N68-27615

X-644-68-228

nasa cr 63244

GEOLOGIC ORBITAL PHOTOGRAPHY: EXPERIENCE FROM THE GEMINI PROGRAM

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JUNE 1968

GSFC

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ABSTRACT

Most of the Gemini flights carried a terrain photography experiment, whose objective was to obtain small-scale color photographs, with 70 mm hand-held cameras, of selected land and ocean areas for geologic, geographic, and oceanographic research. The experiment was highly successful, with nearly 1100 usable pictures being returned. This paper describes the terrain photography experiment, presents specific geologic applications of the Gemini pictures, and discusses the advantages and disadvantages of geologic orbital photography.

Equipment used for the terrain photography included Hasselblad 500-C and SWC cameras, and the Maurer 70 mm Space Camera, with 38 mm, 80 mm, and 250 mm focal length lenses. Most pictures were taken with Ektachrome; also used were Anscochrome D-50 and Ektachrome Infrared film. Haze filters were used with the Hasselblad cameras.

Specific geologic applications of the Gemini photographs include: (1) study and remapping of part of northern Baja California, Mexico, in the vicinity of the Agual Blanca fault, (2) study of the tectonics and geology of northern Chihuahua, Mexico, in the vicinity of Palomas, (3) unsuccessful search for the Texas Lineament, (4) study of a regional dune-fracture pattern surrounding the Tibesti massif in Chad and Libya, and (5) study of the theory that the Arabian Sea is a sphenochasm, formed by continental drift.

The major advantages of orbital photography, as shown by the Gemini pictures, appear to be large area per picture, global coverage, unlimited dissemination, availability of color or multispectral coverage, and wide range of scales. Major disadvantages, compared to aerial photography, include difficulty of changing the flight path and of obtaining high-latitude coverage, the necessity for continual spacecraft orientation, high degree of global cloud cover, daylight restrictions, resolution limits, target acquisition, film degradation due to radiation, loss of resolution and color rendition from atmospheric scattering, and the necessity of vertical or near-vertical camera orientation. All of these problems can be overcome if mission planning and spacecraft design allow fully for photographic requirements.

It is concluded that the geologic value and feasibility of orbital photography have been demonstrated. The most promising geologic uses of orbital photographs appear to be in regional geologic mapping, tectonics, sedimentation, planning of geological and geophysical field work, and interpretation of regional geophysical surveys.

GEOLOGIC ORBITAL PHOTOGRAPHY: EXPERIENCE FROM THE GEMINI PROGRAM

INTRODUCTION

The potential geologic value of photography of the earth from space has been recognized since high-altitude pictures from sounding rockets became available after World War II (Merifield, 1963; Lowman, 1964; Garcia, 1966). Project Mercury Astronauts W. Schirra and L. G. Cooper performed the first orbital photography specifically for geological purposes in 1962 and 1963 (O'Keefe, et al., 1963). Study of these and other hyperaltitude photographs led to the proposal for a Synoptic Terrain Photography Experiment for the Gemini Program. The experiment was carried out by astronauts on most of the Gemini flights with remarkable success (Gill and Foster, 1968), and in fact all but the aborted (though successful) Gemini VIII flight produced some geologically useful photographs.

Study of these pictures, of which there are nearly 1100, has produced considerable information of inherent value. From a broader viewpoint, the Gemini terrain photography is of great value as the first major attempt at systematic geologic studies of the earth conducted from orbiting spacecraft. The purpose of this paper is, first, to describe the objectives and results of the terrain photography experiment and, second, to summarize the major conclusions which can be drawn from it as to applications, advantages, disadvantages, and planning of orbital photography for geologic purposes.

THE SYNOPTIC TERRAIN PHOTOGRAPHY EXPERIMENT

The objective of the Synoptic Terrain Photography (S-5) experiment (Lowman, 1966) was originally to obtain high-quality, small scale color photographs of selected parts of the earth's surface for geologic study. However, the striking quality and coverage of the pictures obtained during the Gemini III, IV, and V flights demonstrated the usefulness of such photography in other fields. Accordingly, the scope of the experiment was expanded from Gemini VII on to include areas of geographic and oceanographic interest as well. Meteorological photography was covered by the Synoptic Weather Photography (S-6) Experiment, which used the same cameras and films; principal investigators for this experiment were K. M. Nagler and S. D. Soules of the Environmental Science Services Administration. It should be pointed out here that the S-5 and S-6 experiments were only two of a total of fifty-two experiments carried on the various Gemini flights (Foster and Smistad, 1968). Furthermore, these were strictly subsidiary to the main objectives of the Gemini Program, which were essentially to develop the capability for long, complex space missions (Mueller, 1968).

EQUIPMENT, CREW TRAINING, AND METHODS

Three 70 mm hand-held cameras were used during the 10 manned flights for operational, weather, and terrain photography (Thompson, 1967; Underwood, 1968):

1. Hasselblad 500-C – This camera, modified for space use by Cine Mechanics, Inc., and equipped with a 65-frame capacity magazine built by Cine Mechanics, Inc., was the basic camera for most terrain photography. The lens used for most pictures was the standard 80 mm Zeiss Planar; a number of pictures were taken on Gemini VII with the 250 mm Zeiss Sonnar telephoto lens.

2. Maurer Space Camera – This camera was developed especially for astronaut use, and could accommodate a wide variety of components. Terrain photography with the Maurer was done with the 80 mm Schneider Lens.

3. Hasselblad Super Wide Angle – The 90° field of view of the Zeiss Biogon lens made this camera useful for general purpose photography, but a large number of good terrain photographs were also taken with it despite the short (38 mm) focal length. It was used with the same magazine as the Hasselblad 500-C.

The Hasselblad cameras, when used with color film, were fitted with haze filters (Haze 50 or 63) cutting off light below 3400 A. When used with Ektachrome Infrared, they were fitted with infrared filters cutting off light below 5000 A. No filters were used for terrain photography with the Maurer 70 mm camera.

During the Gemini V flight, the Surface Photography Experiment (D-6) was carried out. Equipment used included a Zeiss Contarex camera and a 200 mm Nikkor and 1270 mm Questar lenses. The objective of the experiment, to acquire, track, and photograph objects on the ground, was accomplished (Ballentyne, 1968), with a number of high-resolution pictures being returned. Although not related to the terrain photography experiment, the D-6 results are of interest because they demonstrate the feasibility of obtaining relatively large-scale photographs from orbit.

The majority of terrain pictures were taken with Ektachrome S.O. 217 or S.O. 368. One magazine of Anscochrome D-50 was used on Gemini V. Ektachrome Infrared, Type 8443, was used on Gemini VII.

The equipment, films, and other pertinent data are summarized in Table 1.

Because of the many types of photography required of the astronauts during the Gemini Program, they were intensively trained in this subject by the Photographic Technology Laboratory. For the terrain photography, the crews were given one or two briefings covering the following subjects:

1. Experiment objectives: These were as stated previously. In briefings for later flights, some time was devoted to summarizing progress to date, with examples of good and bad photography from previous missions.

2. Areas to be covered: With the aid of flight path maps (Fig. 1), the areas desired were discussed in order of priority, with as much time as possible being spent on the geologic reasons for studying each region. For example, considerable weight was put on the African Rift Valley because of its geologic importance, size, and possible relation to continental drift. In all briefings, it was stressed that good pictures of any land area would be of value if planned areas could not be covered because of clouds or other reasons.

3. Techniques: The crews were requested to take vertical pictures at 5 second intervals to obtain 25-mile separation between photographs and roughly 60% overlap at normal altitudes (generally between 100 and 200 statute miles). Recommended time for photography was local noon plus or minus three hours, to avoid having to change camera settings, which were generally f 11 at 1/250 second for Ektachrome. Measures to avoid stray reflections and scattering from the windows were also discussed.

The crews followed the planned procedures as much as possible; their skill and perseverance in this is demonstrated by the quality and quantity of the pictures returned. Three main problems were encountered. First, fuel or electrical power restrictions (preventing use of the inertial platform) frequently prevented the crew from pointing the spacecraft straight down; because of this, many of the terrain pictures are high obliques. Second, cloud cover, especially on the shorter missions, frequently obscured the primary areas. Finally, window obscuration by deposits from boost phase ablation, rocket exhaust during staging, and window gasket degassing degraded some pictures. This problem was especially severe on Gemini VII.

RESULTS OF THE TERRAIN PHOTOGRAPHY EXPERIMENT

The terrain photography experiment was highly successful, thanks to the skill and perseverance of the astronauts and supporting personnel. Nearly 1100

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. On Gemini X, an altitude of over 450 statute miles was achieved on some revolutions.

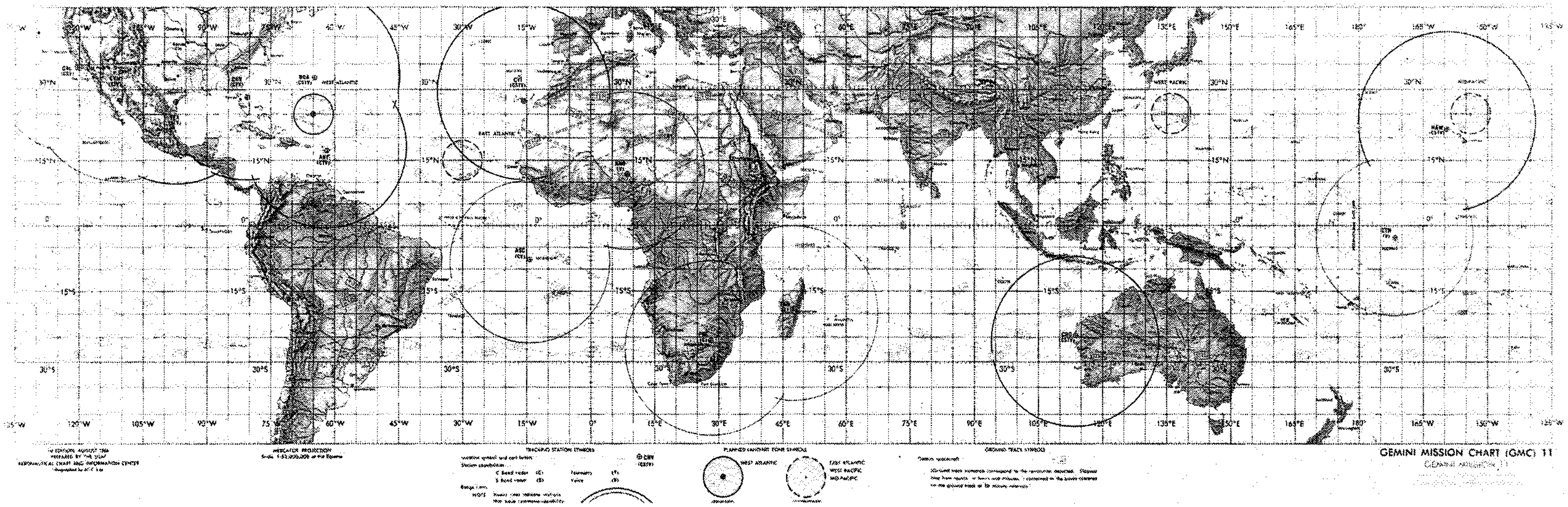

Figure 1–Typical Gemini flight path map, showing areas covered during a 24-hour period. Note latitude restrictions and separation of adjacent flight path segments.

pictures usable for geologic, geographic, or oceanographic study were obtained. Some pictures of all the major areas requested were obtained; some of the areas, such as the northern end of the Red Sea, were repeatedly photographed. Others were photographed at high tilt angles. Some of the smaller areas, such as certain oceanic islands, were not covered. A condensed summary of the results is presented in Table 1.

Dissemination of the pictures has been a difficult problem, especially in view of the high cost of color prints. Most of the usable pictures from Gemini III, IV, and V have been published in "Earth Photographs from Gemini III, IV, and V," NASA Special Publication 129, available from the Government Printing Office, Washington, D.C., for $7.00. A second volume containing selections from the remaining flights is in preparation. A collection of sixty-eight Gemini photographs was published by Lowman (1968). Dissemination of color transparencies and black-and-white prints to scientific organizations is the responsibility of the National Space Science Data Center, Code 601, Goddard Space Flight Center, Greenbelt, Maryland 20771.

A discussion of all the usable terrain pictures would obviously be beyond the scope of this paper; in addition, interpretation will take several years of work. Therefore, a few selected pictures will be presented and their geologic content summarized in some detail.

GEOLOGIC APPLICATIONS

The photograph in Figure 2 was the first in a spectacular series of 39 overlapping pictures taken on the Gemini IV mission by J. A. McDivitt and E. H. White which is at this time the longest continuous strip taken from manned spacecraft. It shows several thousand square miles of northern Baja California, Mexico, in which a number of major geologic features are visible. This picture and the three succeeding have been used to prepare a geologic map with 1:250,000 scale by F. Garcia, Consejo de Recursos Naturales Non-Renovables, Mexico.

An aspect of special interest in this picture is the synoptic view it provides of the regional geologic structure. The pronounced lineament at lower left is the Agua Blanca fault, discovered only as recently as 1956 by Allen, Silver, and Stehli (1960), although it is one of the most prominent tectonic features in Baja California. The Gemini picture reveals that the Agua Blanca fault is one of a series of at least 3 and probably more faults with similar trend. Furthermore, it appears that, although Allen, et al, describe the Agua Blanca fault as a right lateral wrench fault, its companion to the north has little if any noticeable lateral displacement. Evidence for this conclusion lies in the circular feature, underlain partly by a granite pluton and partly by Cretaceous sedimentary rock.

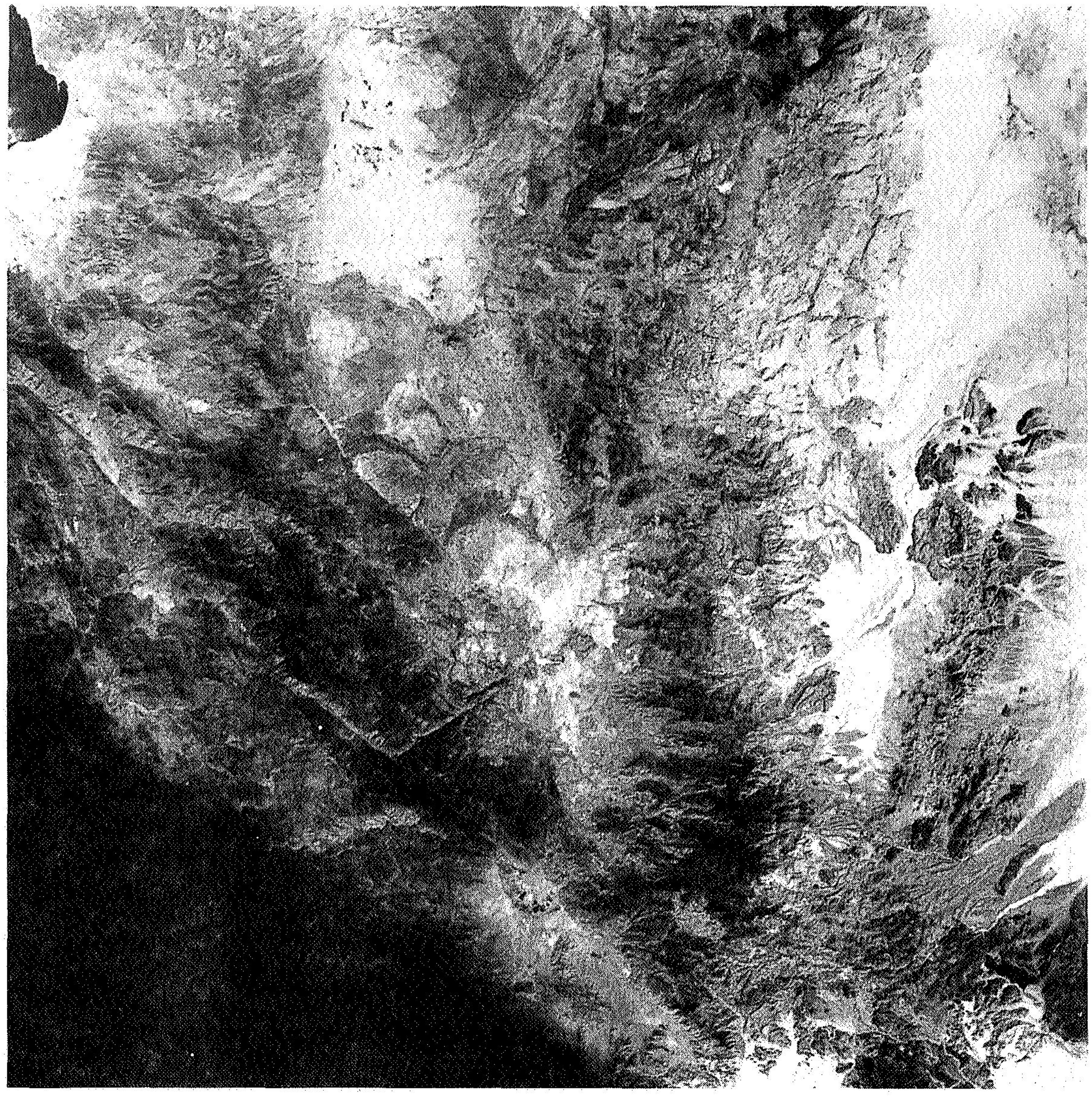

Figure 2–Northern Baja California, Mexico, showing an area about 70 miles wide (north at top). Agua Blanca fault zone at lower left, parallel to spacecraft window. Note semi-circular pluton north of Agua Blanca fault at center. Dark areas are generally mountains, light areas valleys or coastal desert near Gulf of California. Gemini IV photo; original in color.

This outcrop pattern is consistent with vertical displacement, but the circular structure is apparently not offset laterally.

The usefulness of orbital photographs in revising geologic maps and in studying regional structure is demonstrated by Figure 3 (Palomas), a later picture in the overlapping series by McDivitt and White (Lowman, McDivitt, and White,

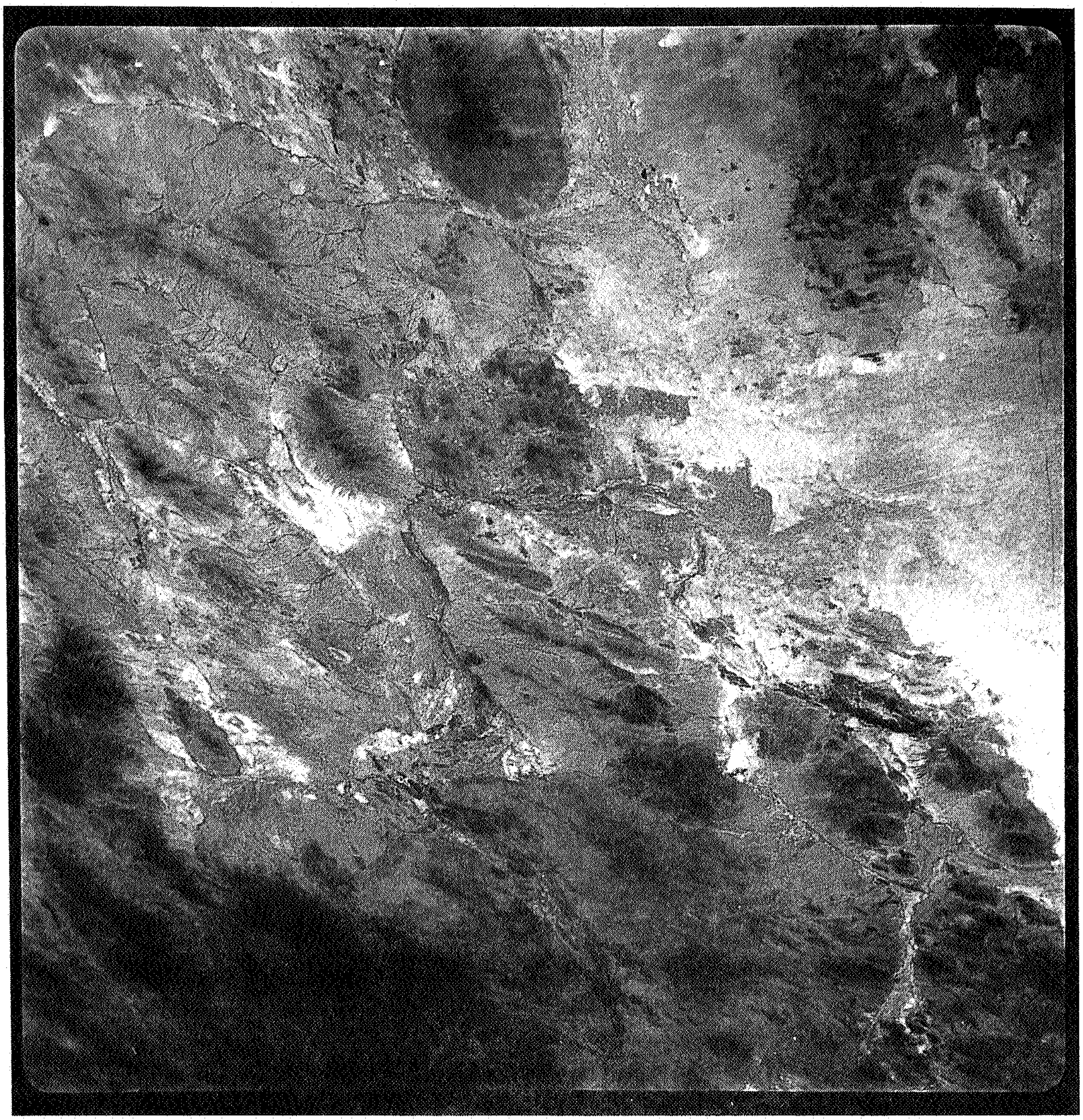

Figure 3–Northern Chihuahua, Mexico, and southwestern New Mexico, showing an area about 70 miles wide at the top of the picture (north at top). Palomas volcanic field at center; West Potrillo Mountains volcanic field at upper right. Note gradation of structure from folded mountains at lower right to block-faulted mountains at upper left, trending about N60° W. Tres Hermanas Mountains are just north of the Palomas volcanic field, and the Florida Mountains are just north of them, at top center; both are surrounded by conspicuous pediments. Gemini IV photo.

1967). This photograph shows part of southern New Mexico and northern Chihuahua, Mexico. One of the most conspicuous geologic features on it is the large volcanic field in the center, which will be referred to as the Palomas volcanic field, although some maps show it as the Sierra Carizarilla. This feature is not shown on the most recent geologic map (1965) of North America, although it is about 15 miles in diameter, similar in size to other Quaternary volcanic fields which are shown. There is no mention of it in a pertinent reference (Griswold, 1961) covering the geology of Luna County, New Mexico, although some of the volcanics just over the American border are clearly related to the Palomas field. In a sense, then, this prominent feature can be said to have been discovered by orbital photography. Field and aerial reconnaissance by the writer and H. A. Tiedemann have confirmed the volcanic nature of the Sierra Carizarilla; preliminary petrographic study indicates the rocks to be a uniform olivine basalt.

This picture also provides considerable insight into the regional structure. Perhaps the most striking tectonic characteristic of the area is the continuous gradation from folds (lower right) in the extension of the Sierra Madre Oriental to the faults (upper left) of the Basin and Range Province in the various ranges of New Mexico. This implies considerable control of the faulting by pre-existing fold axes in the latter area, as proposed by Jones (1961). In addition to the concordance of fold and fault trends, however, a comparison of this picture with geologic maps of the area shows that the folds are largely confined to the folded Mesozoic sedimentary rocks and the faults to areas of Tertiary volcanics. This tends to support Mackin's (1960) hypothesis that the block faulting of the Basin ranges is the result of crustal subsidence following the immense ignimbrite eruptions of the Tertiary.

Still another aspect of the tectonic pattern revealed by the Gemini photograph related to the Texas lineament (Moody and Hill, 1956), a major fault system believed to extend in a N60°W direction from western Texas through El Paso into California. Study of this and adjoining photographs in the Gemini IV series reveals no definite evidence of a single lineament west of the Quitman Mountains, some 75 miles south-east of El Paso. For example, the West Potrillo Mountain volcanoes show no evidence of a N60°W alignment; they appear instead to be at least partly controlled by fold axes (Merifield, 1964). Furthermore, there is no evidence to support Griswold's (1961) suggestion that the Texas lineament passes between the Florida and Tres Hermanas Mountains. There is, however, a dominant fault trend of N60°W in these and other nearby ranges which is the "Texas Direction" suggested by Moody and Hill (1956), although the influence of fold axes on this direction, shown on the Gemini photographs, implies that north-south compressional stresses alone are not the only cause of this direction.

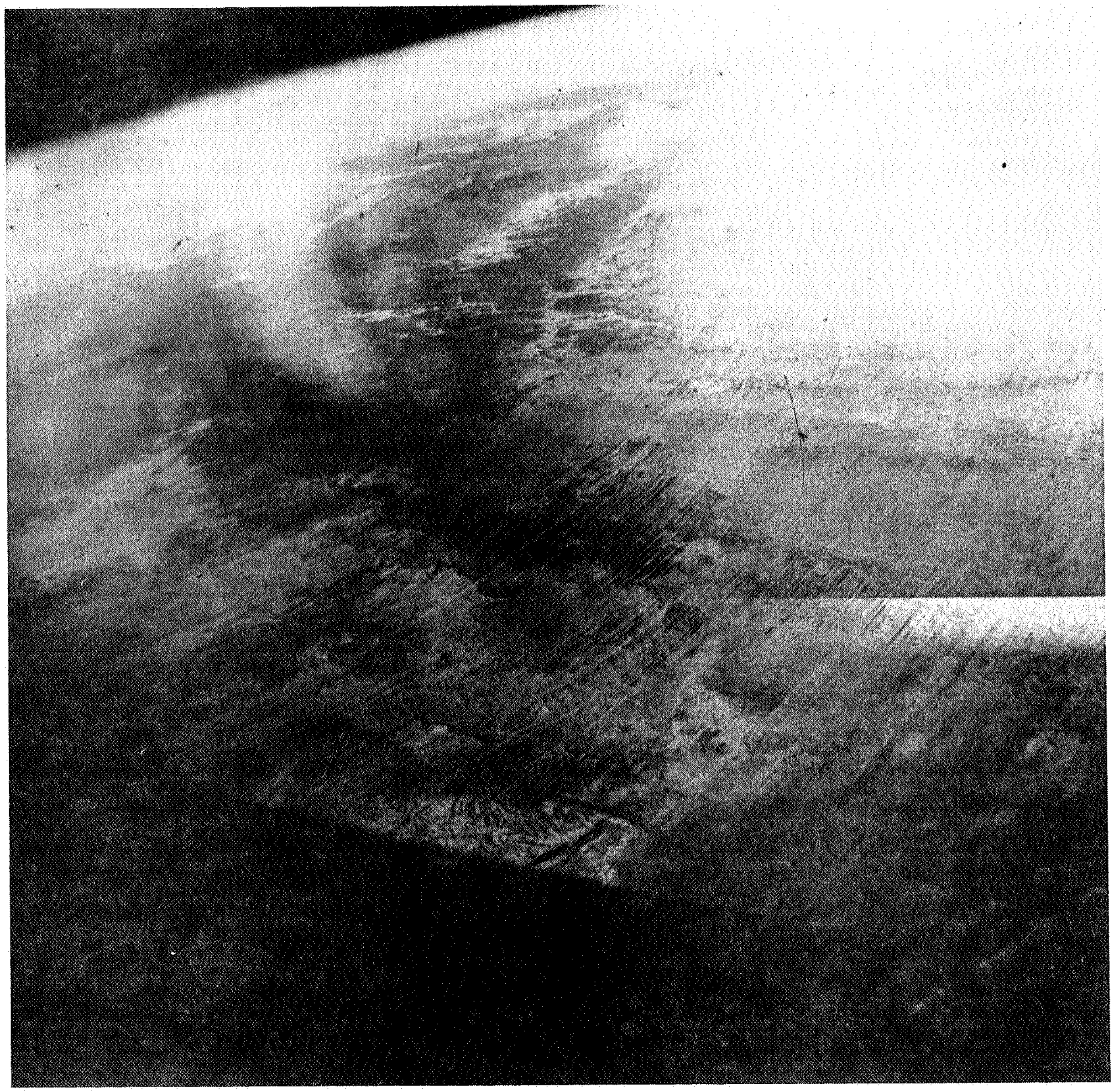

Figure 4—North-central Africa, looking toward the north-west over Libya, Chad, and Egypt. Tibesti Mountains, with Emi Koussi, at left. Concentric pattern in foreground believed to be combined erosion and dune features. Circular feature at center is unknown structure discussed in text. Gemini IV photo.

Finally, it should be pointed out that this photograph provides an excellent synoptic view of pediments in this area, and should be valuable in studying the relation of pediment formation to structure, rock type, and other geologic factors.

Because of the generally good weather over North Africa, as well as the geometry of the flight paths, this area was extensively photographed during various Gemini flights. Figures 4 and 5, though not photogrammetrically the

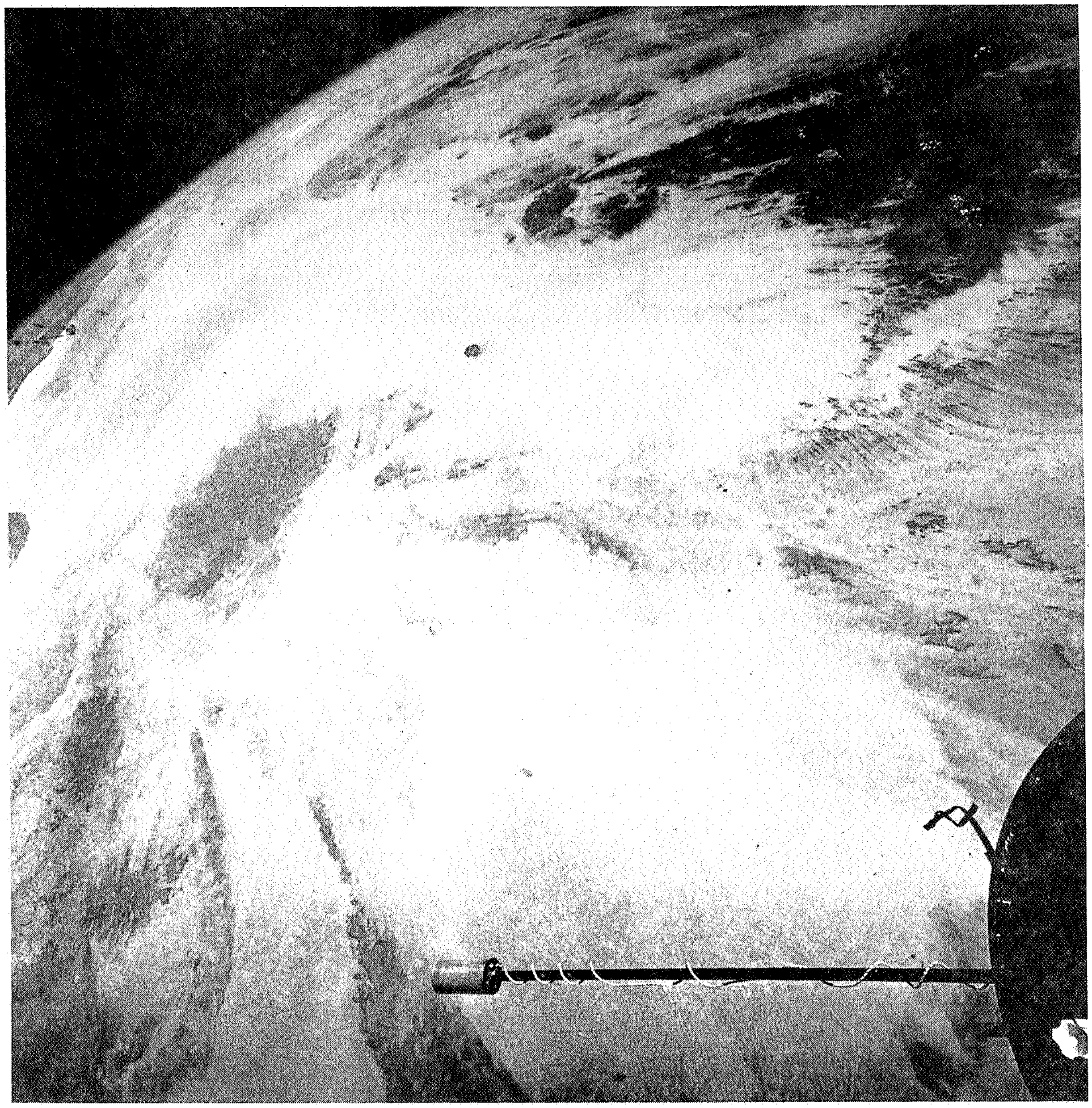

Figure 5—North-central Africa, looking toward the north-east, over Libya, Chad, and Egypt; Mediterranean Sea at upper left. Marzuq Sand Sea at lower right; Haruj al Aswad (Recent volcanic field) at left center. Tibesti Mountains at upper right; note concentric ridge and dune features. Gemini XI photo.

best of these pictures, are of considerable geologic interest. Figure 4, taken on the Gemini 4 mission, attracted immediate attention because of the striking linear pattern shown southeast of the Tibesti Mountains. Later pictures, such as Fig. 5, clarified the nature of this pattern, whose true extent and shape is not shown on even recent topographic maps such as the Largeau 1:1,000,000 sheet of the Institut Geographic National (Paris, 1961). It appears to be a composite feature, consisting primarily of fractures enlarged by the prevailing winds, which have also produced linear sand dunes in some places. Grove (1960) illustrates features northwest of the Tibesti Mountains which, on air photos, appear similar. The regional extent of the fracture pattern surrounding the Tibestis appears to have been unsuspected. In accordance with the findings of Lattman and Nickelson (1958) and Wobber (1967), the fractures are interpreted as joints, probably formed by tension during the uplift of the Tibesti massif. It is interesting to speculate on the possible connection between this uplift and the generation of magmas which formed the extensive Quaternary volcanic fields; one is reminded of Rich's "magma blister" hypothesis, Von Haarman's "geotumor," or King's "cymatogeny" (1967).

Another intersting structure revealed on Figure 4 is the circular structure east of the Tibesti Mountains. Although shown on the Largeau sheet as a series of concentric sandstone ridges about 9 miles in diameter, there is no mention of it in the geological literature, such as Gerard's (1958) report on the geology of Chad. Since undiscovered impact structures have been one of the objectives of the terrain photography experiment, this feature was immediately suspected. An igneous origin (e.g., a laccolith or stock) seems more likely, in view of its proximity to the vast Tibesti volcanic field; a salt or sedimentary diapir may also be responsible. However, an impact origin should also be considered, and in particular evidence of shock metamorphism should be searched for in rock from the center of the disturbance.

Pictures taken in the vicinity of the Arabian Sea on Gemini IV, XI, and XII have been used by Lowman (1967) to study the possibility of continental drift in this area. It has been proposed by Carey (1958) that the Arabian Sea (Fig. 6) is a "sphenochasm," or wedge-shaped rift produced by rotation of the Indian subcontinent away from the Arabian Peninsula and Africa. This theory is based partially on the belief that the Oman Range and the Kirthar and other ranges in West Pakistan are the disrupted ends of a formerly continuous structure. The Gemini photographs contradict this theory in three ways. First, they show (Fig. 7) that the Oman Range turns south at the east end of the Arabian Peninsula, rather than east, as formerly supposed. Secondly, they demonstrate the strong dissimilarity in physiography between the ranges of the two areas. Third, they demonstrate an equally strong dissimilarity in lithology, the ranges of Sind (Fig. 8) being primarily sedimentary rock of great thickness, while the Oman Range is primarily a geanticline of igneous rock mantled by relatively thin sedimentary rock. Arguments that these differences are to be expected in view of the considerable distance between the two areas can be answered by still another orbital photograph (Fig. 9) showing the prevailing continuity for great distances along strike characteristic of the Makran Ranges. It appears, in summary, that there is no close relationship between the Oman Range and the supposed corresponding ranges in West Pakistan; to the extent that continental drift in this area is based on such a relationship, the Gemini photographs tend to disprove its reality.

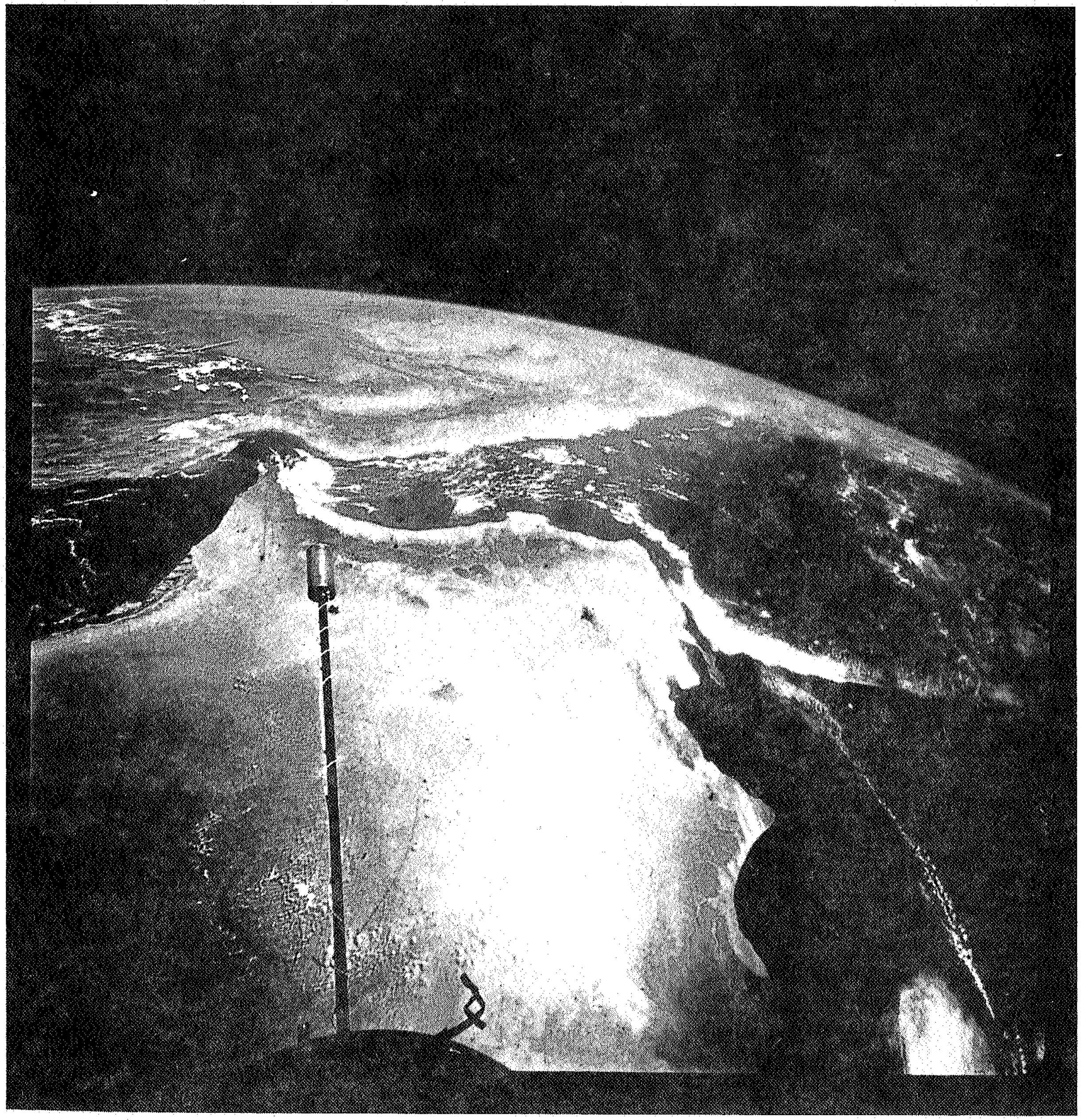

Figure 6—Eastern half of the Arabian peninsula, looking northeast toward Iran and Persian Gulf (right), Pakistan (top center), India and Arabian Sea (right). Oman Range just above Agena transponder antenna, at center. Taken from about 260 nautical miles during the high revolutions of the Gemini XI flight.

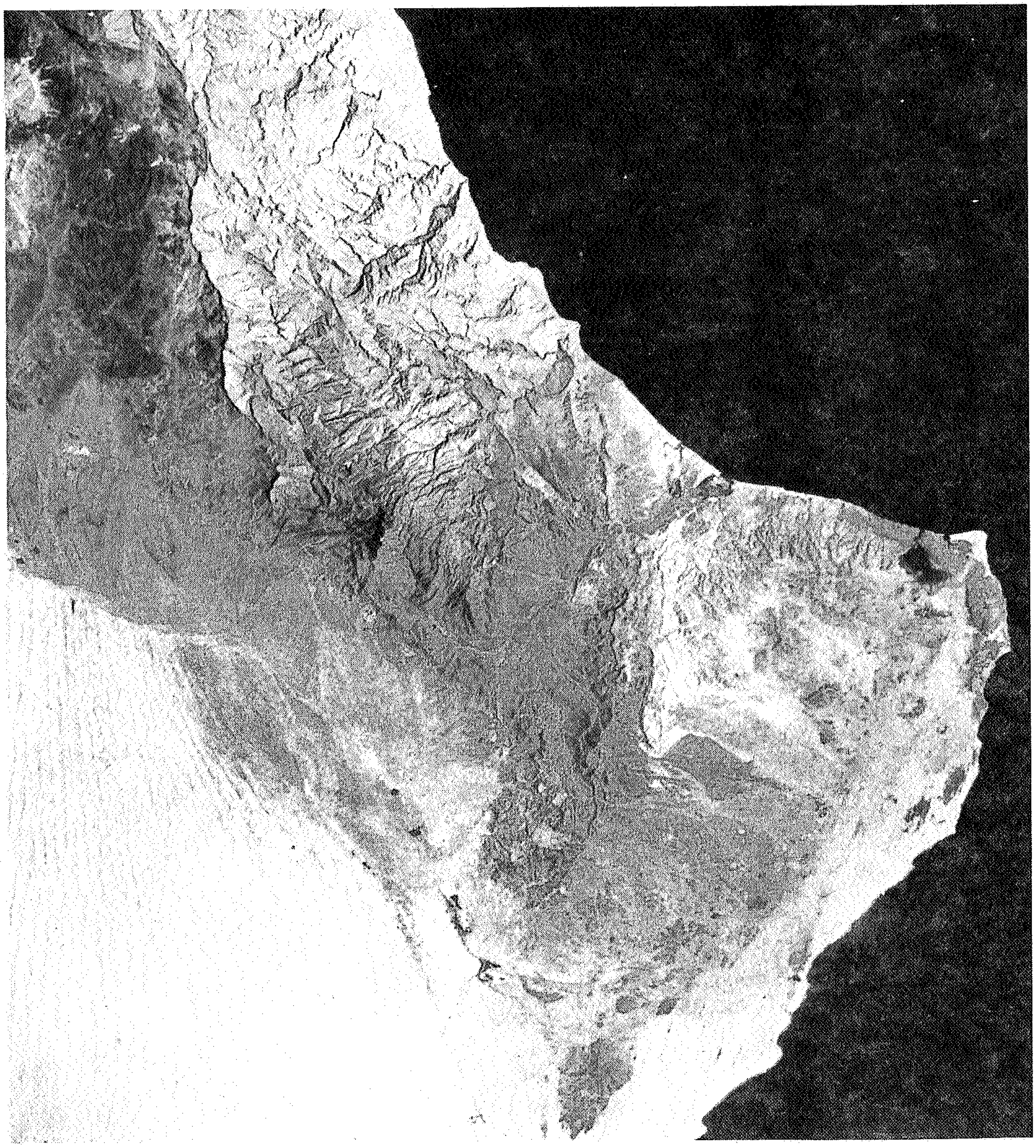

Figure 7—Eastern end of Arabian Peninsula and the Ras al Hadd; Oman Range at upper left. Wahibah Sands at lower left (North at top). Note the pronounced southward trend of the structure at Center. Gemini IV photo.

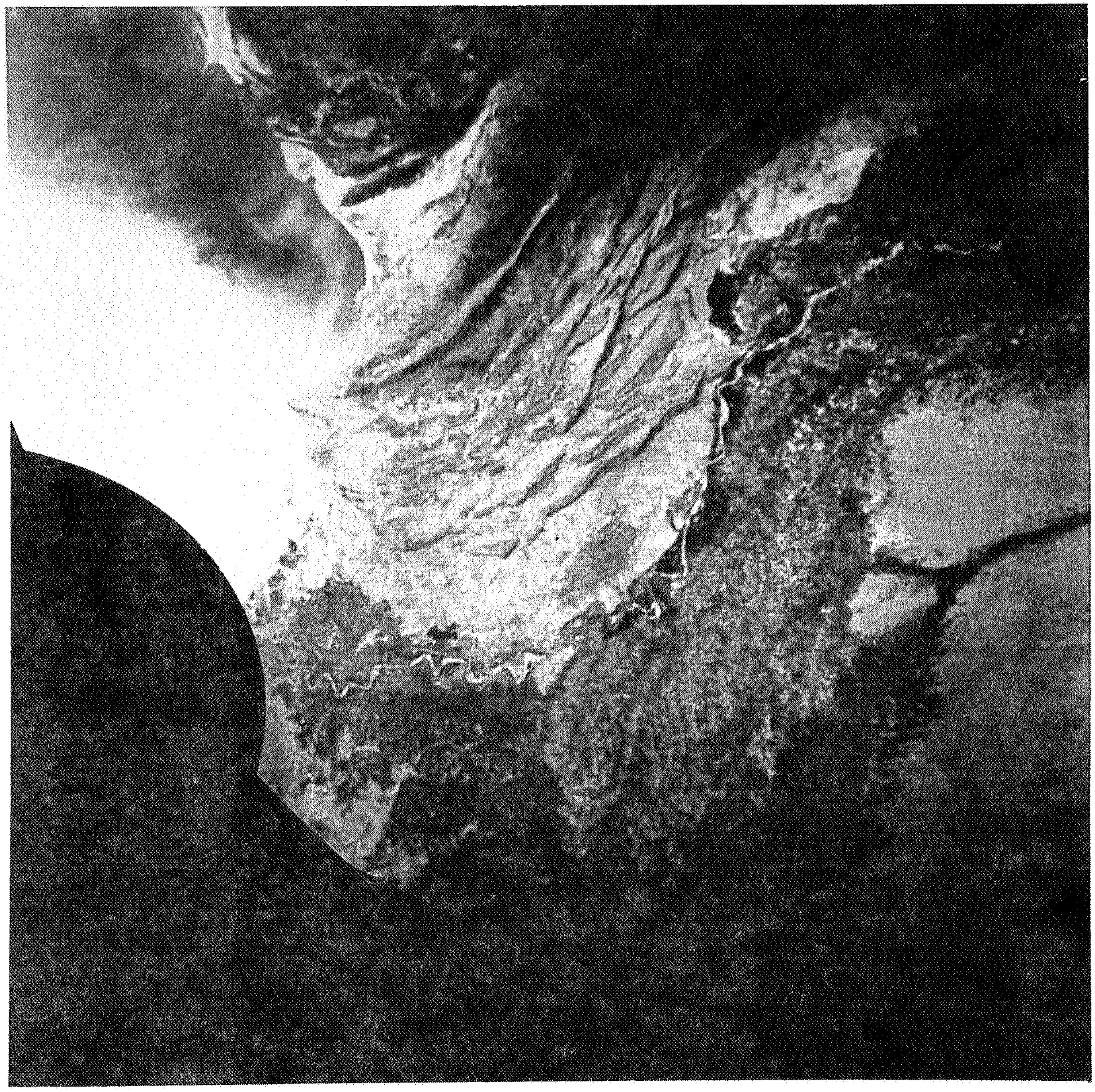

Figure 8–Kirthar Range, West Pakistan, and Indus River (right) (North at upper right). City of Karachi is the small dark spot on the coast just above the spacecraft nose. Note discordance of Kirthar Range with coast. Gemini XII photo.

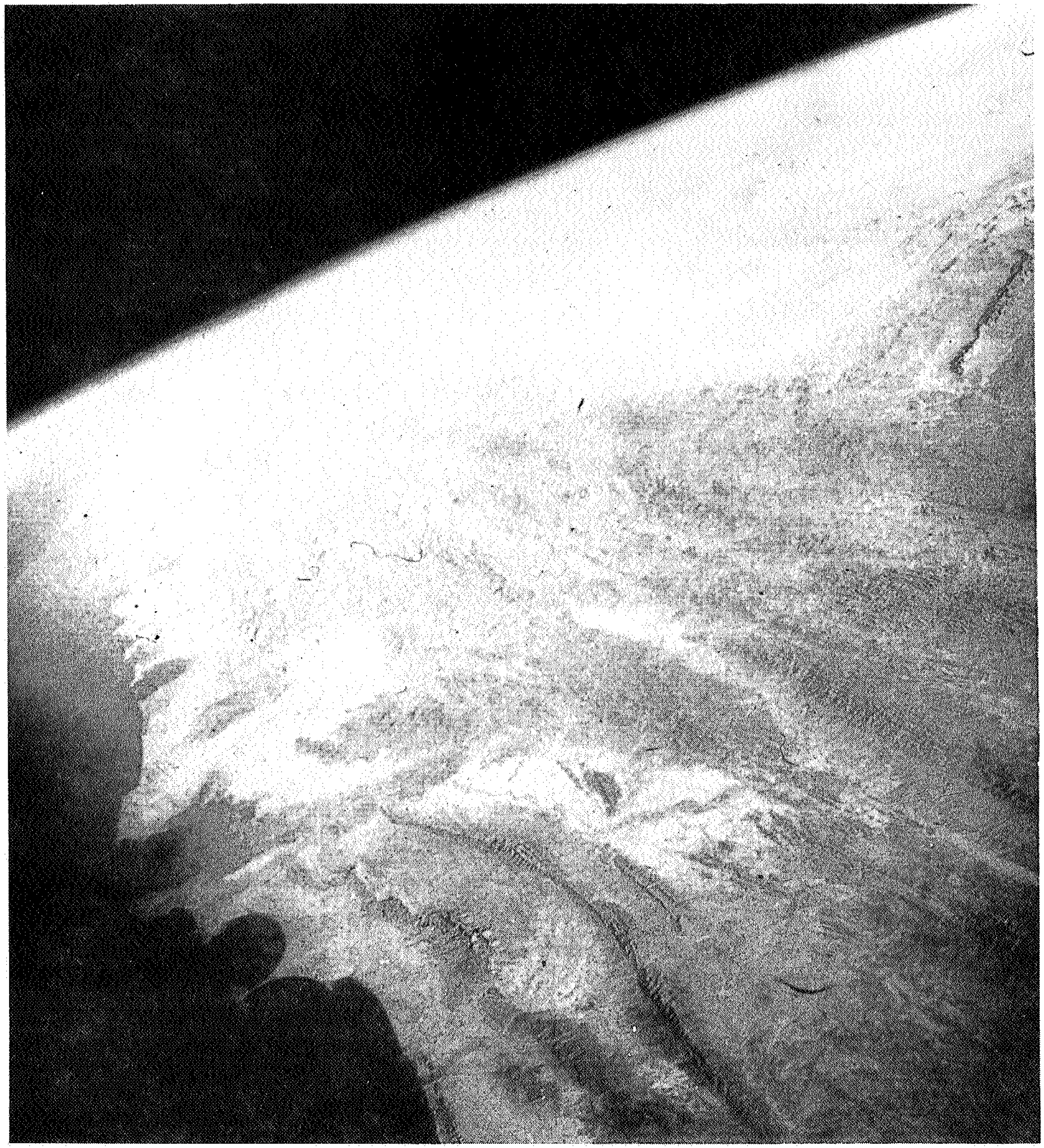

Figure 9—View to the west over the Central Makran Range, West Pakistan and Iran. Note prevailing continuity of structure along strike. MA-9 photo.

ADVANTAGES OF ORBITAL PHOTOGRAPHY

In comparison with aerial photography, orbital photography for geologic purposes appears to have the following advantages.

Large Area Per Picture

This is of course the most striking difference between photos taken from aircraft and those from spacecraft. Standard vertical air photos generally cover an area measuring roughly 3 to 9 miles on a side, whereas vertical orbital photos such as those shown here typically measure at least 70 miles on a side. The importance of this for geological studies is that it becomes possible to see on one picture large features, such as the volcanic field south of Palomas, and regional structure covering immense areas.

The question naturally arises as to whether this coverage can be duplicated with mosaics (Lowman, 1967). The answer appears to be that even if a mosaic of a given area can be prepared (and this is not possible for many remote or restricted areas, or because of the expense), the dodging necessary to remove tone differences between adjoining pictures necessarily removes considerable tonal or color information of geologic importance. Furthermore, the mosaic does not provide stereoscopic coverage of large areas as can orbital photograph pairs. Obviously, mosaics will continue to be used where possible, but it seems clear that there is no real substitute for hyperaltitude photography if large area coverage is needed.

Global Coverage

Peculiar to geology is the need to see over the next hill – or the next ocean. Many geologic problems insoluble in one area may yield quickly to studies in another area in which critical relationships are exposed. Werner's belief that basalt was a sedimentary rock arose partly from the fact that his travels were confined to the Freiberg region, where the hill-capping basalts could reasonably be interpreted as sedimentary strata. Had Werner been able to visit the Auvergne, his erroneous theory might not have been formed.

Orbital photography provides a global view of the earth's geology which will clearly prove invaluable in studies of regional tectonics, orogenesis, and continental drift, because it becomes possible to ignore natural and artificial boundaries. In the study of continental drift around the Arabian Sea just cited, the geologically crucial areas lie in several different countries, some of which are separated by major topographic, oceanic, or political barriers. Furthermore, there is no one organization charged with investigating such regional problems: for example, the Hunting Survey Corporation, whose Colombo Plan report (1961) on the geology of

West Pakistan was a major advance, could give only peripheral attention to the Oman-Pakistan problem. Orbital photography can contribute to the solution of such regional geologic questions, first, by bringing them to the attention of a large segment of the geological community, and second, by providing a synoptic view of large or widely separated areas.

Unlimited Dissemination

Most of the world's land area has been photographed at one time or another by civil, commercial, or military organizations, but much of this photography is not easily available, or is not available at all, for geologic studies. Oil companies, for example, commission considerable aerial photography, but having paid for it, are naturally not inclined to give it away. Military secrecy also prevents dissemination of much geologically valuable photography.

The situation in regard to orbital photography obtained by the National Aeronautics and Space Administration is quite different. The NASA 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." One result of this requirement is that the 70 mm photographs taken on Mercury and Gemini flights have been made available to qualified investigators from all over the world. This will clearly lead, in a few years, to a much better acquaintance with the geology of remote areas, and will help avoid provincialism in geologic education and research.

Availability of Color Coverage

It is generally realized that color aerial photography is inherently more valuable than black-and-white photography because of its greater information content. A major disadvantage of color photography, however, is its higher cost. Orbital photography may make color coverage of a large part of the world practical, for several reasons. First, the addition of color film to the photographic payload adds a negligible amount to the overall mission expense. Second, the greater coverage area per picture obviously reduces drastically the number of prints or transparencies necessary for a given area. This is probably a major advantage of orbital photography, since most of the added expense of color aerial photography is that of reproduction.

This discussion applies to multi-spectral coverage as well, which may be geologically valuable in areas where vegetation distribution provides clues to structure and lithology.

Range of Scales

Orbital photography has a one-way advantage over aerial photography in that it is easy, from altitudes of 100 miles or more, to obtain coverage with scale numbers of several million. From aircraft, by contrast, the highest scale numbers of geologically useful photography are probably on the order of 250,000, although balloon photographs with scale numbers of 700,000 have been taken (Katz, 1960). The advantage of satellite-borne cameras is that they can go down to much smaller scale numbers by the use of long focal lengths. This was demonstrated by the D-6 Experiment on Gemini V, which produced usable pictures with scale numbers between 50,000 and 100,000 using a 56-inch focal length (McKee, 1966). In principle, then, although scale and resolution are not perfectly reciprocal (Katz, 1960), orbital photography can duplicate aerial photography to a considerable degree, while the reverse is true only to a very limited extent.

This conclusion should not, of course, be considered a recommendation that spacecraft replace airplanes for photography; it does, however, indicate the inherently greater versatility of orbital methods.

DISADVANTAGES OF ORBITAL PHOTOGRAPHY

It is unfortunately easy to fall into the habit of unconsciously thinking of spacecraft as remarkably fast, high-flying airplanes. Such thinking tends to obscure certain real limitations of orbiting spacecraft as camera platforms, such as the following.

Orbital Characteristics

For photography, the major difference between spacecraft and aircraft is that the spacecraft flight direction (relative to the earth) is primarily determined, after injection into orbit, by the laws of celestial mechanics, whereas an aircraft can fly in any direction and can change this direction as often as necessary. This point cannot be over-emphasized, since, as Harman, et al, (1966) point out, proper choice of flight direction is vital to efficient photography. Slight changes in spacecraft direction (orbital plane changes) can be made, but are extremely expensive in terms of fuel; for example to make a 2° plane change from a 100 mile altitude requires a velocity change of about 1000 feet per second. Altitude changes, on the other hand, are relatively less expensive if accomplished by coplanar orbital transfer.

Among the orbital parameters affecting photography of the earth are the apogee and perigee heights and the ellipticity. The effects of altitude on scale need no elaboration here. However, it may be pointed out that, because of atmospheric drag, the lowest practical earth satellite altitude is about 100 miles. Below this, the satellite will re-enter within a few hours at most.

Probably the most important orbital characteristic of concern here is the inclination of the orbital plane to the equator. This is equal to the latitude coverage; e.g., an orbit with 32° inclination will cover a latitude band between 32° north and south of the equator. Low inclinations of this order were typical of the Mercury and Gemini flights, and are the reason for the relatively restricted geographic coverage of their photography. High inclinations are clearly desirable for efficient photography, but are not easy to attain for several reasons. First, a launch in any direction but due east loses some of the potential extra velocity added by the earth's rotation (about 1500 feet per second at the equator). Second, range safety requirements for some sites restrict launch azimuths; rockets launched from Cape Kennedy, for example, must use a corridor between azimuths of 45° and 108°. As pointed out previously, moreover, plane changes can be very expensive in terms of fuel requirements. To give a pertinent case: to increase the latitude coverage of a spacecraft launched into a 30° inclination orbit 5°, by a plane change from a 100 mile circular parking orbit, would require energy equivalent to a velocity increase of about 2000 feet per second. Gaining the additional 5° by launching more nearly north, on the other hand, would require only a few hundred feet per second equivalent velocity change (from loss of the increment from the earth's rotation), but range safety requirements set limits to this approach from some sites. The USAF Western Test Range at Point Arguello, California, permits launches due south, and for this reason is used for polar and retrograde orbits.

The implication of the foregoing discussion for orbital photography of the earth is that latitude requirements must be factored into mission planning from the very beginning, since they will strongly affect major decisions such as choice of launch site and type of vehicle.

Another photographic problem arising from the characteristics of satellite orbits is that of obtaining sidelap. The difficulty arises from the fact that the minimum orbital period of a photographic satellite is around 90 minutes, during which time the earth will rotate eastward some 22°; for low-inclination orbits, nodal regression caused by the equatorial bulge will increase this westward movement of the flight path. As may be seen from Fig. 1, the resulting separation of adjoining flight lines was between 800 and 900 miles for Gemini orbits, and for swath widths of about 80 miles, typical of the 70 mm photography on these flights, precluded sidelap over most of the latitude band covered. There are compensating factors, such as the convergence of flight lines at higher latitudes, and the intersection of flight lines near the top of the latitude band and other points (Fig. 1). Furthermore, the use of wide-angle systems will increase the swath width, although as will be discussed under "Camera Orientation," the valu of oblique photography from orbital altitudes is questionable. A useful example of the allowance that must be made for sidelap in mission planning is presented by Bock and Lane (1967). A technique for obtaining low-latitude sidelap is to design the spacecraft orbit so that it does not complete an integral number of revolutions in 24 hours, and hence does not follow precisely the same path (John Thole, personal communication).

Spacecraft Orientation

Unlike airplanes, orbiting satellites have relatively little inherent tendency to maintain a particular orientation, but can roll, pitch, and yaw rather freely if no measures are taken to prevent this. The problem of spacecraft orientation for photography was a severe one on Gemini flights because of restrictions on thruster fuel or power for the inertial platform, and many of the photographs were taken during drifting flight. The importance of orientation for systematic photography requires some discussion of the topic; for a general description of satellite attitude control, see Corliss (1967). The Gemini systems are described by Carley, et al (1966).

A wide variety of attitude control systems are available, using gas jets, momentum storage, the gravity gradient, magnetic field torques, and spin stabilization. Gas jets and momentum storage devices such as flywheels appear to be the most promising for photographic missions, providing fast, accurate spacecraft orientation. Nimbus I, for example, was stabilized to within 1° in all three axes. However, both have limited lifetimes because of the gas supply (most momentum storage devices use an auxiliary pneumatic system), which must be allowed for in mission planning.

A more general orientation problem is the conflict among attitude requirements. A large spacecraft, for example, may have to keep solar panels turned toward the sun and may carry other experiments with individual pointing needs which will not necessarily coincide with the photographic requirements. This particular problem is a strong argument for unmanned, single-purpose photographic satellites, such as the Tiros series.

Cloud Cover

Orbital photography shares the problem of weather with aerial photography, in particular, that of cloud cover. The earth has proven to be dismayingly cloudy when seen from orbit; it is estimated that about 50% of the earth's surface is covered by cloud at any one time. The percentage is greater, moreover, at high latitudes. Obviously, this average is meaningless when applied to any one area, but since orbital photography is global by definition, it is clear that the world cloud cover is a severe problem. As early as 1962, orbital photography of South America was prevented by clouds (Lowman, 1964).

The problem can be approached in several ways. The conventional measure of staying on the ground when the weather is too bad for photography is hardly practical for orbital photography. Another technique is to plan the mission with the aid of cloud cover statistics, as suggested by Bock and Lane (1967), and to include extra film to allow for unusable pictures. More generally, weather statistics could be used to adjust launch schedules for the best photography of large areas.

A method used on the Gemini IX-A mission shows considerable promise for future photographic missions. During the IX-A flight, cloud cover charts were prepared by the Environmental Science Services Administration from weather satellites about every six hours as an aid to recovery operations and the S-6 Synoptic Weather Photography Experiment. Personnel of the Flight Crew Support Division (MSC) noticed on these charts that South America at one time was remarkably cloud free. Knowing that photography of this area was an objective of the S-5 experiment, they notified the flight crew that an opportunity existed. Accordingly, Astronauts Stafford and Cernan took a remarkably useful series of a previously uncovered area. Since meteorological satellites are now in routine operational use, this technique should be useable for other photographic satellites, including unmanned ones if delayed ground command or real-time satellite-satellite-ground relay is feasible for areas outside the direct range of ground stations.

Daylight Restrictions

The global nature of orbital photography makes it necessary to take the availability of daylight into account; on some 4-day Gemini flights, for example, it was not possible to photograph areas south of about 10°S latitude because they were dark during possible photographic passes. For long missions, this difficulty is minimized, but allowance must be made for it and, more specifically for the suitability of sun angles. A computer program, ERSOS, has been prepared by IIT Research Institute (Bock, 1967) that takes into account not only solar illumination but also orbital elements, instrument performance, and other specifications to produce a schedule for photography during a given earth orbital mission.

Window Obscuration and Similar Problems

Slight window obscuration was noticed on terrain photographs taken by W. Schirra during the MA-8 flight, which turned out to be the first encounter with what proved to be a troublesome condition during the Gemini flights. McDivitt and White noticed, during the Gemini IV flight, a substantial coating on the left-hand window when White's boot accidentally scraped part of it off during EVA. Although it caused little loss in picture quality, a similar coating during Gemini VII (Lowman, 1966) greatly reduced the value of the pictures (Fig. 10). Post-flight investigations showed that the deposit was a combination of residues from the rocket exhaust during staging, ablation from the front of the spacecraft during the boost phase, and degassing of window gaskets.

Although various measures can be taken to protect spacecraft windows, or to clean them after injection into orbit, it appears that the best technique in the

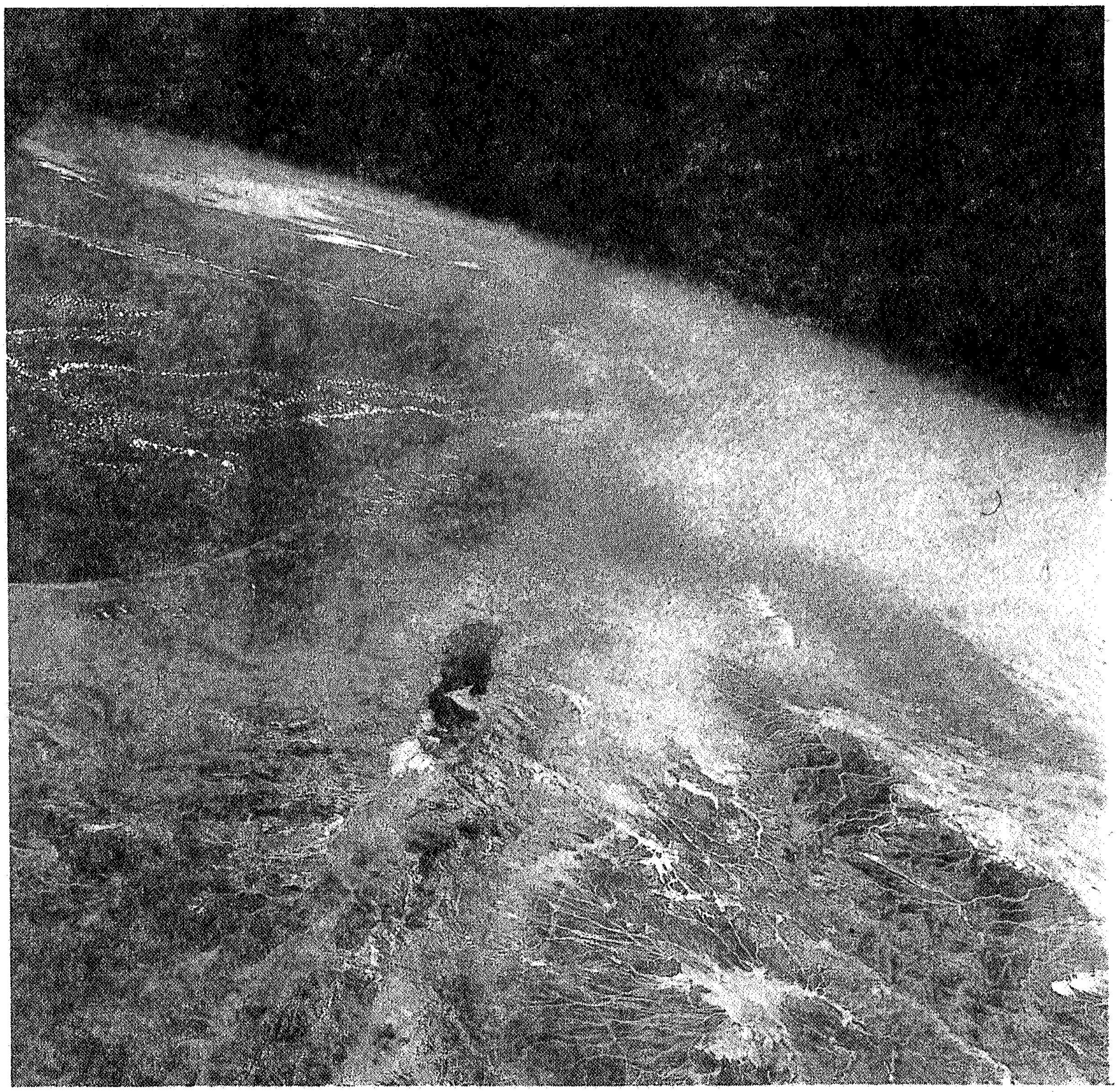

Figure 10—Gemini VII view to north over the Dead Sea, with the Mediterranean Sea at left. Prevailing haziness of photograph in center is the result of deposit on spacecraft window.

long run will be to have the cameras completely outside the spacecraft, or at least exposed directly to space, during photography. This would also eliminate the problem of restricted spectral transmission; windows on the Apollo command module, for example, do not transmit much radiation beyond about 8000 A.

A related situation that could affect orbital photography is the existence of what amounts to a transient atmosphere around spacecraft. First noticed during the MA-6 flight (Glenn, 1962), when the pilot sighted "fireflies," (later found by Carpenter (1962) to be ice sticking to the spacecraft), various solids, liquids, and gases given off by life-support systems and thrusters may stay around the spacecraft for some time. Although this has so far caused no problem during terrain photography, it obviously should be considered in spacecraft design and mission planning.

Resolution Limits

The ground resolution obtainable from orbital altitudes must obviously be relatively low compared to that of aerial photographs taken with comparable equipment, a fact which has led to skepticism about the geologic value of orbital photography. It must therefore be asked if in fact resolution limits will be a serious handicap in this respect.

First, let us examine the performance of the camera/film combination used in the S-5 experiment. According to an unpublished report by the Data Corporation, edge analysis of a Gemini IV picture taken with the Hasselblad 500-C (80 mm lens) and Ektachrome S.O. 217 film indicated a resolution of 30 lines/mm for a medium contrast target, a coastline on the Arabian Sea (Preflight laboratory tests had achieved 50 lines/mm). The ground resolution can be calculated, using this value at a typical scale number of 2,250,000, to be about 245 feet. However, many linear features with medium to high contrast, such as roads, railroads, and airport runways, as narrow as 40 feet, can easily be seen on the Gemini pictures, confirming previous experience (Katz, 1960) indicating that calculated resolution alone is not a reliable guide to the amount of detail visible in a hyperaltitude photograph.

Next, consider the geometric nature of geologic targets. Among the most important of these are edges representing contacts between major geologic units. If the units are large in area, low resolutions can be tolerated since the contact can be consistently delineated, although located with relatively low precision. A second important type of target includes lineaments (used here solely as a geometric term), which may be drainage features, dikes, or dipping strata. Here the fact that long lines are more easily detected than small objects (Katz, 1960) comes to our aid, and it is apparent from experience with Gemini photos that lineaments, even small ones, are easy to map from orbital photographs. In general, the type of targets important in geological mapping are big ones (Table 2) compared to those of interest in other fields, such as individual buildings, vehicles, or aircraft. It is clear, in summary, that resolution limits will not be a serious handicap in most geologic applications of orbital photography. However, every effort must be made to obtain the highest resolution possible without sacrificing the unique value of orbital photographs, their great coverage per picture. Larger format sizes, 9" × 9" or larger, are especially needed, coupled with focal lengths of 6" to 12". The remarkably high resolution of the Gemini photos, taken on 70 mm film chiefly with 80 mm focal length lenses, emphasizes the quality of the pictures to be expected with photogrammetrically adequate equipment.

Target Acquisition

Although the amount of ground detail visible from orbital altitude to the unaided eye has turned out to be surprisingly great, it was found that acquiring specific points on the ground can be difficult or impossible. During the Visual Acuity Experiment (Duntley, et al, 1966) on Gemini V and VI, for example, the

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 × 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

crews had relatively little trouble seeing the ground targets but found it hard to locate them first. The pilots recommended that coastlines and major rivers be used as landmarks.

A technique for finding specific objects with known positions was developed by engineers at the Manned Spacecraft Center (R. D. Mercer, personal communication). A series of curves were computed for time of closest approach of the spacecraft to any point on the earth, in space, or on the celestial sphere, from which the necessary pitch and yaw angles for aiming the spacecraft could be derived. This method can be used on future photographic missions. However, the great value of vertical photography implies that the most effective target acquisition method will simply be the orientation of the cameras straight down at a pre-determined time, so that it will be unnecessary for the astronaut to find points on the ground.

Film Degradation

Conditions tending to degrade film in orbital flight are generally similar to those encountered in high-altitude aerial photography, such as low temperature, low humidity, and static electricity discharges. The near-vacuum of space tends to accelerate drying and cracking of film on long exposure to space, but this too is essentially enhancement of an effect already encountered. The major new degrading factor in orbital photography is radiation. The subject is obviously too broad for more than a brief outline here; a review of the effects of radiation on film is given by Harvey (1965), and a bibliography of particles and fields research by Hess and Mead (1966).

There are three potentially serious sources of film-damaging radiation in orbital flight: the Van Allen belts, solar flare radiation, and radiation from sources on the spacecraft.

Radiation in the Van Allen belts is chiefly electrons and protons, trapped by the geomagnetic field, of both natural and artificial origin (the latter from high altitude nuclear explosions). It increases sharply at altitudes of between 300 and 500 miles, and slightly with increasing latitude at low altitudes. A prominent feature of the trapped radiation is the South Atlantic anomaly; partly because the earth's magnetic axis does not coincide with the rotational axis, the radiation belt over the South Atlantic Ocean is abnormally low, and dose rates may be several hundred times those outside the anomaly at a given altitude. The most obvious way of avoiding film damage from the Van Allen radiation is to keep the satellite orbit below 300 miles for missions of more than a few days, and perhaps to avoid extravehicular camera exposure while going through the South Atlantic anomaly.

Protons produced by solar flares are a sporadic but potentially serious radiation hazard. Flares occur chiefly during the maximum of the 11 year solar cycle; most are relatively mild in terms of corpuscular radiation. Because protons with energies characteristic of flare events are strongly deflected by the earth's magnetic field (i.e., have low rigidities), they are strongly latitude-dependent: for major events, the proton flux received by a polar-orbiting spacecraft would be several thousand times that received in a 30° inclination orbit. Beyond the protection of the earth's magnetic field (i.e., above several thousand miles altitude), the flux also is much greater. Because of the rarity of major flares, they should not be a serious detriment to earth-orbiting photographic missions if precautions are taken. One that seems indicated for future flights is use of the flare warning system developed for the Apollo Program to detect major events; since the protons take several hours to reach the earth, while the flare is seen (in Hα light) some 8 minutes after it occurs, it should be possible to abort the mission if necessary to avoid film damage.

A third source of damaging radiation is the spacecraft itself (such as thorium-containing alloys) or part of its payload (such as radioisotope power sources). This problem can obviously be controlled, but again emphasizes the fact that for best results, a photographic orbital mission should be planned as such from the very beginning.

The main questions remaining to be answered are just what sort of doses are necessary to damage film, and whether earth-orbiting spacecraft will encounter this much radiation. Although much more information is needed on the sensitivity of film to X-rays, gamma rays, and particulate radiation, there seems to be general agreement that one rad (roughly the absorbed dose of any ionizing radiation liberating 100 ergs per gram of absorbing material) is the threshold at which effects such as loss of resolution and contrast become detectable for black and white film. For color film (generally slower), the threshold is about 2 rads. Significant effects begin at about 5 to 10 rads for most films.

There is, of course, an immense amount of information on space radiation from the many satellites flown for this purpose. However, the crew dosimeter results from the Gemini flights (Higgins, et al, 1968), are sufficient to give a rough idea how much radiation might be encountered by reasonably well-protected film in earth orbit. The dose to the left chest of the command pilots, for flights longer than 1 day, ranged from .015 to .770 rads, the highest figure being that received on the Gemini X flight, which made several passes through the South Atlantic anomaly at about 400 nautical miles altitude. The Gemini VII mission – a two week flight at about 160 nautical miles – recorded a total dose of .192 rads. If we assume this to be typical of low altitude, low inclination flights, we see that it would correspond to a dose of about 5 rads for a one year flight. This is obviously a very rough approximation, but indicates that normal radiation should not be a serious detriment to orbital missions under these conditions, especially since the film alone could be shielded much more than were the pilots on the Gemini flights.

Atmospheric Scattering

Since orbital photography must be taken through the entire optical thickness of the atmosphere, scattering effects become important. An excellent summary of the problem is given by Harvey and Myskowski (1965); experience gained during the Gemini program is useful in determining the effects of scattering on color photography.

These appear to be more or less what might have been expected from experience with aerial photography. First, the loss of color in the blue-green region of the spectrum is considerable, even with the filters mentioned. This is largely due to scattering by moisture in the atmosphere, and since the heavily vegetated parts of the world are usually humid, there were relatively few good color pictures obtained of the major tropical forests. Color infrared was used successfully on Gemini VII, however, despite window obscuration (Lowman, 1966). Second, there was considerable loss of contrast and resolution in humid areas due to scattering.

Scattering effects do not appear to be an insurmountable difficulty to geological orbital photography, despite the Gemini experience, for several reasons. First, the colors of greatest geological importance are reds, yellows, and browns – the longer wavelengths which are not very strongly affected by scattering. Second, the best areas for any sort of geological photography are the deserts, which are characterized by dry air. Finally, the use of color infrared film, color film with enhanced red response, or multispectral cameras (Badgely, et al, 1968) promises to overcome the problem of getting good color photography in humid, heavily vegetated areas, and hence to make geologic photography practical to the extent that vegetation reflects structure and lithology.

Camera Orientation

As mentioned earlier, many of the Gemini terrain photographs were taken during drifting flight, and most are obliques with various degrees of tilt. They thus provide valuable experience in the limitations of oblique orbital photography; the main advantage of obliques, their areal coverage, is of course accentuated by the great altitudes of satellites.

Study of the Gemini pictures indicates that obliques lose a considerable amount of detail near the apparent horizon. The geometry of the situation reveals the reason for this; the slant range is inversely proportional to the cosine of the tilt, and the cosine increases very rapidly for angles over 75°. The scale numbers increase proportionately (even neglecting curvature), to values of several million, at which only very large features are distinguishable. However, with this decrease in resolution go two other non-linear effects. The thickness of atmosphere increases with the slant range, causing rapid loss of color and additional resolution loss. Also, the foreshortening becomes extreme, making it difficult to get true impressions of geometric relations, which is extremely important in geologic studies. At the present time, it appears that pictures with tilt angles much greater than about 50° are of little use geologically (except in special cases, as in searching for lineaments parallel to the line of sight) because of these effects. Rectification of Gemini obliques has been done successfully by the Autometric Corporation under a U. S. Geological Survey contract; however, this obviously restores only the geometry, not resolution and color, lost in the original photos.

This situation has important implications for orbital photography. First, it suggests that panoramic cameras will have limited value unless very large formats, long focal lengths, and infrared film are used. Second, it accentuates the importance of planning orbits so that sidelap is obtained without excessive slant ranges.

SUMMARY AND CONCLUSIONS

It is clear that we now, as a result of the Gemini Program, have a firm grip on the "problems and prospects," to use Katz's phrase, of orbital photography of the earth's surface. The major conclusion to be drawn from this report is that orbital photography for geological purposes is clearly feasible and uniquely valuable. Beyond this, several specific areas of geologic application can be delineated.

Regional geologic mapping, at scale numbers of 250,000 and larger, can be done from orbital photographs with a reasonable amount of ground truth from supplementary low-altitude photography and field work (Lowman and Tiedemann, 1967). This includes, of course, revision of older geologic maps. Tectonic problems, such as the study of major wrench fault systems, are especially susceptible to attack with orbital photography. Geologic education can be freed from such problems as provincialism with the global coverage possible from satellites. Studies of currently active geologic processes, such as near-shore deposition (Wobber, 1967), can benefit from the simultaneous photography of extremely large areas.

Orbital photography should also be valuable in planning geological and geophysical field work, making it possible to single out the most potentially interesting areas in advance. The results of regional geophysical surveys may be more easily interpreted when correlated with the regional photographic coverage possible from orbit.

It seems safe to say that in these and other fields, orbital photographs will rapidly become as nearly indispensable as aerial photographs are today.

ACKNOWLEDGEMENTS

The successful accomplishment of the photographic experiments carried by the Gemini spacecraft was the work of many people. The astronauts who took the pictures are to be commended for their perseverance and skill in carrying out exacting scientific tasks under difficult conditions; it should be clear that these men were acting as cooperating scientists as well as test pilots. In addition, thanks are due to the many personnel of the Manned Spacecraft Center who supported the S-5 experiment, in particular the experiment monitors, R. D. Mercer and R. W. Underwood, and the members of the Flight Crew Support Division. Finally, I wish to thank my colleague, H. A. Tiedemann, for his valuable assistance on the later Gemini flights.

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