) Photograph (SL4-203-7808). (b) Sketch map.

were more distinct to the naked eye than in the photographs. The most effective photographs for study of fault features are those taken as vertical or slightly oblique views perpendicular to the length of a fault zone, particularly at low Sun angles.

In summary, the Skylab 4 crew commentary and the handheld-camera photographs have shown that satellite-based observations and photographs have definite potential for discovery and reconnaissance mapping of faults of the magnitude of the Agua Blanca Fault zone and associated small structures.

Fracture patterns in northern Baja California.—The Skylab 4 photographs are particularly useful in providing the basis for an integrated analysis of the fracture



systems in northern Baja California. Figure 4-8(d) is a sketch map of the principal sharp linear features that are visible in figure 4-8(a), a photograph of most of northern Baja California. Several prominent plutons visible in figure 4-8(a) are traced in figure 4-8(d). The sketch map reveals the principal fault and fracture patterns in the region. With similar photographs of the entire peninsula, a photolineament map could be constructed that would be extremely useful in geologic analysis.

Nearly all the linear features in figure 4-8(d) are part of three well-defined sets: (1) a set that is subparallel to the Agua Blanca Fault zone and generally strikes N 70° to 90° W but extends to N 80° to 90° E; (2) a set that strikes N 25° to 35° W parallel to the high mountain ranges and to the axis of the peninsula; and (3) a less well developed set that strikes N 30° to 55° E. The remaining lineaments generally strike N 60° to 80° E.

The linear set that strikes N 70° to 90° W tends to be concentrated in discrete zones such as those just north and south of the San José pluton. North of the Agua Blanca Fault zone, some of the linears have been previously identified as faults and others are probably major fractures or fracture zones without significant offset. Major faults that parallel this trend have not been recognized south of the Agua Blanca Fault zone.

The N 25° to 35° W set is very strongly developed along and parallel to the eastern escarpments of the Sierra Juárez and Sierra San Pedro Mártir. East and west of this zone of maximum development, parallel lineaments are sparse. Some of these linears may reflect major faulting parallel to the escarpments.

A series of alined short features suggests the possibility of a major throughgoing linear feature that extends N 30° W from just east of the largest pluton across the Agua Blanca Fault zone and to the northern edge of the map. This zone is especially striking in the photograph (fig. 4-8(a)); if it is continuous, it suggests that no major lateral offset has occurred along the eastern part of the Agua Blanca Fault zone since the development of this N 30° W structure.

The N 30° to 55° E set is sparsely developed throughout the area and is the least consistent in trend of the three main sets. Neither it nor the N 60° to 80° E set is parallel to any other obvious geographic or geologic features in the area. At present, there is no evidence of major faulting parallel to these fractures.

Sierra Mazatan, Sonora, Mexico

The Sierra Mazatan in Sonora was selected as an important geological subject for study from Skylab because it is topographically distinctive, geologic information is sparse, and detailed topographic maps and aerial photographs are not available. The small mountain range is composed almost entirely of intensely deformed granite that can be distinguished chemically and structurally from adjacent rocks. The crewmen were asked to consider the possibility that the entire

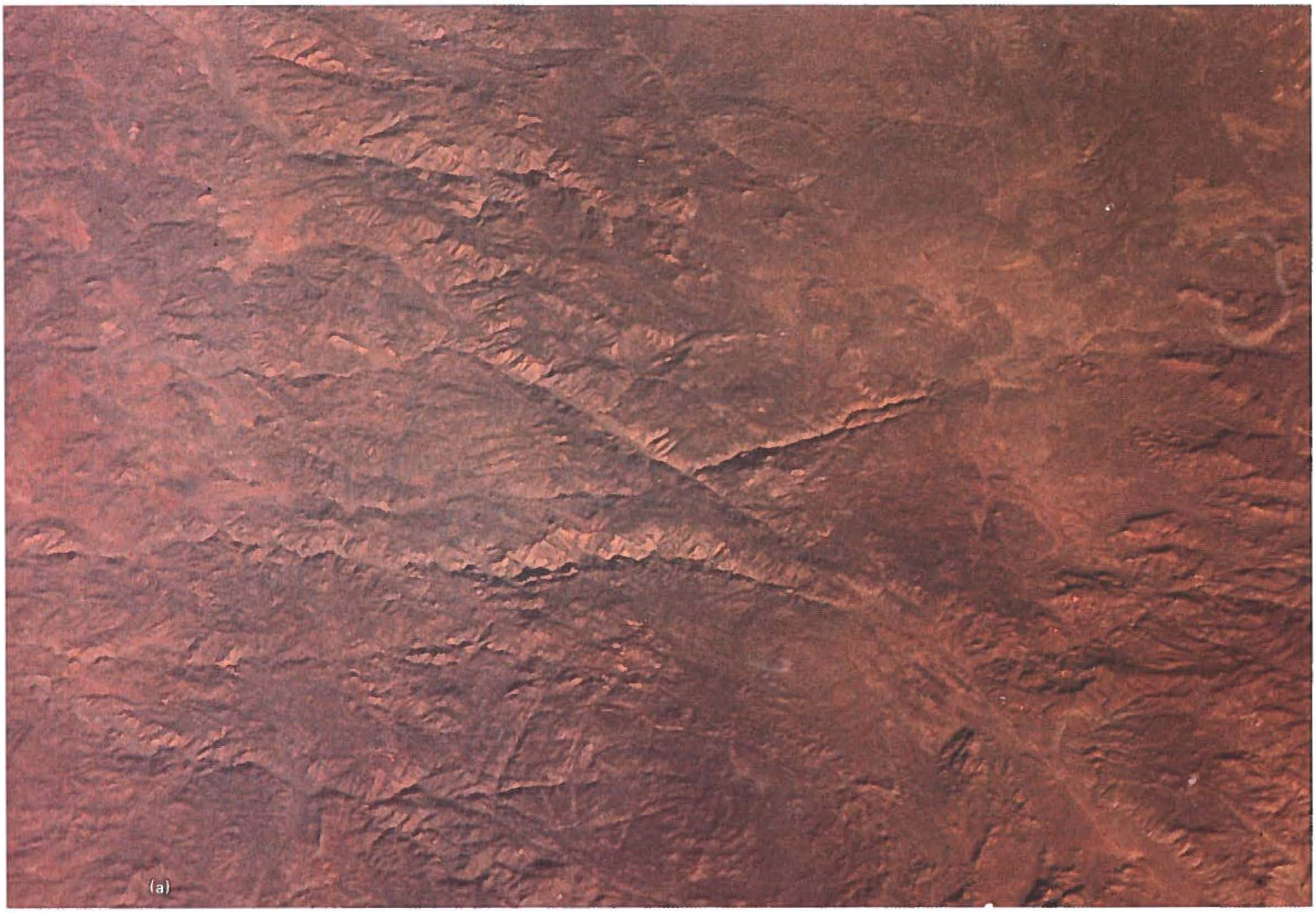


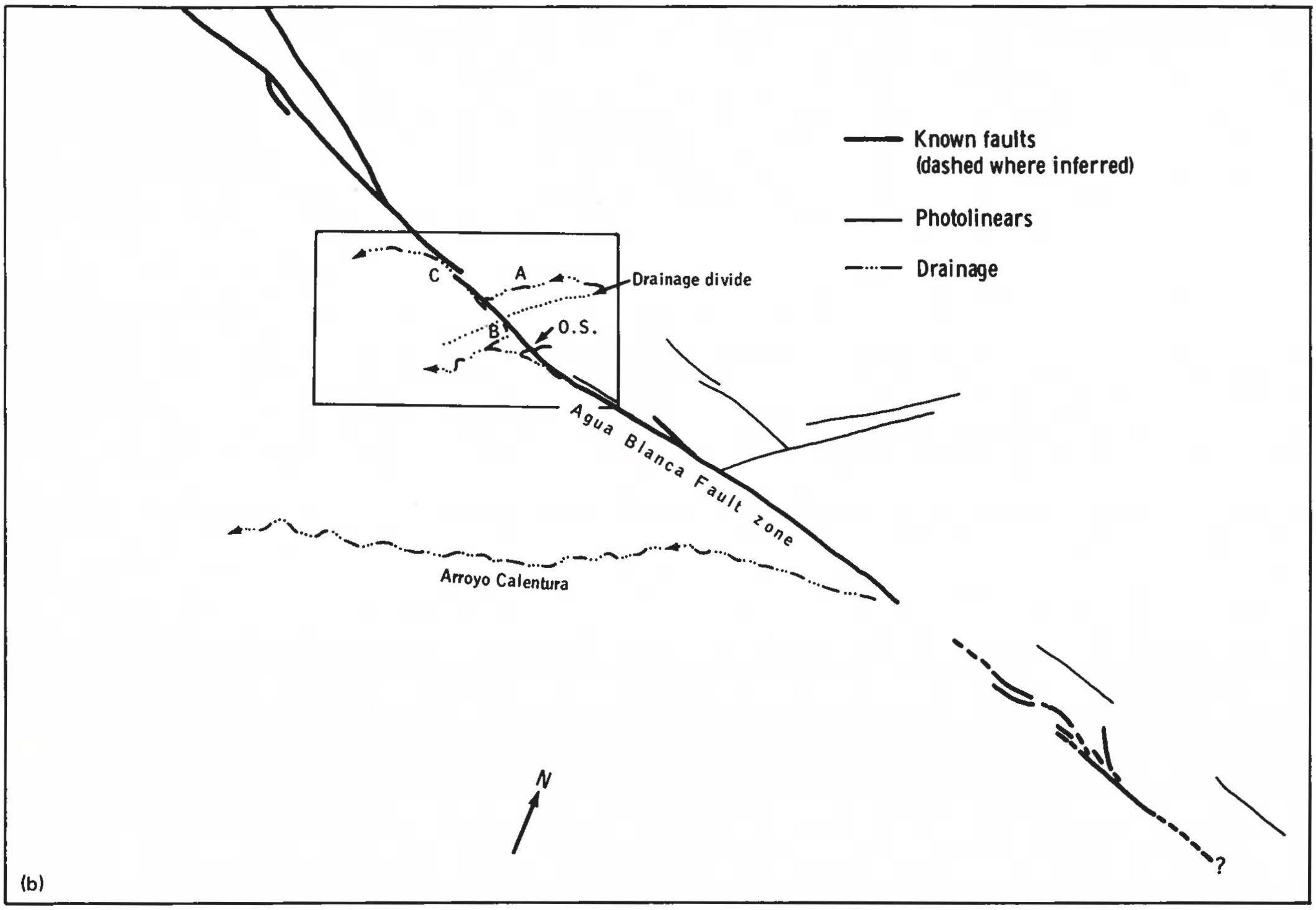
FIGURE 4-10.—Central and eastern portions of the Agua Blanca Fault zone. Letters in inset are explained in text. (a) Photograph (SL4-203-7809). (b) Sketch map.

mountain range may have been brought to its present site by profound faulting. They were requested to observe and photograph linear features that might represent such fault systems and to search in the mountainous region surrounding Sierra Mazatan for topographic characteristics similar to those of the range.

The Sierra Mazatan region was thoroughly photographed, without commentary, by the Skylab 4 crewmen. Inspection of the photographs (e.g., fig. 4-12(a)) has not revealed features similar to Sierra Mazatan within a radius of 50 km. In regard to major fault systems, the Skylab 4 photographs and postmission field studies have identified a north-trending linear feature that passes a few kilometers east of Sierra Mazatan (figs. 4-12(a) and 4-12(b)). This feature may represent a suture structure and can be traced for more than 100 km south toward Ciudad Obregon and about the same distance to the north. Further field studies are necessary to determine whether this is a significant structural feature related to the origin of Sierra Mazatan.

Northwestern Sonoran Coast Fault Zones

The evolution of the continental margin in northwestern Sonora has been investigated by the senior author for several years. Along the coast between Puerto Libertad and Bahía Kino (fig. 4-13), northwest-trending faults that parallel the coast have been mapped. Associated with the region of faulting is the termination of the older crust (Precambrian and



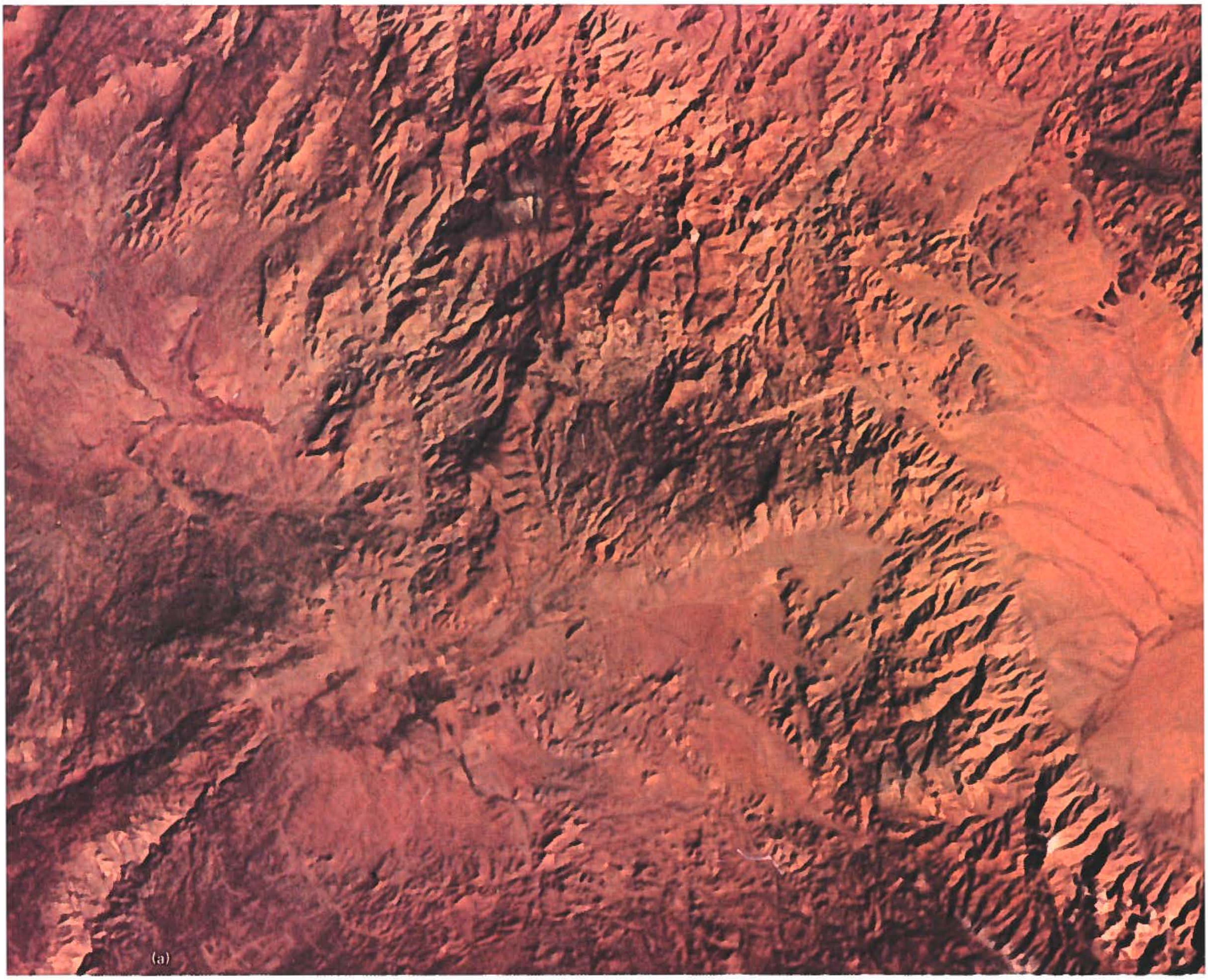
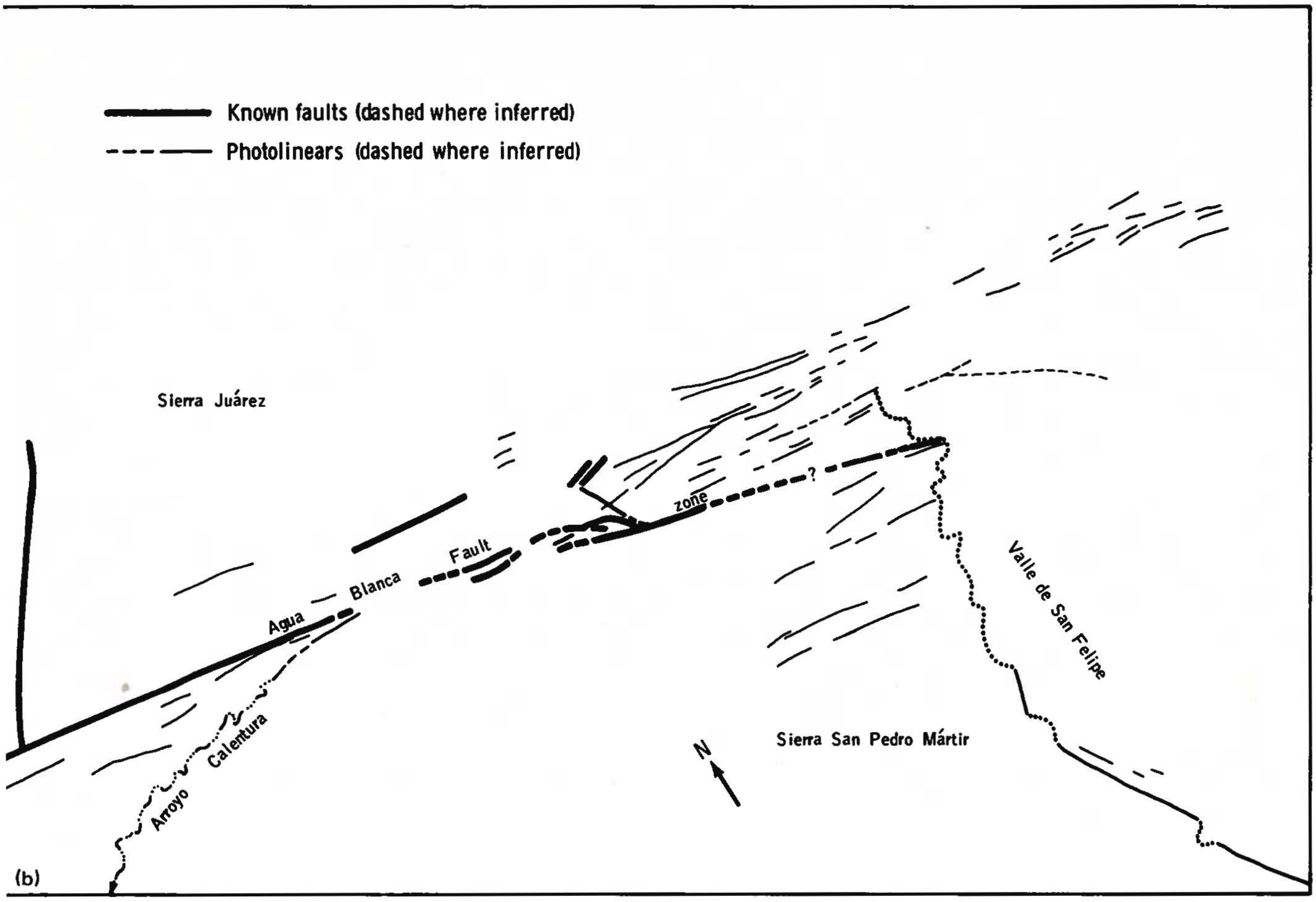


FIGURE 4-11.—Known faults and parallel lineaments at the eastern end of the Agua Blanca Fault zone. (a) Photograph (SL4-193-7190). (b) Sketch map.

Paleozoic rocks) against younger crust (middle and late Mesozoic volcanic and granitic rocks). The Skylab 4 crewmen were requested to search for linear trends in the coastal desert as possible expressions of major fault zones, both active and inactive, that might have modified the continental margin.

An excellent folio of photographs of the Sonoran coast was obtained. Analyses of these photographs have confirmed the presence of throughgoing fault zones. In figure 4-13(b), the general dimensions of the fault zone are visible from north of Puerto Libertad to south of Bahía Kino. In figure 4-14, numerous linear features are

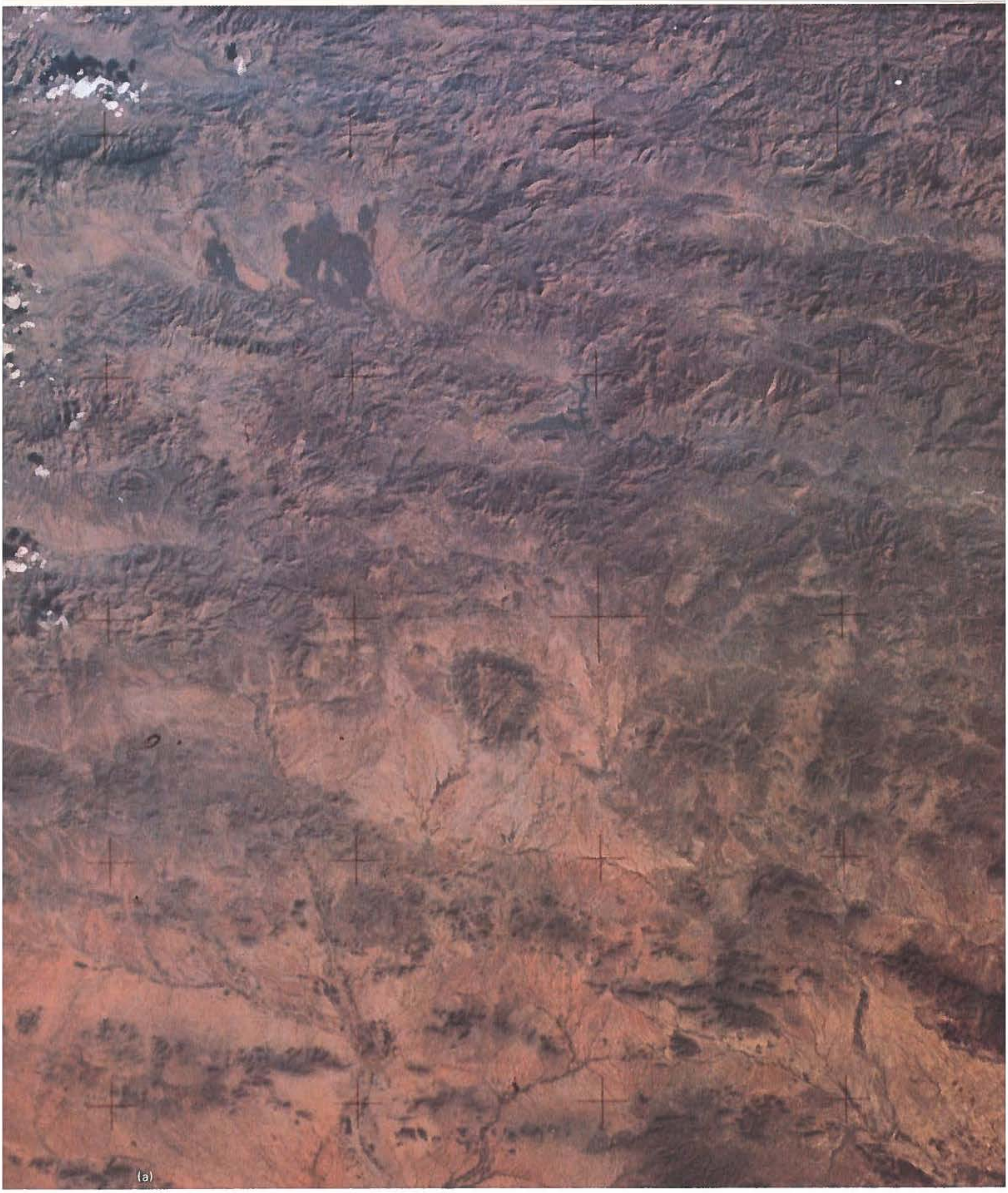


visible in the bedrock that forms the Sierra Seri and Sierra Bacha.

The photographs and ground studies reveal that, in general, there is little evidence of recent fault movement and displacement of the surface. Only at a point just north of Puerto Libertad and east of the tied island of Punta Tepopa were there possible suggestions of active faults. Several major and many minor drainages cross the fault zone without indication of fault offset. The principal fracture systems offset middle (?) to late (?) Tertiary volcanic and nonmarine sedimentary rocks. It is inferred that movement along the major fractures of these zones occurred in the Miocene or Pliocene with perhaps some recent reactivation locally.

The evidence indicates that the coastal structural zone developed before the establishment of the presently configured Gulf of California, which is estimated to be 4 to 5 million years old. The structural zone may be related to the development of a protogulf, a series of elongate marine basins that preceded the throughgoing Gulf of California rift system (ref. 4-7). The sense and magnitude of displacement on the structural zone has not yet been established. As indicated in figure 4-13(b), the fractures parallel the presently known southwestern limit of the older continental crust and are approximately 30 km from the nearest Precambrian rock exposures. An important possibility is that the fractures identified in the Skylab photographs constitute part of a late Tertiary strike-slip fault zone along which two dissimilar crustal blocks have been juxtaposed. This would imply a possible correlation with early movements on the larger San Andreas/Gulf of California transform fault system.

In summary, the visual observations and photographs have provided an integrated view of the Sonoran coastal fault system that emphasizes its regional significance and that will guide future research programs.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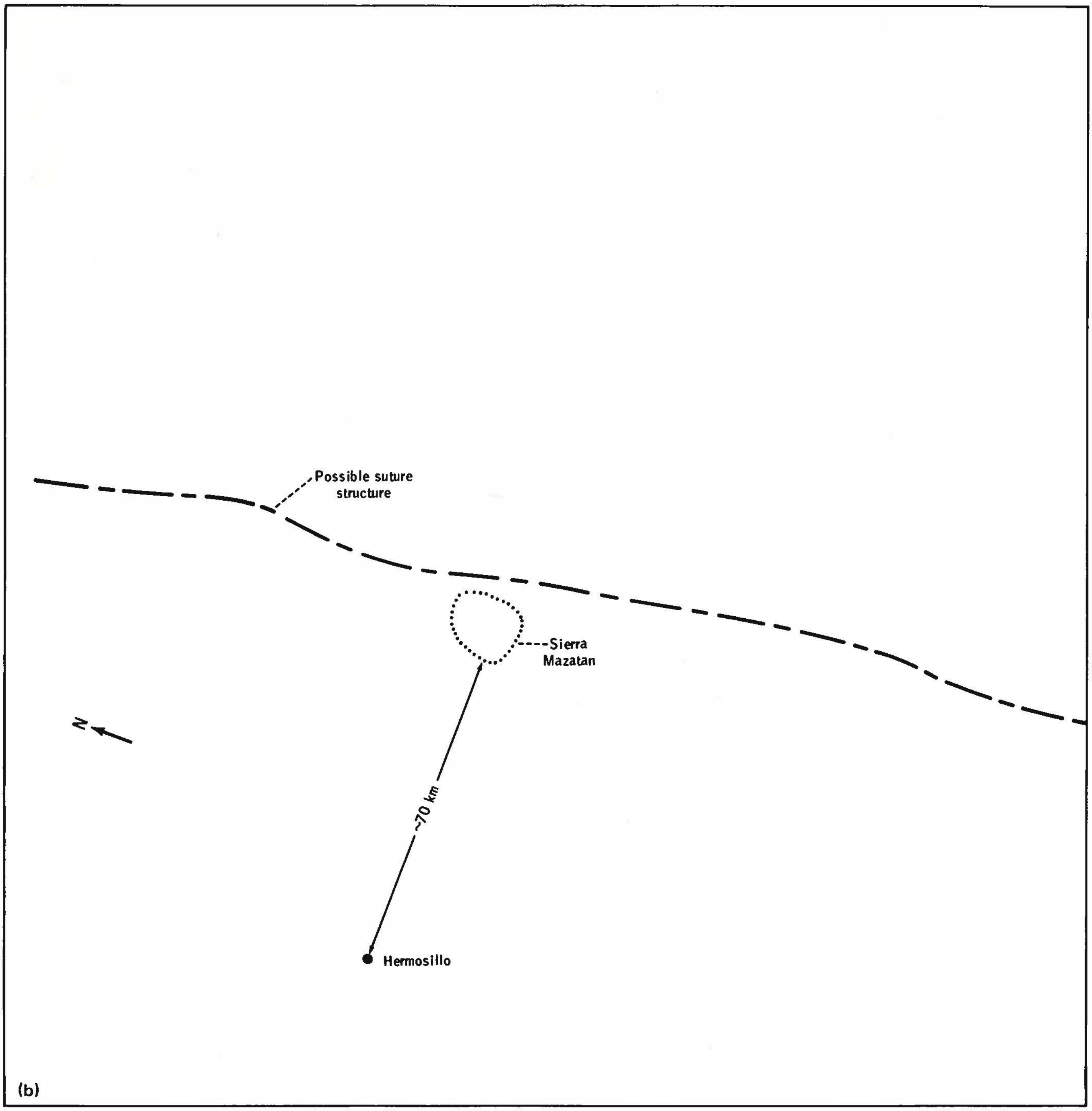


FIGURE 4-12.—The Sierra Mazatan in northwestern Sonora, Mexico, an anomalous mountain range of deformed granite the structural position of which may be related to a possible north-trending fault suture to the east of it. (a) Photograph (SL4-141-4398). (b) Sketch map.

(a)

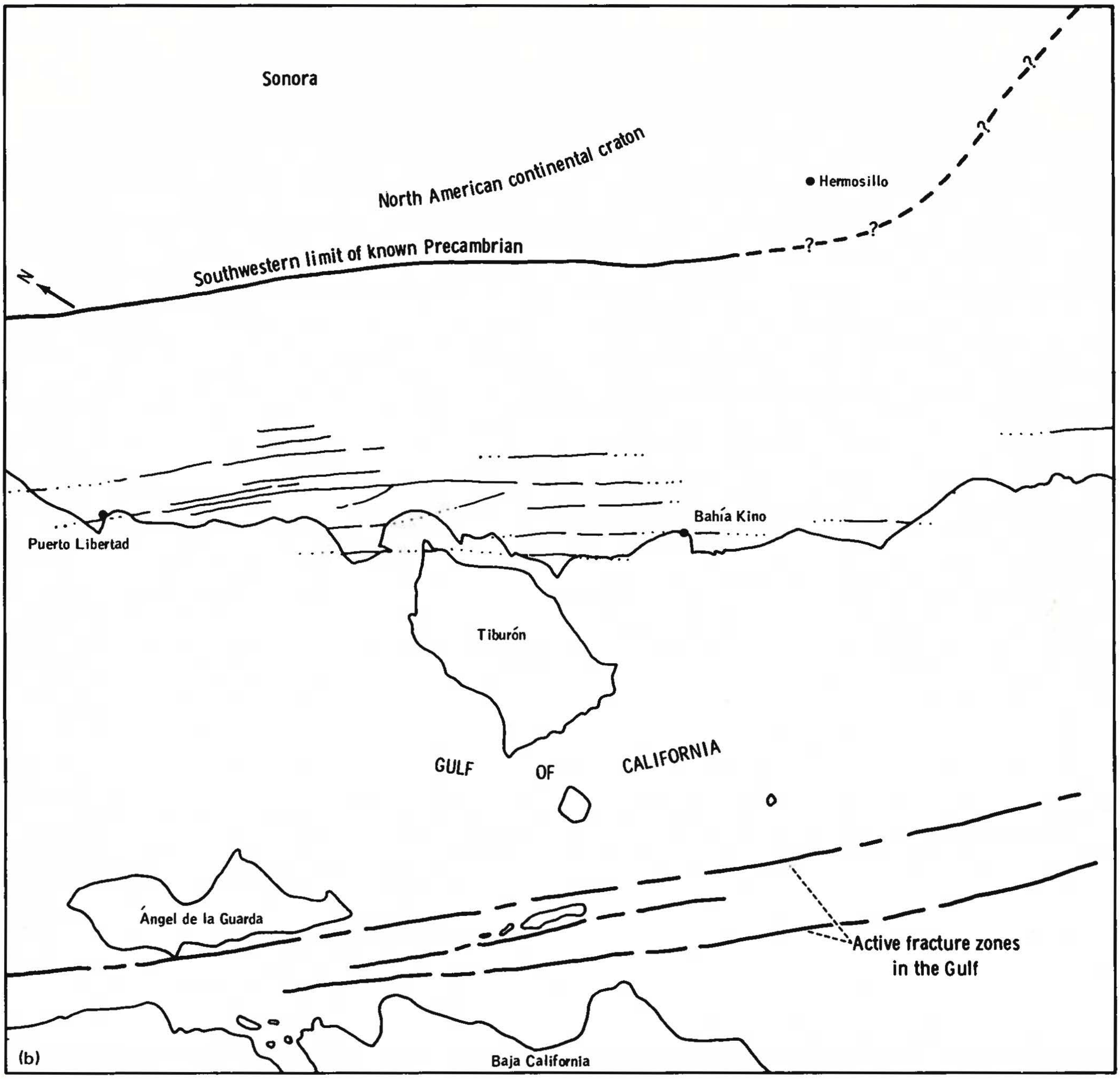


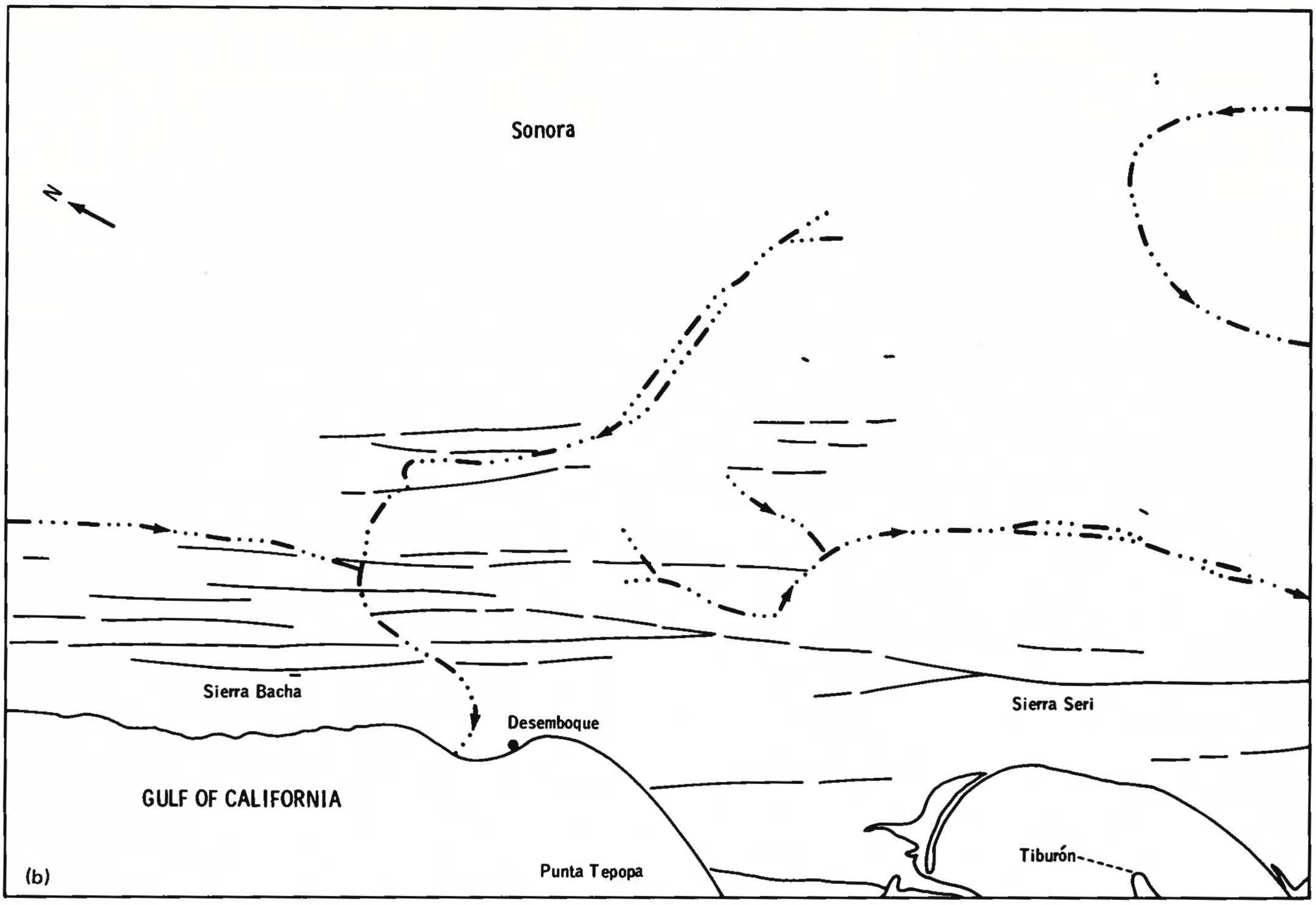
FIGURE 4-13.—The coastal fracture system of northwestern Sonora revealed in this photograph appears to be related to, but older than, the active transform fractures within the present Gulf of California. (a) Photograph (SL4-140-4155). (b) Sketch map.

FIGURE 4-14.—The coastal fracture zones of Sonora, Mexico. (a) Photograph (SL4-194-7236). (b) Sketch map showing details of the coastal fracture zones of northwestern Sonora, Mexico.

Sierra del Alamo, Sonora, Mexico

The color contrasts in the Sonoran desert strikingly reflect the diversity of geologic formations and rock types exposed in the region, despite the homogenizing effects of desert varnish. For this region, the Skylab 4 crewmen were asked to observe and photograph distinct color and textural units in the Sierra del Alamo and adjacent ranges to the south.

Analysis of one of these photographs (fig. 4-15) revealed the occurrence of previously unrecognized Precambrian "basement" rocks south of Sierra del



Alamo in the northern and central region of Sierra Viejo. The dark zone adjacent to the granitic terrain was found to contain a variety of metamorphic rocks including granitic gneisses and metasedimentary schists. South of the granitic rocks, a complex structural belt of late Precambrian and early Paleozoic sedimentary rocks extends to the southern tip of the range. The combination of Precambrian and Paleozoic formations in the Sierra Viejo represents the most southwesterly extension of the North American craton (older crust) identified thus far (fig. 4-13(b)).

Arizona

The yield of observational data for the Arizona region, although less extensive than for the other study areas, included excellent photographs of the Colorado River system. The erosional features and the principal structures of the Grand Canyon and the adjacent plateaus were captured by the astronaut photographers in a remarkable demonstration of man's ability to optimize an opportunity for obtaining unique photographic data of the Earth's surface. Two areas in Arizona to which the Skylab 4 handheld-camera photographs have contributed new geologic insight are discussed in the following sections.

Central Arizona.—Linear or arcuate features, due primarily to faulting, have been identified in the photographs of the central Arizona study area. Some of these features were known faults, some are extensions or connections of known faults, and some were previously unrecognized.

Of specific interest are the arcuate features. Conway (ref. 4-8) has mapped a system of northeast-southwest faults in northern Gila County, some of which swing around to the north to trend north-south. A very similar arcuate feature is one of the salient features of the

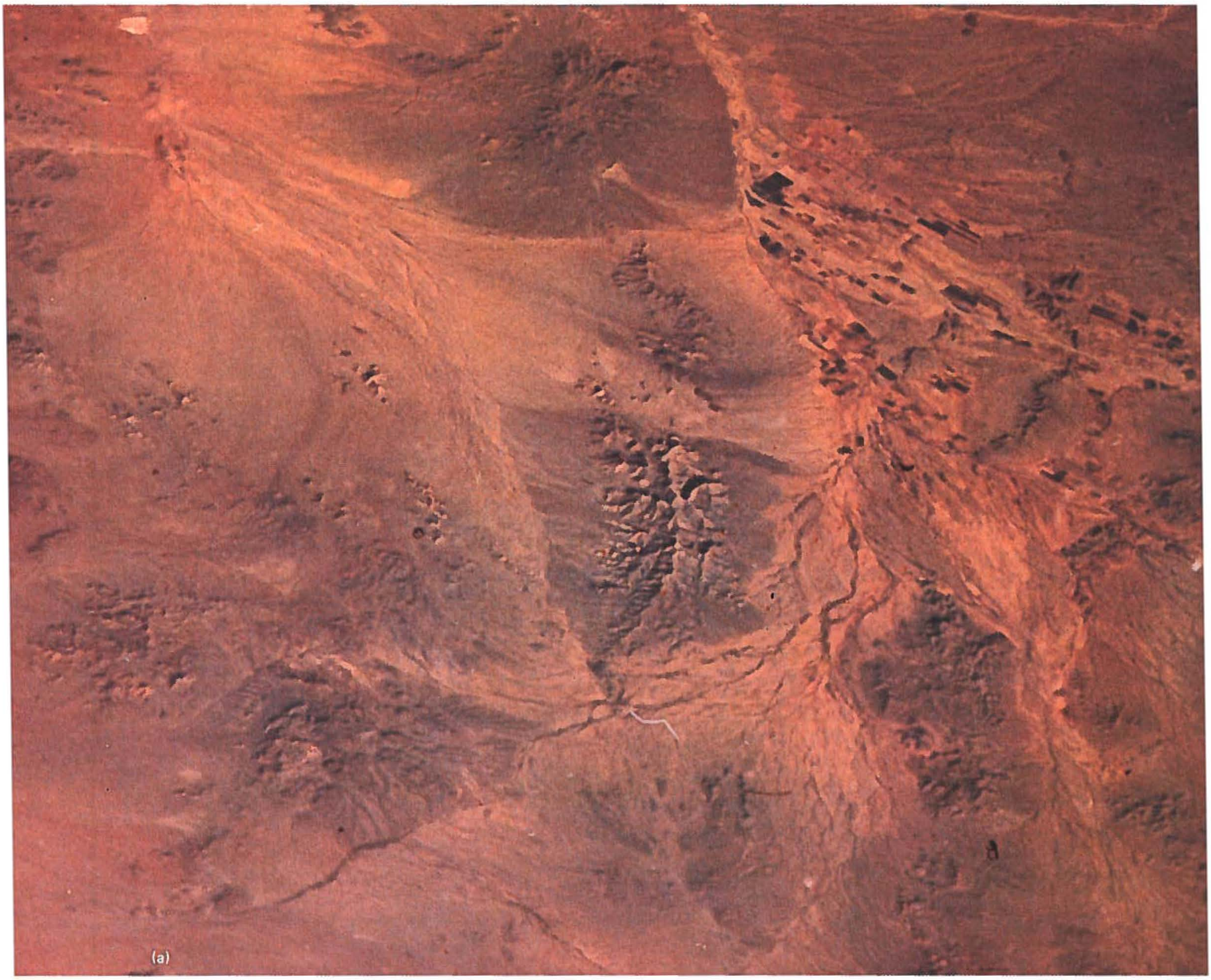
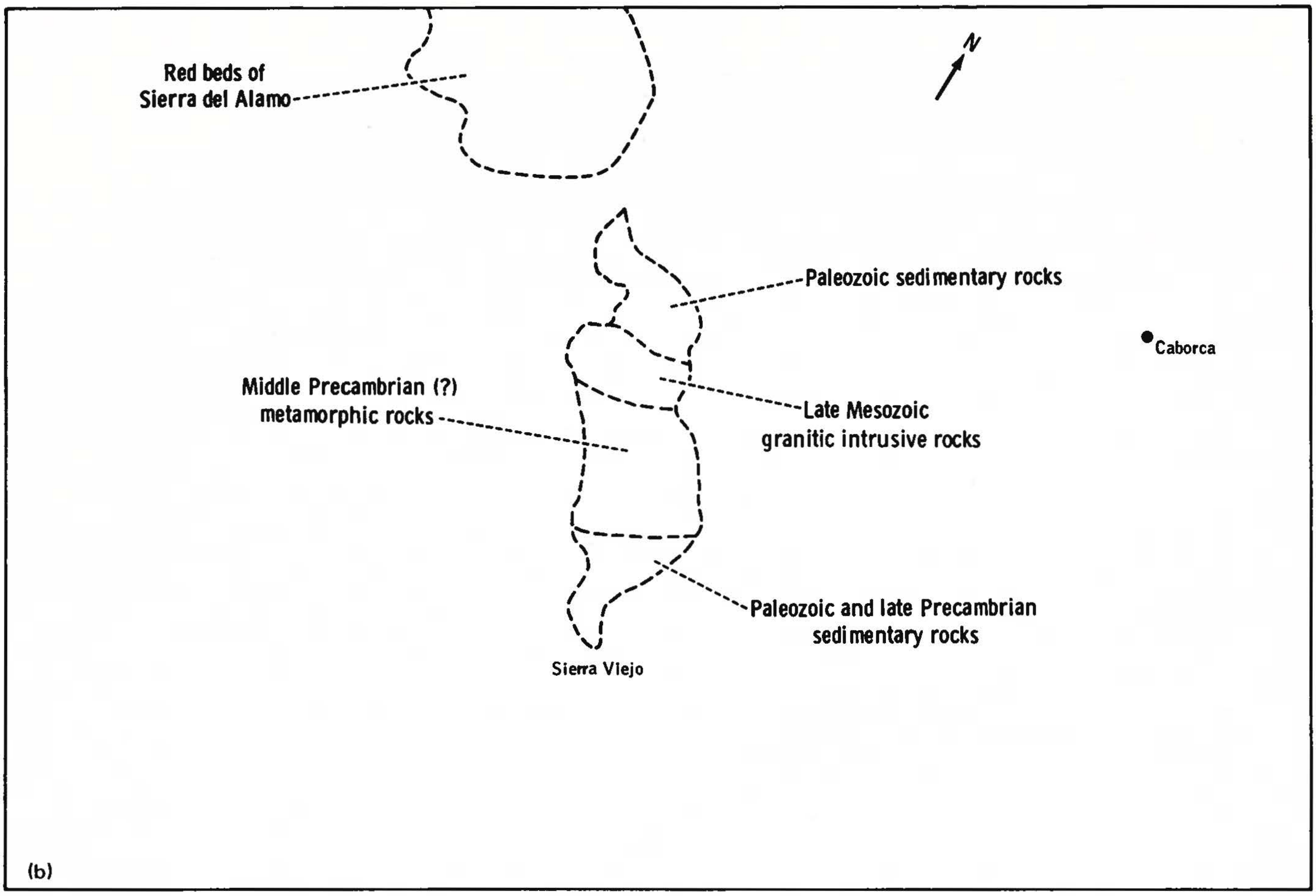


FIGURE 4-15.—Sierra Viejo in northwestern Sonora, Mexico. (a) Photograph (SL4-203-7821). (b) Sketch map showing geologic subdivisions.

northern Mazatzal Mountains (fig. 4-16). A part of this feature was earlier mapped (ref. 4-9) as an almost straight fault, the Deadman Fault. This entire arcuate feature is almost certainly a fault and probably of the same origin as the arcuate faults first identified only 32 km to the east by Conway. There are much weaker suggestions of other such arcuate features. Recognition in the photographs of arcuate faults, and possible arcuate faults, in a much broader area than that in which similar features were first mapped is very exciting. Further search for and confirmation of these features in Skylab Earth resources experiment package (EREP) photographs is important; understanding such a distinctive regional fault system will have significant implications

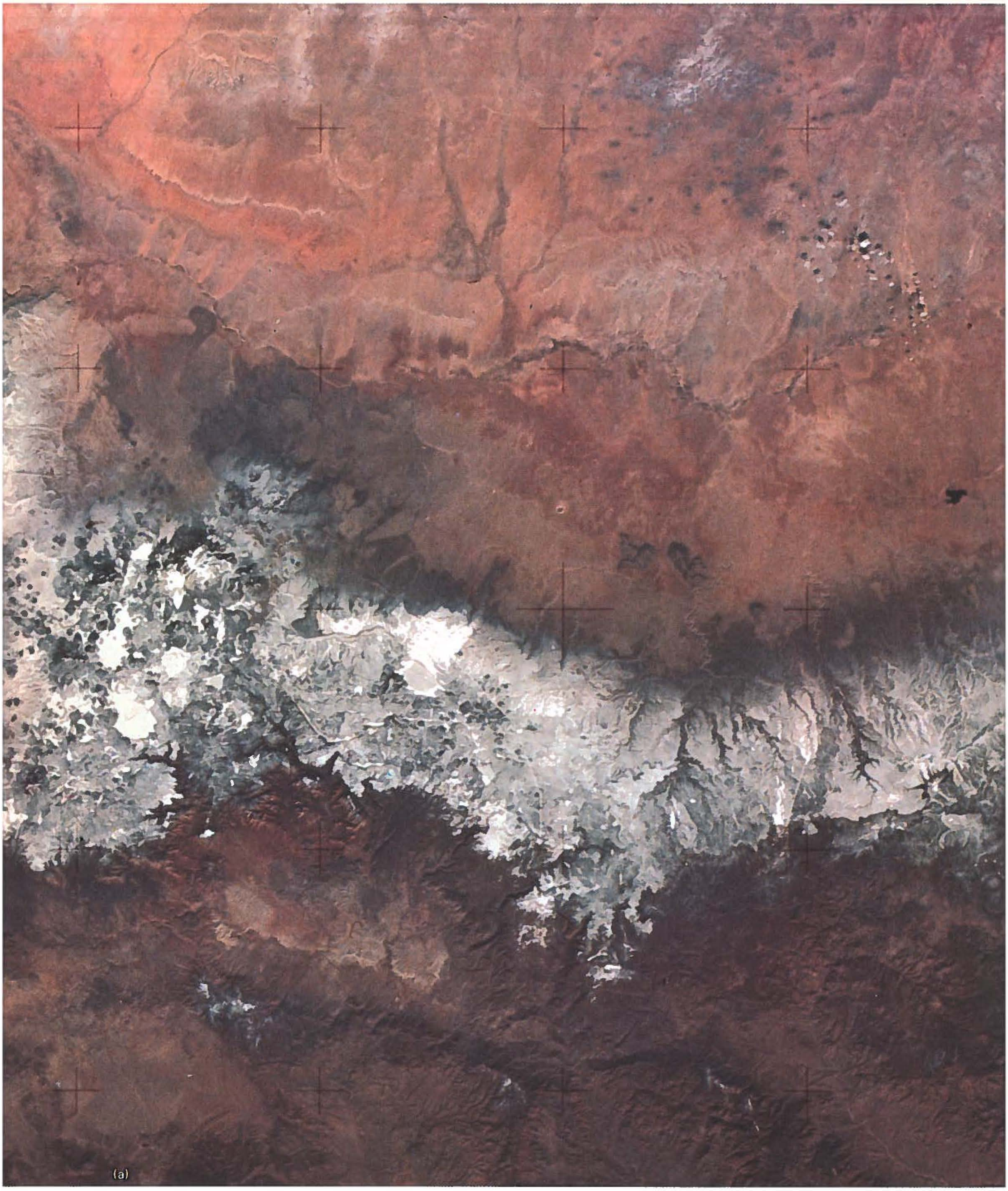


for the nature of the tectonic regime in which this old portion of the Earth's crust was both formed and subsequently modified. Work is proceeding on this project.

In regard to Precambrian structures, the northeast-southwest grain was noted throughout the Sierra Ancha-Mazatzal Mountains area (fig. 4-16), thus confirming and clarifying what has been noted by many geologists over the years. The usefulness of the photographs in this regard is the identification of lineations in areas where detailed mapping has not yet been done. This will aid the future determination of the nature and extent of faulting. There are suggestions of continuation of faults only partly mapped in earlier studies.

Tertiary faulting in the Sierra Ancha-Mazatzal Mountains area has extensively modified the Precambrian terrain. These faults are more difficult to see in the photographs than the Precambrian structures but are nevertheless decipherable. One probable Tertiary fault is newly identified in figure 4-16. This fault is a prominent linear feature that runs northwest-southeast for more than 24 km in the northern Mazatzal Mountains and is on trend with the central Verde Valley to the northwest. There are numerous other lineations of similar trend and probably of related Tertiary origin.

The understanding of Tertiary structure in this area is exceedingly important because it would provide clues to the nature of the profound transition from the thick, relatively undeformed Colorado Plateau crustal block to the much thinner, structurally complex Basin and Range crustal block. Understanding the nature of this transition is particularly important in understanding geologically recent crustal activities that have been (and still may be) modifying the southwestern North American crust and that have played an important role in the origin of some metallogenic processes.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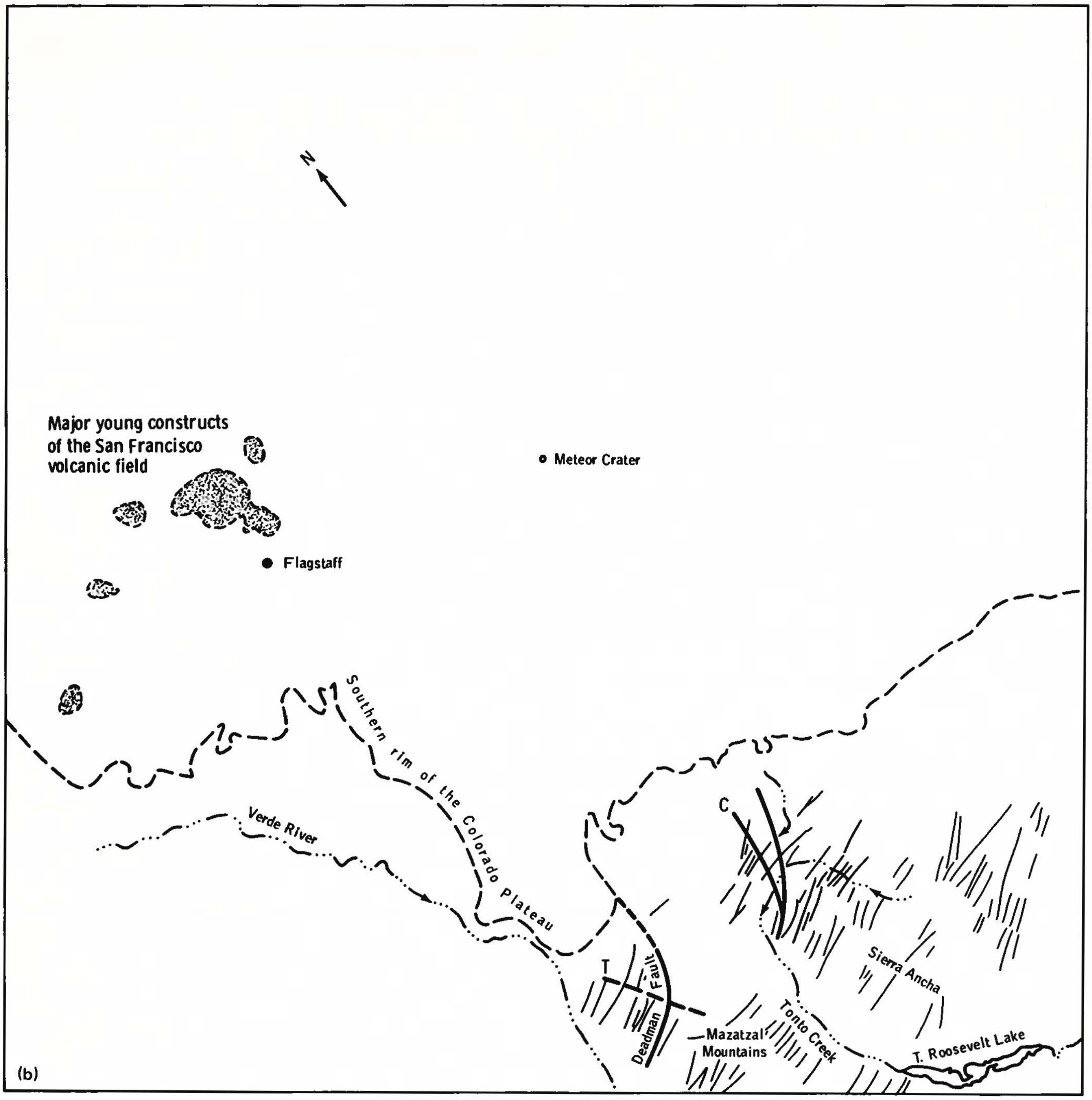

FIGURE 4-16.—The northern Sierra Ancha and the Mazatzal Mountains. (a) Photograph (SL4-142-4438). (b) Sketch map showing northeast-southwest structural grain and major northward-curving faults. The straight northeast-southwest segment of the Deadman Fault was mapped by Wilson (ref. 4-9), but the northward-curving extension is a new suggestion based on figure 4-16(a). Arcuate faults (C) were mapped by Conway (ref. 4-8), and a probable Tertiary fault (T) is parallel to the projected extension of the central Verde Valley.

Northern Arizona linear features.—Skylab 4 photographs of the Grand Canyon area of northern Arizona (figs. 4-16(a), 4-17, and 4-18(a)) are remarkable in clarity, resolution, and color contrast. The conditions that prevailed during photography (early to midafternoon winter Sun, excellent visibility, cloudless skies, and light snow cover at higher elevations (greater than 1525 to 1825 m)) combined to make these photographs unusually valuable to the geologist. Although the Grand Canyon was extensively photographed by the Skylab 4 astronauts, the other photographs do not compare in quality.

The light snow cover is particularly helpful in enhancing some linear features and in providing contrasts both in elevation and in vegetation cover. For example, the unforested areas and drainage bottoms are sharply defined in white. Abundant lineations, which reflect faulting, jointing, and monoclinal flexing (all only partly mapped) are spectacularly highlighted on the photographs. Some structural features, however, are not visible under the conditions in which these photographs were taken. In the summer or in morning light, other lineations might appear and some that are visible in these photographs would disappear.

All lineations suggestive of jointing, folding, or faulting were determined from analyses of figures 4-16(a), 4-17, and 4-18(a) and were compiled on topographic maps. As an example, figure 4-18(b) was compiled from a Skylab 4 photograph (fig. 4-18(a)) and illustrates the technique and the detail in which throughgoing lineation systems can be seen. Only a few of these features correlate with structures shown on the geologic map of Arizona (ref. 4-10). These include a few discontinuous major north-south faults that are irregular in trend. In a recent structural study of a central portion of this area (fig. 4-18(b)), Lucchitta (ref. 4-11) has mapped numerous north-south faults. The lineaments traced from the Skylab photograph correspond well with the faults shown on this map.

Lucchitta hypothesized that the straight portion of the Grand Canyon from the mouth of Kanab Creek (A, fig. 4-18(b)) southwest to the first major southward bend of the river (B) is a structurally controlled segment. He also noted on a Landsat image a zone of lineaments that trend northeast. A major discovery from analysis of the Skylab photograph (fig. 4-18(a)) is a pronounced set of lineaments along, and particularly on trend to the southwest of, the straight segment of the canyon. This documentation supports Lucchitta's suggestion of structural control for this segment of the river.

Shoemaker et al. (ref. 4-12) compiled a structural map of northern Arizona (fig. 4-19) from published sources and Landsat imagery. A mosaic of lineaments from the photographs was prepared from figures 4-16(a), 4-17, and 4-18(a) and generally there is good agreement between the two maps. As expected, many faults shown in figure 4-19 were not detected in the Skylab photographs. Conversely, a surprising number of Skylab photograph lineaments was found to be without analogs in figure 4-19. Skylab photograph lineaments that do not correspond to faults on the map by Shoemaker et al. are shown in figure 4-20. Most pronounced are the northeast-southwest lineations that are best shown in the western part of the Grand Canyon. Numerous faults of this trend are shown by Shoemaker et al. in the far eastern part of the Grand Canyon in and near the Bright Angel Fault system and farther south and east in the Mesa Butte Fault system, but the lineation system seen so clearly to the west in the Skylab photographs has essentially no fault representation on their map. The Skylab data show quite clearly a strong structural trend in near coincidence with, though perhaps displaced to the north of, a structural zone inferred by Shoemaker et al.

Fault offset has not been demonstrated on the newly discovered lineaments and, if present, may be very minor. Fault offset on the Sinyala Fault is only approximately 5 m on the bend of the river (attenuating upward to less than 1.5 m in the highest strata of cuts), but the fault is continuous for 48 km and profoundly influences topography (ref. 4-13, p. 331).

Rejuvenation of motion along old Precambrian fault lines is well documented (refs. 4-12 and 4-13) for faults cutting Paleozoic strata of the Grand Canyon area. This is particularly true for those faults trending northeast-southwest, and Shoemaker et al. suggest that the Mesa Butte, Bright Angel, and Sinyala systems are developed on great Precambrian fault zones.

It is well known that the Precambrian basement of Arizona has a strong northeast-southwest structural grain. Skylab photograph lineaments strongly support the suggestion of a Sinyala system and add significantly to the overall northeast-southwest fault pattern. Apparent concentration of these lineaments in the deeper portions of the Grand Canyon area may further support the idea of reactivation on Precambrian faults.

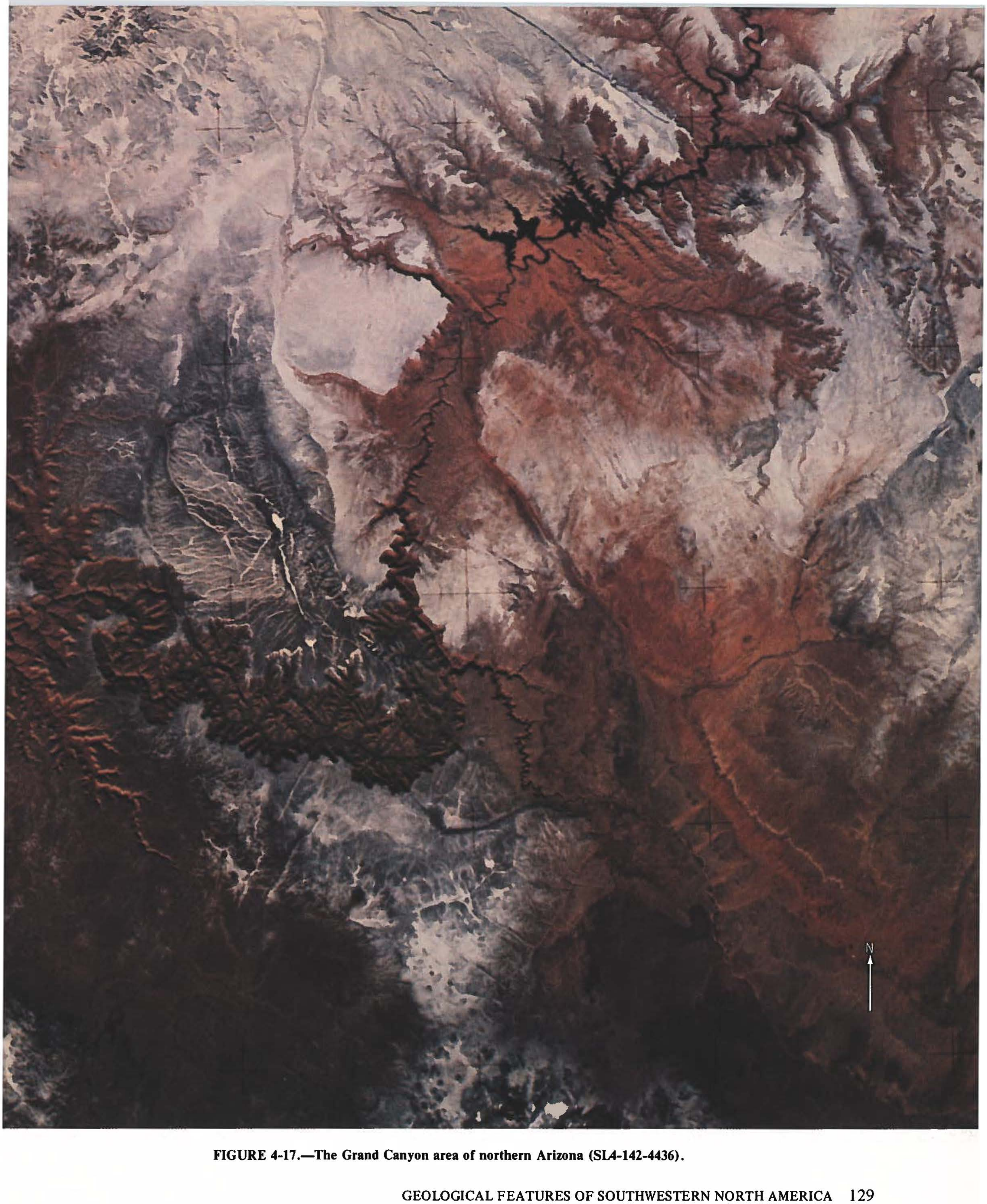

FIGURE 4-17.—The Grand Canyon area of northern Arizona (SL4-142-4436).


(a)

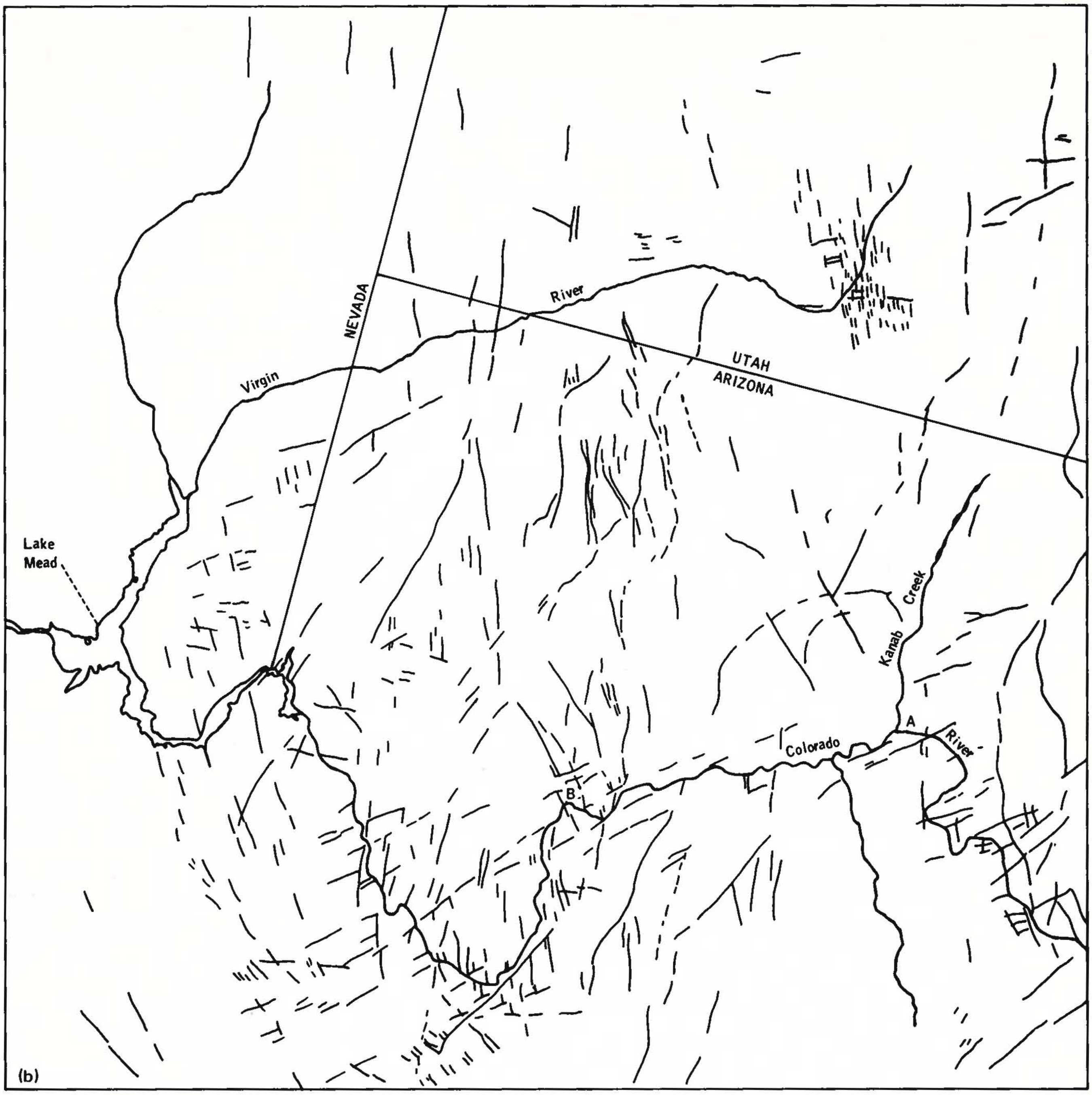

FIGURE 4-18.—The northern Arizona area. (a) Photograph (SL4-142-4435). (b) Sketch map showing linear fractures developed in the surface strata of the Colorado Plateau in the vicinity of the Grand Canyon as revealed in the photograph.

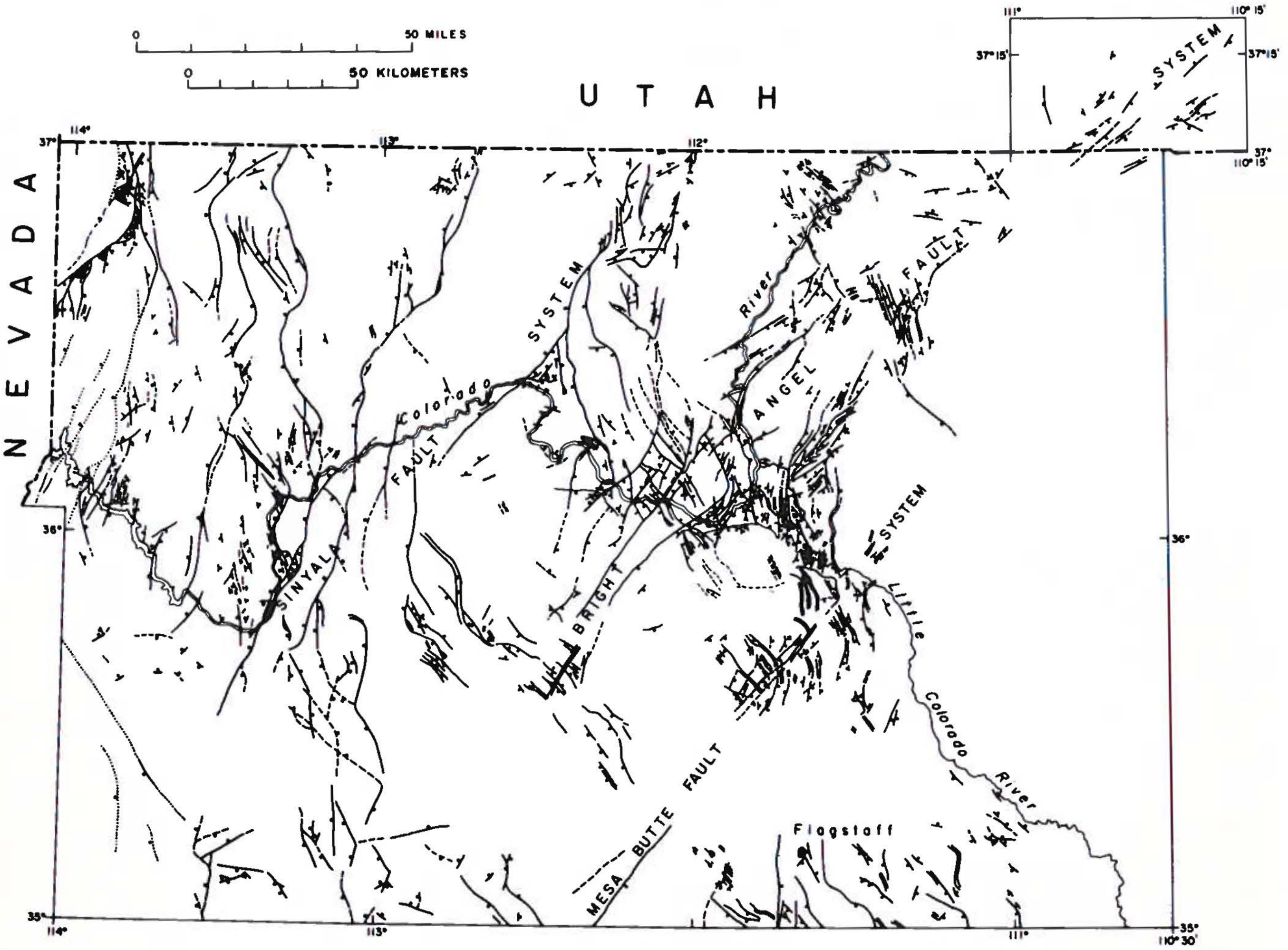

FIGURE 4-19.—Map of faults in northwestern Arizona. Most faults shown are normal faults; bar and dot on downthrown side (from ref. 4-12).

SUMMARY OF SIGNIFICANT RESULTS

The Skylab 4 geologic investigations have yielded the following geologically significant results.

1. Demonstration of an 11-km left-lateral displacement on the Chiriaco Fault zone and of the presence of other previously unidentified faults of similar orientation and sense in the Colorado Desert of southern California
2. Evidence of a previously unrecognized major northwest-trending shear zone on the northwestern coast of Sonora, Mexico
3. No evidence that would dispute the abrupt eastern termination of the Agua Blanca Fault zone in northern Baja California
4. Recognition of the extensive nature of conjugate linear fracture systems in the crystalline rocks of peninsular California over a distance of more than 644 km
5. Identification of a continuous stratigraphic reference zone in the prebatholithic rocks of northern Baja California
6. Discovery of the most southwesterly known occurrence of Precambrian crystalline rocks in the North American continent
7. Discovery of a previously unmapped section of Mesozoic (?) volcanic rocks in the Pinto Mountains of southeastern California

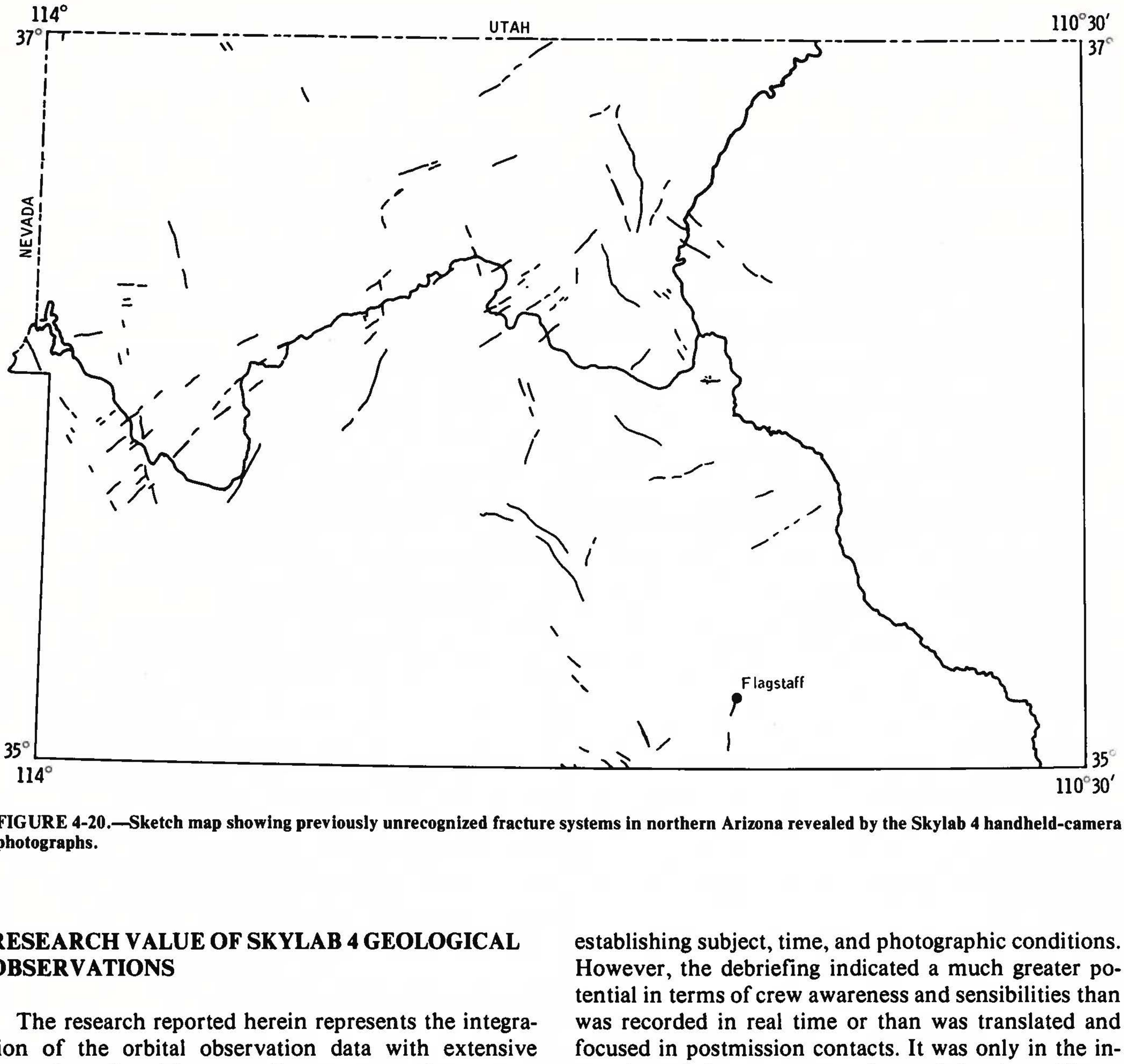

FIGURE 4-20.—Sketch map showing previously unrecognized fracture systems in northern Arizona revealed by the Skylab 4 handheld-camera photographs.

RESEARCH VALUE OF SKYLAB 4 GEOLOGICAL OBSERVATIONS

The research reported herein represents the integration of the orbital observation data with extensive ground studies. These studies were supplements to ongoing long-term research programs, which provided a background of problem awareness for the recognition of research potential in the Skylab 4 observations. It is desirable to establish as clearly as possible the direct research value of these observations.

The primary contribution is in the form of excellent photographs that could be applied in photogeologic appraisals of the several regions. As noted previously, verbal commentary by the astronauts was largely limited to establishing subject, time, and photographic conditions. However, the debriefing indicated a much greater potential in terms of crew awareness and sensibilities than was recorded in real time or than was translated and focused in postmission contacts. It was only in the inspection of the eastern terminus of the Agua Blanca Fault zone that the crew positively verbalized their research conclusions. Our ground studies supported their validity.

The great value of the photographs is in the effective selection of a view of the subject in which lighting and camera position, as well as other transient conditions, permit the geologically significant aspects of the subject to be photographed. This requires a value judgment on the part of the operator of the handheld camera, which distinguishes his work from mapping-camera photography. There is a tendency to view geological subject material as static and therefore automatically capturable. This is erroneous. Informative photographs of geological features are the result of an educated photographer recognizing an effective opportunity.

The astronaut photography was very effective for the majority of the designated sites and for the opportunity sites, which confirms that the astronauts were able to perceive the spatial and geometric relations under consideration. The effectiveness of the photography increased as the mission progressed. Even without seeing their photographic product, the astronauts seemed to learn to appreciate and document the better perspectives of their subject matter. An outstanding example is the sequence of oblique photographs of the California fault systems from which the mosaic in figure 4-3 was created.

There were several sites (e.g., the plutons of the peninsular batholith) in which the camera failed to capture what the astronauts could clearly discriminate. These discrepancies must reflect our lack of understanding of all the factors by which the human eye and brain exceed the camera and film in perception. It is clear that the training of the astronauts for handheld-camera photographic documentation was more or less perfunctory and that the equipment which they carried was good but not optimal.

The photographic product that was introduced into our research, then, was an astronaut-selected view of the Earth from which an attempt was made to recognize the important geological patterns bearing on the research objectives. The scale of the features observed, the ability to interrelate large features in areas measuring 10 000 to 100 000 km^2, and the unexpected revelations about the organization in the surface patterns are contributions almost unique to these types of data. The color values, when the lighting and photographic processing were optimal, were also unprecedented in our experience.

Essentially, this visual information has provided a large-scale framework on which the details derived from surface studies can be organized. In the best circumstances, local investigations can be expanded much more confidently to their proper regional significance.

An appropriate example can be drawn from a recent research report (ref. 4-14) in which it was tentatively concluded that an enormous fault zone, active about 150 to 200 million years ago, sliced northwest-southeast across southwestern North America from California to Mexico and displaced the crust at least 800 km. This was an unsuspected structure the existence of which explained many first-order plate tectonics problems in continental evolution. The research leading to this conclusion was at least 6 years in progress. In the spring and summer of 1974, the implications of the research became apparent, but the regional dimensions seemed too vast to obtain extensive confirmation easily. By the spring of 1974, the handheld-camera photographs of Skylab were available. Although the coverage could not be complete, it provided many clues to important surface sites for detailed inspection and study in California, Arizona, and Sonora. The additional information supported our hypothesis, and it was accordingly reported. The Mojave-Sonora megashear has received much recent attention. If it survives independent scrutiny, the excellent Skylab 4 photographs must be recognized as a valuable source of perspective in refining the final hypothesis. In the studies of coastal Sonora that are reported herein, the possibility exists that still other important features related to the growth and modification of the continental margin can be recognized.

Numerous other observations made by the astronauts or developed from these studies of the photographs also have the potential for significant research yield. It is emphasized that the most effective use of the Skylab 4 data will be made in the course of its continued incorporation and application in ongoing research at the ground level. Until new programs of directed visual observations are initiated, only by additional surface investigations and by ground-truth tests to follow up the many interesting implications of the existing photographs can more of this potential science be realized.

RECOMMENDATIONS

1. The Skylab 4 geology experiment has yielded data of significant scientific value, and the Skylab 4 crewmen have shown that there is still greater potential in this approach. Accordingly, future orbital missions should include plans for manned visual observations of Earth.

2. To achieve the potential yield, a comprehensive planning, facility preparation, and training program is necessary. A basic design for such a program should be considered sufficiently soon so that the Skylab experiences will not be forgotten.

3. An Earth-orbiting observatory on the Space Shuttle may be manned by a professional scientist.

Nevertheless, Shuttle astronaut crews should be given training in geology and other Earth sciences so that their natural observational talents can be directed toward appropriate problems and targets of opportunity.

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APPENDIX

SOURCES OF INFORMATION

The principal sources of information used for preparing this report are as follows.

1. Skylab 4 Visual Observations Flight Book
2. Transcript of Skylab 4 crew comments
3. Skylab 4 handheld-camera photograph logs
4. Skylab 4 summary of completed visual observations and handheld-camera photographs
5. Skylab 4 orbital track map, starting November 10, 1973
6. Skylab 4 indexes of handheld-camera photographs by geographic location
7. Earth-looking video tapes (SL4-165, SL4-175, and SL4-186)
8. Skylab 4 crew debriefing, March 12, 1974
9. Skylab 2, 3, and 4 handheld-camera photographs (Hasselblad (70 mm) and Nikon (35 mm) cameras)
10. Apollo 6, 7, and 9 and Skylab Earth resources experiment package (EREP) photographs
11. Field investigations by the authors
12. Informal discussions with the Skylab 4 crew