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APOLLO 9 MULTISPECTRAL PHOTOGRAPHY: GEOLOGIC ANALYSIS

PAUL D. LOWMAN, JR.

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ABSTRACT

The Apollo 9 mission carried a multispectral terrain photography experiment (SO65) in which the astronauts photographed selected land areas with an array of four 70mm cameras, each with a different film/filter combination, in an effort to determine the feasibility and value of multispectral orbital photography for earth resources studies. Over 90 four camera sets (360 frames) of pictures, covering the southern United States and parts of Mexico, were obtained. This report presents results of a geologic study of selected sets made to determine if multispectral orbital photography offers any advantages for geology over comparable color or panchromatic orbital photography.

Visual comparisons were made of four-camera sets covering Luna County, New Mexico, and the area east of Birmingham, Alabama. In the Luna County pictures, there was little if any difference in relative film response to different rock units among the three black-and-white pictures (Panatomic-X with 25A and 58 filters, Infrared Aerographic with 89B filter). In addition, the Ektachrome Infrared showed fewer hues and less contrast between rock units than comparable Ektachrome S.O. 121 film. It is concluded that multispectral photography offers no unique advantages over color photography in an area of largely bare rock and soil. The Birmingham pictures, however, covering a heavily

vegetated area, showed a definite superiority of multispectral photography in rendering geologic structure, and in permitting easy differentiation among deciduous vegetation, open water, and (by comparison with SO65 pictures of other areas) rock or soil. Since efficient orbital photography must cover a wide variety of terrain, it is apparent that multispectral methods are highly desirable.

An Ektachrome Infrared picture of the Peninsular Ranges, California, was used, in conjunction with a short field reconnaissance, to study the nature of the Elsinore fault. It was found that the fault appears to be dominantly dip-slip rather than strike-slip. Photographs of the Imperial Valley were studied to see if known active faults (San Jacinto and Imperial faults) were visible. No evidence of recent breaks was found, indicating the need for high resolution photography taken shortly after earthquakes if such breaks are to be covered from orbiting spacecraft.

APOLLO 9 MULTISPECTRAL PHOTOGRAPHY:
GEOLOGIC ANALYSIS

INTRODUCTION

It was immediately apparent, when the film was developed, that the SO65 Multispectral Terrain Photography Experiment carried on Apollo 9 had been extremely successful in producing a large number of excellent and often spectacular photographs, and that most of the planned targets in North America had been covered at least once. The purpose of this report is to present initial results of a geologic study of selected multispectral sets. The objective of the study was to find out if multispectral orbital photography offers geology any advantages not provided by comparable color or panchromatic orbital photography.

The SO65 experiment was intended to investigate the feasibility and value, for earth resources studies, of multispectral orbital photography (Lowman, 1969). Equipment used was a window-mounted array of four Hasselblad 500 EL cameras, fitted with the standard Zeiss f 2.8 80mm Planar lens, manually triggered by the astronauts (Figure 1). Four film/filter combinations were used: Panatomic-X with 25A (red) and 58 (green) filters, Ektachrome Infrared with a 15 filter, and Infrared Aerographic with an 89B filter. The cameras were pre-loaded and pre-set so that no adjustments by the crew were necessary.

Photographic procedures were essentially these. The crew was furnished lists and maps of the target areas, and instructed in operation of the cameras. The actual targets for photography were picked on a day-to-day basis by the investigators in the support room on the basis of weather and light predictions, and of the reports from the Apollo 9 crew as to weather over target areas. Before each photo pass, the crew unstowed and mounted the camera assembly, put the spacecraft in Orbital Rate mode, and triggered the cameras manually at the recommended interval. In addition, they frequently took Ektachrome S.O. 368 pictures of the target area from the other windows with a hand-held Hasselblad 500C, also with the 80mm lens.

Areas for the SO65 experiment and for "target of opportunity" photography are shown in Figure 2. The targets of opportunity were chosen for geologic importance, and were intended to fill gaps in the coverage of the S005 Synoptic Terrain Photography Experiment carried on Gemini and the Apollo 7 flights.

The Apollo 9 crew had no trouble in following the planned procedures, and took S065 photographs during five passes over North America in the last four days of the mission (Lowman, 1969). They obtained 128 complete 4-camera sets and a number of partial sets (due to different magazine capacities for different film types). Of the complete 4-camera sets, about 90 are of relatively clear land areas, and thus useful for geologic study. The areas covered include the southern United States (below 35° latitude), northwest Mexico, southern Mexico, and the Carribean-Atlantic area.

Single camera Ektachrome pictures were taken over many areas, chiefly North America and Africa; about 390 frames useful for geology were obtained. Their quality and the detailed notes taken by the astronauts make these pictures by themselves of great scientific value.

ACKNOWLEDGMENTS

The S065 photography involved more people than any previous manned flight photographic experiment, and it is impossible to acknowledge all specific contributions to its success. A major factor was, of course, the outstanding performance and initiative of the Apollo 9 crew—James A. McDivitt, David R. Scott, and Russell Schweikart—who had already completed the most complex manned mission ever flown to that time before beginning the SO65 photography. The co-investigators for the experiment were H. A. Tiedemann (MSC), R. N. Colwell (U. of California), P. N. Slater (U. of Arizona) and E. F. Yost (Long Island University). Project Scientist was John Dornbach (MSC) and Project Engineer Allen Grandfield (MSC). The Staff Support room was manned by personnel of the Earth Resources and Mapping Sciences Divisions, Manned Spacecraft Center. Dr. Warren Hovis (GSFC) supplied spectral data on infrared reflectance of minerals. H. W. Blodget (GSFC) assisted in mission planning and photo-interpretation.

GEOLOGIC ANALYSIS

The approach taken here has been to compare all four pictures from the S065 experiment for two contrasting areas, one the Chihuahua Desert of southern New Mexico and the other the southern Appalachians of Alabama. The multispectral photographs have also been compared as a group with conventional color photos of the same areas taken on Apollo 9 or earlier missions. Analytical techniques were elementary, consisting of visual comparison of the pictures taken with different film/filter combinations. Future analysis should include densitometer traverses across the features studied to provide a quantitative check of the conclusions reached.

The Apollo 9 photographs of southern California were studied for their tectonic value by examination of a second generation transparency with a binocular microscope, mostly at 12X magnification. Structural details were plotted on black-and-white 8 by 8 inch prints. The map thus constructed was field-checked for general correctness during a short field trip in August, 1969.

Luna County, New Mexico and Adjacent Areas

The area of Luna County, New Mexico, has been repeatedly covered by sounding rocket and satellite photography because of its low latitude and nearness to White Sands Proving Ground. A previously-unmapped volcanic field south of Palomas, Chihuahua, was discovered on Gemini 4 photographs (Lowman, McDivit and White, 1967), and subsequent field checks were made by Lowman and Tiedemann (1968). Therefore, the area furnished a good comparison test site for SO65 photography, and excellent four-camera coverage was obtained by the Apollo 9 crew. A fairly detailed though preliminary discussion of the pictures will be presented as a basis for comparing multispectral photography of a desert area with other types of terrain.

The area covered by the photographs studied (Figures 3-6) is about equally divided between New Mexico and Chihuahua, Mexico. It is entirely within the Chihuahuan Desert, and vegetation is typically sparse (Figures 7, 8) outside areas of irrigation farming such as those south of Deming. The bedrock and soil are therefore well-exposed. According to Griswold (1961), Luna County, New Mexico (which includes all the American territory covered by the Apollo 9 picture) lies in the Mexican Highlands section of the Basin and Range Province. From a broader tectonic viewpoint, however, the entire photo covers the gradation from the Sierra Madre Oriental of Mexico into the Basin and Range Province, a relation first demonstrated on Gemini 4 photographs (Figures 9, 10). An extremely wide variety of rock types is represented in the area (Figure 11). Generally speaking, the rocks of the folded ranges in Mexico (lower right in the photographs) are sandstones and limestones, and those of the Basin and Range Province (upper left) are Tertiary volcanics. The Palomas volcanic field is a uniform olivine basalt similar to minor basalt occurrences north of the border. The valleys (bajadas) are underlain by great thicknesses of wind-blown sand and alluvium. Other incidental surficial materials include clays and evaporites in playas, and caliche ($CaCO_3$).

For comparison, the four simultaneous pictures taken by the SO65 cameras are presented, together with an earlier Ektachrome (S. O. 217) Gemini 4 photo (Figure 9) and sketch maps, and an Apollo 6 photo taken with High Resolution Aerial Ektachrome (S. O. 121) (Figure 12). The S065 pictures can be characterized briefly as follows:

Panatomic-X With Red (25A) Filter (Figure 3)

This band was clearly the most effective, from a geological viewpoint, of the three black-and-white films carried on Apollo 9. The picture shows a wide range of tones, and contrast between different rock and soil units is generally high. Referring to the photo, the sketch map, and a portion of Balk's (1962) geologic map (Figures 13, 14) of the Tres Hermanas Mountains, attention is directed to the bedrock/pediment and pediment/bajada contacts, which are in most areas as distinct as on black-and-white prints made from Ektachrome S.O. 217 and Ektachrome S.O. 121. In the Tres Hermanas Mountains, the northwest-trending contact between Tertiary andesite (Ta on Balk's map) and Tertiary rhyolite and latite (Trl on Balk's map) is visible as a tone difference, corresponding to the different rock colors as seen in the field and on Ektachrome S.O. 217 and 121 prints. These particular contacts will also be discussed in relation to the other S065 pictures.

Ground resolution is on the order of 30 to 50 feet for high-contrast linear features, such as the single-track railroad in the upper right corner and the road south from Palomas. This is of course a maximum figure and should not be extrapolated to other features uncritically; for example, the town of Columbus is practically impossible to identify, and Palomas entirely so, because of their low contrast.

It should be pointed out that the generally high quality of the Panatomic-X/25A combination is not particularly surprising, since it would correspond roughly to a standard panchromatic aerial film with extended red sensitivity.

Panatomic-X With Green (58B) Filter (Figure 4)

The Columbus area is shown nearly as well, for geologic purposes, in the green band as in the red (25A) band. However, the contrast is somewhat lower across geologic contacts than in the previous photo. For example, the andesite/latite contact in the Tres Hermanas Mountains just referred to is hardly visible on this picture. However, the southward-trending contact between the Gila conglomerate (QTg on Balk's map) shows up better with the green filter, although it is not completely certain that some vegetation difference may not follow the lithologic contact.

Infrared Aerographic With 89B Filter (Figure 5)

The black-and-white infrared film shows much lower contrast among different rock and soil units in this area than do the two previously-discussed combinations, although the reflectivity in general appears substantially higher (assuming optimum diaphragm setting on the camera). The pediment/bajada contacts around the Florida and Tres Hermanas Mountains are much less distinct than on the other pictures, and are nearly invisible in places. Practically all detail in the alluvium, as between the Florida and W. Potrillo Mountains, has been lost.

A key question bearing on the utility of multispectral photography for geology is whether there are any striking differences in relative film response, between rock units, in changing from Panatomic-X to Infrared Aerographic. This is the basis for the usefulness of infrared films in vegetation photography, and it is of great importance to know if infrared film is comparably more effective in identifying rock and soil units.

Ideally, this question should be approached by making densitometer traverses across the original film or a low-number generation copy. Pending this, a visual comparison was made of several light/dark contacts, corresponding to lithologic contacts, on the three black-and-white films. Areas examined include the following:

1. Bedrock/pediment and pediment/bajada contacts, Florida Mts.
2. Bedrock/pediment and pediment/bajada contacts, Tres Hermanas Mts.
3. Contacts between Tertiary volcanic rocks, and between Tertiary volcanic rocks and Gila Conglomerate, Tres Hermanas Mts.
4. Playa/alluvium contact, Laguna de Guzman
5. Basalt/alluvium contacts, Palomas volcanic field and West Potrillo Mountains.

There were no gross differences in relative density of these units on the three different films; e.g., the pediment surrounding the Florida Mountains was darker than the alluvium of the bajada on all three pictures, and apparently darker in the same degree. More generally expressed, none of the three bands provides any strong tonal clues to rock identification. The implications of this finding will be discussed further in the report.

Ektachrome Infrared With 15 Filter (Figure 6)

The color infrared pictures, viewed as transparencies, show the same general increased reflectance coupled with decrease in contrast seen on the black-and-white infrared. The colors on a second generation transparency are shades of pink and pale red. No bright reds are seen, even in the cultivated areas around Deming and Columbus, presumably because the crops were not up yet.

A black-and-white print of the color infrared picture is very similar to the black-and-white infrared one. The only noticeable difference is the somewhat greater detail visible within the lava flow of the West Potrillo Mountains. No major tone or color differences along major contacts were seen between the color infrared and the other three pictures. Apart from the greater inherent information content of color film, therefore, the color infrared film does not seem to have any advantage over the black-and-white films used here.

Discussion of the Luna County Pictures

Several tentative conclusions can be drawn from this preliminary analysis.

1. The multispectral photographs of the Columbus area do not offer any obvious advantage over standard color film such as S.O. 121 in a desert region of this sort, in which vegetation is sparse, and the rock and soil show through. Furthermore, the color infrared film is inferior to S.O. 121 in information content; many more hues, with higher contrast, are visible on the S.O. 121. This conclusion is not unexpected, because previous studies have indicated that multispectral photography in the visible and near-infrared is not especially helpful in identifying rock types. Colwell, et al., (1966) photographed a variety of rock and soil samples with various film/filter combinations equivalent to those used on Apollo 9. Two contrasting rock types, granodiorite and serpentine,

showed little obvious change in relative contrast in the various photos taken; as in the case of the Apollo 9 pictures, their film response appeared to change together.

Infrared reflectivity measurements made by Hovis (1966) provide an explanation for the apparent ineffectiveness of the multispectral photography in differentiating rock types. As typified by the curve for silica (Figure 15), common minerals, soils, and sand show a relatively smooth rise in reflectance in the 5,000-10,000 angstrom region, with few peaks or valleys. The useful identifying features, the strong absorption bands and restrahlen peaks, only occur in the range beyond 10,000 angstroms (i.e., beyond the range of photographic film).

2. If multispectral photography is taken over desert areas such as this one, it can probably be used about as effectively as equivalent single-camera orbital color photography. This conclusion rests on, first, the demonstrations by Yost and Wenderoth (1968) and Orr (1968) that multispectral bands can be additively combined to produce reconstituted images. (Such work is being done with the Apollo 9 photographs by Yost.) Also, it depends on the fact that the main value of orbital photography in geology is in the study of regional structure from elements of shape, size, and arrangement, rather than in compositional determinations from color. Therefore, a good black-and-white picture, such as those taken in the red band, would be of considerable value alone, even without reconstitution.

3. For desert areas, a visual range color film with enhanced red sensitivity, such as S.O. 121, is probably the best single film for geologic purposes.

Coosa Valley, Alabama and Adjacent Areas

For comparison with the Luna County SO65 pictures, a series taken over the southern Appalachians east of Birmingham, Alabama, was studied. This area lies between 33 and 34 degrees latitude, and hence had never been covered with high-resolution orbital photography before. The SO65 pictures are thus of inherent interest, in addition to their multispectral nature. The frames selecte (Figures 16–19) cover an area largely included in an Ektachrome S.O. 368 phot (Figure 20) taken with the hand-held Hasselblad out the window, thus permitting comparison of the multispectral pictures with conventional color film.

The area covered by the SO65 pictures includes parts of three major physic graphic provinces: the Piedmont, Blue Ridge, and Valley and Ridge Provinces, which, with the Appalachian Plateau, make up the southwestern Appalachian Highlands. As shown on the sketch map (Figure 21), the area includes a wide variety of rock types, all of which have been folded along northeast trends and in many places thrust-faulted toward the northwest. Unlike the New Mexico photographs, these show practically no exposed rock and little soil; almost the entire area is covered by forest or farmland.

Panatomic-X With Red (25A) Filter (Figure 16)

This picture can be considered intermediate in contrast compared to the others of this set. The main light and dark areas correspond, respectively, to cleared and cultivated land or to large built-up areas (e.g., north Birmingham at far left). The dark areas along Talladega Mountain and elsewhere correspond very closely to the area of woodland coverage shown on the U.S.G.S. Birmingham 1:250,000 map, and it seems clear that this and the color infrared pictures could easily be used to make a generalized vegetation map.

The physiography is shown with moderate clarity in the Valley and Ridge and Blue Ridge Provinces, but little structure is visible in the Piedmont.

Panatomic-X With Green (58B) Filter (Figure 17)

In this picture, contrast is very low compared with that taken through the 25A filter. The main vegetation patterns can still be seen, as can major roads, but little geologic detail is visible outside the Valley and Ridge Province. Drainag is extremely hard to recognize; the Coosa River, for example, is nearly invisible in several places where it was distinct in the previous picture. This picture was definitely the least valuable of the four.

Infrared Aerographic With 89B Filter (Figure 18)

The black-and-white infrared frame has one outstanding characteristic compared with the other two black-and-white pictures, namely the extreme contrast of bodies of open water. The Coosa River and others are easily delineated along their entire length by the dark tone, and even small lakes, reservoirs, and ponds are clearly visible. The importance of this for hydrology is evident.

In general, however, the contrast among other features with this film is low. The main physiographic outlines can be followed, but the detail identifiable is definitely less than on Panatomic-X with red filter, though more than the Panatomic-X with green filter.

Infrared Ektachrome With 15 Filter (Figure 19)

This picture is clearly far superior in information content to any of the three previous ones alone. In addition to showing bodies of water as distinct blue, it has many hues of pink and red, presumably vegetation. Substantially more geologic structure is visible in the color infrared than in the best black-and-white picture (Panatomic-X with red filter). This is well illustrated in the upper left part of the picture, where many subdivisions of anticlines can be seen that are difficult or impossible to distinguish on any of the others.

Ektachrome S.O. 368 (Figure 20)

Although this picture is of generally high quality and of considerable inherent interest for its coverage, it is clearly inferior to the color infrared for all purposes. In particular, the geologic detail identifiable is much less than on either the color infrared or Panatomic-X with red filter.

This interpretation is of course preliminary, but the conclusion was expected because of the generally poor performance of standard color films over heavily vegetated areas due to atmospheric scattering in the blue-green part of the spectrum.

Discussion of the Alabama Pictures

The New Mexico and Alabama pictures do not make an ideal comparison selection, because in addition to their different vegetation cover, the two areas are greatly different in structure and geologic age. The Appalachians of today are entirely the result of differential erosion long after the last (Paleozoic) folding and faulting episodes, whereas in New Mexico the main features are relatively young (Cenozoic). A better comparison would be possible if part of the Appalachians were in a desert.

Despite the foregoing qualification, it seems clear that the value of aerial and orbital photography in direct geologic mapping is far less over the Appalachians because of the vegetative cover. However, considerable structural mapping could be done with the color infrared pictures, and to a lesser degree with the others. It seems safe to say that infrared photography of some sort is mandatory for this area or ones like it. The great value of the Ektachrome Infrared pictures for geology further dictates that either a broadband sensor with near-infrared sensitivity be included, or that a multi-spectral system including narrow-band infrared be used to permit equivalent color reconstitution.

Southern California

One of the Apollo 9 sets (Figure 22) provides an exceptionally good vertical, nearly cloud-free view of the Peninsular Ranges northeast of San Diego, an area already under study with the Apollo 7 photographs (Lowman, 1969). It has therefore been used to construct a tectonic map (Figure 23) of the area and in a brief field reconnaissance.

The general tectonics of the Peninsular Ranges are not well understood, judging from the published literature. One particular problem is the nature of the Elsinore fault. This northwest-trending fault, over 150 miles long, is apparently a member of the San Andreas fault zone of southern California, which includes the San Jacinto, Imperial, and "San Andreas" faults. The "San Andreas" fault is the southeast extension, or fusion, of the Mission Creek and Banning faults, and is not necessarily the direct continuation of the San Andreas fault north of San Bernadino; for this reason, Allen (1957) questions the name "San Andreas" for this segment. The northwest-trending faults in this area are characterized by right-lateral movement, and Dibblee (1954) suggests several miles of such movement for the Elsinore. Sharp (1967) found evidence for about 15 miles of right-lateral movement on the San Jacinto fault to the northeast.

Study of Apollo 7 and Gemini V photos has revealed the existence of several un-mapped fractures which appear to cross the Elsinore fault without visible lateral displacement, despite the fact that their physiographic expression (deep valleys) indicates an age similar to, or greater than, the Elsinore fault. The Apollo 9 photograph (Figure 22) confirms the existence of these northeast-trending fractures, and reveals further evidence against major lateral movement along the Elsinore fault as a whole. This evidence is the complete absence of physiographic expression of the Elsinore fault along its continuation through the southwest flank of the Agua Tibia Mountains. Such expression would include a typical San Andreas type erosional rift, disconnected aligned stream segments, and perhaps displaced stream valleys. None of these are visible on the Apollo 9 photograph, although there is a possible extension of the Elsinore fault turning due south at the northwest end of the Agua Tibia Mountains. Larsen (1948) mapped such an extension, or branch, in the area.

To check this interpretation, a very rapid and necessarily superficial road reconnaisance was made along the part of the Elsinore fault between Elsinore Lake and the Vallecito Mountains, a distance of about 60 miles. The Apollo 9 photo was used for navigation, without either air photos or topographic maps; the only supporting data was Jahns' (1954) geologic map (Figures 24, 25) of the Peninsular Ranges. It was found that there is no obvious evidence for a fault in the location shown by Jahns, such as notches in stream divides, stream offsets, or large crush zones in road-side outcrops.

Any conclusions reached on the basis of this preliminary work are obviously provisional. However, the Apollo 9 photo shows unequivocally that there is at least very dissimilar physiographic expression of the Elsinore fault at different segments of its length. Between Elsinore Lake and the Agua Tibia Mountains it forms the west wall of a very wide, deep valley so conspicuous as to be visible on Viking photos taken over White Sands Proving Ground, New Mexico (Lowman, 1964). But in the Agua Tibia Mountains, it has no expression visible at the 1-200 foot ground resolution of the Apollo 9 photos. (It should be noted that Larsen (1948) showed no bedrock dissimilarities along the supposed location of the fault in the Agua Tibia Mountains.) To the extent that generally similar causes (movement on the Elsinore fault and subsequent differential erosion) should have generally similar effects (fault zone physiography) on the crystalline rocks of the Peninsular Ranges, it appears that the Elsinore fault does not extend southeast through the Agua Tibia Mountains. Because of the necessary geometry of wrench faults, this casts doubt on the reality of major lateral movement.

A possible reconciliation between this conclusion and the previous work showing a continuous fault may be the following. The fault may have originated by dip slip (normal or reverse), but has been transformed into a lateral fault more recently by changing regional stresses. Mechanically, this seems intuitively more plausible than initial formation as a wrench fault, which would require shearing of perhaps 150 miles of continental crust; origin by dip-slip movement would require at most shearing of the thickness of the continental crust, and perhaps only tensional failure.

There are several preliminary operational conclusions to be drawn from the Apollo 9 photograph of the Peninsular Ranges and its use in the field:

1. The color infrared film is a distinct asset to field work in evergreen-forested areas, because the deciduous vegetation (grass, etc.) of valleys stands out sharply, thus outlining the topography. Urban areas are also clearly shown as gray-blue colors.

2. The ground resolution is barely good enough for field use. An improvement of 20-30% would have made the work considerably easier. It is recommended that consideration be given to the 100mm lens if Hasselblads are used in future photographic experiments of this type.

3. The perspective afforded by the orbital photograph cannot be duplicated by ground observation even in an area of high mountains and generally good visibility; nor by 1:250,000 topographic maps. Air photos of this area have not, however, been studied yet.

In addition, it should be pointed out that this picture also shows a prominent series of northeast-trending fractures in the Peninsular Ranges that is almost completely overlooked on regional geologic maps (e.g., Dibblee, 1954; Allen, et al., 1965; Goddard, 1965). The apparent lack of attention given to these fractures is probably due, in part, to the fact that they are evidently not active; as shown by Allen, et al. (1965), this block is notably quiet seismically (although the southern San Andreas fault is also). However, the possibility that any northeast-trending valley in this area is fault controlled should be taken into account in reservoir planning because of the possible danger of reactivating old faults, either by the weight or lubricating action of the water.

Several of the Apollo 9 photographs cover the Imperial Valley under reasonably cloud-free conditions. Since a number of currently active faults that have produced major earthquakes pass through the Imperial Valley, the pictures have been examined to see if they have any value in the study of active faults. The specific question attacked is, whether known active faults, in particular the Imperial, San Jacinto, and "San Andreas" (Mission Creek-Banning) faults, are visible on the pictures. In view of the just-demonstrated ease of fault delineation on orbital photos, such a question might seem unnecessary. However, as pointed out by Richter (1958) and Allen, et al. (1965), the relation between faults with surface expression and earthquakes is by no means clear, and reputable scientists have even argued that faults may be an effect, rather than a cause, of earthquakes. Consequently, the question is an important one.

The multispectral photographs (Figures 26-29) have been examined in conjunction with published maps (referenced in Richter, 1958) showing the location of recent breaks on the Imperial, San Jacinto, and San Andreas (or Mission Creek-Banning) faults. There is no obvious evidence for any of them on the four frames studied, either along the recent breaks or on their extensions. There appear to be several possible reasons for this somewhat surprising discovery:

1. The offsets on recent breaks are probably below the limits of resolution of the Apollo 9 pictures. According to Richter (1958), for example, the offsets produced on the Imperial fault in the 1940 earthquake were no greater than 19 feet and the trace considerably narrower, while the maximum ground resolution on the Apollo 9 pictures is probably about 35 feet for high-contrast linear objects.

2. Much of the area underlain by the faults studied is farmland, and damage caused by breaks, such as offset fences and boundary lines, is rapidly repaired or obliterated by crops within a year or two. Also, areas not under cultivation in the Imperial Valley are open desert underlain by alluvium and wind-blown sand, and do not readily produce recognizable permanent fault traces.

3. The segments of the faults looked for have formed so recently that there has not been time for erosion to produce recognizable features, such as aligned

stream segments, by differential erosion. A related explanation is that alluvium deposition outpaces fault movement, so that the trace is covered as fast as it forms.

Regardless of the precise reasons for the lack of visible expression for these active faults, it has implications for orbital systems intended for detection or mapping of recent breaks. First, the highest possible resolution must be attained consistent with wide area coverage. Even ground resolutions of 5 to 10 feet are desirable for specific small areas. Second, non-visual sensors should be considered for advanced earth resources satellites. Infrared detectors and radar may be more effective than photography in fault detection. Even with such sensors, however, detection of recent fault lines may always be difficult from orbital altitudes. Third, faults should be photographed within a few months after earthquakes on them.

One possible application of orbital photography in avoiding earthquake damage is in public education. Publication of easily-understood photographs such as those presented here, with known faults plotted on them, can hardly fail to impress realtors, contractors, and all potential builders with the reality of earthquake hazards.

SUMMARY AND CONCLUSIONS

The S065 photographs are of great potential value for their quality and for the areas covered. Most important, however, is the light they throw on the feasibility and value of multispectral photography from orbiting spacecraft for geological studies.

First, the success of the experiment demonstrates that, operationally, there are no insuperable obstacles to systematic high-quality photography from large manned spacecraft. All the problems encountered during similar photography from Gemini spacecraft, such as orientation, window obscuration, and target acquisition (Lowman, 1969), were overcome by the organization and techniques developed for the Apollo 9 flight.

With regard to the value of multispectral photography, its value and indeed its necessity for orbital earth surveys has been demonstrated beyond reasonable doubt, despite the fact that standard color photography was apparently of equal value over the New Mexico site. The reasoning behind this conclusion is that, as shown by the Alabama photography, color photography over heavily-vegetated areas is of relatively little value because of atmospheric scattering in the blue-green region of the spectrum. Infrared photography, however, is at its best under such conditions, and multispectral methods combine the advantages of selective narrow-band photography and broad-band color photography. Since orbiting spacecraft must cover a wide variety of terrain, including heavily-vegetated areas, multi-spectral photography is mandatory if useful coverage is to be obtained over all the different areas overflown.

An incidental application for orbital multispectral techniques such as those developed for the Apollo 9 mission is here suggested. The S065 cameras provide an excellent test bed for comparative exposure of different films and filters. Their use in an orbiting spacecraft permits photography of an extremely wide range of physiographic provinces, vegetation zones, seasons, and cultural features, in a very short time. To obtain test coverage of the areas photographed by the Apollo 9 astronauts with aircraft would involve several high-performance aircraft and probably many months of time, to say nothing of the legal problems encountered in covering foreign countries. Therefore, it appears that the techniques used in the Apollo 9 SO65 experiment might be applied on future missions to testing aerial photography films, on a nominal cost basis, for government agencies and private industry.

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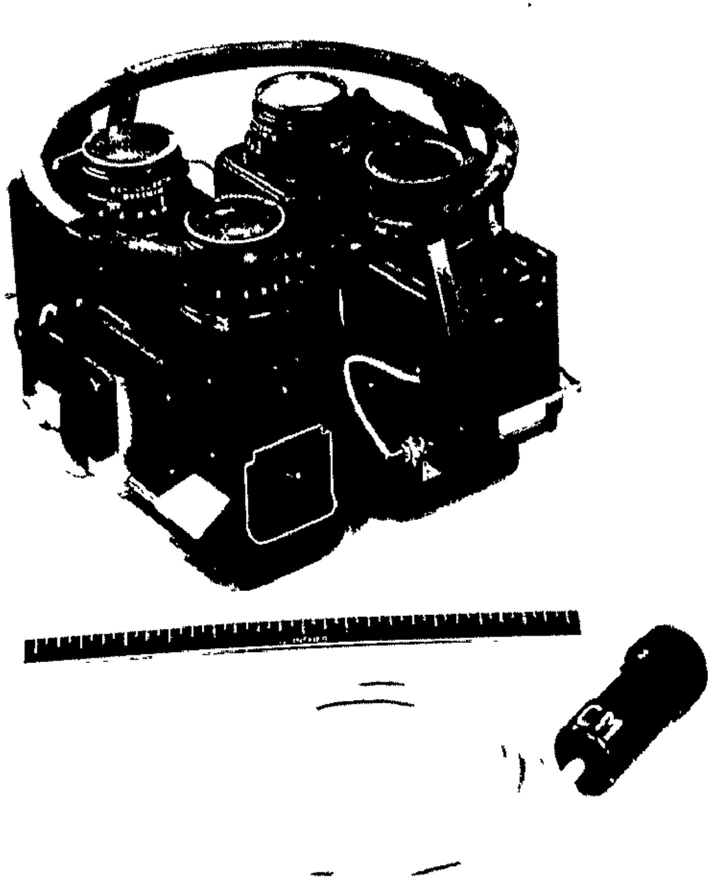


Figure 1a. Array of four Hasselblad 70mm cameras used for S065 experiment. Ring is used to mount array to command module hatch window. Cameras are triggered manually with switch in foreground. Film/filter combinations used include Panatomic-X with 25A (red) and 58 (green), Infrared Aerographic with 89B, and Ektachrome Infrared with 15.

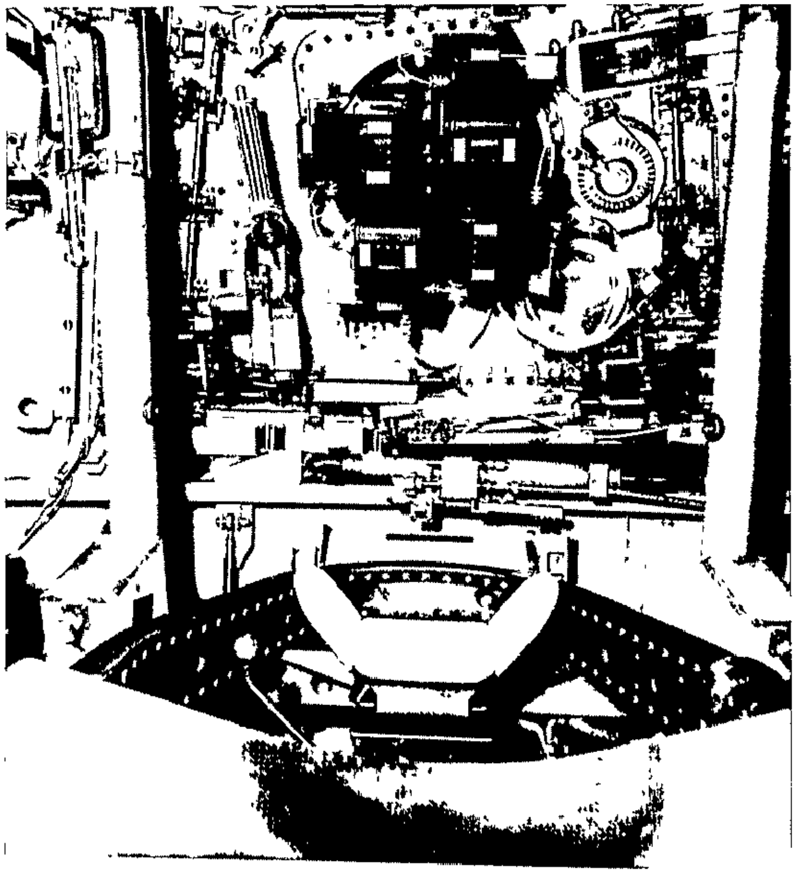


Figure 1b. Camera array mounted in command module hatch window. Switch at right.

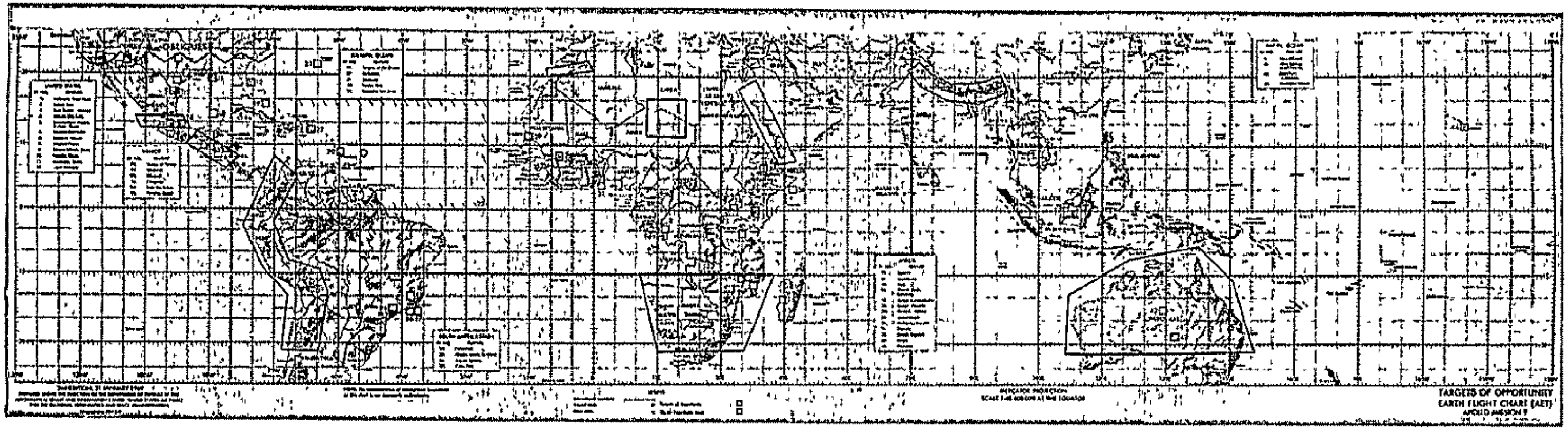


Figure 2. Apollo 9 map showing areas for multispectral terrain photography and targets of opportunity for single camera hand-held 70mm photography. Small squares are multispectral target areas.

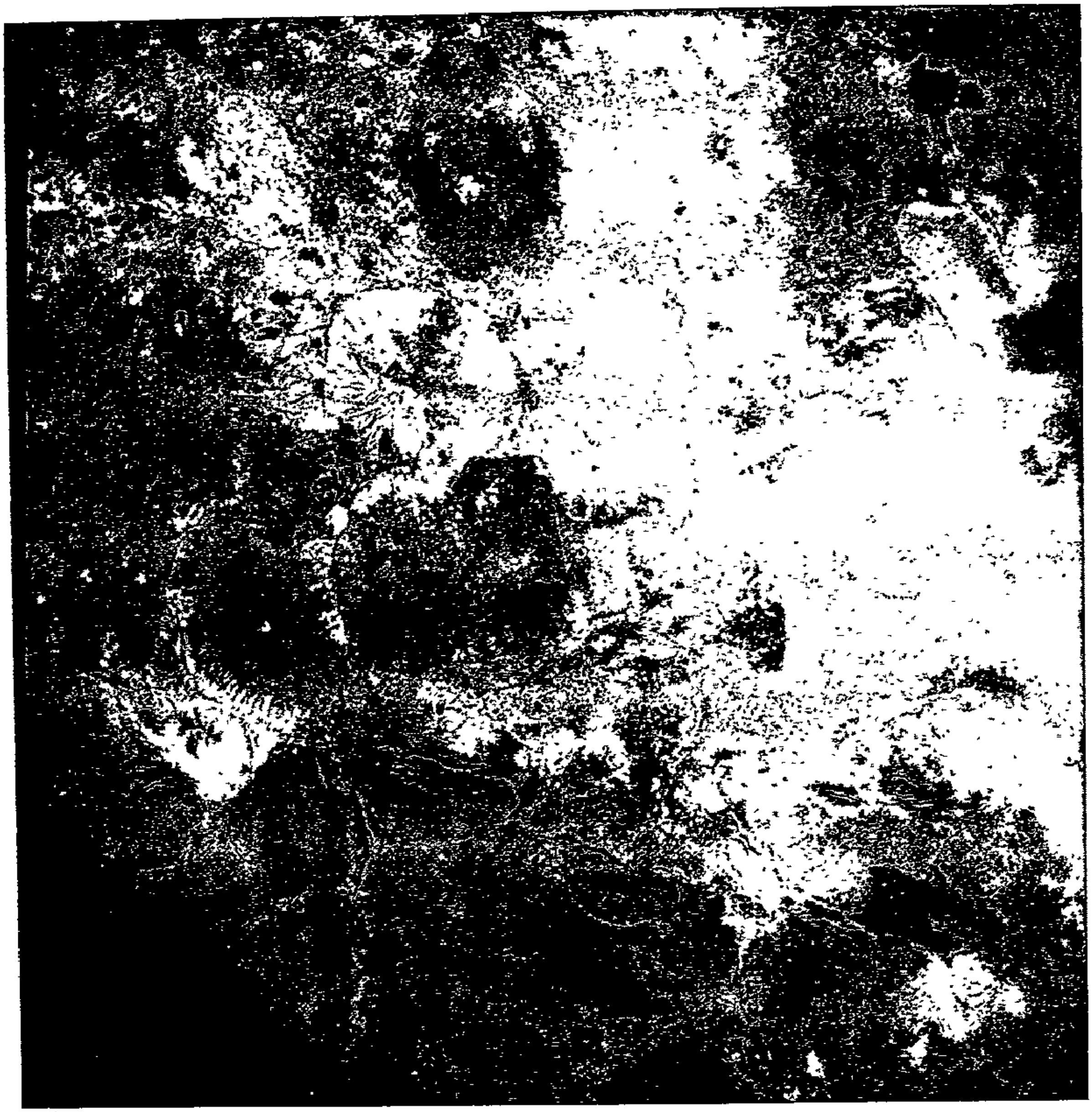


Figure 3. Apollo 9 photograph AS 9-26-3757D of Luna County, New Mexico, and adjacent Chihuahua. Taken with Panatomic-X and 25A (red) filter at 1/250 second, f 4.

Figure 4. Apollo 9 photograph AS 9-26-3757B, taken simultaneously with Figure 3, with Panatomic-X and 58B (green) filter at 1/125 second, f 4.

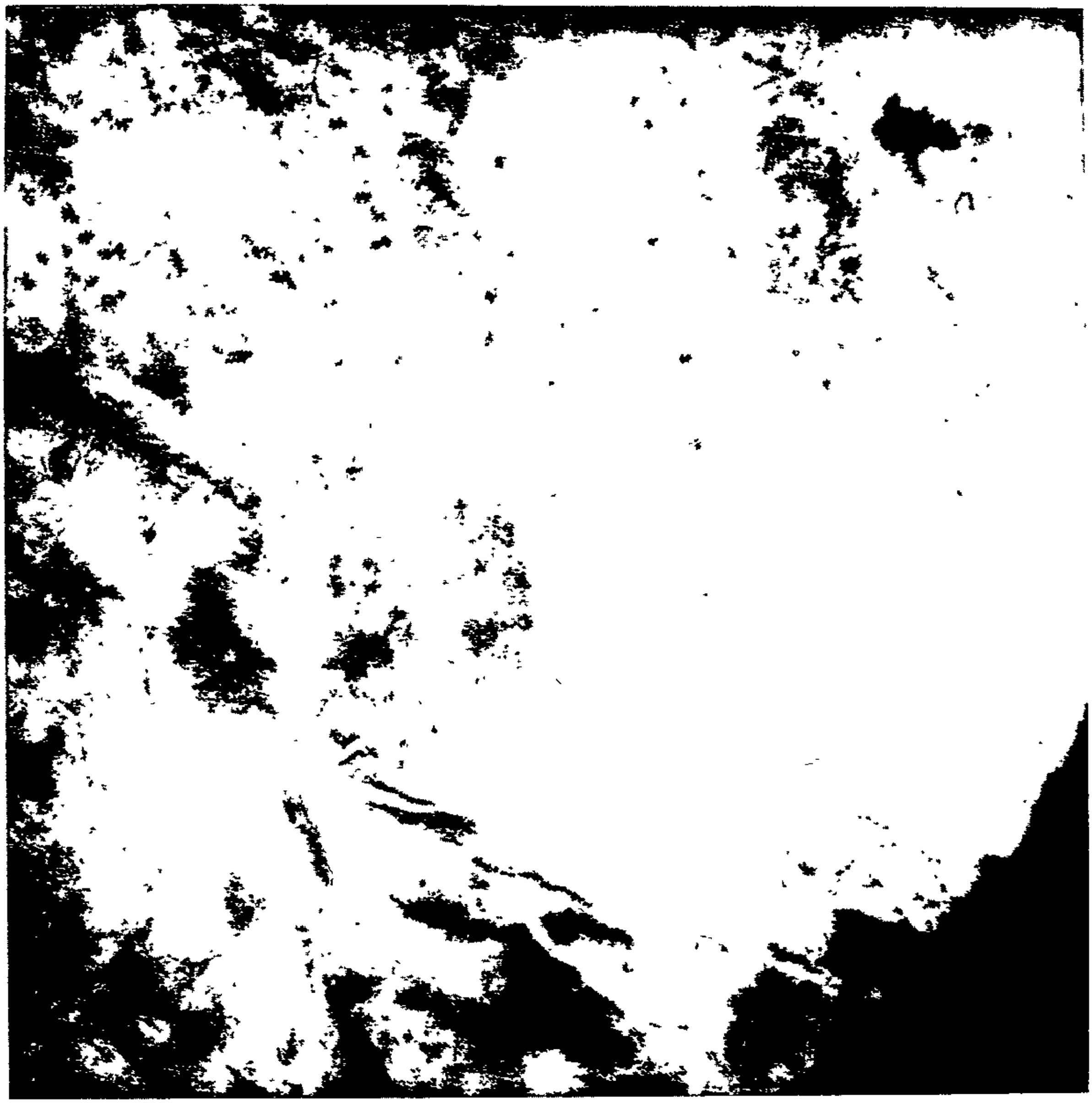


Figure 5. Apollo 9 photograph AS 9-26-3757C, taken simultaneously with Figure 3, with Infrared Aerographic and 89B filter at 1/250 second, f 16.

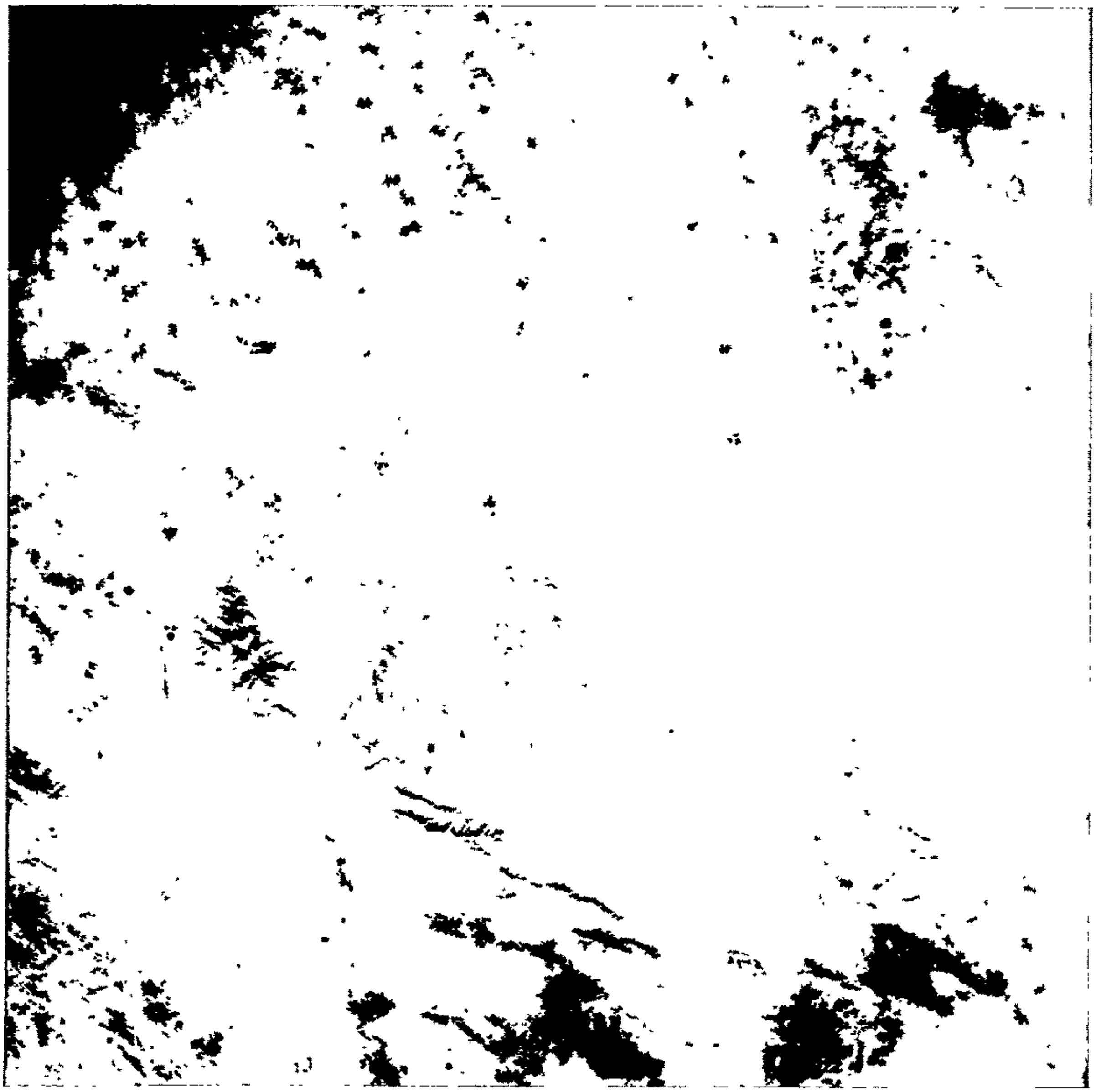


Figure 6. Apollo 9 photograph AS 9-26-3757A, taken simultaneously with Figure 3, with Infrared Ektachrome and 15 filter at 1/250 second, f 8.

Figure 7. Aerial view of desert terrain about 15 miles southeast of Palomas, Chihuahua, showing typically sparse vegetation and bedrock exposures. Taken from 2500 feet altitude above terrain, 50mm focal length, Kodachrome II with haze filter.

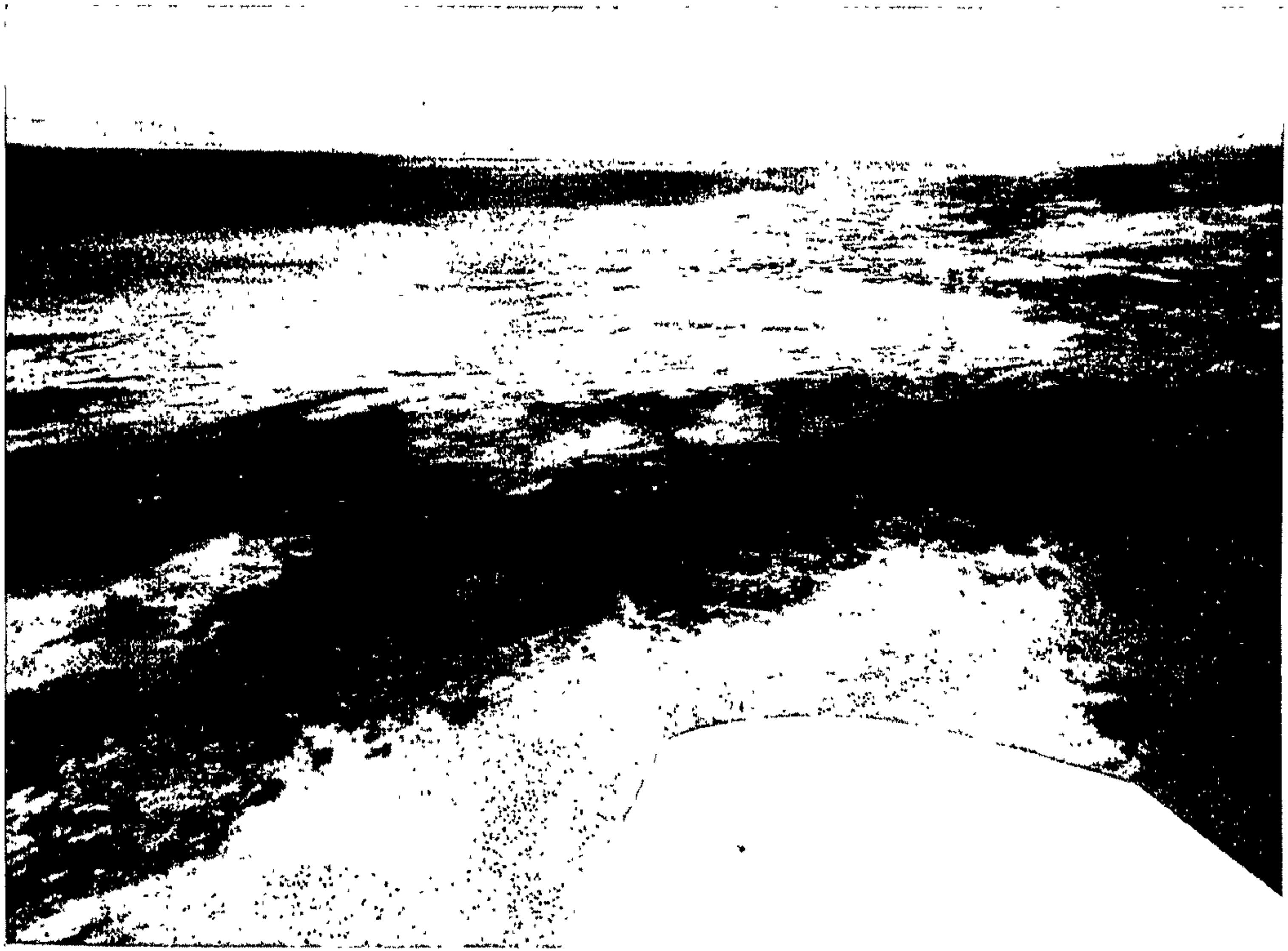


Figure 8. Aerial view to west showing desert terrain about 15 miles east of Palomas, Chihuahua. Playa at center, surrounded by lava flows, is visible on Apollo 9 photo; see Figure 11 for location.

Figure 9. Gemini IV photograph S-65-34689, showing southern New Mexico and northern Chihuahua. Taken by J. A. McDivitt and E. H. White, II, with Hasselblad 500C, 80mm lens, Ektachrome S.O. 217 and haze filter cutting off at 3400A.

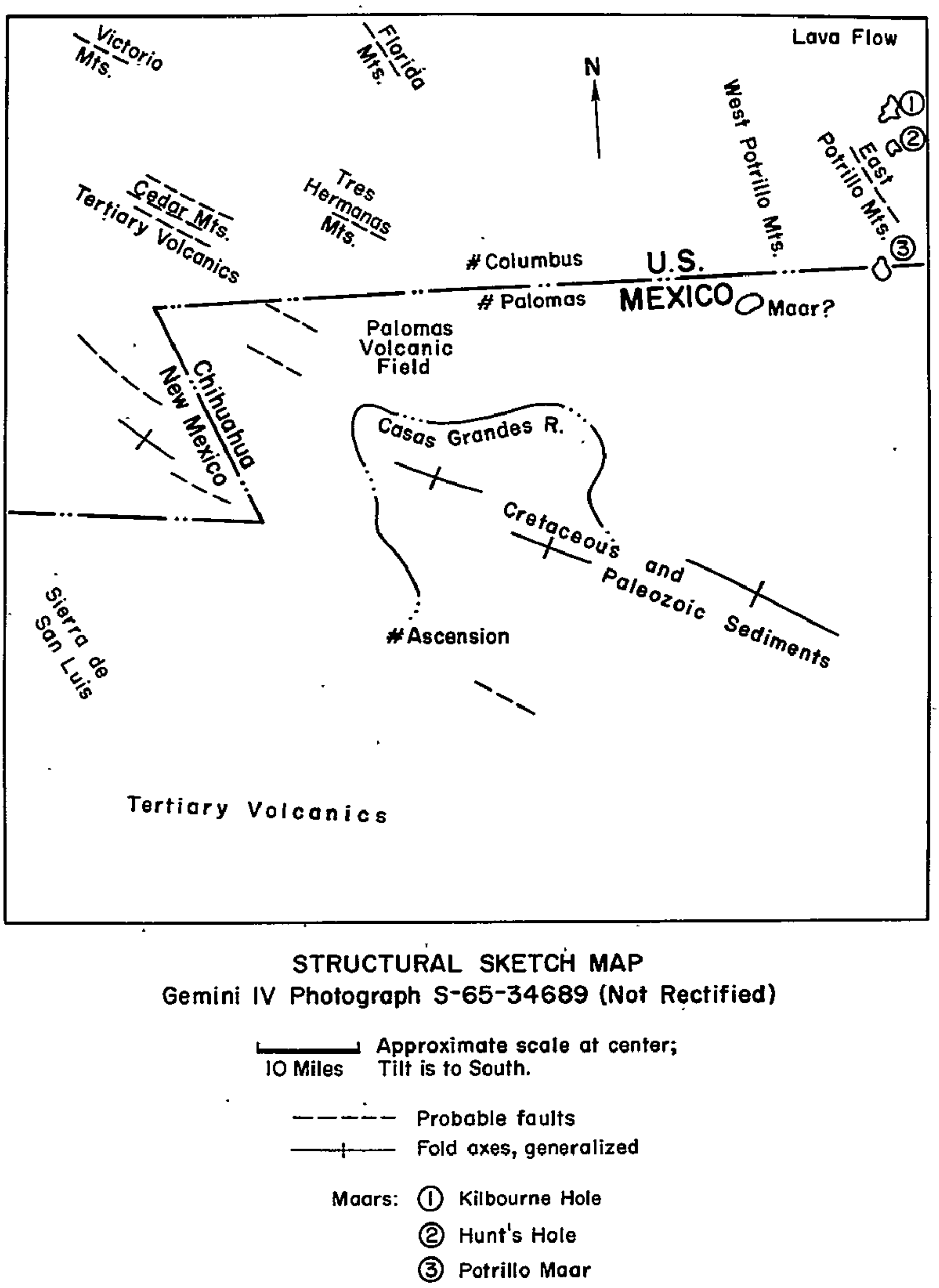


Figure 10. Structural sketch map of previous figure. Feature labeled "maar?" east of Palomas is a playa, shown in Figure 8.

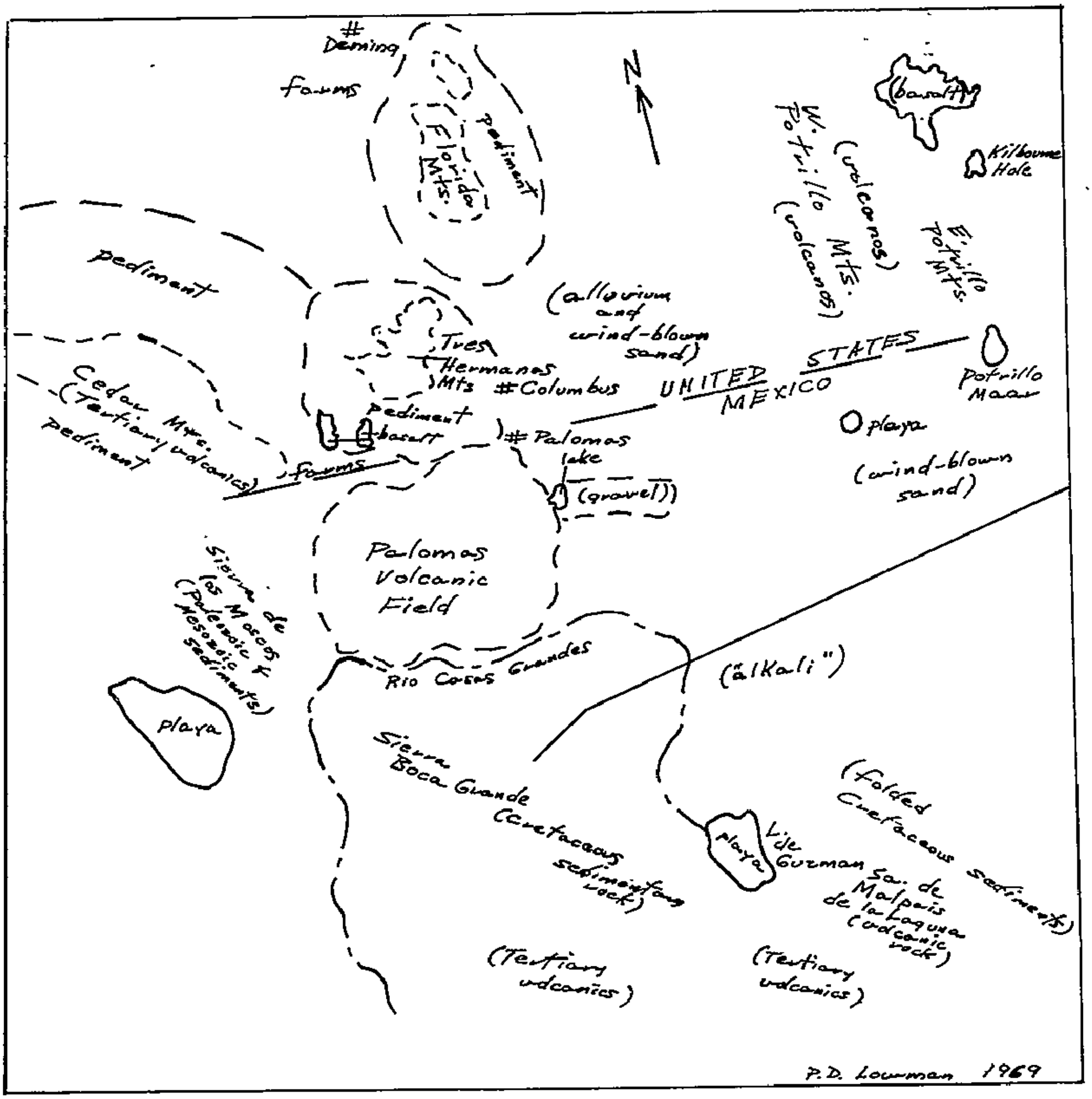


Figure 11. Geologic sketch map of Apollo 9 photo of Palomas area, AS 9-26D-3757D.

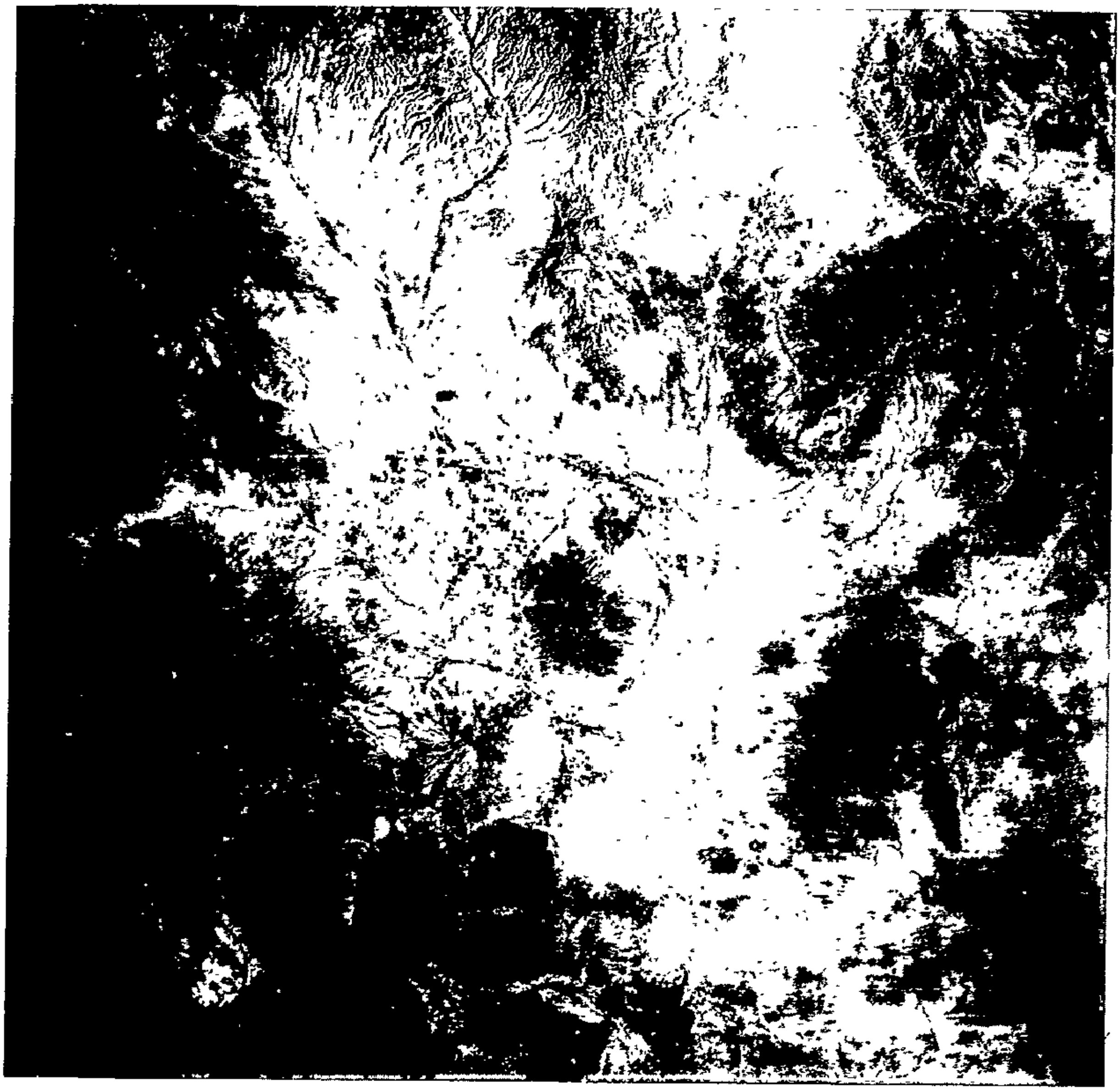


Figure 12. Apollo 6 photo AS 6-2-1446, taken with High Resolution Aerial Ektachrome S.O. 121 and Maurer 220G camera, over Luna County, New Mexico, at about 9 A.M. local time. Note increased contrast compared with other pictures of same area (Figures 3-6 and 9).

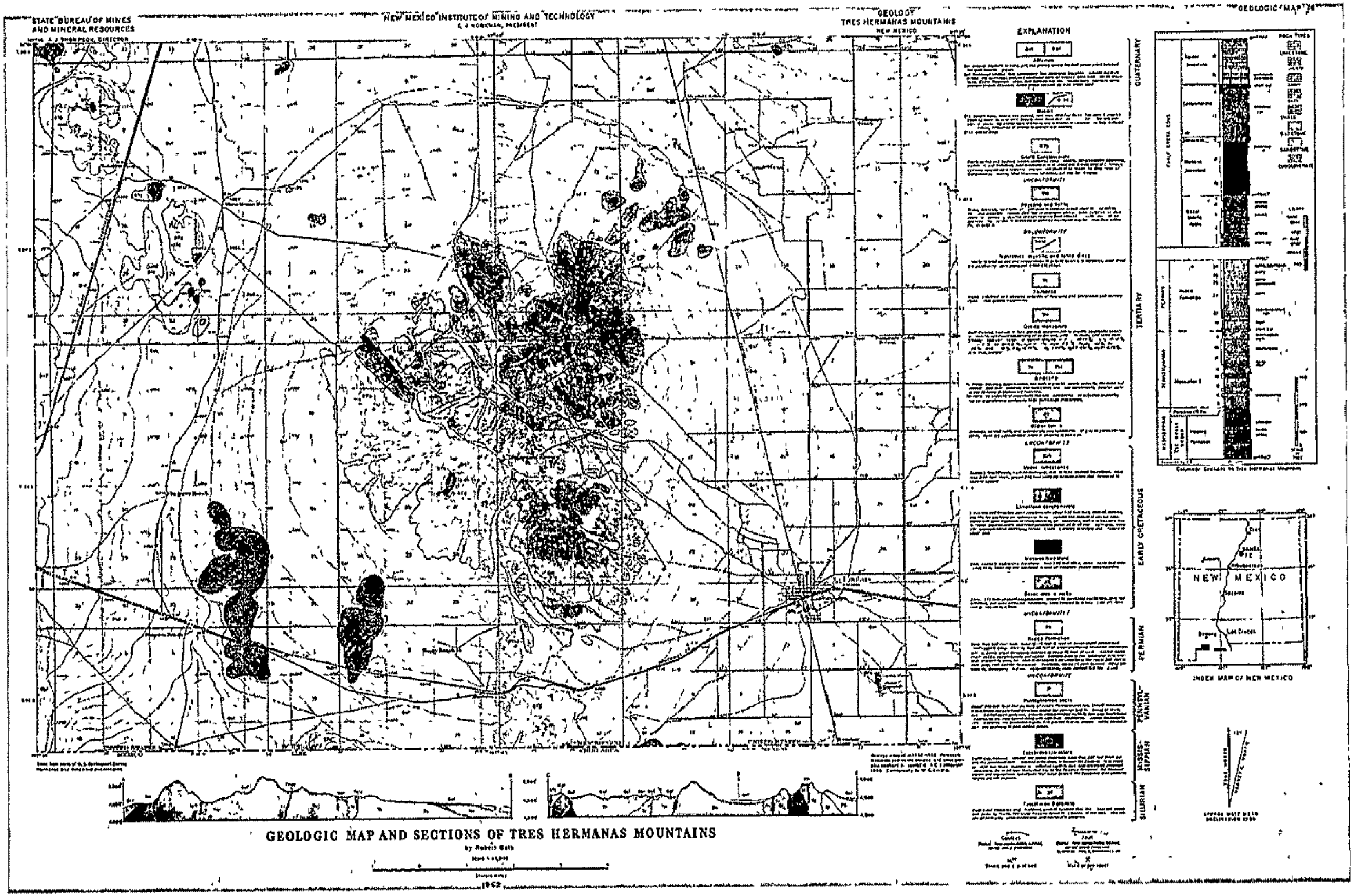


Figure 13. Geologic map of Tres Hermanas Mountains, southern New Mexico, by Robert Balk. See Figures 3-6, 9, and 12 for Tres Hermanas Mountains.

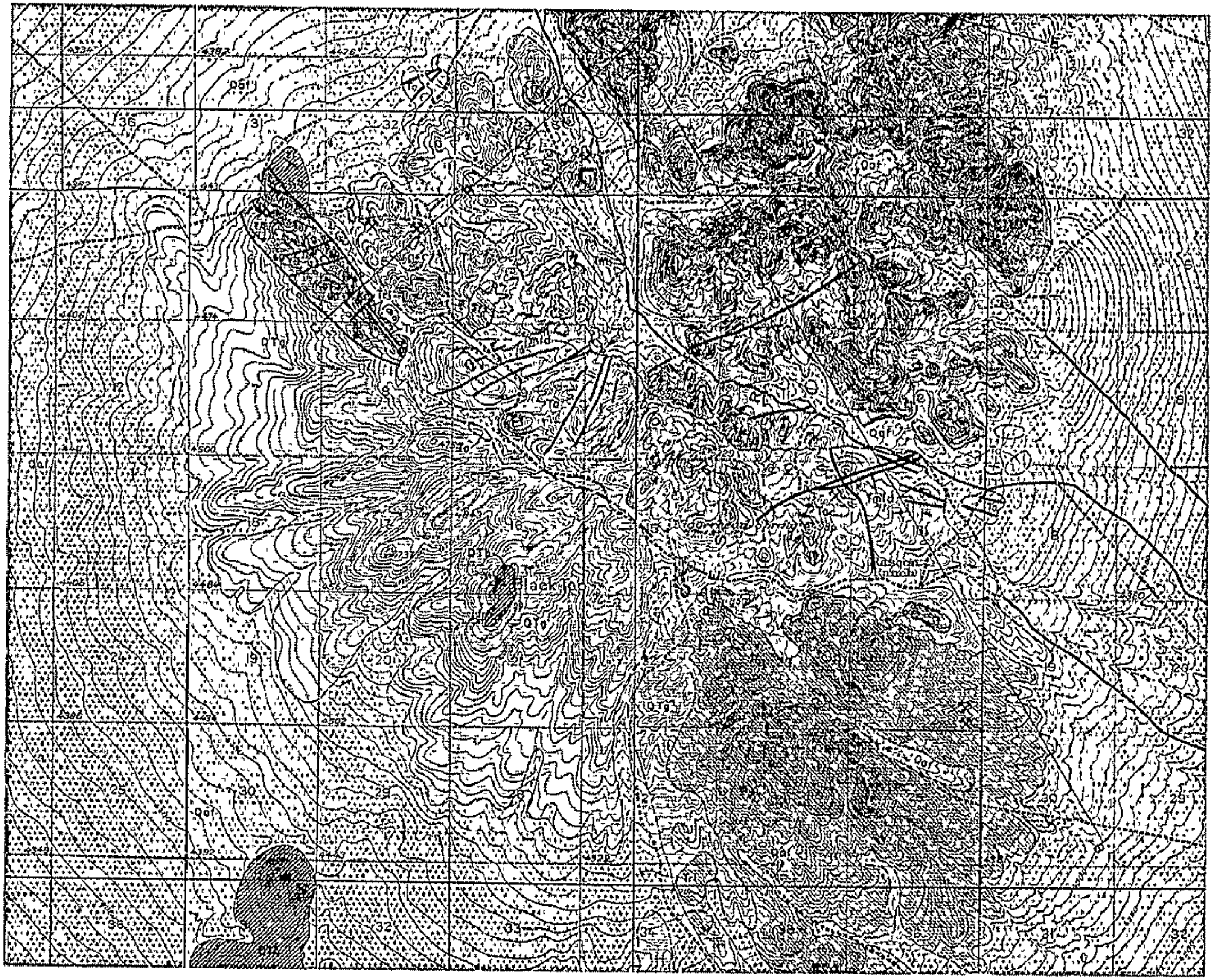


Figure 14. Enlarged center portion of Figure 13.

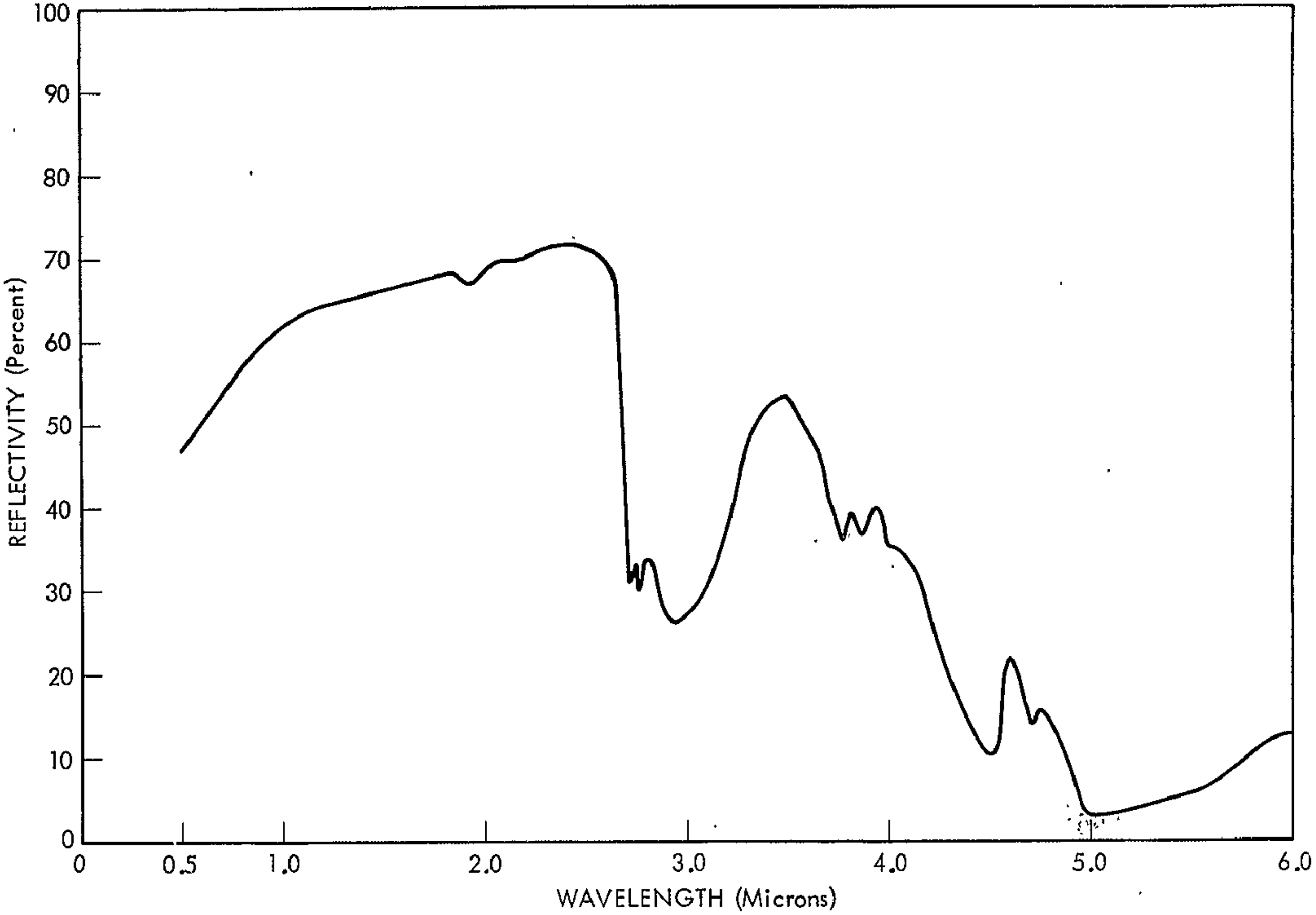


Figure 15. Reflectivity as a function of wavelength for quartz (SiO_2), from Hovis (1966). Note relatively featureless part of curve between 0.5 and 1.0 microns (approximate range of films in S065 experiment).

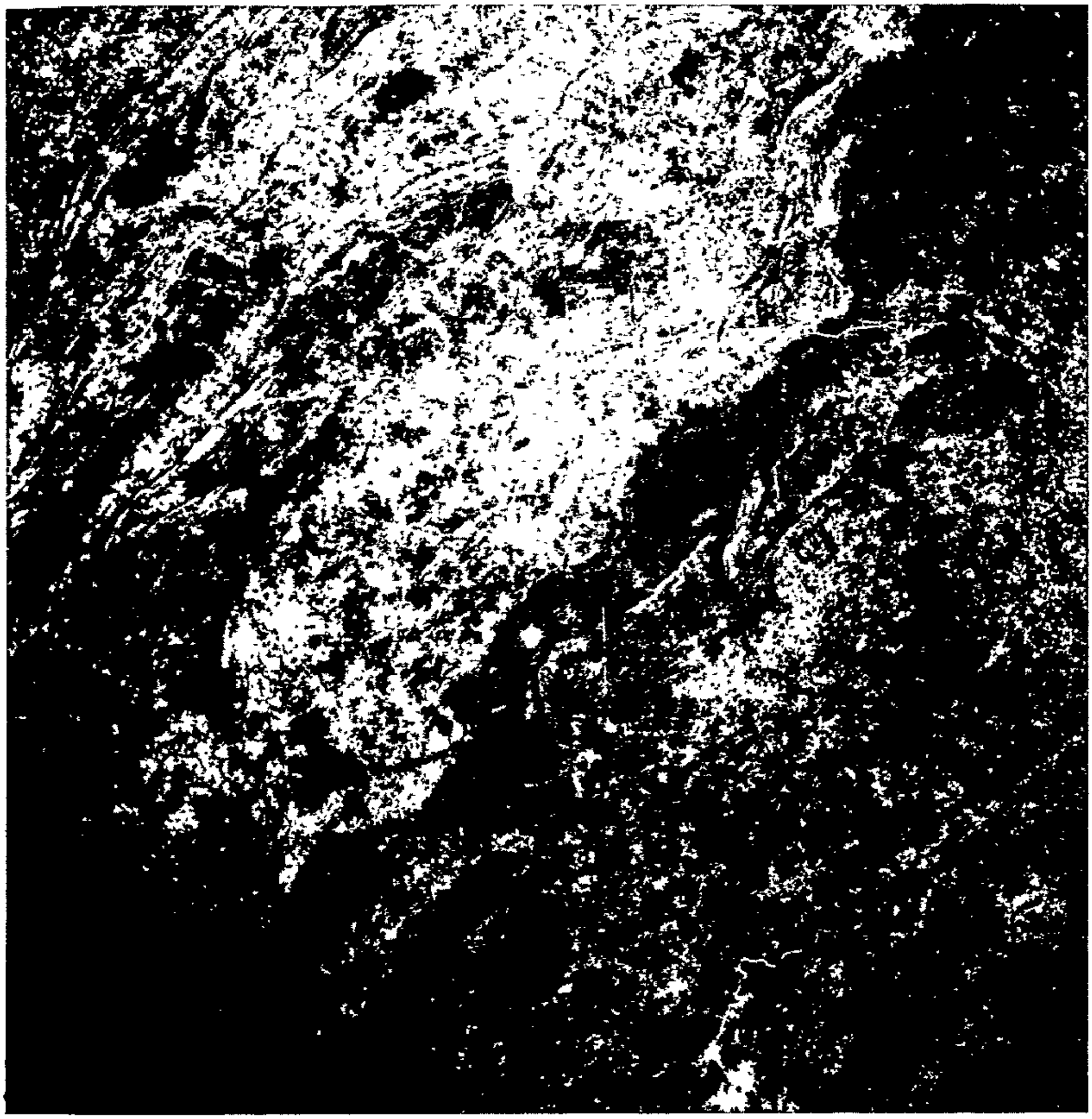


Figure 16. Apollo 9 photograph AS 9-26-3790D, of eastern Alabama (see Figure 21 for location), taken with Panatomic-X and 25A (red) filter at 1/125 second, f 4.

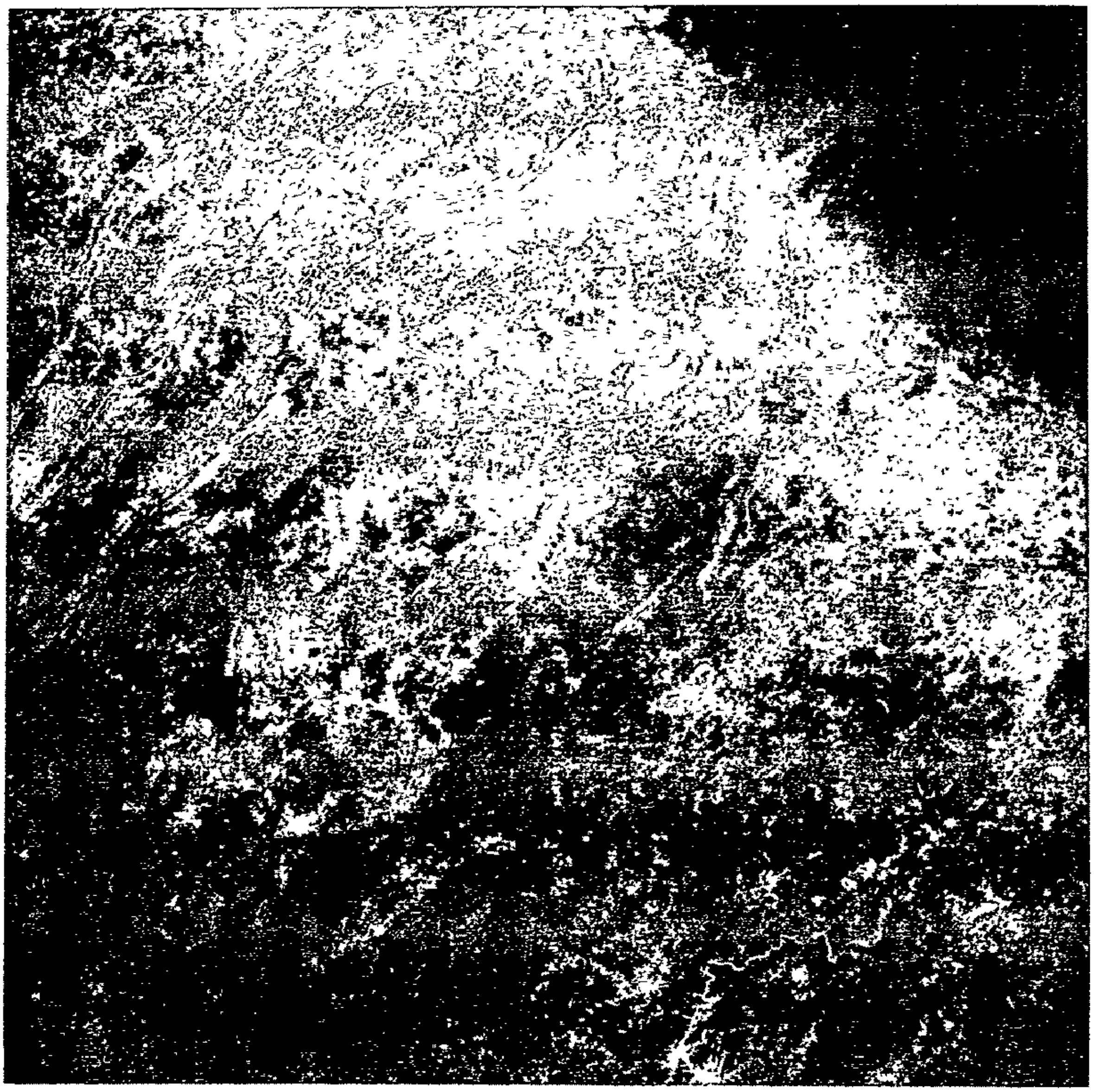


Figure 17. Apollo 9 photograph AS 9-26-3790B, taken simultaneously with Figure 16, with Panatomic-X and 58B (green) filter at 1/125 second, f 4.

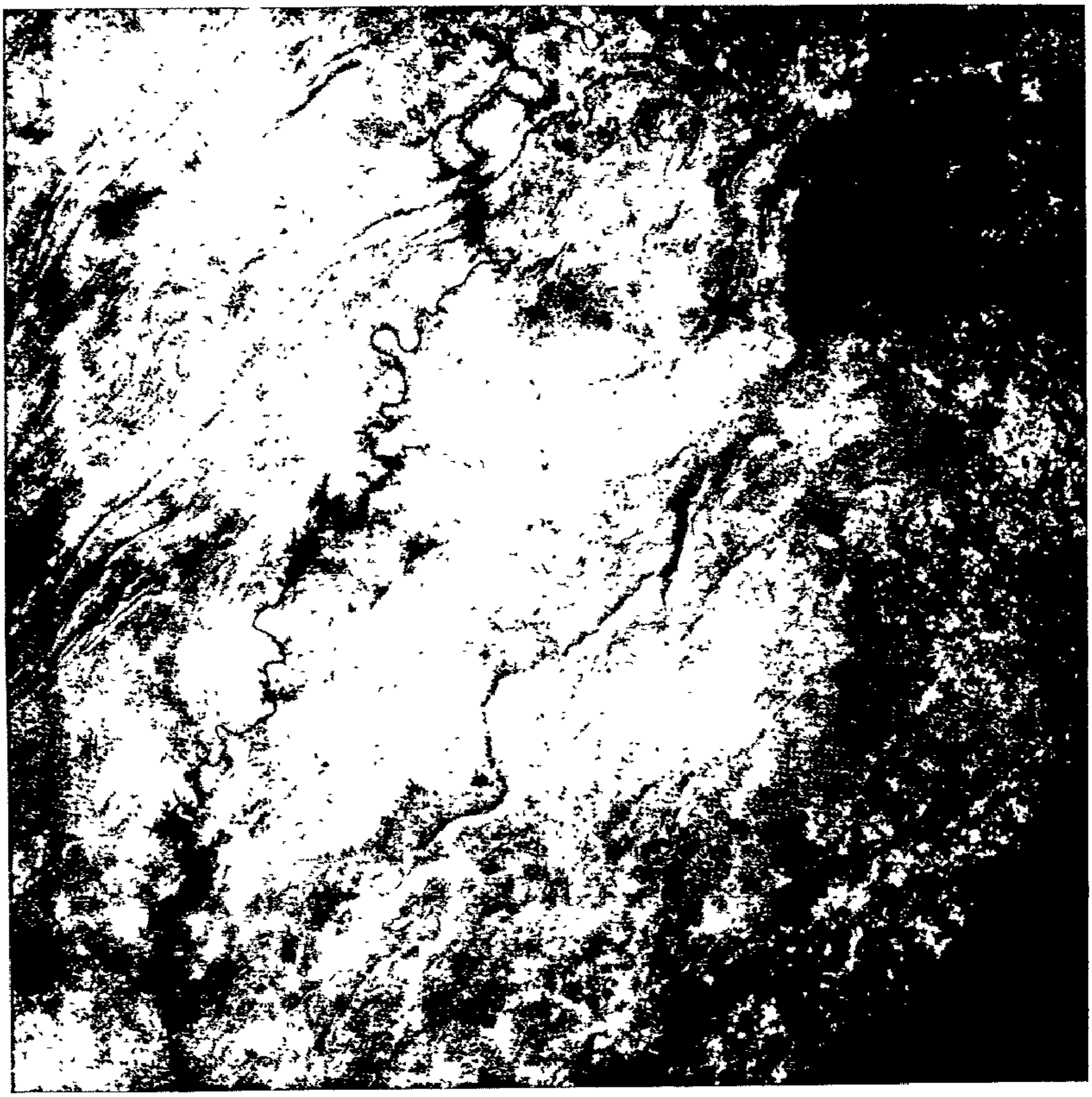


Figure 18. Apollo 9 photograph AS 9-26-3790C, taken simultaneously with Figure 16, with Infrared Aerographic (black-and-white infrared) and 89B filter at 1/250 second, f 16.

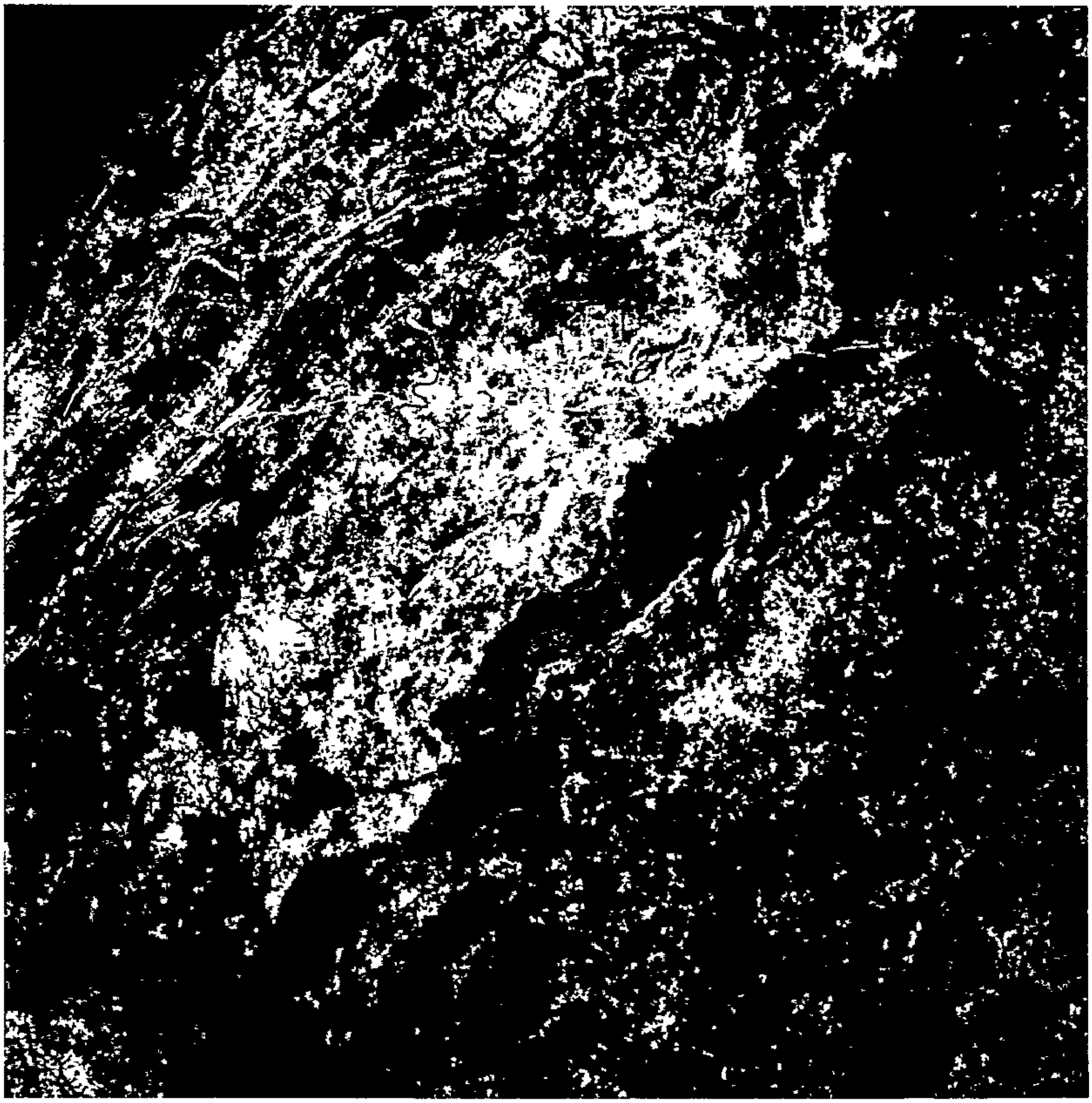


Figure 19. Apollo 9 photograph AS 9-26-3790A, taken simultaneously with Figure 16, with Ektachrome Infrared and 15 filter at 1/250 second, f 8.

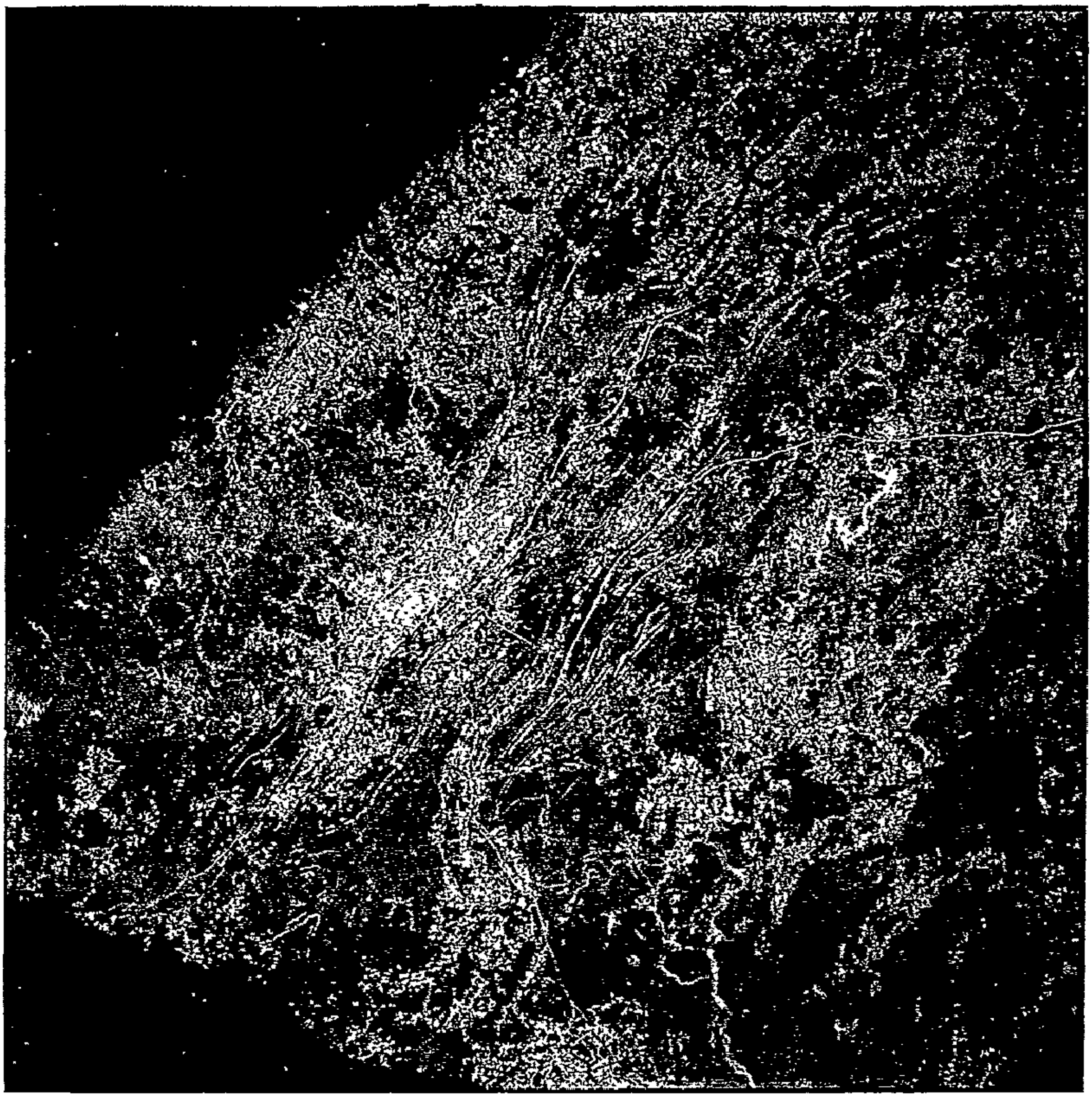


Figure 20. Apollo 9 photograph AS 9-23-3566, taken with Ektachrome S.O. 368, and haze filter shows roughly the same area as previous four photos; Birmingham is at left center. North at top. Film sensitive to radiation between 4600 and 7100A.

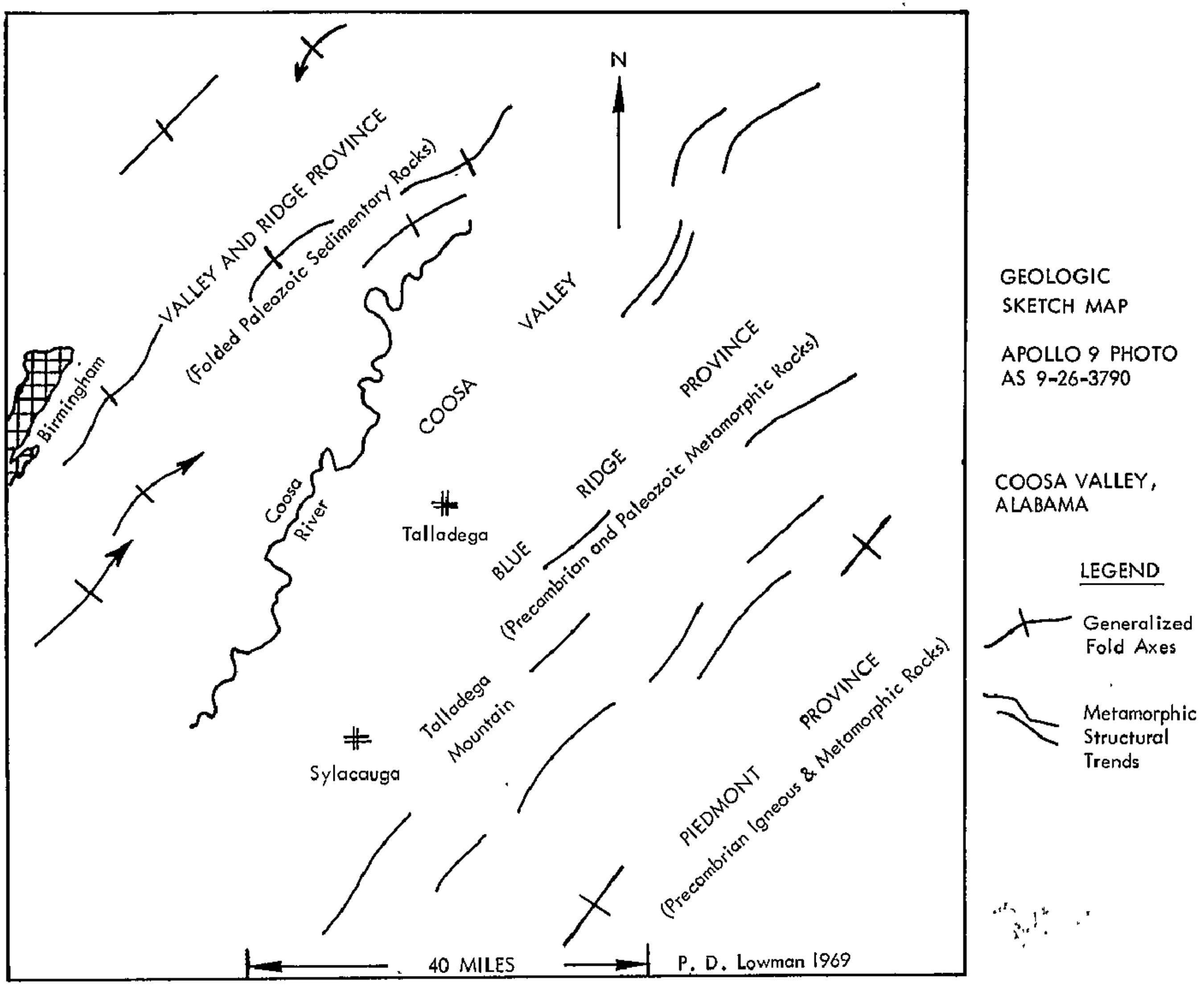


Figure 21. Geologic sketch map from Figures 16-19.

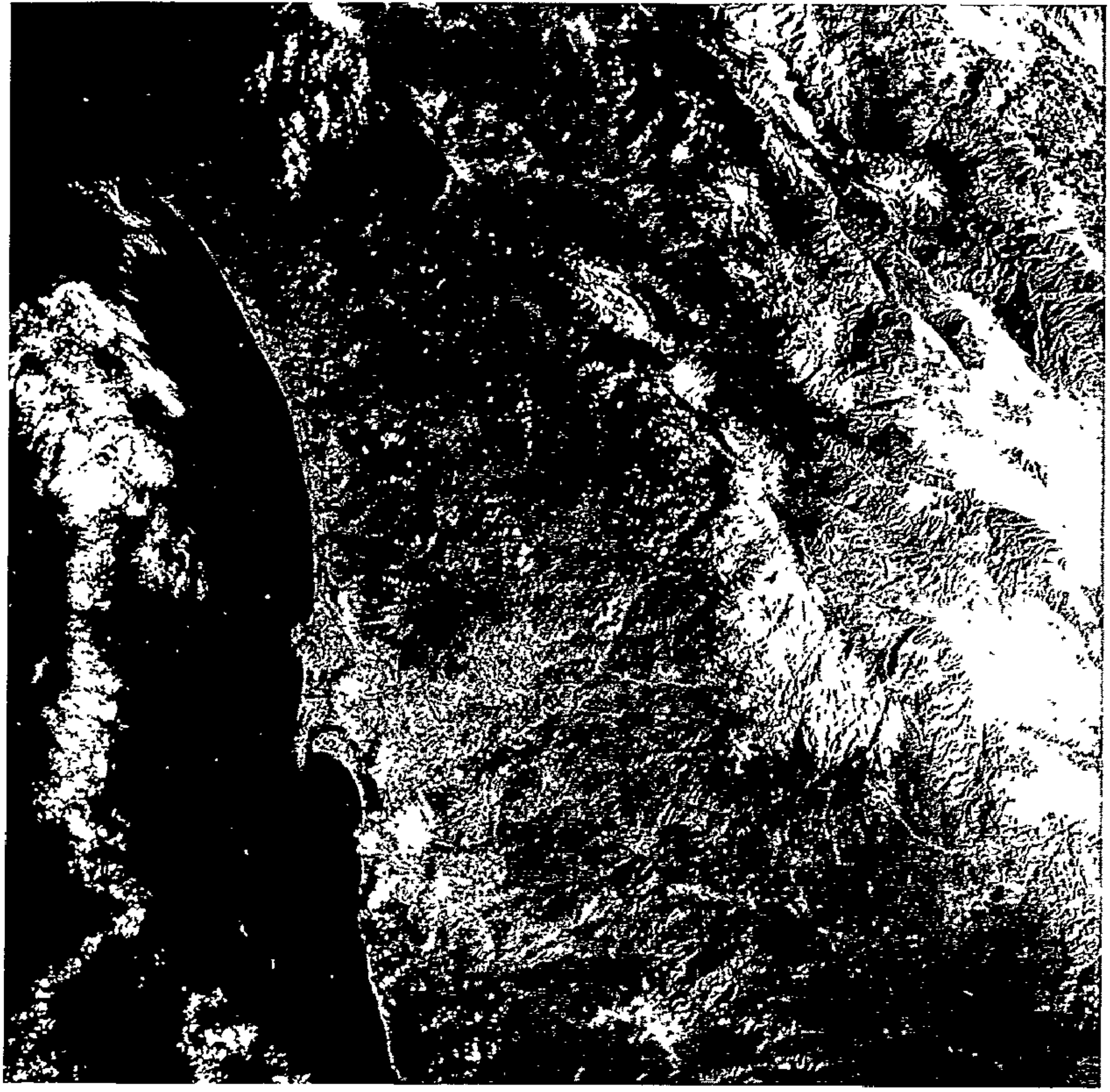
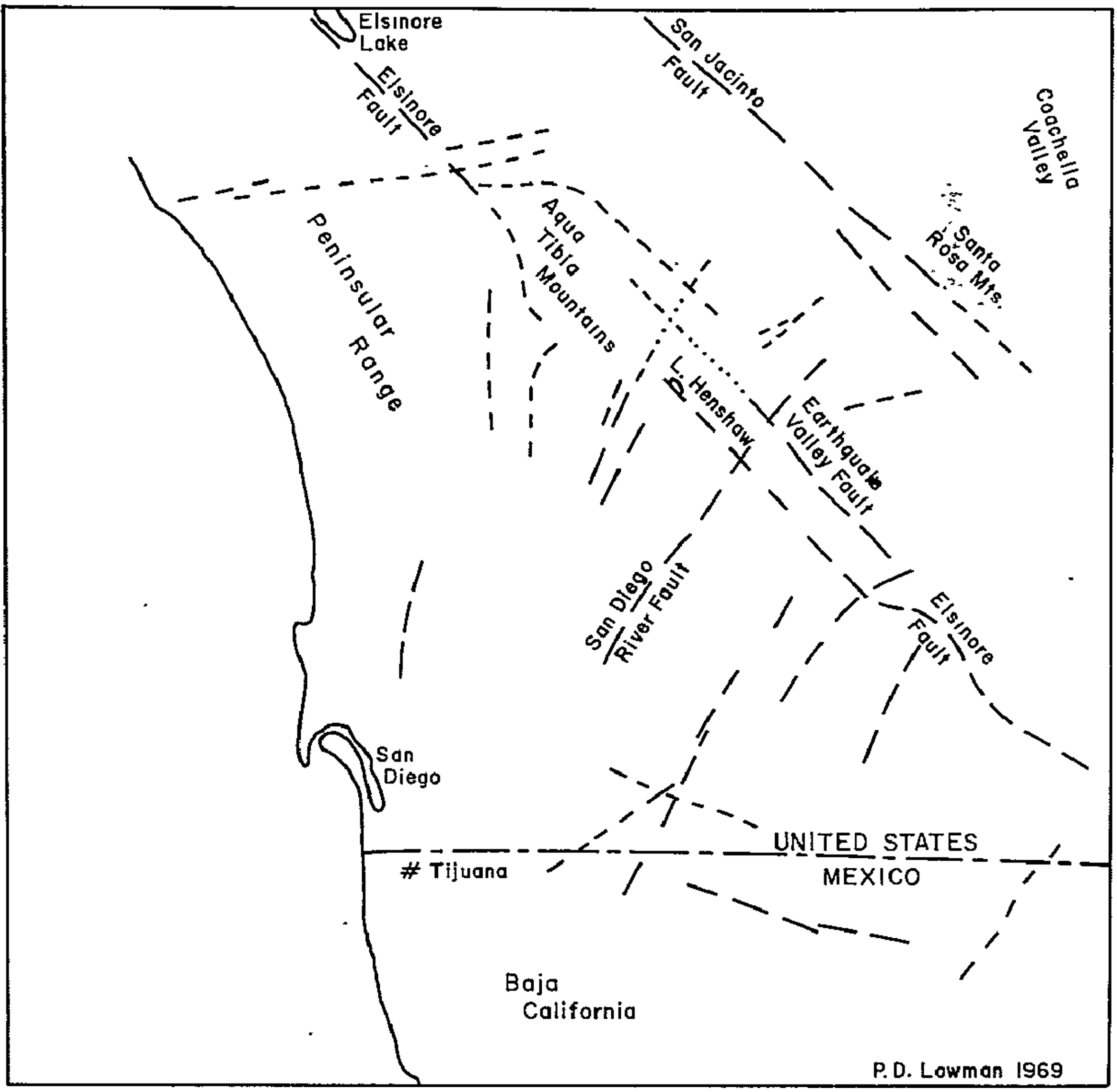


Figure 22. Apollo 9 photograph AS 9-26-3733A, Ektachrome Infrared and 15 filter, taken at 1/250 second, f 8. See Figure 23 for locations.



STRUCTURAL SKETCH MAP OF SOUTHERN CALIFORNIA
FROM APOLLO 9 PHOTOGRAPH

30 Miles
Approximate Scale

- Major Fracture;
length of dash proportional to certainty
of interpretation.

Figure 23. Structural sketch map of Figure 22.

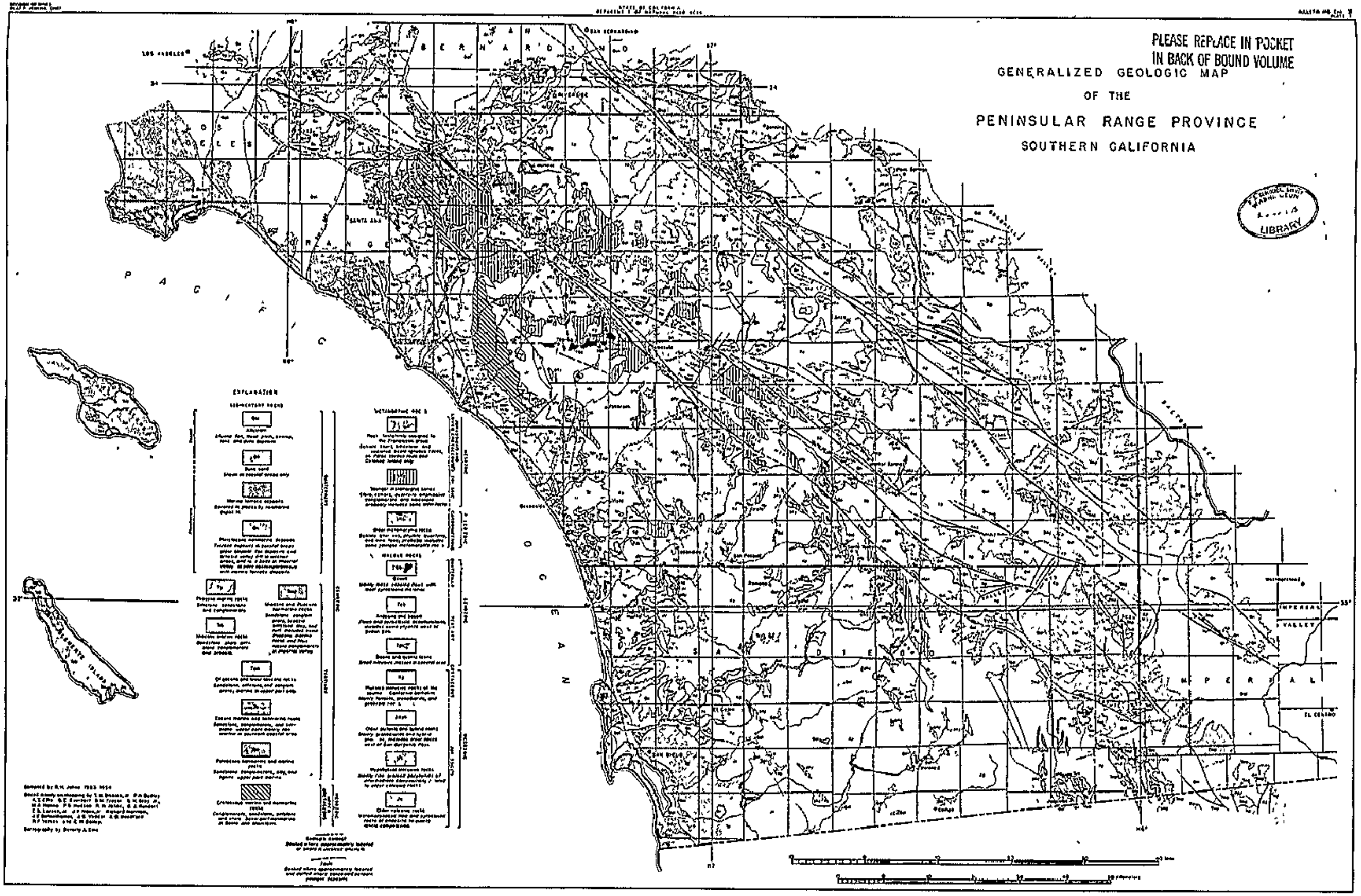


Figure 24. Generalized geologic map of area including that covered by Figure 22, from Jahns (1954).

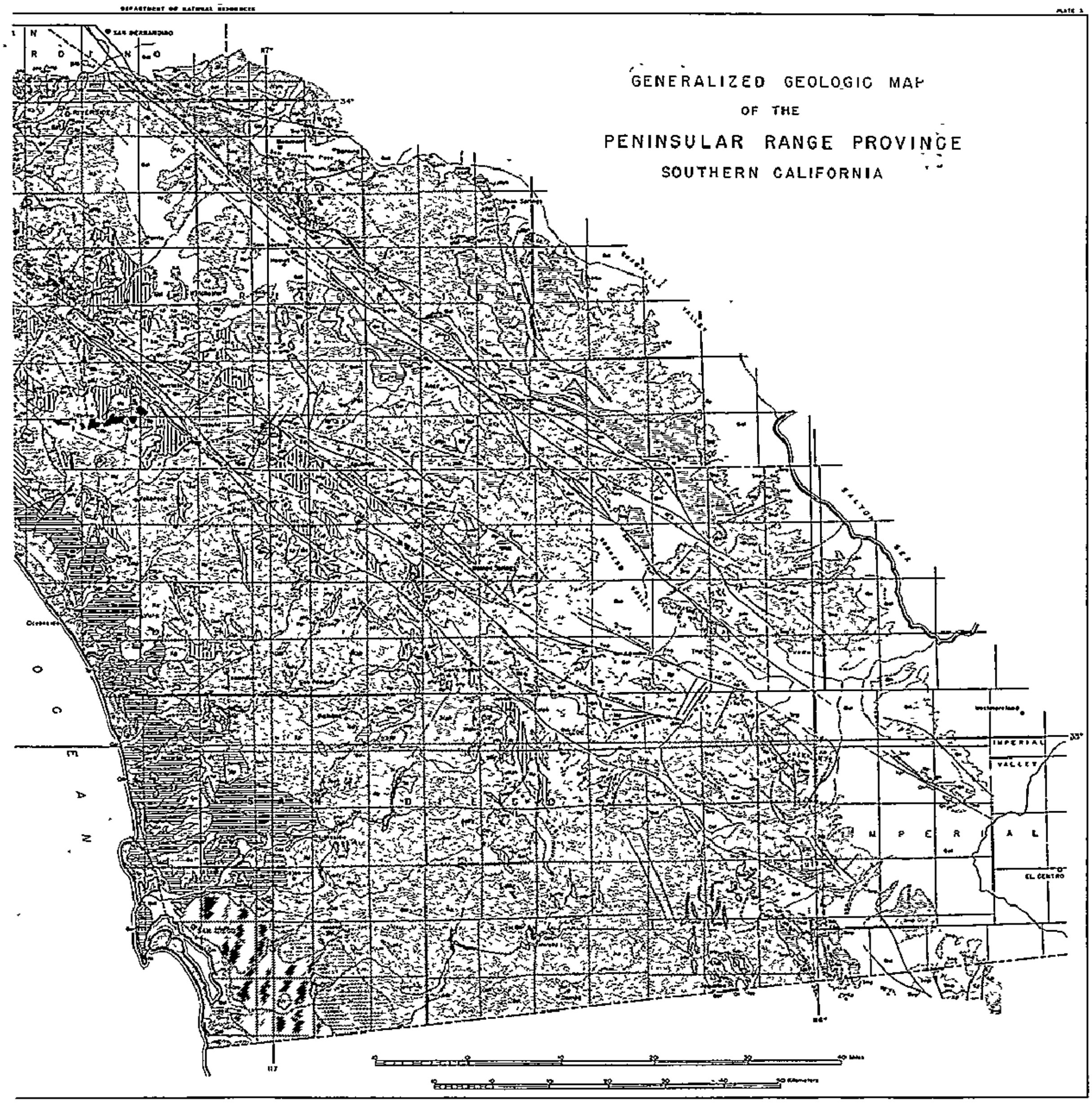


Figure 25. Enlarged center portion of Figure 24.

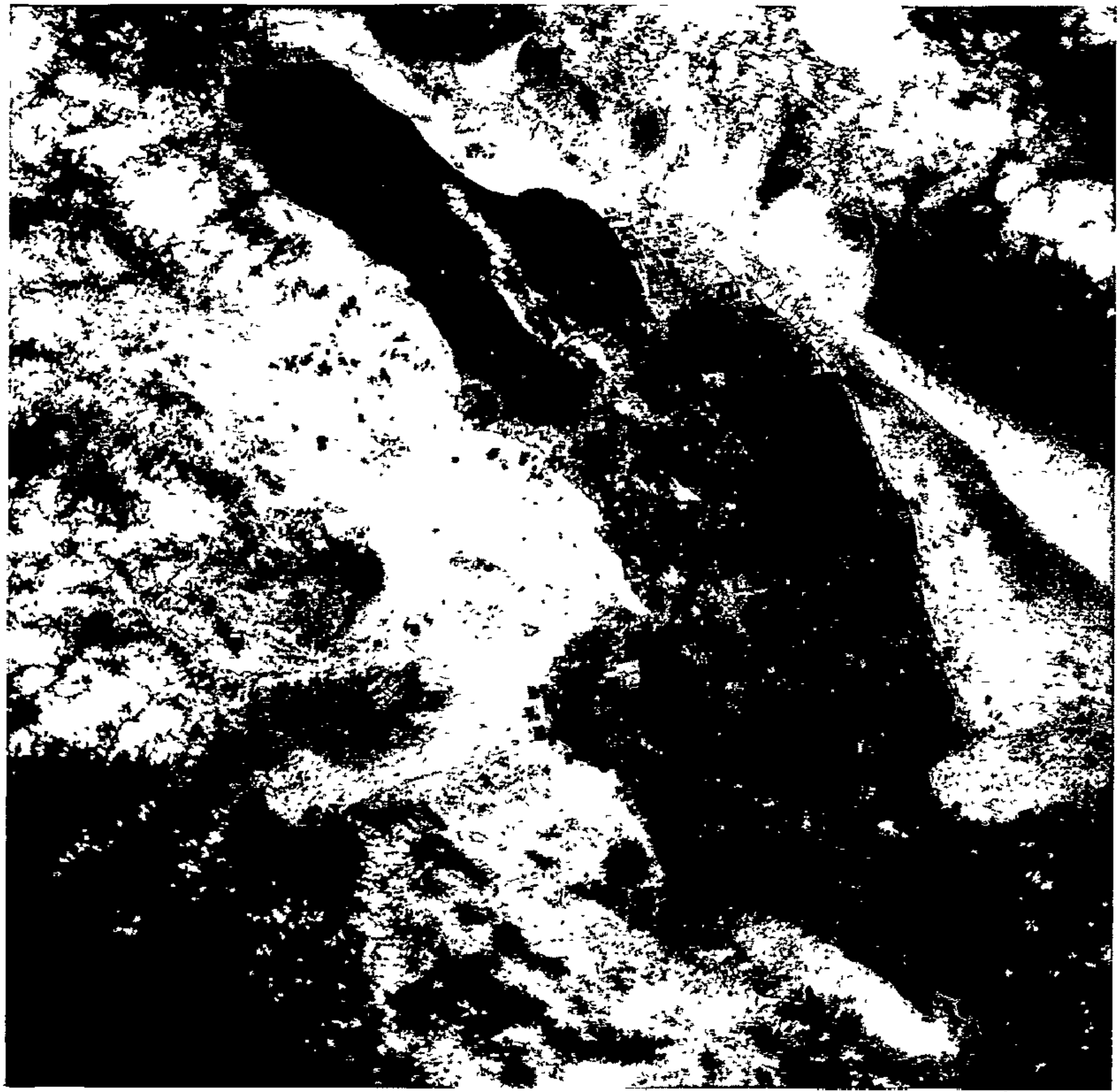


Figure 26. Apollo 9 photograph AS 9-23-3748D, of Imperial Valley, California, and Salton Sea (upper left), taken with Panatomic-X and 25A filter (red). Dark areas southeast of Salton Sea are irrigated fields. Algodones Dunes at extreme right.

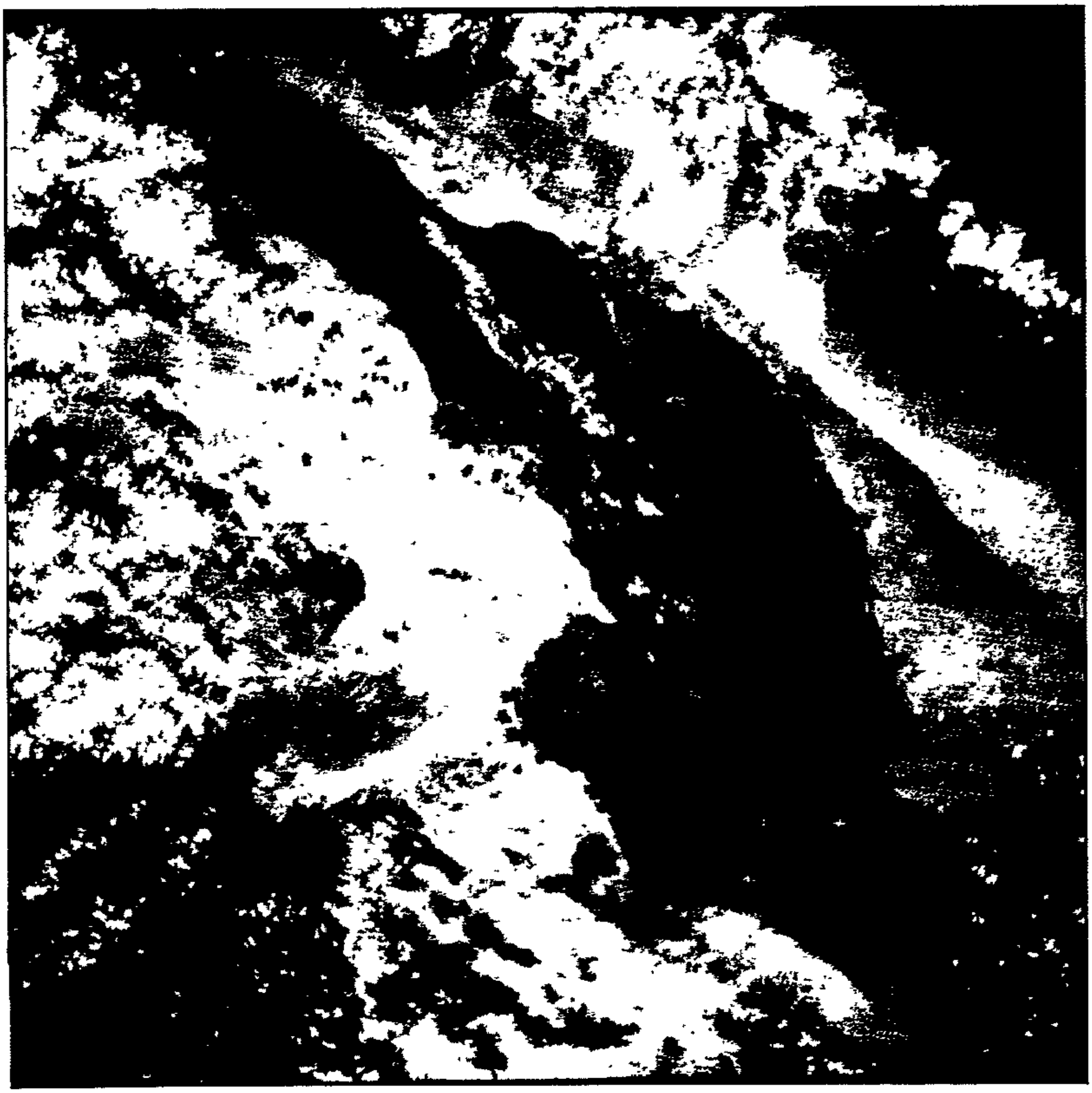


Figure 27. Apollo 9 photograph AS 9-3748B, taken simultaneously with Figure 26, with Panatomic-X and 58B (green) filter at 1/125 second, f 4.

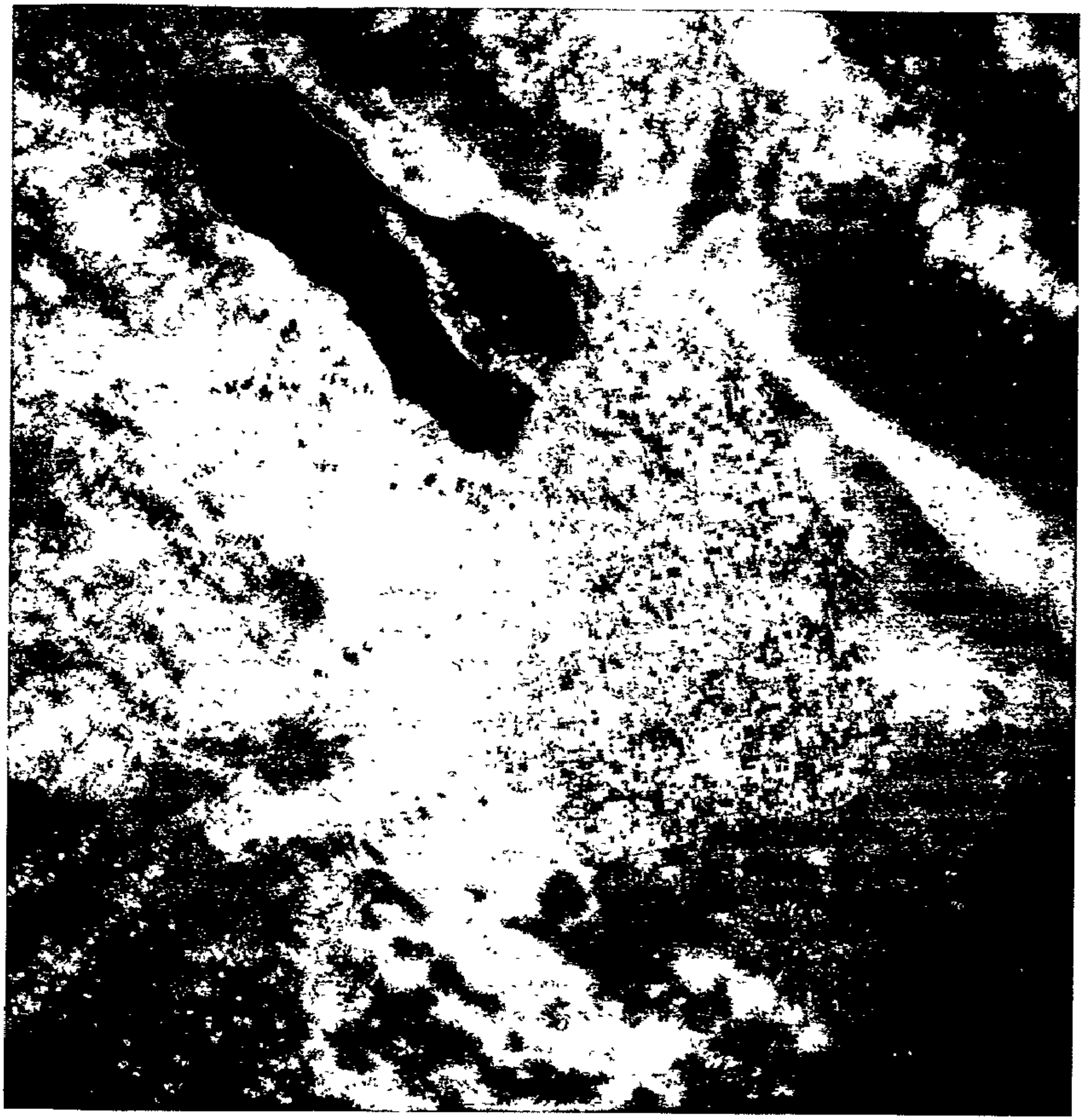


Figure 28. Apollo 9 photograph AS 9-26-3748C, taken simultaneously with Figure 26, with Infrared Aerographic and 89B filter at 1/250 second, f 16.

Figure 29. Apollo 9 photograph AS 9-26-3748A, taken simultaneously with Figure 26, with Ektachrome Infrared and 15 filter at 1/250 second, f 8. Imperial Fault broke in 1940 between arrows (Richter, 1958); no evidence of break visible on Apollo photo. Distance between arrows about 25 miles.