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GEOLOGIC APPLICATIONS OF ORBITAL PHOTOGRAPHY

BY

PAUL D. LOWMAN, JR.

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

Since 1946, several hundred thousand pictures of the earth from altitudes of 50 miles or more have been returned from sounding rockets and satellites. This paper discusses the potential geologic applications of orbital photography (photography of the surface of the earth or similar bodies from orbiting spacecraft, by returned film or television), with illustrations from various Gemini flights.

Advantages of orbital photography over conventional aerial photography include the following: large area per photograph, rapid coverage, rapid repetition of coverage, world-wide coverage (subject to orbital parameters), absence of restrictions on dissemination of American photography, availability of color photography at small added cost, and wide range of scales. The major limitations of orbital photography include: restriction by orbital characteristics (inclination to equator, apogee, and perigee), the generally high global cloud cover, daylight restrictions, atmospheric scattering, resolution limit inherent in extremely small scales, loss of resolution and color fidelity in oblique photos, site acquisition, and degradation of film by radiation and other space environmental conditions.

Three major specific geologic uses of orbital photography can be predicted: regional geologic mapping (including revision of existing maps), monitoring of variable properties, such as stream channel changes, and geological education. Based on these specific uses, orbital photography is expected to be valuable in the study of major geologic problems, such as continental drift, structure of rift valleys, study of transcurrent faulting, the existence of a global tectonic pattern, frequency and effects of major meteoritic impacts, and evolution of topography in arid regions. For maximum usefulness, orbital photography should be supplemented by other space-borne sensors, such as intrared detectors, radar, and geophysical instruments. Field checking, by use of large scale aerial photography and conventional ground methods, will continue to be necessary.

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Goddard Space Flight Center
Greenbelt, Maryland

Introduction

The first photographs of the earth from space were taken in 1946 with small cameras flown in V-2 rockets. These and others taken from later sounding rockets indicated the potential geologic value of hyperaltitude photography. Since 1960, several hundred photographs of the earth have been returned from orbiting spacecraft; several hundred thousand images have also been telemetered from meteorological satellites. The ways in which the vantage point provided geologists by orbital altitudes is valuable are rapidly becoming clear. The purpose of this paper is to discuss, with examples of recent Gemini and Nimbus photographs, the geologic applications of orbital photography.

The term "orbital photography" is used here to mean photography, by means of returned film or television, of the surface of the earth or similar bodies from orbiting spacecraft. The term "hyperaltitude photography," also used, does not carry the implication of global coverage, which is one of the greatest advantages of satellite-borne cameras. "Space photography" may be misleading, including by implication all photography done in space.

Review of Previous Work

Orbital photography began on April 1, 1960, with the successful launch of Tiros I, whose objective was transmission of pictures of cloud cover. The first known orbital photography using returned film was done on the first (unmanned) orbital flight of a Mercury spacecraft, the MA-4 mission, in 1961. Although not taken for geologic purposes, the pictures of northern Africa from this mission stimulated considerable geologic interest, leading to photography intended for such purposes during the manned Mercury flights. A summary of photography of the earth from sounding rockets and satellites through the last Mercury flight (MA-9) in 1963 is presented by Lowman (1964). Reviews of non-meteorological uses of Tiros and Nimbus photography are presented by Singer and Popham (1963), Morrison and Chown (1964), and Merifield and Rammelkamp (1964). A useful collection of papers on remote sensing from spacecraft has been edited by Badgley (1965).

Beginning with the Gemini IV mission in 1965, several of the Gemini flights have carried a terrain photography experiment whose purpose was to obtain high-quality color photographs of the earth's surface for geologic, geographic, and oceanographic study. Results of this experiment are summarized in Table 1.

Advantages of Orbital Photography

Although in many ways orbital photography is simply an extension of aerial photography to extreme altitudes, it has a number of distinct advantages over conventional photography for geologic purposes, including the following.

1. Large area per picture

This is the most fundamental difference between hyperaltitude and conventional aerial photography, and is the basis for many of the applications to be discussed here. The area per picture is of course proportional to the square of the scale number. Thus, a 9 x 9 inch vertical photo at 1:40,000 scale covers about 32 square miles, but a 9 x 9 inch vertical photo at

1:2,000,000 scale (typical of many Gemini pictures shown here) would cover about 81,000 square miles.

It is natural to ask if mosaics could not duplicate this coverage. Even neglecting the photogrammetric axiom that the minimum number of pictures necessary for any given purpose should be taken, the answer seems to be a definite negative, for several reasons. The first of these is the sheer size of mosaics which could give coverage comparable to that provided by orbital photographs. A 9 x 9 inch vertical photo at 1:2,000,000 scale covers an area about 284 miles on a side. A 1:40,000 scale mosaic of this area would be 37.5 feet wide. Furthermore, the number of pictures necessary for such a mosaic would be immense: 2500 with no overlap, and about 8800 with 60% forward lap and 30% sidelap.

Assuming that such mosaics were to be prepared, however, they would still not duplicate the properties of individual orbital photographs. The patchwork appearance of mosaics makes them difficult to use for geologic interpretation--especially when one is searching for lineaments. Dodged mosaics may be misleading, as Miller (1961) points out, because subtle tone differences may be removed. Finally, mosaics do not provide stereoscopic coverage of large areas, as do overlapping orbital photographs.

2. Speed of coverage

The speed of satellites--on the order of 18,000 miles per hour for circular orbits with altitudes of a few hundred miles--is of course one of their most striking characteristics. Its photogrammetric importance is obvious, since it becomes possible to photography extremely large areas essentially instantaneously. This is of course one of the bases for the success of meteorological satellites, whose value lies in the synoptic pictures they provide of global cloud cover.

Table 1

S-5 Photography on Gemini Flights

Flight	Camera	Film	No. Usable Pictures	Land Areas Covered
3	Hasselblad 500C	Ektachrome	7	NW Sonora, Rio Grande Valley, Bermuda
4	Hasselblad 500C	Ektachrome	100	NW Mexico, SW U.S.A., N. Africa, Bahama Islands, Arabian Peninsula
5	Hasselblad 500C	Ektachrome Super Anscochrome	175	SW U.S.A., Bahama Islands, South West Africa, Tibet, India, SW Asia, China, Australia
6	Hasselblad 500C	Ektachrome	60	NW, central and eastern Africa, Australia, Canary Islands
7	Hasselblad 500C	Ektachrome Ektachrome IR	250	N Africa, Arabian Peninsula, India, Caribbean Sea and adjacent land areas, Brazil, Mexico; infrared film: Gulf Coast, U.S.A.; northeast Brazil
9	Hasselblad 500C Hasselblad SWC Maurer Space Camera	Ektachrome	160	N Africa, northern South America, Caribbean Sea, Mexico
10	Maurer Space Camera Hasselblad SWC	Ektachrome	75	N Africa, China, Taiwan, NE South America
11	Maurer Space Camera Hasselblad SWC	Ektachrome	102	N Africa, Arabian Peninsula, S India, NW South America, Gulf Coast of U.S.A.
12	Maurer Space Camera Hasselblad SWC	Ektachrome	160	Southern U.S., N Mexico, N Africa, SW Asia, Arabian Peninsula

NOTE: Spacecraft altitudes in Gemini flights ranged from about 100 to 200 statute miles. On the Gemini 11 flight, however, the orbit was changed for two revolutions from about 174 statute miles (circular) to 174 (perigee) and 850 (apogee) statute miles. Most of the pictures taken on Gemini 11 were from the two high revolutions, at altitudes of about 400 to 850 miles.

The value of rapid coverage is not as obvious for geologic purposes. However, two specific advantages may be suggested. The first is simply the convenience of being able to photograph entire states or continents in a few days; for example, a satellite in 300 mile polar orbit passes within line of sight of every point on the earth in slightly more than four days. Making allowance for bad weather, daylight conditions, and other inherent limits, we see that it should be possible to obtain, perhaps 1:1,000,000 coverage of North America in a few months from a satellite, as well as selective coverage of smaller areas at larger scales.

A more subtle advantage of orbital speeds is that we can obtain regional coverage of rapidly changing conditions which could never, practically speaking, be photographed from aircraft. An interesting example of this is provided by Figure 1. The Sayan fault, outlined here by elevation-controlled snow, would probably be visible in this way for only a few weeks each year. Earlier, the snow would not have fallen: later, it would probably blanket the entire area, including the valley floors. Similar variable phenomena of geologic interest which could be photographed from orbit include the distribution of turbid effluent from large rivers (Figure 13), rainfall distribution, and distribution of volcanic ash from active volcanoes.

3. Speed of repetition

Closely related to satellite speeds, but dependent as well on the geometry of satellite orbits, is the speed with which large areas can be re-photographed. A Gemini spacecraft, for example, will approximately retrace its orbital path over the earth's surface every 16 revolutions, or about every 24 hours (this is another way of saying that the orbit is fixed in inertial space, neglecting perturbations, while the earth rotates under it).

The geologic value of this ability would seem to lie in the study of regional phenomena which change on a time scale of months or years. For example, it would be possible to monitor major channel changes in rivers such as the Colorado by means of pictures like Figure 4. Other possible applications might be the study of sand dune migration (Figure 5), changes in bottom topography caused by major storms (Figure 6), or rapid assessment of landform changes caused by major earthquakes.

4. World-wide coverage

Within the limits imposed by orbital parameters, orbiting spacecraft cover the entire world without regard to the nature of the surface overflown, and more importantly, without regard to national boundaries. The latter is sanctioned by Resolution 1721, passed by the United Nations General Assembly, which states that "Outer space (is) free for exploration and use by all States . . . and (is) not subject to national appropriation." This resolution has been interpreted as permitting scientific photography of the entire earth from space (Meeker, 1963), and precedents have of course been set by the many meteorological television satellites.

Many specific examples of the value of this characteristic will occur to any geologist; for example, the Mesozoic-Tertiary orogeny in the eastern hemisphere produced folded mountains which span some 30 or more countries (the Himalayas-Zagros-Caucausus-Alps-Atlas chain). Anything like a complete study of the structure of this belt would be impossible by conventional methods because of variations in map coverage and other difficulties: orbital photography, however, can circumvent primarily political boundaries and permit the extension of geologic mapping into poorly mapped areas.

5. Absence of restrictions on photography from space

Most of the world's land area has been photographed at one time or another by civil, commercial, or military organizations. Much of this photography, however, is inaccessible to geologists of any one country because of various restrictions. Two factors, however, suggest that orbital photographs will be more readily available.

First, the photography itself is quite legal, as pointed out previously, by virtue of United Nations Resolution 1721. Second, and more important, is the fact that the National Aeronautics and Space Administration, which has produced virtually all the orbital photography published to date, is required by the National Aeronautics and Space Act of 1958 (P.L. 85-568) to ". . . provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof." An important effect of the 1958 act has been that virtually all the orbital photography taken by NASA spacecraft and sounding rockets is available to the public.

A further factor tending to prevent undue restriction of orbital photography of the earth is the fact that the most useful pictures are those with very small scale, as mentioned previously (Section 1). Inherent resolution limits, however, appear to make such pictures of little use for military purposes.

6. Availability of color or multi-spectral coverage

Color photographs contain far more information than panchromatic photographs because some 20,000 hues can be distinguished, as opposed to only 200 distinquishable shades of gray. This fact tends to outweigh the lower resolution of color film for geologic purposes, especially when quantitative analytical methods are used (Fischer, 1962). Multiband photography, already proven invaluable for aerial photography of vegetation (Colwell, 1961), will probably be equally useful for geologic purposes.

Color photography has not to date been widely used for geologic mapping. One major reason for this is the high cost of color photos (Miller, 1961). However, color film adds a negligible amount to the expense of orbital photography, and as discussed before, only a small number of pictures are needed to cover immense areas. Orbital photography may therefore lead to greater use of color photography, in addition to its other advantages.

7. Wide range of scales

The outstanding superiority of hyperaltitude photographs lies in their uniquely small scales. The smallest scale usable for geology attainable by aircraft-borne cameras is probably on the order of 1:300,000 (assuming a 3 inch focal length lens at 75,000 feet), but, as demonstrated here scales of 1:2,000,000 and over retaining geologically useful resolution are routinely obtained from orbital altitudes. However, hyperaltitude photography is inherently more versatile than aerial photography because it can duplicate to a considerable degree the large scale coverage of the latter with long focal length lenses.

Orbital photography thus has a two-way advantage: in addition to its unique capabilities, it can in principle match those of conventional aerial photography as well.

Limitations of Orbital Photography

Orbiting spacecraft present certain disadvantages as well as advantages for photography. A discussion of the chief limitations of orbital photography may be helpful in the interpretation of the photographs presented here. It will be centered on conditions which most strongly affect orbital photography; problems also encountered in aerial photography, such as lens design and film stability, will not be covered.

1. Orbital characteristics

The coverage of a photographic orbital mission is of course affected most strongly by its orbital parameters: apogee, perigee, and inclination of the orbital plane to the earth's equator. The effects of altitude need no explanation. The importance of inclination, however, should be stressed because it is the most important single parameter governing coverage.

The inclination of a satellite's orbit, equal to its latitude restraints, depends on the launch azimuth; this in turn is governed by such factors as location of the launch site, range safety, and payload. All American manned flights to date have been restricted to latitudes of about 32^{o} or less, thus excluding some of the most geologically important regions such as the Canadian shield. It is not possible to extend this coverage by in-flight plane changes (i.e., by increasing the orbital inclination) with present manned spacecraft because of the extremely large amount of fuel required. Therefore, in planning missions for orbital photography, the latitude coverage desired must be taken into account from the very beginning in decisions as to launch site, launch inclination, and payload.

2. Cloud cover

The importance of cloud cover in orbital photography is as great as in aerial photography. The total amount of cloud cover around the world has proven dismayingly great; Schirra (1962) estimated that about half of the earth's surface seen during the MA-8 flight was cloud covered, in accord with estimates from meteorological data. This has been further confirmed by pilots on later missions. However, properly planned orbital photographic missions of sufficient duration can overcome this difficulty because they cover any given area on the flight path repeatedly, and can take advantage of favorable weather.

3. Daylight

The availability of daylight must be taken into account in planning photography from space. This limitation is especially important for short missions (i.e., several days in length); for example, on certain 3-day Gemini missions, no areas south of 10° south latitude could be photographed because of darkness. Like other factors listed here, however, daylight restrictions can be circumvented either by lengthening the flights or placing the satellite in a sun-synchronous orbit--one in which the flight path moves around the earth at the same speed as the terminator.

4. Scattering effects

Atmospheric scattering effects are noticed at altitudes of only a few thousand feet, and vertical photography from altitudes of over 35,000 feet is affected nearly as much as photography from orbit since most scattering takes place below this altitude (Harvey and Myskowski, 1965). Nevertheless, since all orbital photography is taken through the entire thickness of the atmosphere, scattering effects are especially marked. There are two major ones: color distortion and contrast attenuation (with consequent loss of resolution).

Color distortion has been a consistent problem in orbital photography taken to date. It is chiefly the result of Mie scattering (Harvey and Myskowski, 1965), i.e., scattering by suspended particles of water and other substances, and consequently is especially bad for low-lying, humid areas. Scattering is strongly wave-length dependent, as is well known, being much stronger in the blue and green wavelengths. These colors are of course just those which are most characteristic of humid areas, whereas browns, yellows, and reds are most characteristic of arid areas. For this reason, color orbital photography of areas such as the Gulf Coast and Amazon basin has been relatively unsuccessful, in contrast to that taken over the southwest United States and north Africa.

Contrast attenuation is a factor limiting resolution in hyperaltitude photography. No quantitative studies have been made of its effect in orbital photographs, but results of the study by Mazurowski, Silvestro, and Rinaldo (1963), which covered photography from altitudes up to 50,000 feet, should be quite applicable. One of their conclusions is of considerable interest in planning orbital photography: they found high-altitude photography to be most successful when the target area was under a continental polar air mass, and least successful under a maritime tropical air mass. This suggests that orbital photography should be planned to take advantage of such weather conditions.

5. Resolution

The extreme altitudes of orbital photography taken to date, combined with the effects of contrast attenuation, have produced resolution very low by conventional standards. Typical ground resolutions from orbital altitudes are on the order of 100 feet (Lowman, 1964; Morrison and Chown, 1964), although on the original film of Figure 4 two lane highway under 40 feet wide in the desert (admittedly a linear, high contrast object) can be clearly seen. These low resolutions must of course be taken into account in planning and interpreting the results of orbital photography; for example, it must be realized, as Morrison and Chown (1964) point out, that what would be texture on an air photograph would be tone on a comparable hyperaltitude photograph. Two studies, one by Merifield (1964) and one by Morrison and Chown (1964), present data bearing on the effects of ground resolution in geologic interpretation of orbital photographs. Tables 2 and 3 are extracted from these sources.

Table 2 (Modified from Merifield, 1964)

Resolution Necessary for Identification of Geologic Features
(10 lines/mm image resolution assumed)

Feature	Minimum Ground Resolution (meters)	Equivalent Scale No. on an 8 x 10" Print
Relief	450	3,000,000
Major drainage (e.g., Rio Grande)	450	3,000,000
Tributary drainage (e.g., arroyos, streams)	150	1,000,000
Erosion and deposition surfaces (e.g., terraces, bajadas, pediments)	200	1,350,000
Playas	1,000	6,500,000
Large faults (e.g., San Andreas)	450	3,000,000
Smaller faults and fractures	100-150	800,000

Minimum resolutions necessary for geologic interpretation are expressed differently by Morrison and Chown, as multiples of the size of the feature to be mapped.

Table 3 (from Morrison and Chown, 1964)

Minimum Ground Resolutions for Mapping

Feature	Minimum Acceptable Ground Resolution
Lithology	1/4 - 1/2 width of the narrowest unit to be separately mapped
Structures (folds)	1/16 - 1/8 the dimension of the structure being mapped
Structure and landform patterns	About 1/2 - 1 times the "wavelength" of the pattern
Structures (fractures)	No specific resolution; optimum when entire feature is on one frame
Landforms, linear	1/4 - 1/2 times width of objects
Landforms, areal	1/8 times size of objects
Vegetation boundaries	1/8 - 1 times distance across boundary, depending on contrast

6. Camera orientation

Most of the terrain photographs taken to date on American manned flights have been high and low obliques, taken in drifting flight, and there has been ample demonstration of the effects of camera orientation. There are three such major effects: distortion of shape, loss of resolution, and loss of color fidelity.

Study of Gemini photographs of the southwest United States indicates that shape distortion becomes seriously misleading when the tilt is greater than about 60°. In particular, it becomes difficult to see lineaments nearly parallel to the principal line because of the foreshortening, which is accentuated by the earth's curvature. An example of such distortion is presented in Figures 9 and 10; a prominent east-trending series of lineaments near Tucson is invisible in the oblique Viking photograph, whereas the San Andreas fault, which is much farther away but more nearly normal to the principal line, is clearly visible.

Shape distortion can of course be corrected by rectification, but loss of resolution in oblique photographs can not. This stems from the great increase in slant range with large tilt angles; slant range = height/cosine of tilt, and the cosine decreases very rapidly for angles over about 75°. For example, in Figure 10 the scale near the principal point is on the order of 1:6,000,000--more than four times the scale of a vertical photograph from the same altitude with this camera. As indicated by Table 2, only the largest geologic features can be seen at such scales. High obliques from orbital altitudes are thus clearly inefficient (apart from the obvious fact that they waste film on sky). An incidental implication of this fact is that sounding rocket photography is also inefficient because its effective coverage is limited to a relatively small area around the launch site.

Atmospheric scattering, with consequent color distortion and contrast attenuation, becomes severe in oblique photographs, because the thickness of atmosphere which the light must penetrate, like the slant range, is also inversely proportional to the cosine of the tilt. As would be expected, the far portions of hyperaltitude oblique photographs with standard color film are usually excessively blue, even with the use of minus blue filters.

7. Target acquisition

Although it has been proven that astronauts with good eyesight can see remarkably small objects on the ground from orbit, target acquisition is still a problem when photography of individual points is desired. This was also demonstrated by the visual acuity test performed on Gemini V and VII (Duntley, 1966): the astronauts were able to see the majority of targets, but had difficulty in finding them first. This problem has been overcome by computer techniques developed by the Manned Spacecraft Center (R. D. Mercer, personal communication), by which detailed instructions on time of exposure and spacecraft orientation for photographing any object on the ground or in space can be sent to the astronauts in flight. The application of this technique, however, requires that the sites to be photographed must be picked well in advance and the necessary preliminary data computed.

8. Environmental degradation of film

No gross deterioration of film has been noticed on terrain photography taken during Gemini or Mercury flights, although in some of these flights involving extravehicular activity the cameras have been exposed directly to space for some time. However, on longer missions the space environment may have substantial effects; in particular, extremes of temperature, low pressure, and radiation must be taken into account. Radiation in particular may cause a decrease in resolution (Harvey, 1965). Although fairly long flight times in space would be needed to fog film by natural radiation (excluding flares), it has been discovered that radioactive sources such as radioluminescent dials and thorium-containing alloys in the spacecraft itself may present a problem (NASA SP-88, 1965).

Specific Uses of Orbital Photography

Although systematic photography of the earth from space for geologic purposes has only begun, specific geologic uses of this photography are already apparent, and will be discussed under the following broad categories.

1. Regional geologic mapping

The uniquely small scale of hyperaltitude photographs makes them especially valuable, in principle, for the preparation or revision of geologic maps of comparable scale, i.e., 1:1,000,000 or smaller. (I include the preparation of tectonic maps in this general category.) Map revision using orbital photographs will undoubtedly be done first, because the extension of geologic units from well mapped into poorly mapped areas will require relatively little field-checking.

The Pinacate volcanic field is exceptionally well-delineated on Figure 11. However, on the 1960 Geologic Map of Mexico, it is not shown at all, although the field is well known to Mexican geologists. The immediate reason for this is that in this particular map, Cenozoic volcanics and alluvium derived from them are a single unit. With the use of the Gemini photograph, however, the Quaternary alluvium/Quaternary volcanic contact can be accurately and quickly drawn.

The Sierra Carizarilla (Figure 12) in Chihuahua are also not shown on this map in their entirety. Furthermore, this large volcanic field is labeled as Middle Cenozoic, but is almost certainly Quaternary: in addition to the slight degree of dissection apparent onthe photograph, the field is almost certainly related to the few isolated volcanoes just north of the border which are shown as Quaternary on the Geologic Map of New Mexico (Dane and Bachman, 1964).

In some areas, geologic mapping from orbital photographs can be done at scales considerably larger than those of the original picture. This is demonstrated by Figure 15. Although the original scale of the picture is about 1:2,500,000, most of the geologic detail shown on the 1:375,000 Geologic Map of Yuma County (Wilson, 1960) can be delineated.

2. Monitoring of variable properties

Although geologists are accustomed to thinking in extremely long time spans, there are nevertheless a number of geologically important phenomena which take place in months, days, or even minutes, and which could be profitably studied by orbital photography.

The color and distribution of the turbid effluent from large rivers has been photographed on a number of Gemini missions, first essentially by accident and then by design. In Figure 13 the effluent pattern over several thousand square miles is distinct. Related to this application is the monitoring of changes in shallow-water bottom topography. This is routinely done in, for example, the United States by aerial photography after major hurricanes, but there is no comparable effort for less-developed coastal regions nor for non-catastrophic bottom changes. The study of Figure 4 by Gettys (1965) demonstrates the potential feasibility of at least qualitative bottom mapping by orbital photography.

The ability to photograph entire drainage basins very rapidly should find considerable geologic application. For example, rivers such as the Mississippi can in flood season make major changes in their courses by cutting off meanders, eroding existing ones, and depositing new bars. These changes are of course now monitored by aerial photography in many countries, but the speed and global span of satellite coverage would permit extension of this service to less-developed regions such as the Amazon basin.

Topographic changes produced by major earthquakes are also routinely mapped by aerial photography. However, many earthquakes in remote areas such as central Asia can not be studied this way for obvious reasons; satellite coverage of these would be of considerable scientific interest and very possibly of immediate value to the countries affected. R. W. Underwood has identified, on pictures taken by T. Stafford and E. Cernan during the Gemini 9 mission, a landslide which occurred during the disastrous Peruvian earthquake of 1962, and a large ephemeral lake in the Andes caused by a much earlier landslide.

Related to this application would be periodic surveillance of active or potentially active volcanoes by orbital photography. For maximum effectiveness, photography should of course be teamed with devices such as infrared scanners, whose usefulness in volcano surveys has been demonstrated by Fischer (Fischer, et al., 1964), and possibly with automatic seismographs, tiltmeters, and thermometers read out on command by the camera-carrying satellite. Erupting volcanoes could be photographed to provide a continuous check on the extent of damage caused by airborne ash, gases, and earthquakes. Such a volcano watch might be only one function of what could be called a geophysical hazards satellite, which, equipped with non-visual sensors and commanding a network of ground monitoring stations, could provide warning of earthquakes, floods, and avalanches, in addition to volcanic eruptions. An added benefit would be the early detection of other natural hazards such as forest fires, crop diseases, locust plagues, and forest diseases.

Numerous other geological phenomena could in principle be studied by orbital photography including seasonal changes in playa lakes (J. T. Neal, personal communication), sand dune movement, snow accumulation, and glacial growth.

3. Geological education

Air photos have been used effectively for many years in geology textbooks, and similar use is beginning of photography of the earth from space. The chief advantage of orbital photography in this application is that it becomes possible to show actual pictures of very large features rather than the stylized diagrams currently used. A good example of this is Figure 7, which shows a large area of folded mountains and a major (scissors) fault at a glance. In Figure 8, a striking example of incipient stream piracy is apparent. Comparison of Figures 7 and 12 illustrates at least the major differences between block-faulted and folded mountains, and could serve as a useful background for a more detailed explanation.

Additional advantages of orbital photography for educational purposes are their objectivity and geometric fidelity (subject to camera orientation and scale). The objectivity of photographs should be especially valuable in the teaching of, for example, regional tectonics. Even the most skillfully constructed sketch maps of major geologic provinces are at least partly subjective; in addition to possible errors of interpretation, sketch maps have the disadvantage of omitting features of possible importance, such as Cenozoic volcanic fields, in order to focus attention on others. The geometric fidelity of orbital photography may prevent unconscious misconceptions of relative size and vertical scale to creep into the student's mind. For example, to show the known cryptovolcanic and impact structures of the United States on a small map (Shoemaker, Hackman, and Eggleton, 1962), it is necessary to represent each one by a dot or circle whose size is an appreciable fraction of the apparent width of the continent; the casual viewer might unknowingly get the impression of a much higher density of such structures than actually exists. However, pictures from orbital altitude such as Figure 11 provide a true concept of their actual rarity and small relative size. Another misconception which may be avoided by the use of orbital photographs is the relative thickness of continents; a student who has seen Figure 10 will probably not carry away the image of thick, iceberg-like continental blocks pictured in many textbooks.

Theoretical Applications of Orbital Photography

The specific uses of orbital photography just discussed will find application to a great variety of geologic problems. A few of the more promising ones will be discussed. It is hardly necessary to mention that the photograph interpretations presented are preliminary; much more definitive work can be expected by specialists familiar with the areas covered.

1. Continental drift

From its position in the limbo of discarded theories 15 years ago, continental drift has sprung back into the spotlight of attention because of recent studies in paleomagnetism and other fields. It is, in fact, again one of the major issues in geology, as evidenced by the fact that its solution is one of the chief objectives of the Upper Mantle Project. Orbital photography may be applied to the problem of continental drift in several ways.

Probably the most immediate of these is by improving our knowledge of the Precambrian structure of continental areas supposed to have been in contact. With D. P. Gold, the writer is using the Gemini 5 pictures of southwest Africa (Figure 14) to study the regional structure. When pictures become available of the corresponding areas of South America, a comparison of these with Africa can be made, as Brock (1956) has done on the basis of conventional maps. If post-Lipalian drift has occurred, we should expect considerable correspondence in the regional Precambrian structure on opposite sides of the Atlantic.

The south Atlantic is of course the most promising for a study of continental drift; if the theory can not be proved here, it is not likely to be proved anywhere. However, corresponding studies should be made of the Precambrian of southern India, Australia, and southeast Africa. An additional area which might be of interest is the Red Sea and adjoining crystalline highlands in Africa and the Arabian Peninsula; if incipient continental separation and rotation is occurring here, systematic relations between the regional fracture patterns of the two areas might be found on orbital photographs.

2. Structure of rift valleys

Because it is part of one of the biggest tectonic structures on earth, the African Rift Valley has been an area of prime interest to the Upper Mantle Project. For this reason, it has been an objective of the S-5 Synoptic Terrain Photography experiment on several Gemini flights (Lowman, 1966), and will also be photographed during Apollo missions. The photographs thus obtained should be of value in studying the overall structure of the African Rift Valley and its supposed counterpart, the Gulf of California. New light on the relation of Cenozoic vulcanism to the rift valleys may result from this study. In North America, it is hoped to attack the problem of how the dominantly normal movement of the rift-bounding faults in Africa and the mid-Ocean ridges changes into the dominantly lateral movement of the San Andreas system. Wilson's (1965) explanation might be tested if a junction between his proposed "transform faults" and a graben can be located on orbital photographs of land areas.

3. Extent and origin of transcurrent faulting

As recently pointed out by Allen (1965), active transcurrent (strike-slip) faults seem to be much more widespread than once thought. The San Andreas fault system, for example, has been demonstrated to be only one of a system of circum-Pacific faults whose other members are in the Phillippines, Taiwan, New Zealand, and Chile. An even more interesting transcurrent fault system, discovered by oceanic magnetic surveys (Vacquier, 1962), includes several east-west trending transcurrent faults in the eastern Pacific. These faults may extend into North America for several hundred kilometers (Zietz, 1965) and all the way across northern South America (Fuller, 1964).

The main reason that these major faults were not better known before this appears to be simply that geologic mapping of the areas in question is not very advanced (Allen, 1965). Allen points out that physiographic criteria are very useful in the study of active transcurrent faults, because they must rapidly straighten with continuing displacement; he suggests, in fact, that all exceptionally straight regional fractures should be suspected of being transcurrent until proved otherwise.

Orbital photography is already being applied to the study of such faults. The Agua Blanca fault, for example, was not discovered until 1956 by Allen, Silver, and Stehli (Allen, et al., 1960), and is exceptionally well-displayed on one of the first Gemini photographs taken specifically for geologic purposes (Figure 20) (Lowman, McDivitt, and White, 1966). It is apparent, from this photograph, that the Agua Blanca fault is probably one of a series of northwesterly-trending faults, which may have some systematic relation to a less-prominent sortheasterly-trending set of fractures.

Allen's admonition to examine all major straight fractures for evidence of transcurrent movement can easily be applied to Figure 7 (Iran). The major fault bounding the Dasht-i-lut can be seen to show primarilly vertical movement, possibly rotational, rather than lateral movement.

The question of whether the major transcurrent faults of the eastern Pacific cross the continent may be susceptible to attack by orbital photography. The geologic evidence for such extension must be relatively subtle in central North America (Gilliland, 1962); there is no obvious alignment of intrusives, structures, or earthquake epicenters. However, hyperaltitude photographs of this area, when available, may show previously unnoticed lineaments, by virtue of their great coverage. Attempts will be made to obtain photographs of the Neovolcanic Plateau of southern Mexico, which may represent the continental extension of the Clarion fracture zone (Maldonado-Koerdell, 1966).

4. Existence of global tectonic pattern

Hills (1963) points out that we do not know at present if there is "a global pattern to which continental and oceanic megalineaments conform," or if the structure of each major region is essentially unrelated to that of other major regions. This reflects the rather surprising fact that we know more of the overall tectonic structure of the moon than we do of the earth; see, for example, maps by Strom (1965) and Fielder (1961). Some geologists, such as Badgley (1965), feel that there are two major directions to world structural trends, and that divergences from these trends are the result of continental drift and attendent rotation.

Study of this problem is hampered by a number of factors, the most obvious being, again, the relatively poor state of world geologic mapping. Orbital photography will clearly be applicable directly to this difficulty. An additional benefit of this photography may be the ability to distinguish truly continent-wide structural patterns from those which are essentially local. Figure 11 illustrates this possibility; the arcuate fracture/dune pattern surrounding the Tibesti Mountains, not shown on existing maps, is clearly related to their uplift rather than to global stresses.

5. Role of major impacts in crustal evolution

Recent investigations of shock metamorphism (French, 1966), stimulated partly by the search of the Canadian Shield for impact structures by the Dominion Observatory (Beals, et al., 1963), have revealed the presence of a large number of ancient impact craters or their roots. This research, together with growing evidence for the impact origin of large lunar craters (Lowman, 1966), suggests that major impacts may have played a surprisingly large role in terrestrial geologic history. Hudson s Bay, for example, is now seriously considered to be the possible site of a former crater comparable to Mare Crisium in size (Shoemaker, 1966). Dietz s discovery of shatter cones at Sudbury, Ontario (Dietz, 1961), and his prediction of their discovery around the Vredefort Dome by Hargreaves (1961), though controversial, have given further impetus to study of the geologic role of impact. Should such major structures be proven of impact origin, it would give a totally new dimension to the concept of uniformitarianism.

Orbital photography can be brought to bear on this problem in several ways. The first of these is simply a search for unmapped circular structures in Precambrian areas--essentially an extension of the search of air photos conducted by the Dominion Observatory. At least one circular structure has been found on Gemini photographs (Figure 11) (Lowman, McDivitt, and White, 1966), although it is probably of igneous origin. Another application of orbital photography lies in study of the relations between suspected impact structures and the regional structure. Geologists such as Bucher (1965) who advocate an internal origin for these structures draw heavily on such relations, which can now be studied from a new vantage point. Finally, orbital mapping should reveal previously unknown Recent craters in areas like South America, for which only two impact craters are now known (Sanchez and Cassidy, 1966).

6. Evolution of topography in arid regions

Most orbital photography using returned film has to date been taken over low latitudes because of orbital restrictions. Because such latitudes include many of the world's great deserts, the study of arid region geomorphology should be an early beneficiary of orbital photography.

Probably the most obvious application lies in the study of sand dune evolution. Many aspects of this process are not at all clear, as pointed out by Smith (1963). Even the existing Gemini photographs, however, (Figures 5 and 14) should be useful in the study of sand dunes because they provide regional coverage, contrasted with the local coverage of aircraft photos previously used. This coverage permits accurate delineation of the distribution and interrelation of various dune types and shows their relation to surrounding topography.

The origin of pediments can also be studied by orbital photography. In Figure 12, for example, several conspicuous pediments can be seen. The availability of color coverage of large arid regions should permit study of entire zones of pedimentation and its relation to the underlying structure and lithology.

The study of the soils of arid regions is uniquely suited to orbital photography. Because there is relatively little agriculture in these areas, there is surprisingly little map coverage of desert soils. This may shortly prove a serious handicap to the increasing use of arid regions, but one which orbital photography promises to alleviate. An interesting research application is being made of Gemini photographs by T. R. Walker (personal communication). Walker has discovered new evidence supporting the once-abandoned classic view that red sediments were formed chiefly in arid regions, and is using Gemini pictures to map the distribution of Recent red sediments, and to plan further field work.

Summary and Conclusions

It is clear that photography of the earth from orbiting spacecraft offers geologists a powerful new tool. This review has barely touched on the general applications of orbital photography. For example, there has been little mention of its use in the utilization of natural resources (partly, of course, because geologic mapping is fundamental to such utilization). However, Fischer (1966) has pointed out that the use of non-renewable resources is accelerating at such a rate that natural resource surveys from space will shortly become a necessity, rather than a scientific luxury. As suggested by Lowman and Chang (1965), the less-developed countries will probably be the first to benefit from applied orbital photography.

It should be stressed that the potential capabilities of earth-orbiting spacecraft will be partly wasted if photography is used alone. A variety of sensors, including radar, infrared scanners, magnetometers, and other non-imaging devices should be carried. Furthermore, the need for conventional aerial surveys will by no means be eliminated; guided to areas of special interest by small-scale orbital coverage, their usefulness should in fact be greatly increased. The need for field checks will also remain. However, the immense coverage per photograph typical of hyperaltitude photography suggests that direct ground surveys using orbital photographs as air photos are used will be inefficient; instead, conventional air photos or visual aerial reconnaissance will probably take the place of field checking. The writer, for example, found a two-hour flight at 2500 feet invaluable in studying the area covered by Figure 12.

Plans are in preparation for more advanced photographic missions. The feasibility and general usefulness of orbital photography have been demonstrated by the experiments performed by Mercury and Gemini astronauts. However, these have been only "piggyback" operations using small hand-held cameras; and the low-inclination orbits so far achieved have missed many of the most interesting geological areas. Pictures and non-visual data obtained by high-inclination missions specifically flown for this purpose should be incomparably more valuable than those presented here.

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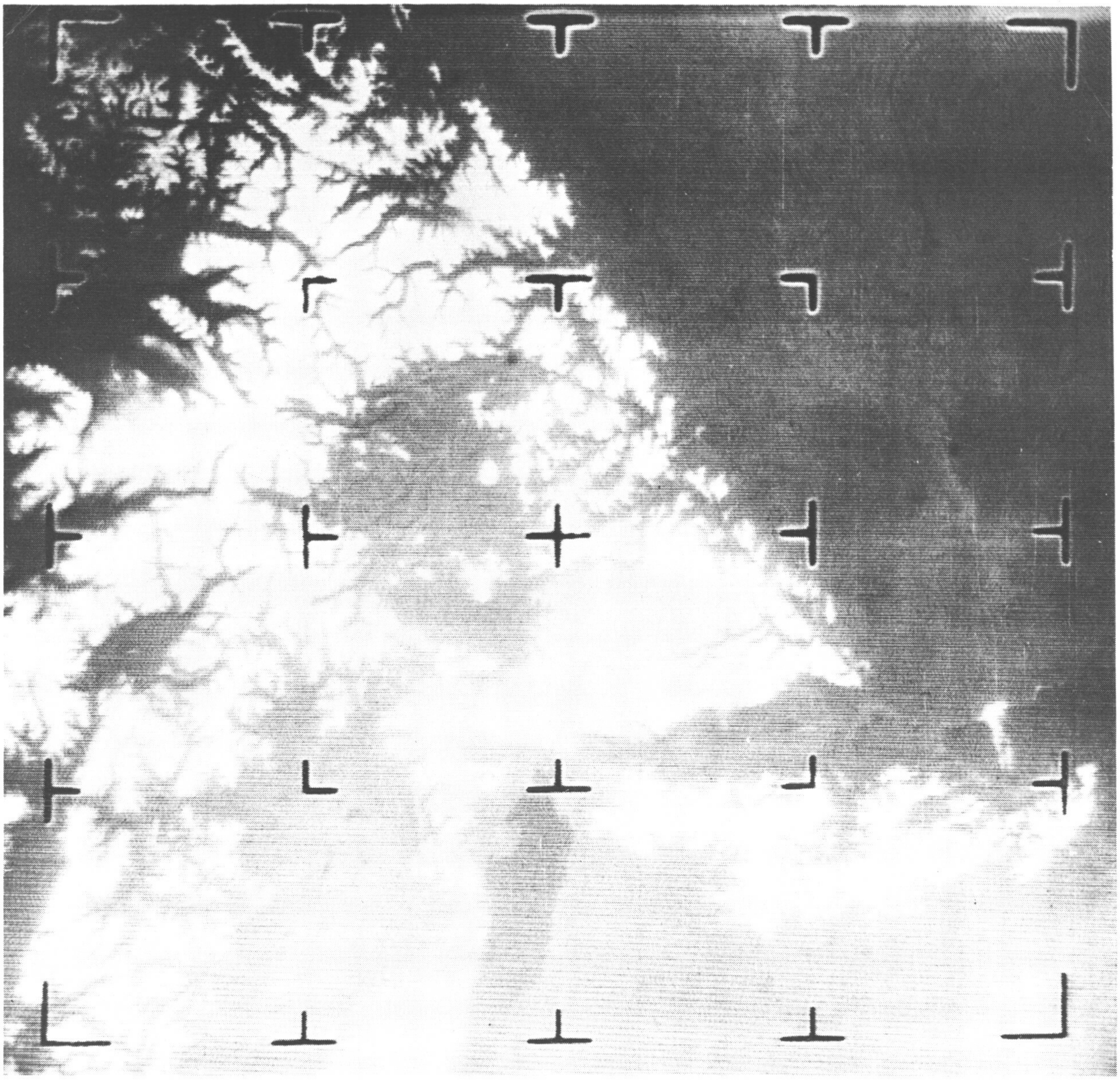

Fig. 1 Nimbus I picture, taken with the Advanced Vidicon Camera System (AVCS) (76mm effective focal length), from an altitude of about 460 kilometers. Lake Baikal at lower right, Lake Koso Gol (Mongolia) at bottom center. Snow covered area includes Sayan Mountains. Note lineament at upper right, believed to be valleys following the Sayan fault: subsidiary faults also visible.

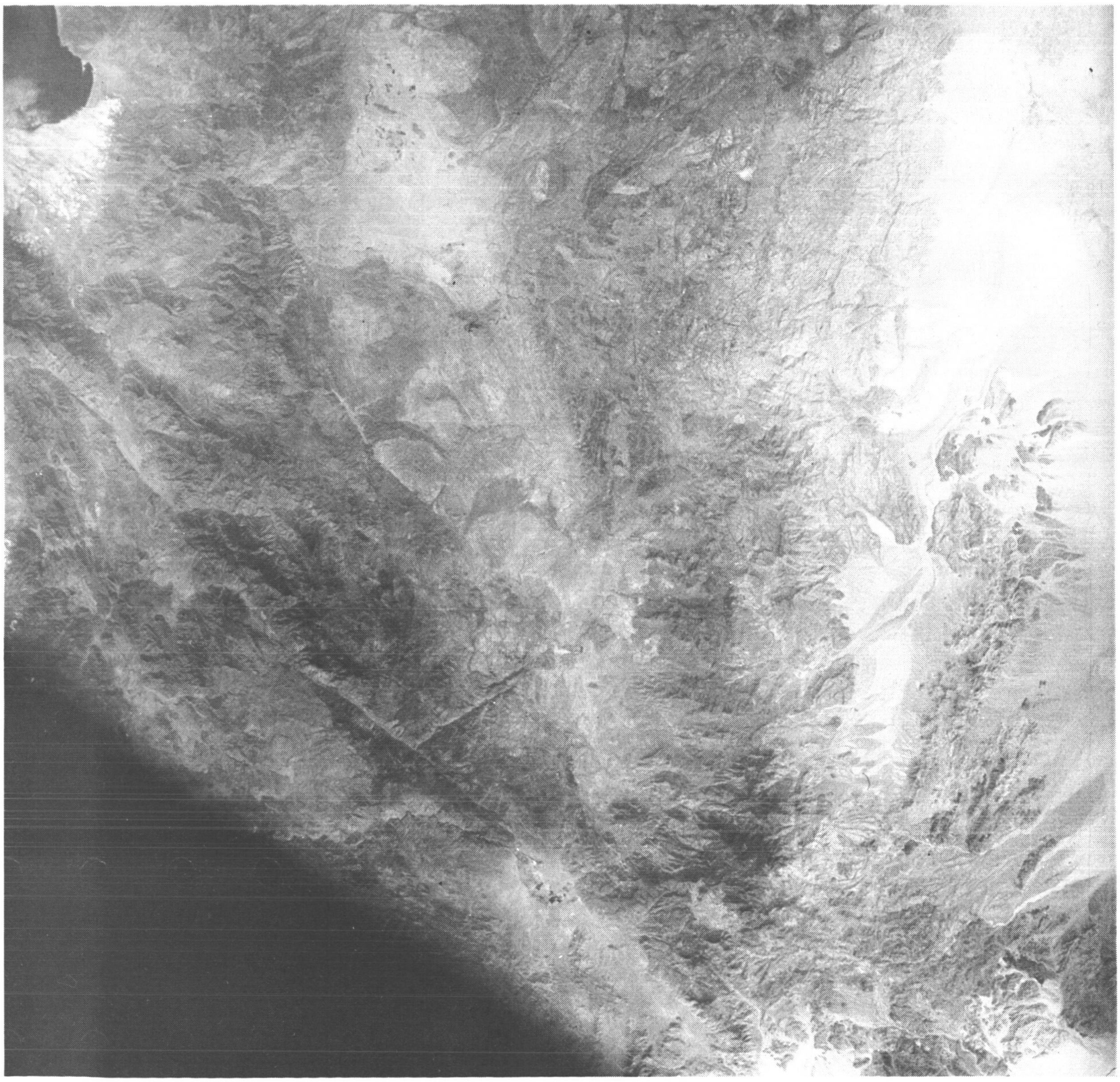

Fig. 2 Gemini IV photograph, showing northern Baja California, Mexico. Bahia de Todos Santos and city of Ensenada at upper left corner: note jetty projecting southward. Sierra Juarez and Sierra de San Pedro Martir at right. Agua Blanca fault zone at lower left, parallel to edge of spacecraft window. Area covered about 65 miles east-west distance at top of photo.

Fig. 3 Gemini IV photograph, taken about 5 seconds after Fig. 2. Colorado River and Gulf of California at right. Sierra Pinta in center. Sinuous feature is probably an ephemeral tidal channel. White areas are salt flats.

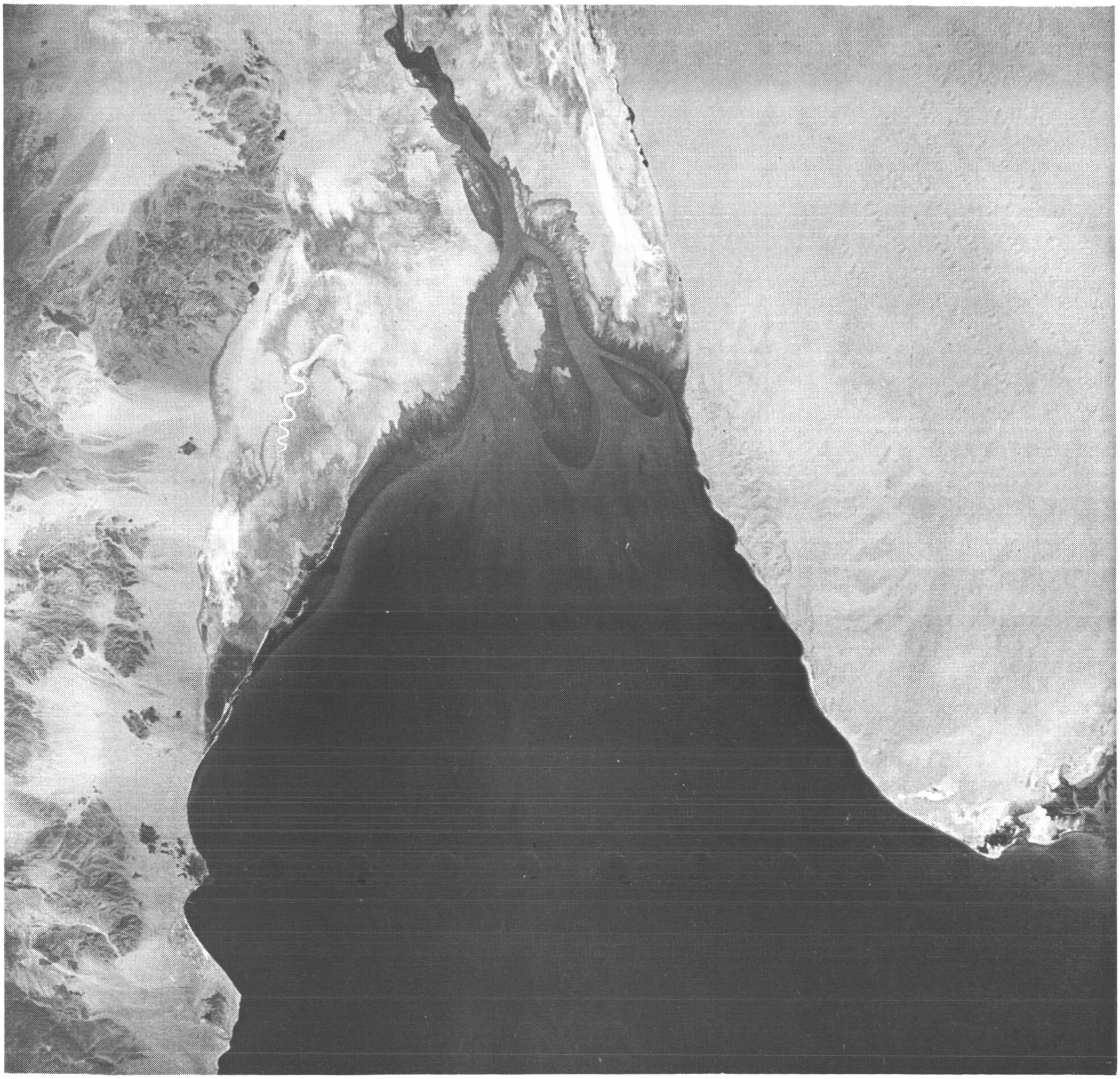

Fig. 4 Gemini IV photograph, taken about 5 seconds after Fig. 3. Northern end of Gulf of California and mouth of Colorado River. Gran Desierto, Sonora, at right, bounded at center (on west) by fault or fault-line scarp. Mission Creek-Banning fault is expressed by linear feature followed by salt flats between Gran Desierto and Colorado River.

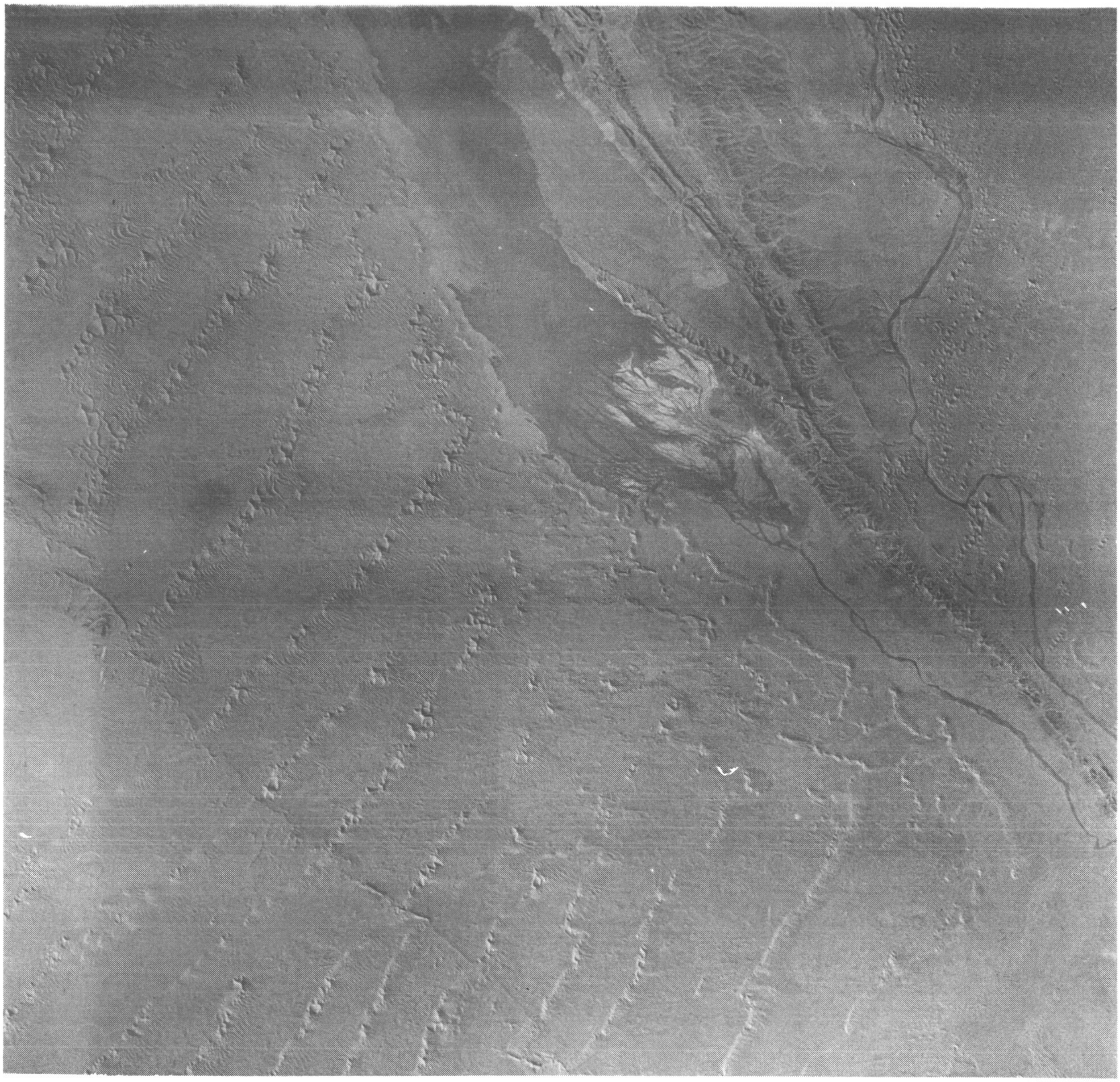

Fig. 5 Gemini VII photograph taken with 250mm lens (Hasselblad 500C), showing northern Algeria, and the Oued Saoura, partly flooded by runoff. Area shown is about 150 miles due south of Colomb Bechar.

Fig. 6 Gemini V photograph showing the Bahama Islands. Tongue of the Ocean is dark area at lower left; water depth there is over 4000 feet. Depth over most of the Bahama Bank (light areas) is generally 15-30 feet.

Fig. 7 Gemini V photograph over southeastern Iran. City of Kerman is in cultivated valley at left. Folds in sedimentary rock at center truncated by major fault at right. Linear features at lower right are ridges in the Dasht-i-Lut, a salt desert. Photograph taken early in the morning, accentuating relief.

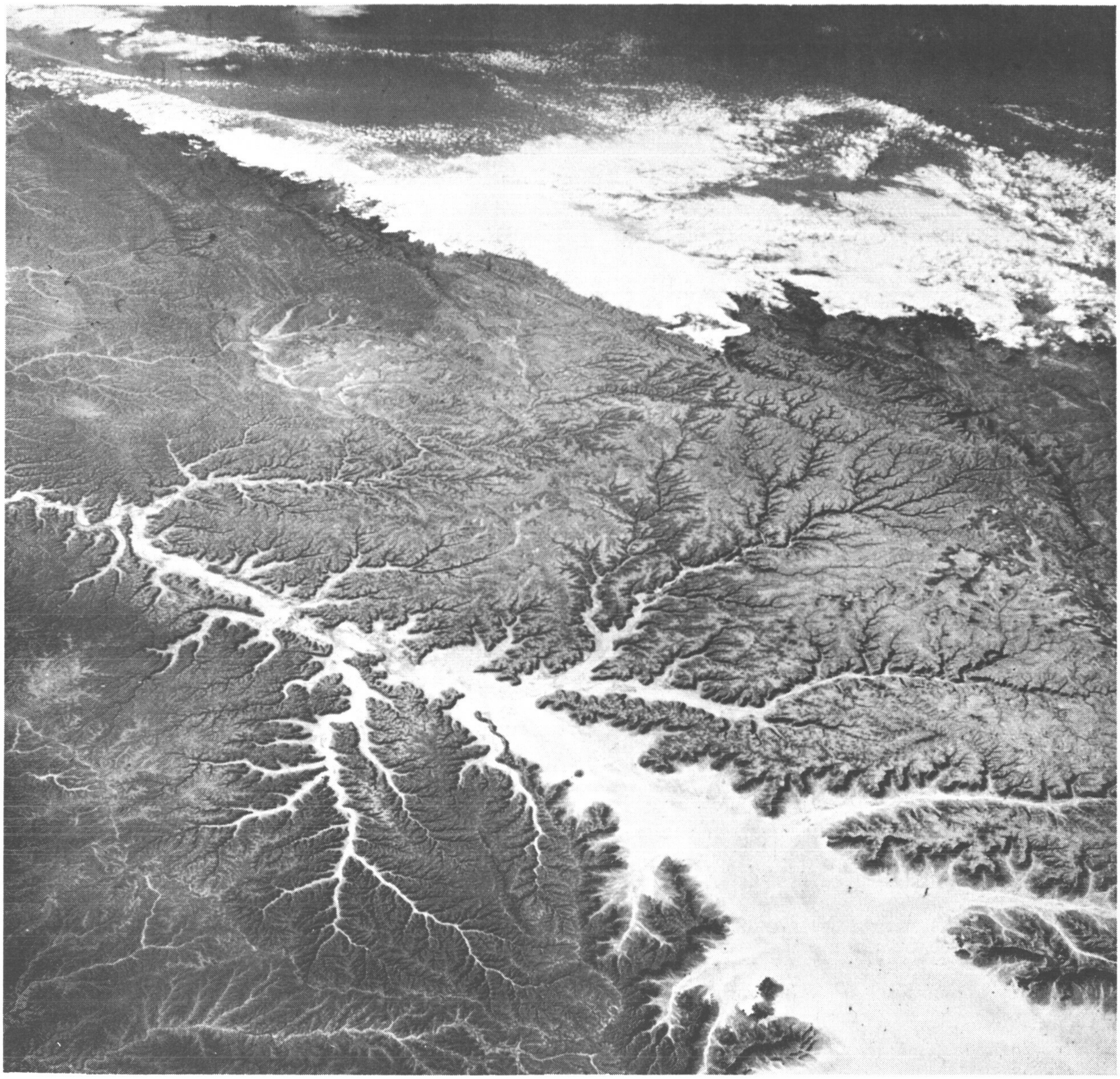

Fig. 8 Gemini IV photograph showing southern part of the Arabian peninsula, looking to the southeast over the Hadramaut Plateau and the Arabian Sea. Dendritic valley in foreground is the Wadi Hadramaut. Note intersecting stream pattern at center, interpreted as structurally-controlled stream piracy.

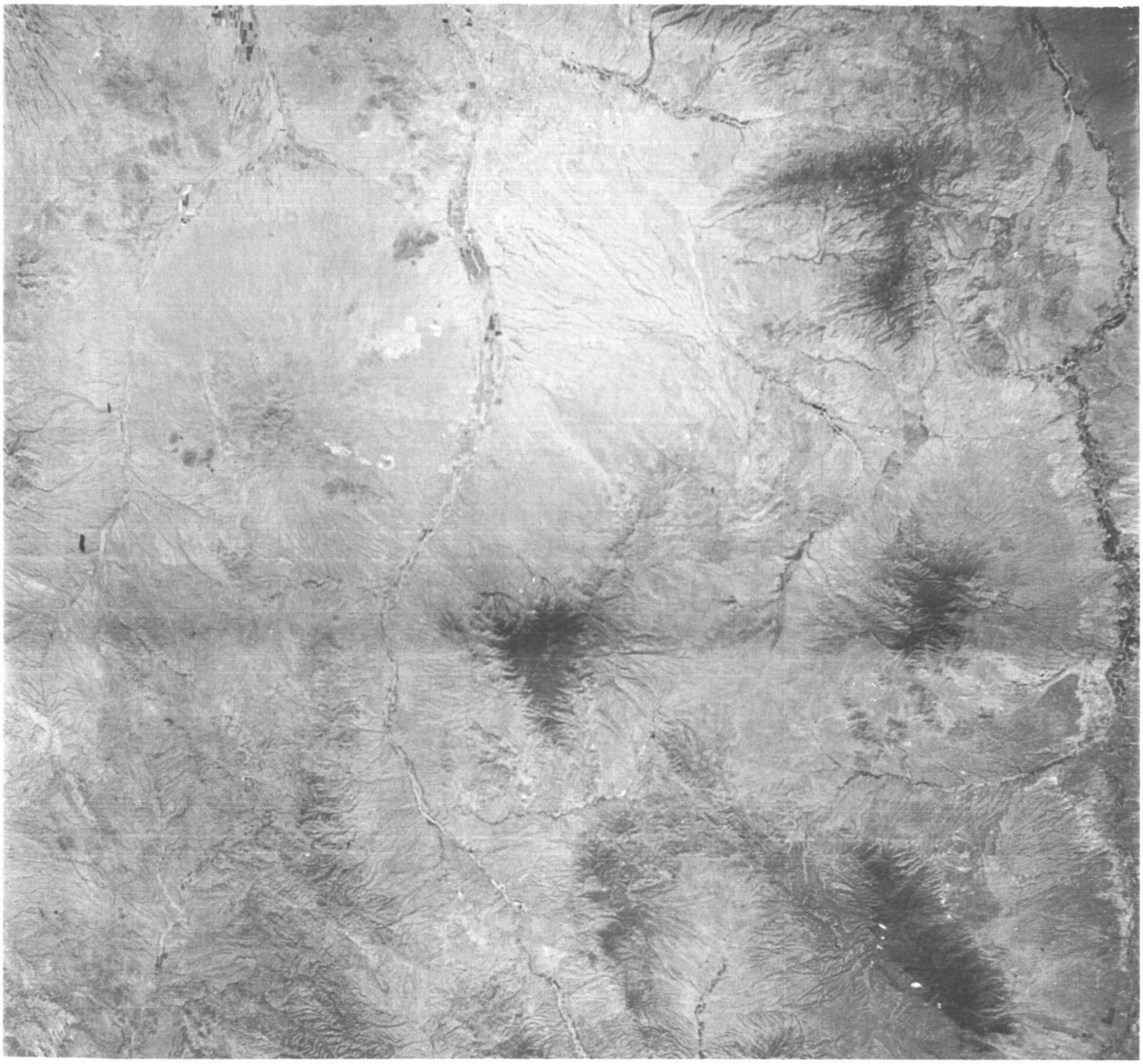

Fig. 9 Gemini IV photograph, taken during the same sequence as Figs. 2, 3, and 4 over southern Arizona. City of Tucson at top. Quaternary basalt flows below and left of Tucson; tailings ponds of open pit mines south of flows. Note southwesterly-trending lineaments in Rincon Mountains (hammer-shaped dark range to right of Tucson).

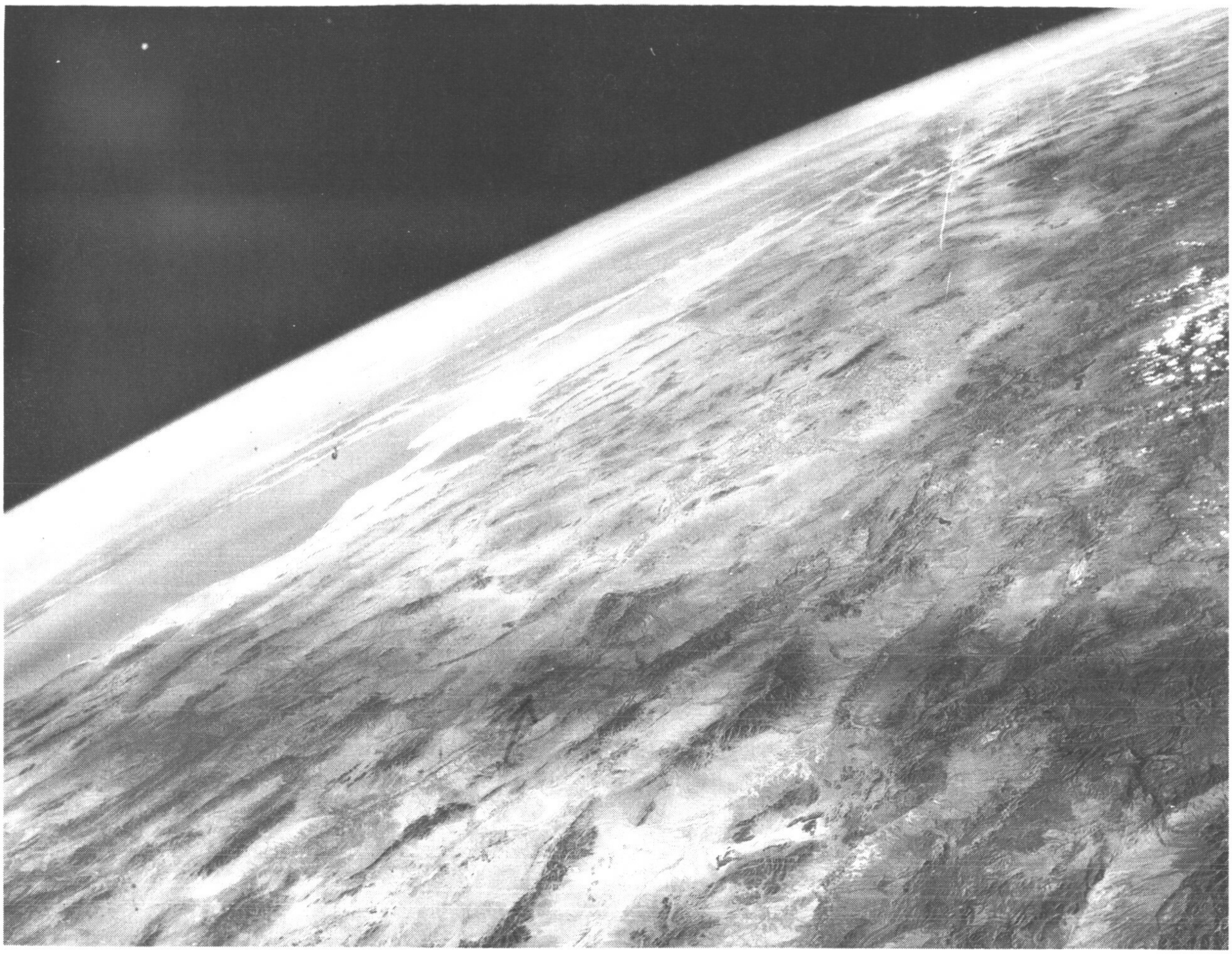

Fig. 10 Viking 12 photograph, taken in 1955 from 140 miles altitude, with Kodak Hi-Speed Infrared film. View to the southwest; Gulf of California at left, Pacific Ocean on Horizon. Rincon Mountains (Fig. 9) indicated by arrow; note that the lineaments visible in Fig. 9 do not show up here. Most of the terrain features shown in Figs. 2, 3, and 4 are visible here.

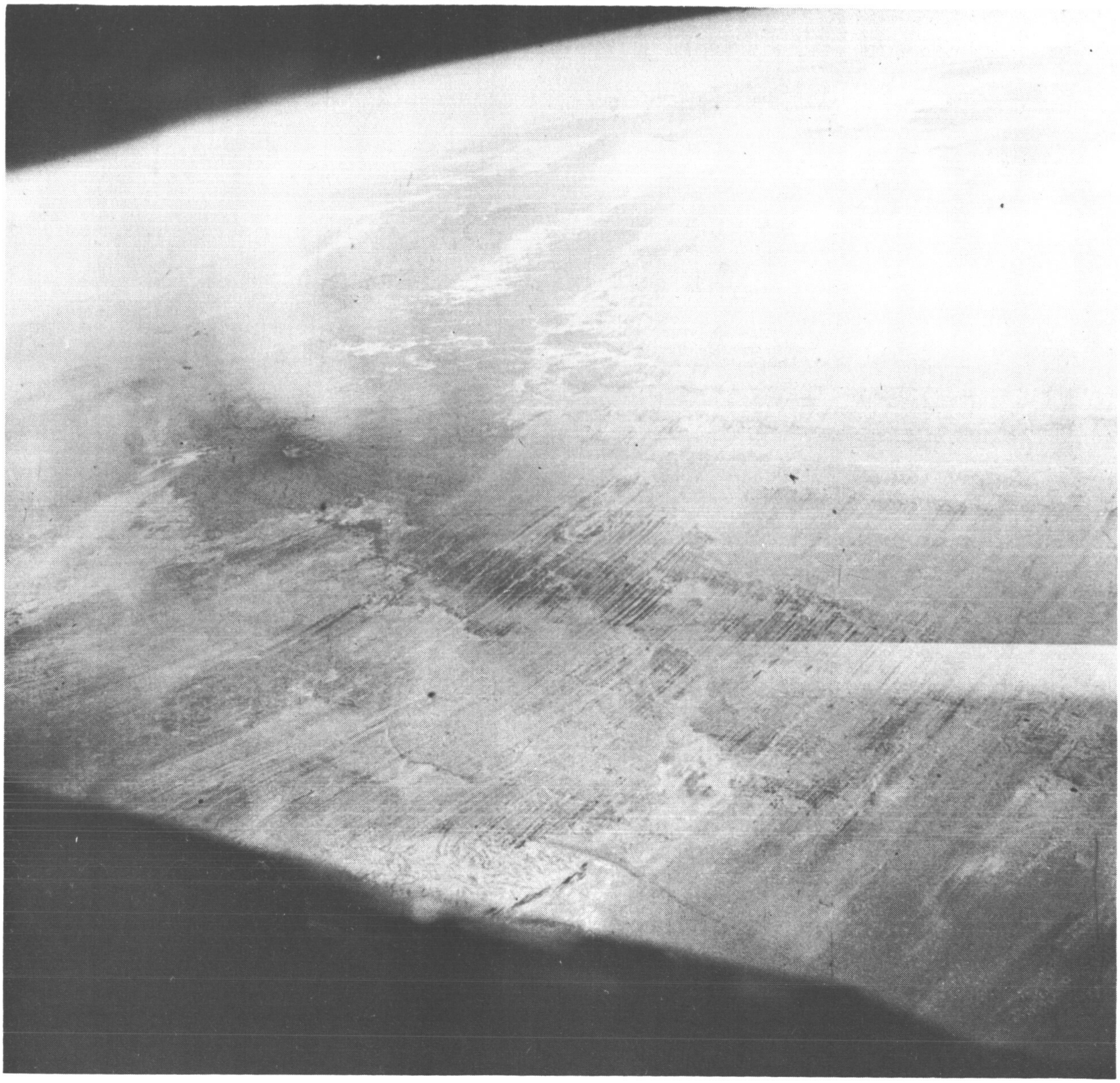

Fig. 11 Gemini IV photograph taken over Chad, North Africa, looking to northwest. Tibesti Mts. at left center; prominent volcano is Emi Koussi. Note arcuate ridges in center: believed to be sand dunes and fractures in sandstone plateau. Circular structure in center of picture is a series of concentric sandstone ridges about 5 miles in diameter; its origin is unknown, but a laccolith is suspected.

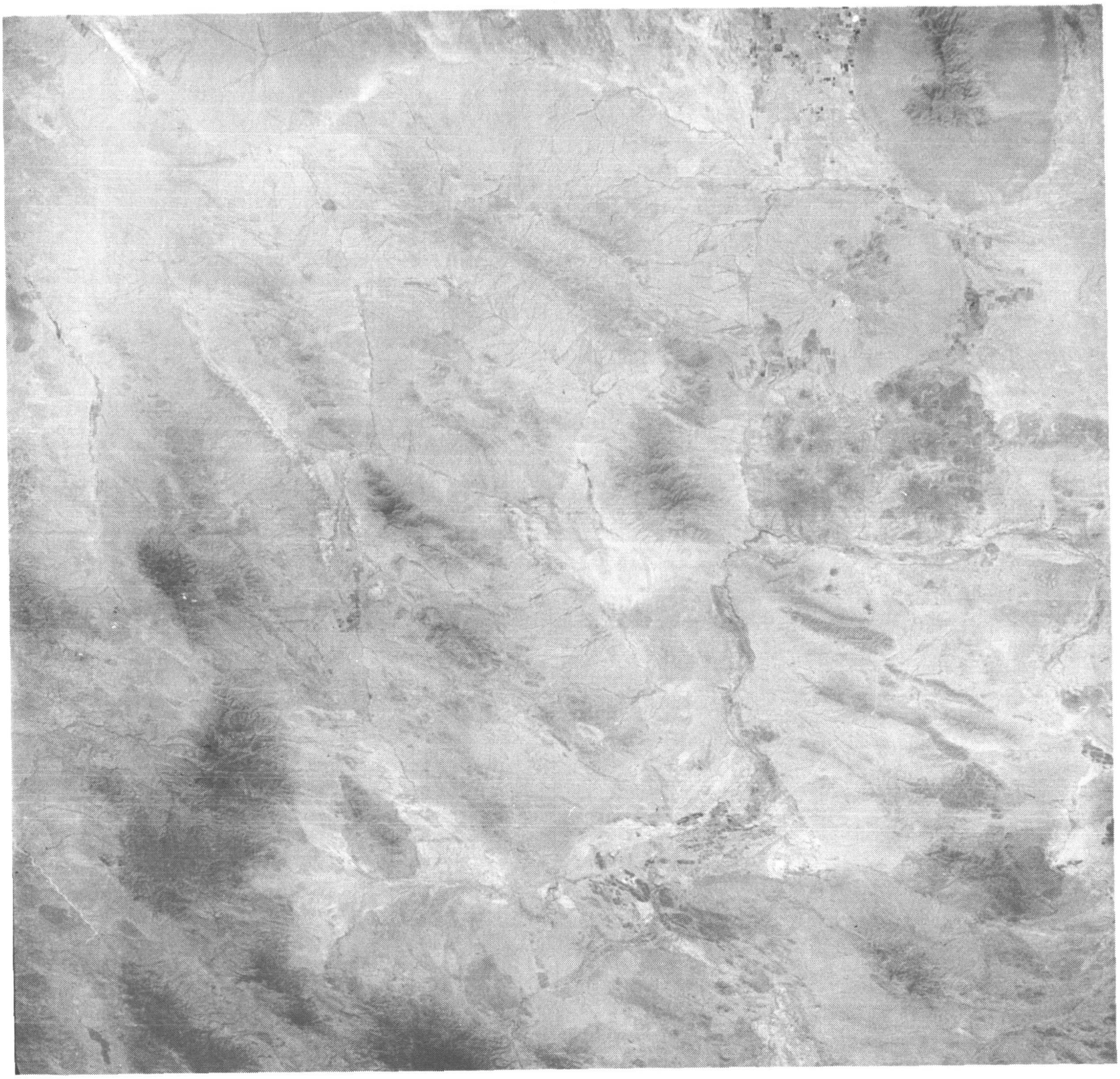

Fig. 12 Gemini IV photograph, taken in same series as Fig. 9. Area shown is northern Chihauhua, Mexico, and southern New Mexico. Note gradation from block-faulted mountains of the Basin and Range Province at upper left to folded structure of extension of the Sierra Madre Oriental at lower right. Sierra Carizarilla, previously unmapped Quaternary volcanic field, is dark area at right center.

Fig. 13 Gemini V photograph showing the southeastern coast of China, just south of Canton. Macao (Portugal) at upper right. Note turbid effluent from Si Kiang River and others.

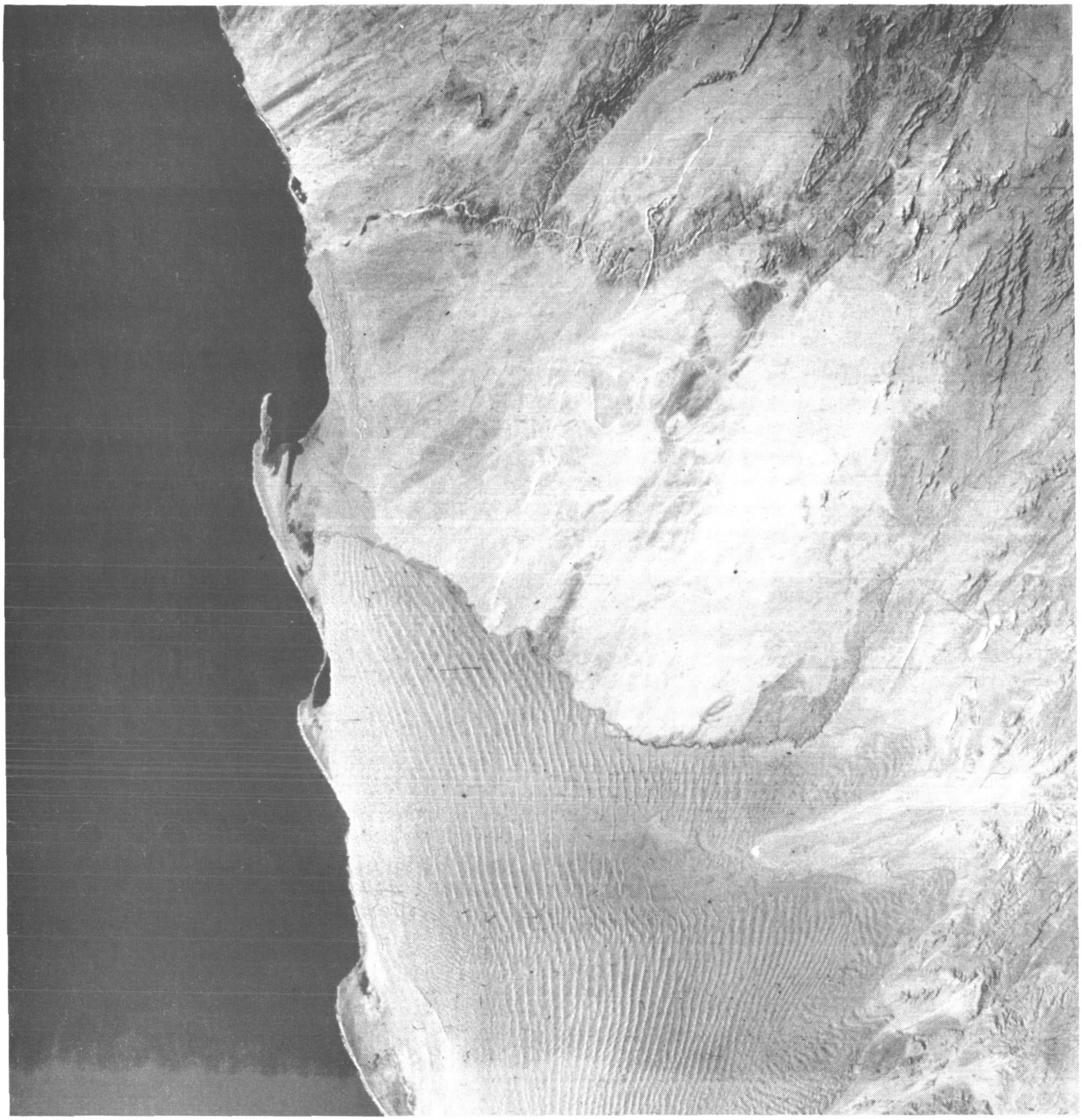

Fig. 14 Gemini V photograph of South-West Africa, vicinity of Walvis Bay (left center). Linear features in bottom half of picture are sand dunes, bounded on north by Kuiseb River. Area north of Kuiseb River is underlain by Precambrian metasediments of the Khomas and Hakos series, intruded by Precambrian granites and by Karoo dolerites.

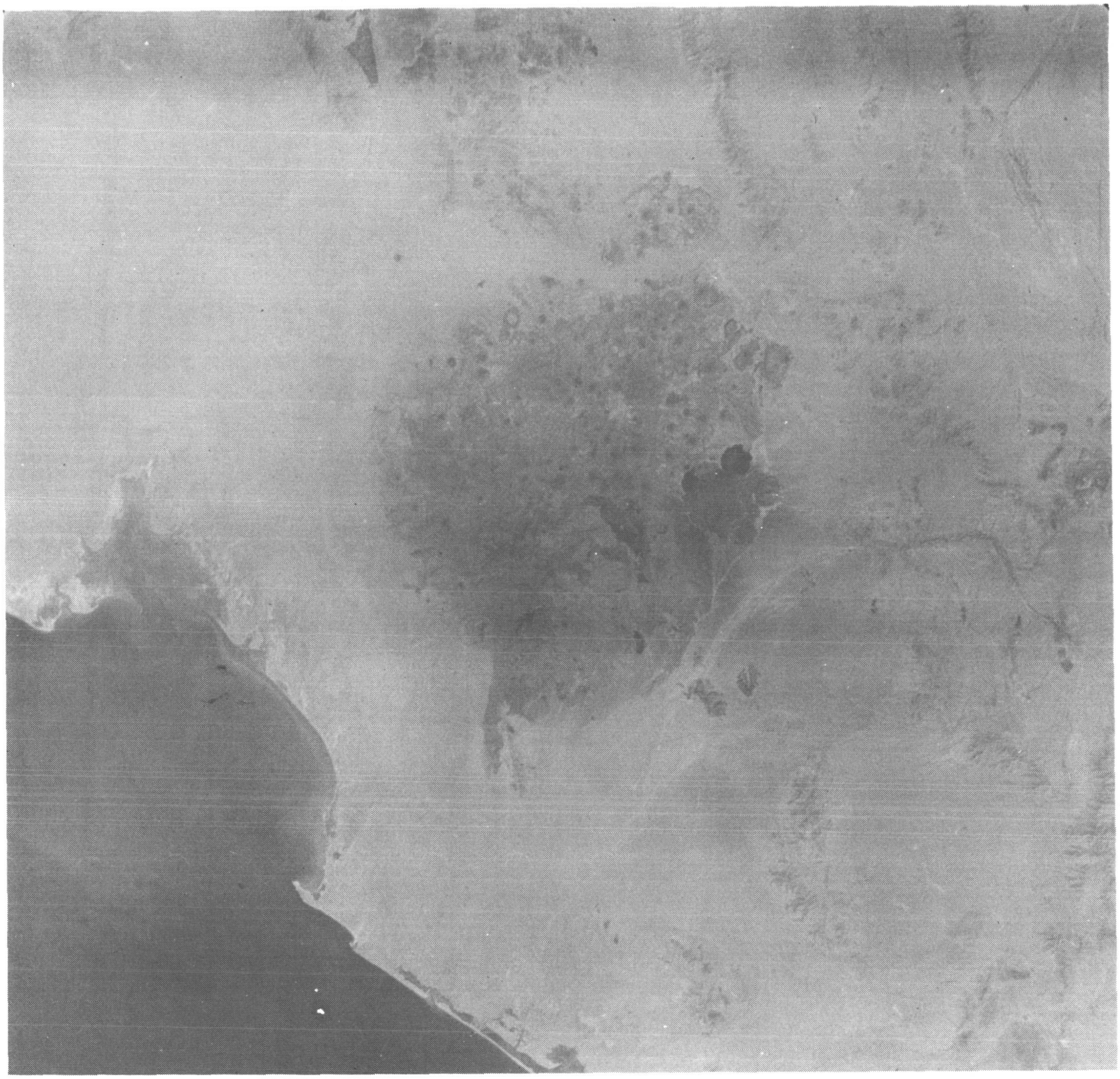

Fig. 15 Gemini IV photograph, taken about 10 seconds after Fig 4, covering part of northwestern Sonora and Southwestern Arizona. Mexico - United States border cuts photo diagonally in upper right corner. In Arizona, linear ranges are underlain by Mesozoic metamorphic rocks, intruded by Mesozoic granites and overlain in places by Quaternary basalts. Sierra del Pinacate, a Quaternary volcanic field, in center of photo.