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SPACE PHOTOGRAPHY: A NEW ANALYTICAL TOOL FOR THE SEDIMENTOLOGIST

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SUMMARY

Geologists increasingly concerned with detailed laboratory analyses at times overlook space-age techniques that promise the collection of valuable sedimentological data. Orbital remote sensing, and particularly space photography, can provide synoptic environmental data for geoscientists including those familiar with applying aerial photography to the analysis of sedimentary environments. Color space photographs obtained incident to the Gemini Program provide unique tools for analyzing sedimentary environments and processes and provide data that cannot be duplicated by conventional aerial photographic techniques. The principal advantages of orbital geoscience data collection include frequency of coverage leading to environmental analysis within the full spectrum of seasonal contrasts, and opportunities for environmental syntheses by synoptic observations. Gemini space photography is an available source of semi-quantitative data concerning changing environmental phenomena and mechanisms of sediment distribution. It also enables the survey and inventory of global sedimentary landforms. With the application of advanced sensors, increased system resolution, and repetitious photographic coverage, speedier and more reliable quantitative sedimentological analyses can be performed.

INTRODUCTION

Recent advances in space technology are generally well documented, but relatively few references are available concerning the impact of space technology on the geosciences. Future use of space photography as a geological research tool can be safely predicted (WOBBER, 1968) considering that aerial photographs have proven historically valuable for rapid geological data collection and for studying relatively inaccessible areas. Petroleum and mining geologists, for example, have exploited conventional aerial photographic techniques and expressed equal interest in space photography. Sedimentologists have in rare instances used aerial photography for regional sedimentological studies. Students of space photography have devoted a major effort to evaluating economic-geological orbital applications but have failed to define its value to sedimentology.

The geosciences have evolved in stages from regional reconnaissance mapping to present-day geochemical or petrological studies that may, at times, be founded upon inadequate data. Space photographs offer new and relatively untapped sources of geological information ranging from the interpretation of geological structure and regional tectonics to the analysis of physical phenomena characteristic of modern sedimentary environments. Following the principal of *uniformitarianism*, space photographs provide geoscientists new opportunities to evaluate sedimentary environments as a means to fully understanding depositional environments in the geological record.

KATZ (1963) described space photography as beginning with camera-carrying rockets fired at White Sands Proving Grounds following World War II; many of these small-scale photographs which varied in scale from 1 : 300,000 to 1 : 3,000,000, proved of geological value. A complete tabulation of photography gathered from sounding rockets and satellites has been compiled by LOWMAN (1964). The most recent space photography useful for geological study (varying in scale from 1 : 2,000,000 to 1 : 5,000,000) was a result of the Gemini Program and was obtained using the Hasselblad camera system. These color photographs provide the illustrative base for this study. Good quality, black and white photographic enlargements can be made from 70 mm Gemini color photographs and serve as a basis for studying a wide variety of sedimentary environments and processes. The use of black and white illustrative material in this paper automatically reduces the abundant interpretation clues ordinarily supplied by color. All vertical photographs shown are 65–90 miles on a side; obliques are indicated with appropriate geographical points for scale.

Color space photography (Plate I and II, pp.273, 280) suggests that orbital survey can prove a useful means for synoptically analyzing modern sedimentary environments and for regional geological mapping. In addition, color manipulation or color enhancement, e.g., placing filters of certain colors between color negatives and black and white paper during printing, can also enhance the data content of the space photography. Preliminary studies by the author show that some geological phenomena (for example, patterns of sediment distribution) may be detected by enhancing subtle variations in photographic tone. Simple enhancement techniques, such as printing space photographs on black and white papers without filtration, have sometimes been sufficient to accentuate moisture variations, terrestrial and marine sediment patterns, and the natural boundaries between sedimentary environments.

Regional studies of modern sedimentary environments have apparently been largely replaced by detailed laboratory-based analyses (Fig.1), and only a small fraction of currently published articles discuss the modern environmental data base. This problem has been compounded by the time-consuming and temporally-inconsistent nature of environmental studies, by the frequent inaccessibility of study areas, and

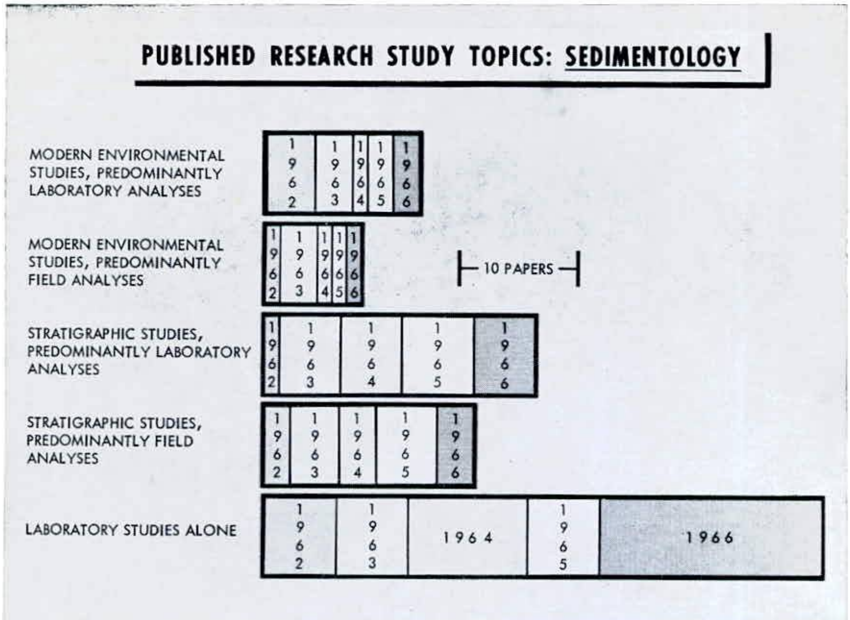


Fig.1. Tabulation of articles from *Sedimentology* classified on general content and study approach, which suggests that modern environmental research studies have generally fallen behind pure laboratory experimental research. Space photography can serve as the impetus for expanding the modern environmental data base as required for sound application of the principle of *uniformitarianism*.

by the absence of means of obtaining worldwide data. Orbital observation promises sedimentologists a "second look" at sedimentary environments and processes which the author suggests is an opportunity not to be overlooked.

This paper will explore space photography as an environmental research tool and will both introduce and define its general value to the sedimentologist. Because space photographic analysis is a photogeological frontier and because operationally, it is in feasibility or equipment testing phase, portions of this study must necessarily border on speculation. For example, evaluating the value of sequential space photography to sedimentology must be inferred in the absence of suitable repetitive coverage. That sedimentologists will discover geological applications for space photographs not here defined is presumed; encouraging sedimentological interest in doing so is the primary reason this paper was written.

METHODS OF ORBITAL DATA COLLECTION

Space photography

Space, or orbital, photography is here defined as that method by which an image is obtained of a planetary surface from an orbital point of observation. More simply, it is the extension of aerial photographic observation to extreme altitudes.

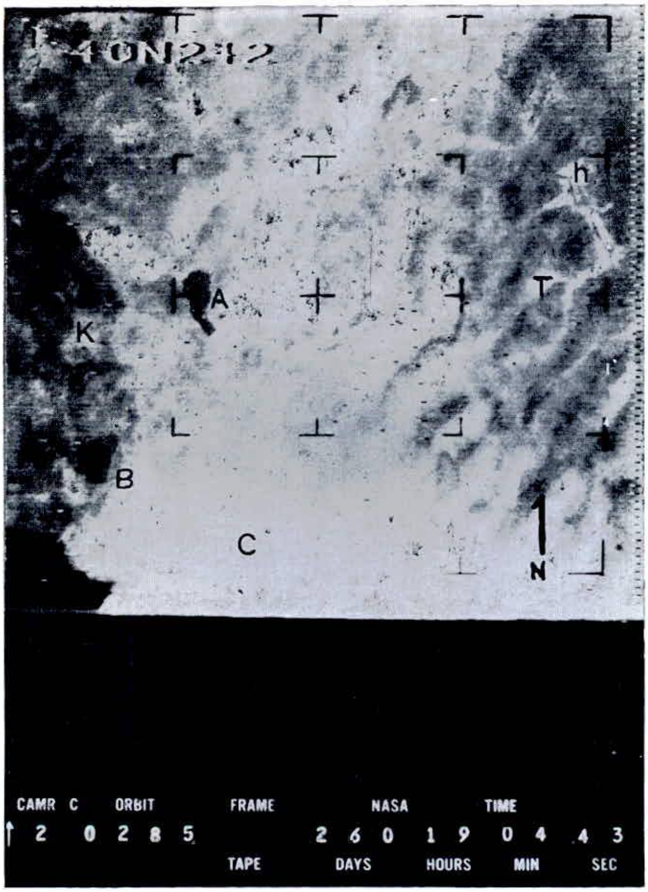


Fig.2. Nimbus meteorological satellite (television) image encompassing a 32,000-sq. mile area in western Nevada and California photographed from an altitude of 700 miles. Tonal variations provide clues to lithology, e.g., Cretaceous acid intrusives (*K*), basin and range topography (*T*) and a portion of the Humbolt River (*h*). Light toned area (*C*) near base of picture is cloud-covered. The resolution of this photograph is approximately 1.5 miles.

Study of the best available meteorological (TIROS and Nimbus) photography indicates that identifiable features include desert areas, water bodies and major tectonic or orogenic features (Fig.2). High contrast targets, such as sand dunes, playas, marine coastal landforms and rivers, can be detected, but not in sufficient detail for sedimentological study. Such photography therefore has possible cartographic applications but is relatively useless for regional sedimentological analysis. Possible applications of TIROS imagery are reviewed in MERIFIELD and RAMMELKAMP (1966), and the reader is referred there for details.

LEUDER (1959, p.10) foresaw no aspect of human endeavor involving relatively large land (or water) surfaces that could not benefit from reliable advance knowledge concerning the qualitative aspects of the area being studied. He further suggested that quantitative data can readily be erected within the framework of aerial qualitative information. Because space photography offers a number of advantages over aerial photographs or mosaics, it cannot be directly correlated with aerial photography. For example, distortions due to relief or differential shinkrage of films and papers during printing are generally more serious when constructing mosaics from conventional aerial photographs than with photographs obtained from space. Also,

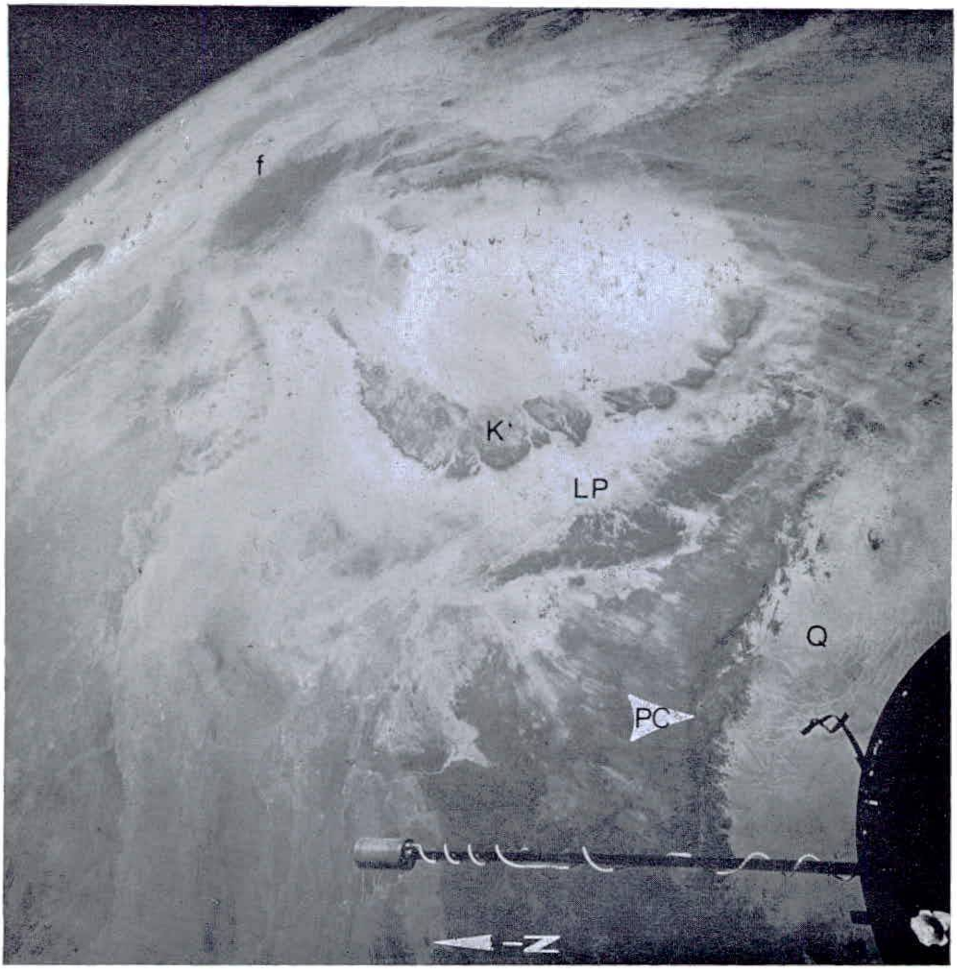


Fig.3. Gemini XI photograph (S66-54525) of the North African Desert, Algeria, Chad, Libya, Niger and the Mediterranean Sea (far left) from an altitude of 175 miles; useful area for sedimentological survey approximates 600,000 sq. miles. Southwest–northeast trending dune sands overlie and flank Cretaceous (*K*) and Lower Paleozoic (*LP*) sedimentary rocks throughout the area. Locally shallow Quaternary sediments (*Q*) overlie Precambrian granitic rocks (*PC*) in foreground and basaltic flows(*f*) of El Harug al Asued in background.

matching large numbers of conventional aerial photographs of varying tones (indicative of changing illumination conditions) is much more time-consuming than with space photographs. Research advantages of space photography include synoptic overview of large geographical areas (Fig.3) and the ability to make regional studies with a greater perspective and analytical continuity.

Although suitable for geological analysis and representative of current orbital techniques, Gemini photography was obtained under adverse operational conditions including an unstable photographic platform (use of hand-held camera) and lack of suitable geological targets owing to low-latitude orbital constraints. None of the space photography collected by the U. S., and presumably the U.S.S.R., was obtained expressly for geological studies. It came as a by-product of manned space vehicle testing. The sedimentologist should not interpret the resultant lack of suitable illustrative material as meaning that space photography for sedimentological studies is an impracticability. These limitations merely reflect the constraints under which usable space imagery has thus far been obtained.

The analyses in this paper show clearly that color anomalies are particularly useful for detecting phenomena of sedimentological significance. Space photographic tonal contrasts are governed by such factors as the reflectivity of the target and background, illumination angle, atmospheric absorption, film sensitivity, and the spectral transmission of a photographic filter if employed. Color contrast between target and background are normally low judging from available Gemini photography, and image sharpness may be reduced because of focusing difficulties or constraints including astronaut (spacecraft) confinement.

The most significant problems in orbital photography (considering Gemini coverage) are cloud cover and atmospheric haze. The negative effects of atmospheric transmission caused by airborne dust particles, atmospheric moisture, or atmospheric turbidity often result in low contrast target renditions. Where the collection of space photography is limited to a few weeks each year, as in polar regions, it seems feasible to collect useful data by other than photographic sensors to reduce the effects of low angles of solar illumination, heavy cloud cover, or abnormally dense haze. Alternatively, coordinating timely weather satellite data with geological photographic missions can guarantee maximum efficiency using orbital camera systems.

A variety of technical problems need solving before increasing regional sedimentological analyses using space photographs. There has, for example, been only limited experimental study of the filter–film combinations or conditions of solar illumination most useful in evaluating critical environmental phenomena and of photographic clues useful in interpreting the compositional or textural significance of the space color photographic record. The author suggests that sensing geobotanical (environmental) indicators may prove fruitful as certain vegetative systems represent a composite textural, compositional and chemical sample of earth surface material.

Photographic color deterioration and the consequent loss of system resolution and color fidelity caused by the spacecraft window or atmospheric scattering become severe with increasing obliquity. However, high angles of solar illlumination prove valuable for detecting subaqueous features. Except for selected geological mapping requirements, e.g., regional studies of otherwise subtle landforms, photography at low solar angles increases atmospheric scattering, results in a loss of contrast, and can complicate interpretation difficulty by lengthening shadow patterns.

As reported by LOWMAN (1967), environmental deterioration of film was not detected during Gemini flights despite extra-vehicular activity that exposed hand-held cameras to space for extended periods. The problem of rapidly returning exposed film to earth may therefore not be critical. The requirement for speedy return (fast response time) of geological data is generally less critical to sedimentology than for analyzing catastrophic events. The results of geological surveys can be returned to earth by a system of film scanning in space and the telemetric transmission of images to ground stations, e.g., as done with weather satellites. This process currently results in a loss of resolution sufficient to reduce the value of sedimentological data obtained. A preferable method for geological study is to return high-resolution photography directly to earth by orbital ejection of the film cannister or by vehicle recovery as in the Gemini Program. For future space missions, it is obvious that film loads would be prohibitive suggesting an application for television. High-resolution space photographs are not always compatible with geologically-oriented scientific satellite objectives because advantages including synoptic wide area coverage would be downgraded in favor of small area observation and photographic detail now available from conventional aerial surveys.

Other sensors

General

Under the auspices of the Natural Resources Office, National Aeronautics and Space Administration and industrial research teams, a program is underway to develop a wide range of orbital sensors for geological study. Besides a wide variety of cameras that will provide most of the geological data in the 1970's such sensors as magnetometers, gravity gradiometers, vapor-sensing devices, radar, microwave and infrared imagers, and laser altimeters are being developed to collect geological information. For near future geological study, both radar and thermal infrared sensors appear especially promising.

A recent review of the status of natural resources research and general characteristics of remote sensor instruments as well as a definition of program objectives and its impact on future geological research is included in BADGLEY (1966).

Radar

Experimental radar systems are currently collecting geologically useful high-resolution imagery over large geographic areas. Long wave length radar penetrates surface soils or clearly defines areas of exposed bedrock surface and promises to be effective all-weather tools capable of penetrating dense cloud cover. Using such systems, geological data could be continuously collected despite climatic constraints.

A general description of the use of orbital radars for geological studies is included in ROUSE et al. (1966) to which the reader is referred for details.

The primary advantages of radar mapping to geology are the relatively large area covered (compared with conventional photography) and the enhancement of regional structural detail over unimportant cultural or vegetative detail. FISCHER and SHEPPS (1965) found that the analysis of gray scales on radar imagery also permits the broad differentiation of varying lithologies. With additional research and refinement of radar imagery, sediment textural variations can probably be detected as well.

In space studies of the glacial environment, radar could be effectively employed to survey mountain and continental glaciers and define ice fracture patterns, periglacial landforms, or zones of sediment concentrations within glacial ice.

For analyzing spatially defined sedimentary landforms, such as sand dunes, channel bars or alluvial fans, and geological factors including degree of consolidation, radar can be a valuable substitute or supplement for space photography. For orbital sedimentological studies, however, it would be difficult to replace the information content of color aerial photography with the highest quality radar imagery.

Infrared

Recording infrared emissions through the earth's atmosphere is possible regardless of daylight conditions, although variations in atmospheric CO_2 content or water vapor result in attentuation of radiation, which is fortunately not constant across the infrared spectrum. Zones of peak transmission (windows) are present, and it is these windows that can be exploited in collecting geological data. For geological studies, the region of from 7 to 14 μ is that of minimum natural reflection and maximum terrain emission.

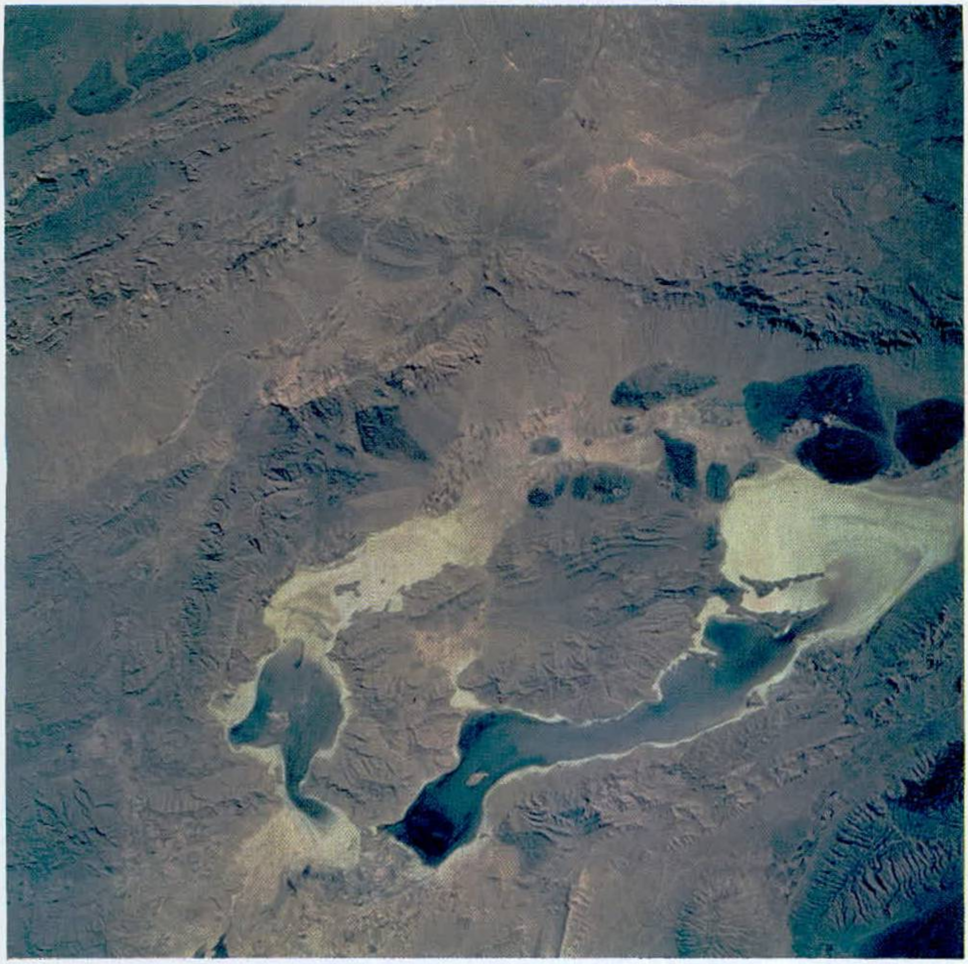
The value of infrared aerial surveys has already been proven by the U.S. Geological Survey which is actively exploring these techniques for orbital geological application including the detection of terrestrial and submarine springs. Of interest to the sedimentologist is that variations in infrared emissivity within an environment reflect such differences as, for example, sediment moisture content, sediment texture, density of areal vegetation, or some combination of these effects. Such data could usefully supplement space photographs and add new dimensions to environmental interpretation.

SEDIMENTOLOGICAL STUDIES

Desert environment

Available space photographs are valuable sources of data in arid regions where structural and lithological details of outcrop surfaces are rarely obscured by vegetation (Fig.4). In vegetated, semi-arid areas, clues as to the depth of the water

PLATE I



Gemini color-faithful photograph (S65-45720) east of Shiraz, Iran, showing salt lakes and well-defined regional structure and stratigraphy over an area of approximately 5,000 sq. miles. This photograph fully demonstrates the value of color space photography for both cartographic and sedimentological study, and the value of color for increasing data yield. The reader is referred to Fig.19 for appropriate annotations and explanatory text.

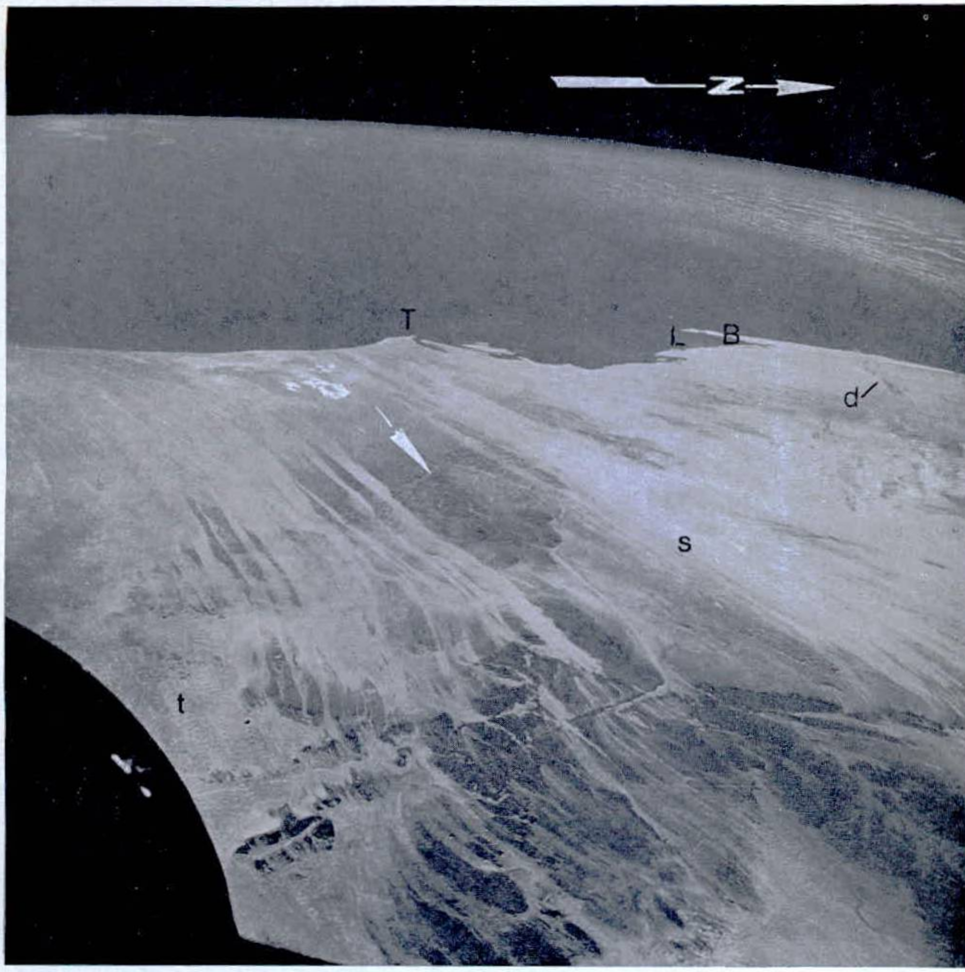


Fig.4. Gemini VI photography (S65-63255) over Spanish Sahara and Mauretania, viewing west to southwest; Capes Blanc (*B*) and Timiris (*T*) 85 miles apart are identified. Cambro-Ordovician rocks including scattered faults (foreground) exhibit well-defined stratification which in places has been accentuated by aeolian erosion. A zone of intrusive granite is indicated (arrow). Dune and sand streamer orientation is locally controlled by outcrop orientation, and both low seif (*s*) and transverse (*t*) dune areas are evident. Area (*t*) also contains scattered small barchan dunes interspersed with bedrock outcrops which are presumably the remnants of wind erosion. Light-toned area south of Levrier Bay (*L*) appears to be dust blowing westwards into the Atlantic Ocean and a well defined dust storm (*d*) can be detected north of Cape Blanc. Coastal salt pans, and marshes (dark tones) occur about 50 miles south of Cape Timiris on Tertiary sediments.

table or presence or absence of mineral salts could also be inferred with improved photographic resolution.

The large quantity of cloud-free orbital photography obtained over low-latitude deserts indicates the value of space photography in analyzing the origin, development,

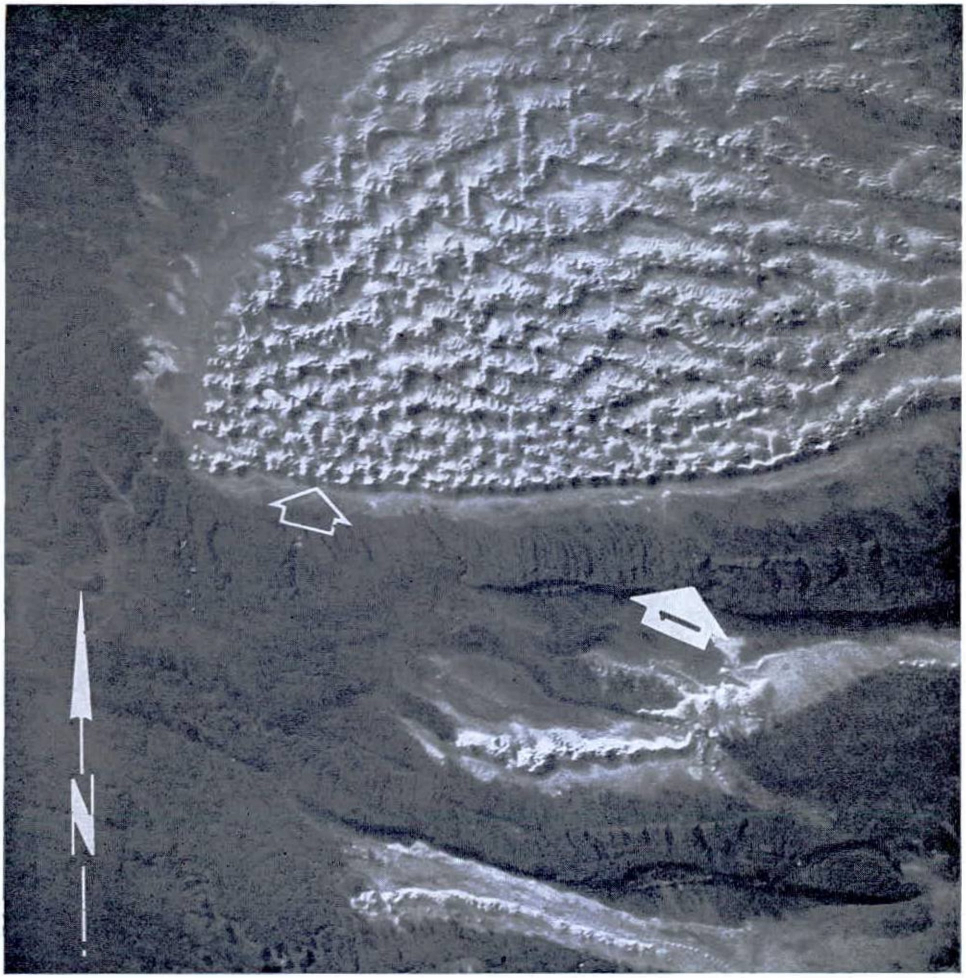


Fig.5. Gemini VII photograph (S65-63829) of a compound barchan dune field, Algeria; sedimentary rocks in the area are of Carboniferous age. The wide variety of dune sizes and shapes including abundant multiple crescentic forms are produced by the merging of individual barchans resulting in a quasi-linear to curvilinear arrangement. Peaked dunes (hollow arrow) parallel westerly-trending ridges suggesting the obliteration and/or alteration of barchan dunes by topographically-channelled winds. Probable wind scouring of the bedrock surface can be seen west of arrow (*1*), resulting in the obliteration of faint bedding perpendicular to wind-scoured ridges. This photograph was taken with a long focal length (250 mm) lens, and is 65–70 miles on a side.

and changing morphology of sand dunes. Space photography can readily be used to map dune distribution accurately (Fig.5) and, despite a lack of comparative (repetitious) space coverage over major dune areas, its value in studying rates of dune movement over extended periods can also be inferred.

Much of the time-consuming mensuration associated with field analysis of dunes or interdune areas can be reduced by repetitious photographic coverage from

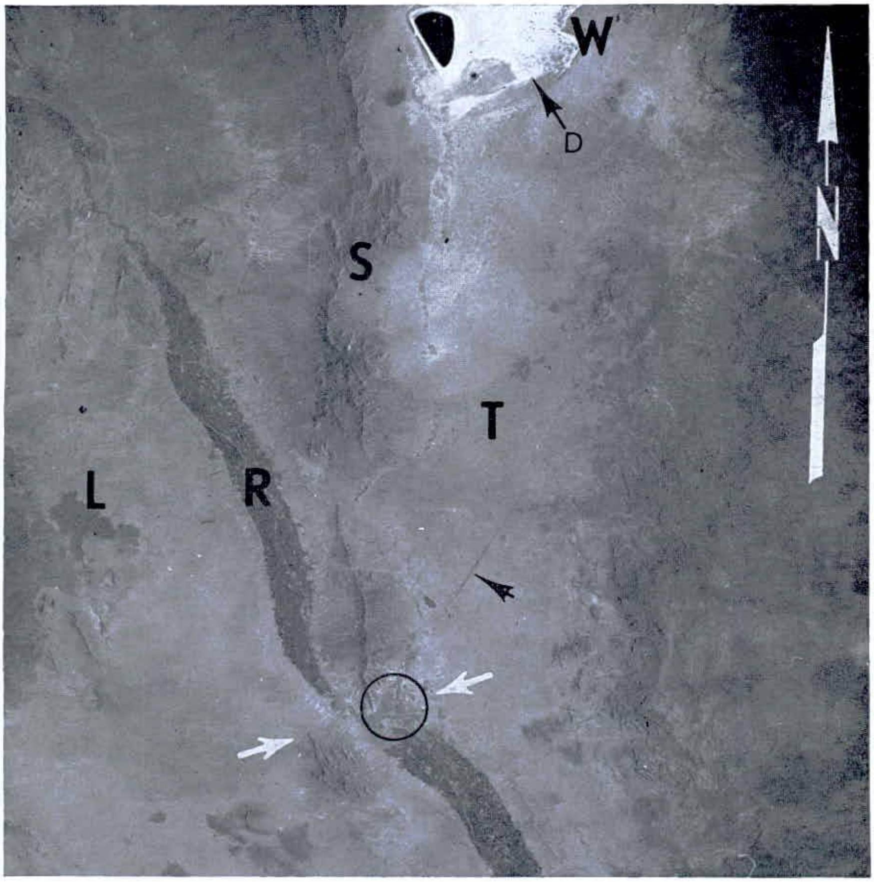


Fig.6. Gemini V photograph (S65-45671) over the southwestern United States (Texas–New Mexico) and Chihuahua State, Mexico, showing the El Paso–Juarez area (circled: see also trace of railway, arrow), Rio Grande River valley (*R*), and White Sands National Monument (*W*); dark spot at top of image is a film flaw. Also shown are the San Andreas Mountains (*S*) composed of Tertiary intrusives surrounded by (grey-toned) Quaternary continental sediments which fill the Tularosa Basin (*T*). Lava flows can be identified in area (*L*), and a fault between white arrows can be identified by displacement of north–south trending strata. The distribution of (gypsum) sands and rock outcrops at White Sands can generally be determined from this photograph, as can probable dunes at (*D*), although the image is insufficient for detailed dune analysis.

space platforms. McKEE's (1966) studies at White Sands, New Mexico, included regional dune measurements from aerial photographs taken at six-month intervals. Similar techniques were used by SMITH (1963) in North Africa. Such coordinated environmental-aerial photographic studies are unfortunately uncommon. Space systems with improved resolution could be applied either independently or coincidentally with conventional aerial methods to collect worldwide arid climate data.

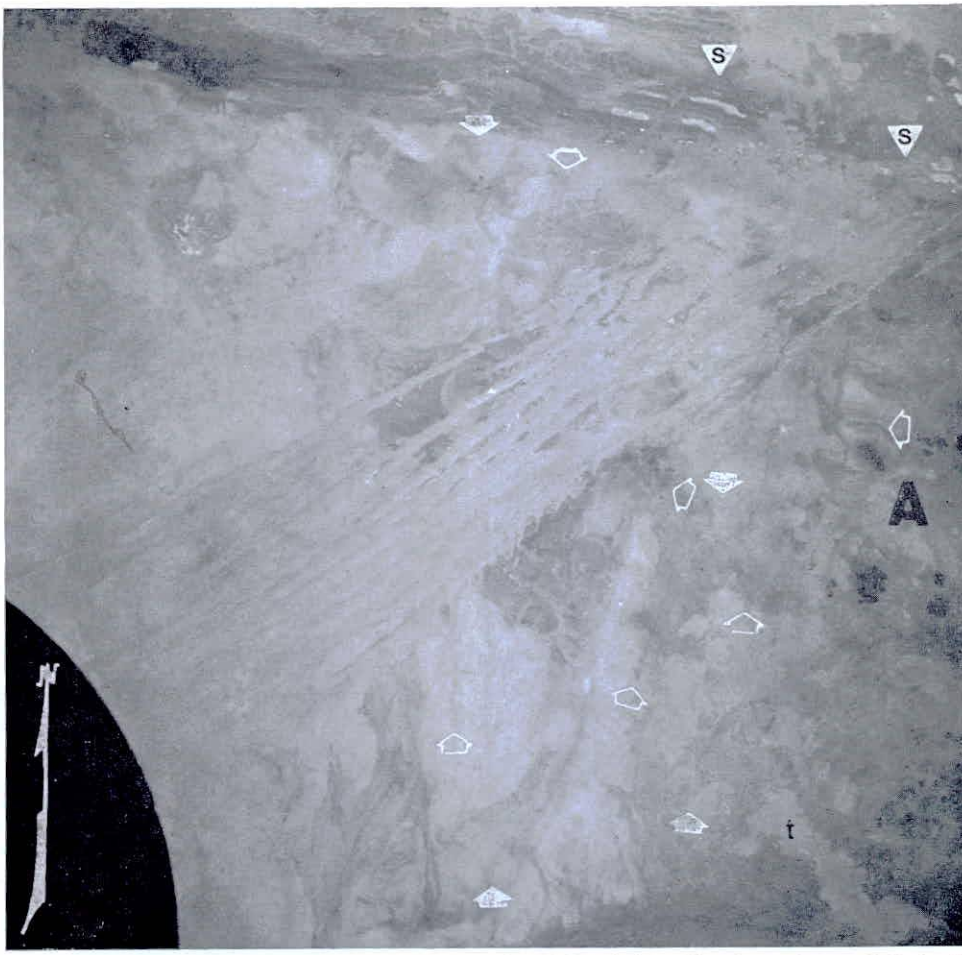
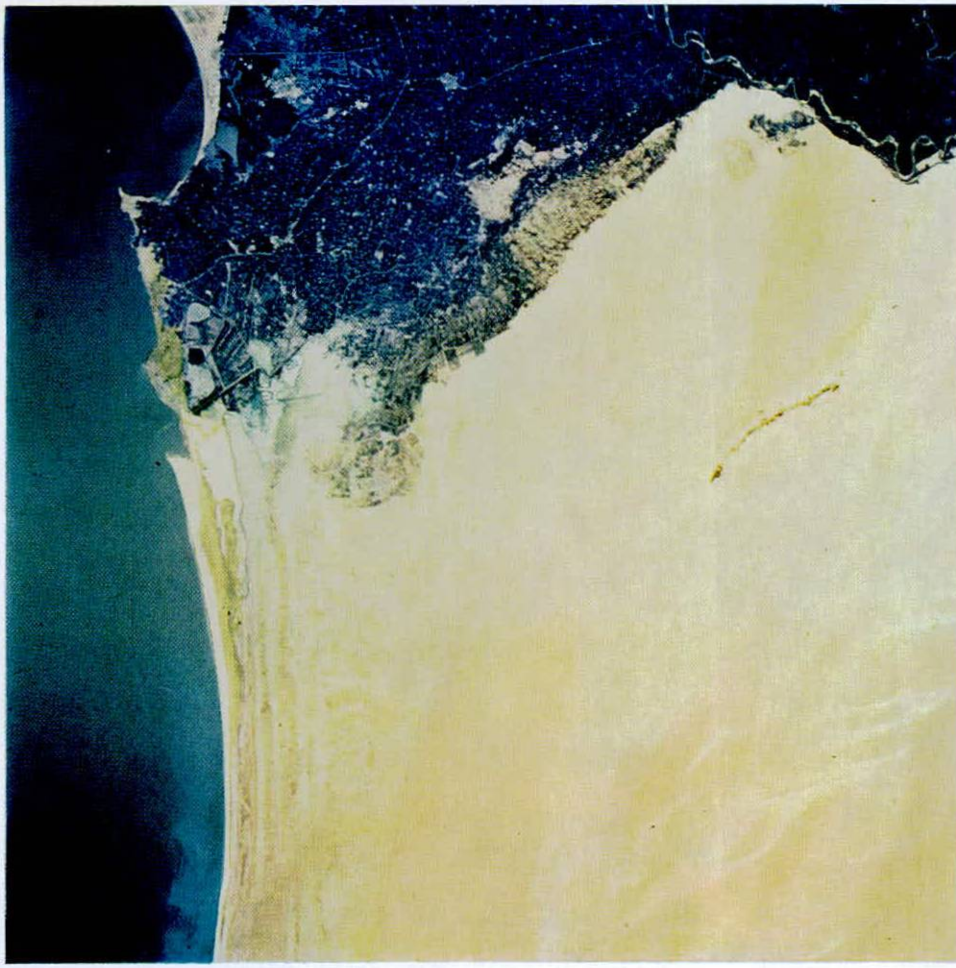


Fig.7. Gemini VI photography (S65-63155) over Mali and Algeria (Erg Chech), southwest of Tindouf, Algeria, showing sand streamers gradational into seif dunes overlying Precambrian basement rocks. Rock outcrops in this region commonly form sand trapment areas and channels for aeolian sand distribution. Scattered elliptical to irregularly-shaped salt pans (*s*) occur between the dip slopes of Silurian and Devonian marine sedimentary rocks infilled by thin sediment blankets; basic intrusives are indicated by black tones in area *A*. Major fault traces (some of which are not recorded on existing geological maps) are identified between solid arrows, probable fault traces by single hollow arrows. Tertiary continental sediments (*t*) overlie Cambro-Ordovician and Precambrian bedrock to the southeast.

For example, Gemini photography of the White Sands National Monument (Fig.6) contains insufficient detail to record the environmental phenomena which McKee and Smith detected using conventional aerial photographs. However, useful analyses can be made with existing space imagery in North Africa (Fig.7) including detection of buried strata (Fig.8).

Space studies can provide a means of resolving conflicting opinions concerning the development of sand dunes and changing dune morphology or dune pattern

PLATE II



Gemini V color-faithful photograph (S65-45736) over the Nile River delta, Alexandria, and the Western Desert showing exceptionally fine cultural detail. The brown haze is identified as dust moving west-northwest into the Mediterranean Sea. The reader is referred to Fig.26 for appropriate annotations and explanatory text.

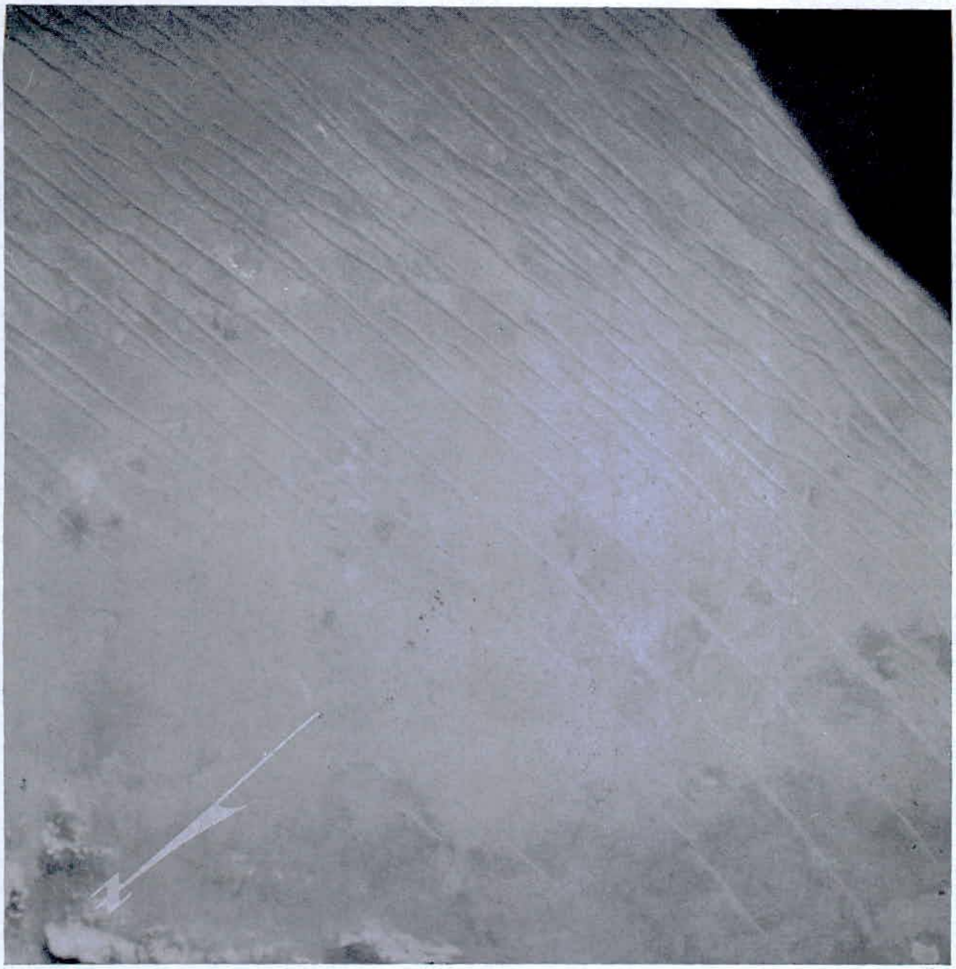


Fig.8. Gemini V photograph (S65-45734) of Erg Chech, southwestern Algeria, showing linear and divergent curvilinear arrangements of seif dunes which truncate dark tonal patterns identified as sand-blanketed Lower Paleozoic (Cambro-Ordovician) rocks. Detecting and mapping the distribution and contacts of shallowly-buried rock masses is often a relatively easy task using space photographs, while difficult or impossible using conventional aerial photographs or photographic mosaics. Scattered cumulus cloud forms occur near tip of the north arrow, and left of center of the photograph, and could be effectively used for estimating wind velocity using orbital cloud motion techniques.

irregularities versus areal vegetative or structural obstacles. Although the progressive change from barchan to longitudinal dunes has been recorded (VON ENGLIN, 1942), the responsible aeolian mechanisms are as yet poorly understood. Moderate resolution space photographs can be used to detect variations in sand dune development over extended periods in response to changing mean wind vectors and to synoptically study related desert environmental processes. Gemini photography of desert regions provides a semi-quantitative data for analysing sand provenance and interdune areas, topographic factors affecting dune movement and orientation, and variations in sediment texture or depth as suggested by tonal anomalies not immediately obvious on the ground (Fig.9).

Fig.9. Gemini VII photograph (S65-63784) over Algeria between the Hoggar Uplift and Tadameit Plateau showing locally saline sandy depressions (*s*), a sand plain (*P*), and barchan dune field (*B*). Bedrock includes Devonian marine (*D*), Carboniferous (*C*) and Cretaceous marine (*K*) sediments cut by primary faults (between white arrows), some in excess of 150 miles long. Elliptical, circular and irregular deflation depressions many of which are structurally-influenced by faulting, folding and doming are common in the lower one-third of the photograph. Residual ridges shaped by aeolian erosion (apparently with irregular sand accumulations on lee sides) are highlighted on color originals by low angle (solar) illumination which also accentuates dune details. Sand blankets, e.g., arrowed *2*, *3* and *4*, image dark in tone in areas of shallow bedrock and such tonal variations can be used to estimate changing rates of sand accumulation or zones of sand removal. *Note:* Many of the depressions in this photograph resemble those described by SMITH (1963, pp.10–11) as "deflation basins"; area indicated (serpentine arrow) is probably that illustrated by SMITH (1963, p.29, fig.1) and described as having formed on the "crest of a structural dome".

Sedimentologically-related meteorological factors influencing dune movement (wind duration, direction, and velocity) may also be conveniently measured in inaccessible desert regions from orbital altitudes. An IBM experimental technique (N. W. Woodrick, personal communication, 1967) to estimate wind velocity using cloud motion promises to provide a means for correlating wind velocity and direction

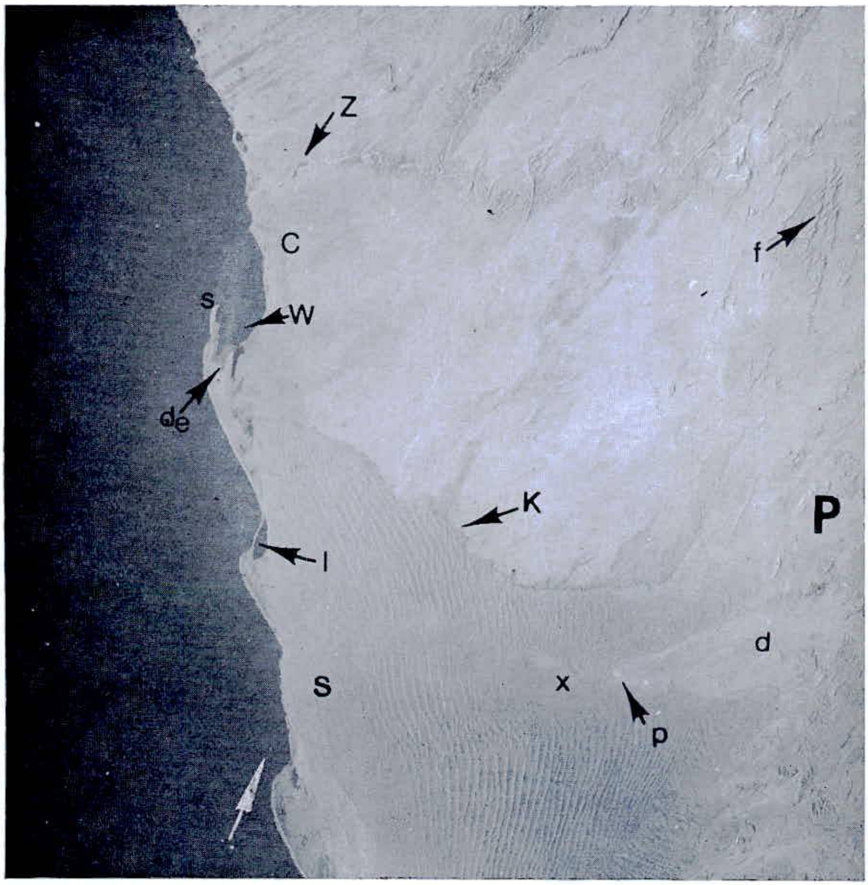


Fig.10. Gemini V photograph (S65-45579) over Walvis Bay (*W*), South Africa, showing dunes extending 50 miles into the Namib Desert and backed by a shield area containing fractured (*f*) Pre-cambrian rocks. Transverse dunes are bounded by Kuiseb River (*K*) on the north, which seasonally has sufficient flow to carry away encroaching sands. Drift marks (*d*) indicate that the prevailing wind direction is from the east. An apparent discontinuity in dune orientation (area *S*) is controlled by onshore sea breezes (white arrow) which appear to come predominantly from the southwest; other coastal dunes occur at (*C*) and are truncated by the Swakop River (*Z*). Shallow sand area (*x*), and a salt pan (arrow *p*) can be detected in the desert. A coastal delta (area d_e) a spit (*s*) produced by longshore sediment drift, nearshore bars (*I*) and scattered tidal lagoons can be identified in coastal areas. This excellent quality photograph fully demonstrates the potential value of space photographs for rapid in-depth analysis of dune orientation, development and long term rates of movement and synoptic evaluation of meteorological or topographic influences on desert processes.

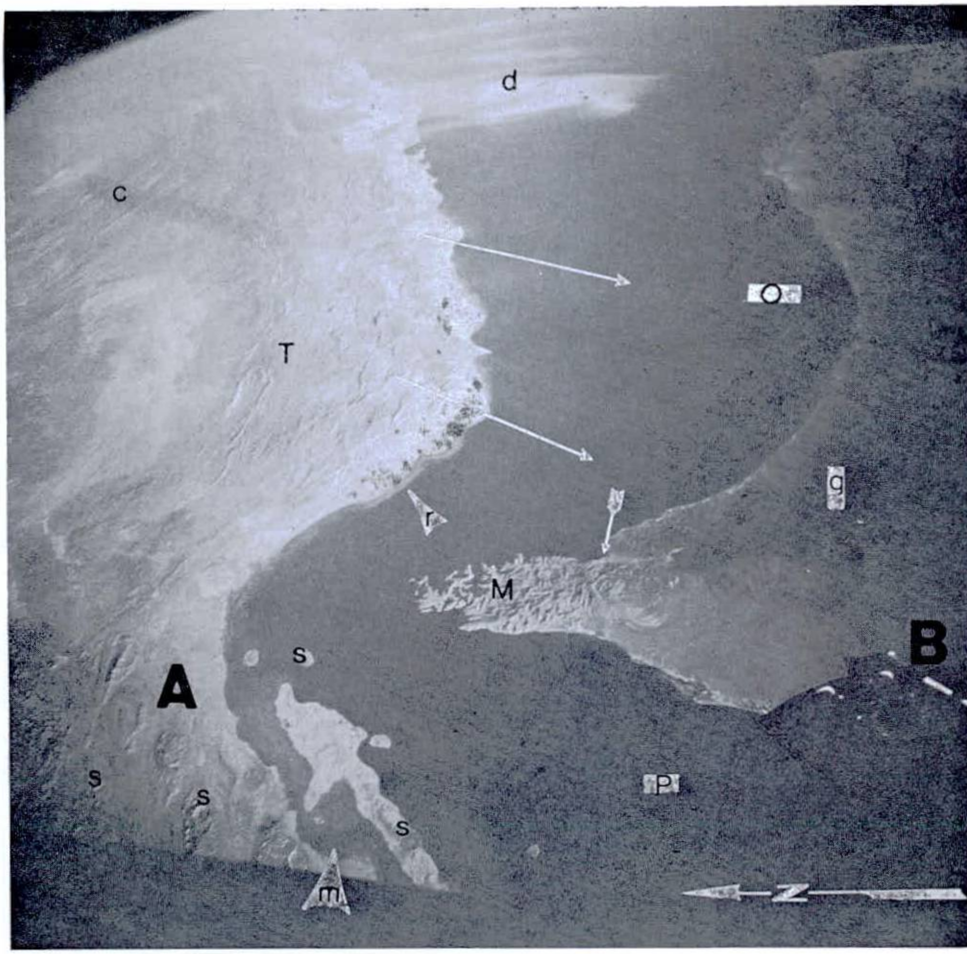


Fig.11. Gemini XII photograph (S66-63486) of Iran, Trucial Coast-Oman and Qeshim Island, looking east over the Persian Gulf (*P*) and Gulf of Oman (*O*). In Iran, faulted marine Tertiary rocks (*T*) overlain by light-toned Quaternary gravels, sands and silts are interspersed by salt domes (*s*) some of which are not recorded on existing geological maps. Along the Trucial Coast, recent sands and undifferentiated Quaternary coastal sediments overlap Mesozoic rocks including a belt of greenstone (*g*) shown as a wide dark curvilinear tone. Triassic limestones are brought into juxtaposition with Cretaceous greenstone by faulting (arrow) on Cape Muscandam (*M*). Dust storms (*d*) are well defined, and the boundaries of nearly continuous southerly-moving dust plumes (long-tailed arrows) are defined by barely perceptible tones. Light tones paralleling the Iranian Coast and Qeshim Island trace zones of shelf sediment mixing and closely correspond to the 100 ft. bathymetric line in this area. Shallow water marshes (*m*) are indicated by irregular dark tidal drainage traces, and sediment drift east between Qeshim Island and mainland Iran, are imaged in grey tones; sharp light and dark tone contrasts image forereef boundaries and backreef sedimentation, as indicated (*r*). Area (*B*) includes instrument light reflections from inside the spacecraft.

with dune morphology and orientation in support of regional arid climate studies.

Using space photographs, a comparative analysis could be made of processes of sand dune sedimentation in coastal deserts (Fig.10) versus that in major low-latitude deserts. The influence of shoreline orientation, wind directions related to sediment accumulation, and the occurrence or orientation of hinterland topographic and vegetative obstacles could be compared along with available sediment sources and environmental moisture distribution to inland desert dune morphology, migration rates, or detectable soil moisture effects.

Space photographs are also valuable for studying the general occurrence of aeolian dust storms, particularly their abundance, distribution, provenance areas, and response to changes in regional moisture budget. Such storms have already been recorded on space photographs over Iran and Iraq, West Africa (Fig.4), along the Trucial Coast (Fig.11), and probably near the Nile delta (Fig.26). The presence of finely divided dust patterns can also be detected from space but, at times, cannot be differentiated from atmospheric haze in near-coastal areas. The size and sedimentological significance of desert dust storms can likely be evaluated with equal or better precision from orbital platforms than by ground or conventional aerial studies alone. Space probably provides the only opportunity to examine large aeolian dust storms and to plot accurate data concerning regional aeolian sediment distribution and rates of dust movement.

Besides its value in a study of arid climate processes, space photography can be used to analyze sediment distribution and hydrological factors as affecting desert bajadas or pediments. The integration of desert basins might likewise be correlated with meteorological variations resulting in changes in the intensity of desert sedimentological processes. For example, in Gemini photography (Fig.12) one can evaluate seasonal sheet flooding and zones of significant downslope sediment movement by highly erosive but infrequent heavy rainfalls. Closely related would be the evaluation of gross sediment movement, changing development of alluvial fans, and ultimately the growth of compound fans. The rates of sediment accumulation in desert alluvial fans can probably be estimated by repetitious space coverage. Changes between readily detectable pediment, desert, and alluvial fan boundaries could also be determined.

NEAL (1965) studied the geology of U.S. playas and showed a wide variety of playa types based on moisture and surface sediment. He also observed, using aerial photographs, giant contraction stripes (possibly caused by variations in stress different from those of smaller desiccation fissures), which were not detected during ground studies. Despite resolution constraints inherent in available Gemini photographs, broad playa moisture differences have also been detected. NEAL (1965, p.22) found that playas were dynamic environments continually changing in response to variations in precipitation, evaporation, sedimentation, and water table fluctuations. He emphasized that water table fluctuations were of primary importance in analyzing playa changes and suggested that most playa processes or features were directly or indirectly related to ground water regimen.

In studying the playa environment using Gemini photographs, the author found that black and white photographs may be more useful than color photographs for analyzing moisture. Although hampered by a lack of suitable photography over such

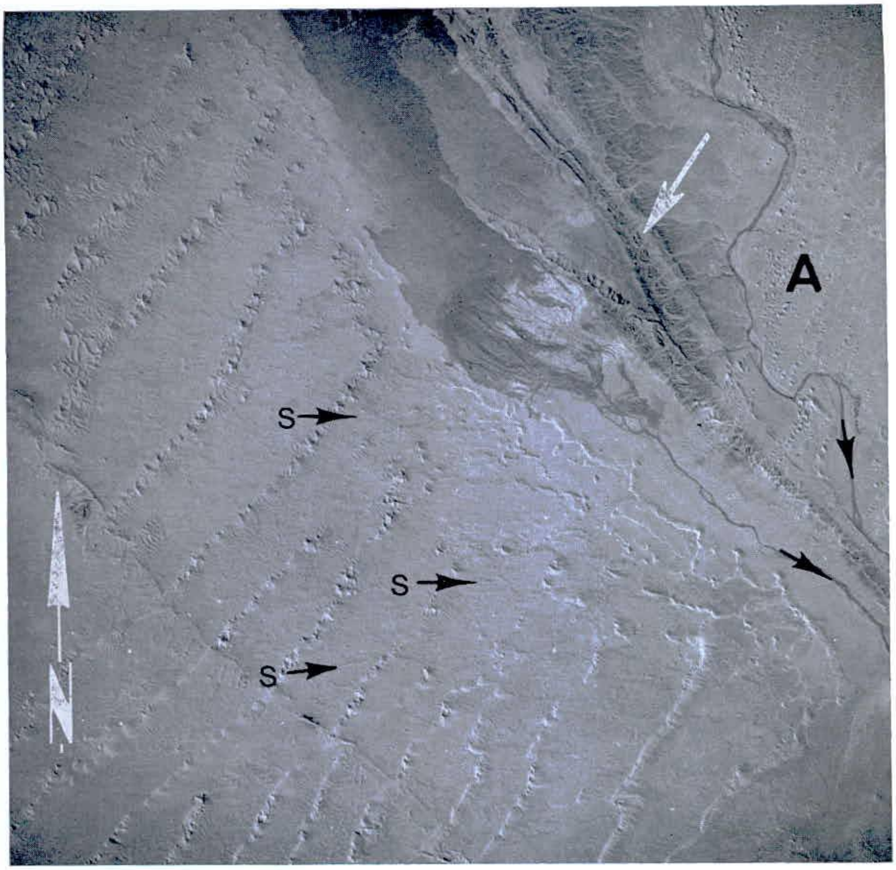


Fig.12. Gemini VII photograph (S65-63830) taken with a long focal length (200 mm) lens north of Grand Erg Occidental, Algeria, showing sheetflooding following heavy desert rainfall; lakes in this area are usually dry. Drainage in this area is to the southeast parallel to southeast–northwest trending Cambrian and Cambro-Ordovician sedimentary rocks (white arrow). Blue tonal variations on original color photographs are useful in determining relative water depth. The orientation of peak dunes trending northeast–southwest is locally controlled by the presence of rock outcrops or (normally dry) stream channels (e.g. area *A*); a secondary less well-defined, quasi-linear sand pattern also appears to be present (e.g., arrows, *S*).

areas, the use of selective photographic filters for enhancing playa moisture differences is now being tried. With resolution constraints imposed by existing Gemini photographs, no detail other than regional moisture or moisture-related textural differences have thus far been detected (Fig.13). With increasing resolution, it can be predicted that regional sedimentological or structural strand lines produced by Pleistocene changes to lake chains (e.g., western United States) in arid areas can likewise be studied. Based on evidence from many areas of the world (Fig.9 and 11), deflation effects can be readily detected and probably correlated with variations in regional moisture distribution.

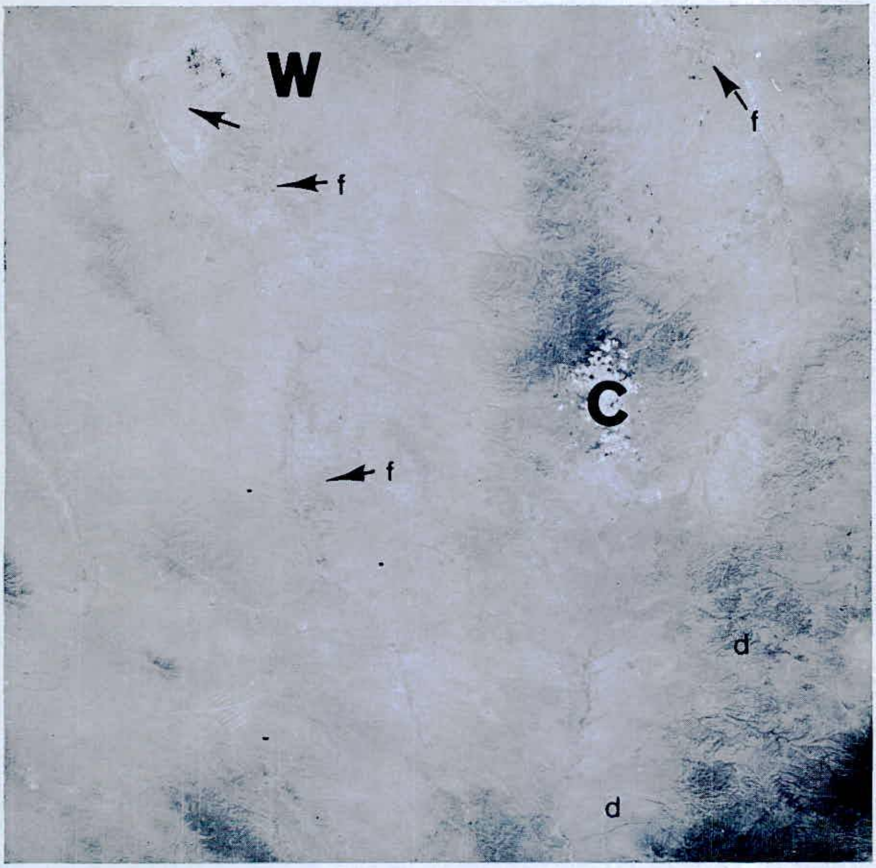


Fig.13. Gemini IV photograph (S65-34683) over Willcox Playa (*W*) and the Chiracahuca Mountains (*C*), Arizona, composed of Precambrian igneous rocks and scattered Tertiary volcanics flanked by Quaternary alluvium. Scattered field patterns (*f*) and obvious variations in drainage density (*d*) can be identified in the area. The central portion of Willcox playa is dark in tone, presumably because of the presence of moisture or the texture of playa sediments; a drainage channel (arrow) can be identified. Frequent observations over such areas would permit the monitoring of changes in playa regimen, but increased photographic resolution would be desirable. The use of selected photographic filters has proved successful in enhancing tonal differences over such playa surfaces.

Glacial environment

Because orbital sensors of sufficiently high resolution for the sedimentological study of glacial environments, i.e., excluding meteorological satellite sensors, have yet to be placed in polar orbits, photographic coverage of continental glacier regions is currently unavailable.

Space photography can cover areas that might otherwise be (seasonally) constrained for field observations. Polar, and some areas of mountain glaciation (Fig.14), are seasonally characterized by such adverse conditions as heavy cloud

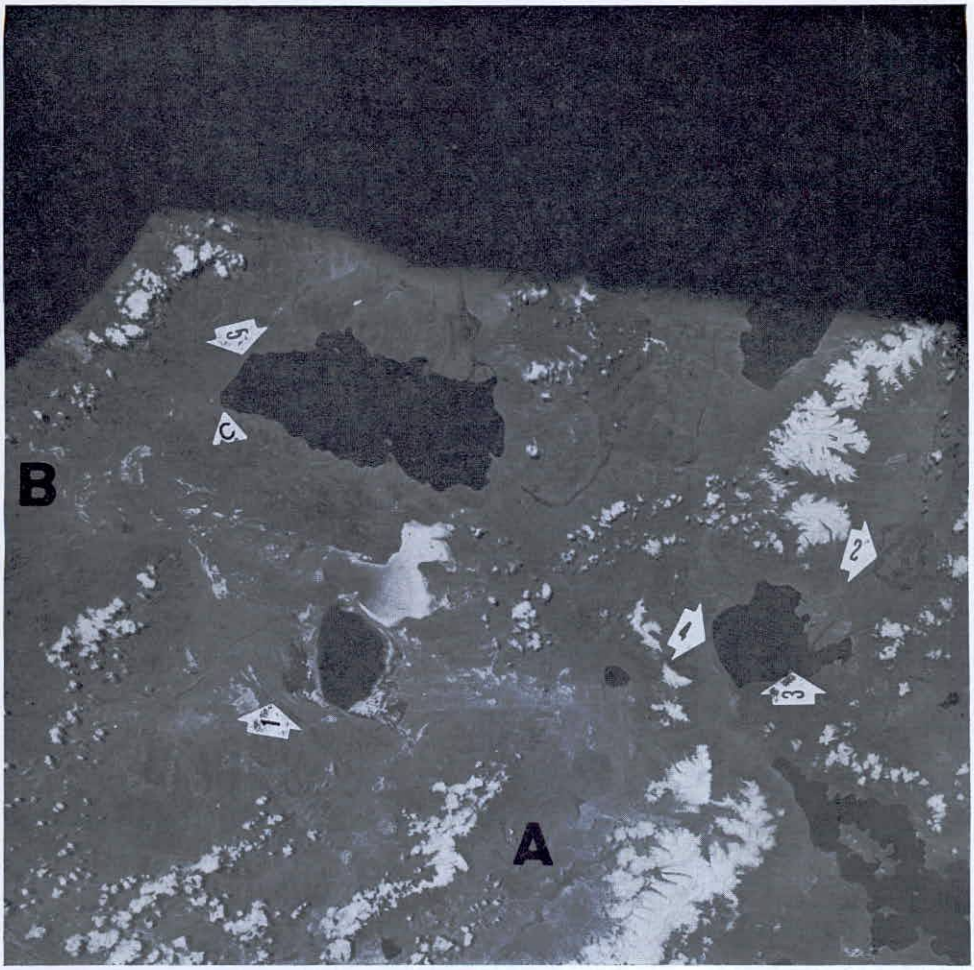


Fig.14. Gemini V photograph (S65-45624) over Tibet, showing an area southwest of Lhasa. The difficulty of immediately differentiating even discontinuous snow cover from clouds is exemplified in area *A*. Discontinuous outcrop patterns in valleys suggests that glacial debris from past mountain glaciation and recent colluvium veneers valley bottoms. Lakes charged by sediment-laden snow meltwater are seasonally more extensive judging from sediment tones in areas of low relief (e.g., area *B*) and the occurrence of subtly-defined lake strandlines (arrow *1*). Braided stream channels (arrow *2*) and fluvial sediment plumes (arrow *3*) suggest large volumes of sediment are being transported; natural topographic dams, possibly due to the presence of valley moraines, are suggested (arrow *4* and *5*), one with an apparent overflow channel (*c*). Spacecraft obscures upper portion of the photograph. Variations in lake size, sediment distribution in response to seasonal melting, and shifting fluvial channels, could be studied with additional space photography.

cover fog, or haze, that limit conventional aerial photographic operations. But they can be observed from space over long periods of time.

Orbital sensors, including radar, could be employed to avoid observation limitations, or else could be used in conjunction with photographic systems. Distribution and changes in glacial crevasses might be studied by radar imagery as a means to analyze general rates of glacial movement, and possibly rates of sediment infilling of large crevasses.

A continuing difficulty in analyzing space photographs obtained over active glacial belts is differentiating cloud from snow or ice cover. This difficulty first arose during the interpretation of weather satellite imagery and is obvious despite limited space photographic samples obtained during the Gemini Program (Fig.14). Sedimentologists can, however, expect space photographs to provide abundant data concerning glacio-fluvial processes and their effects on sediment distribution. Coordinated ground studies of Recent glacial sediment sorting might, for example, be correlated with the density of glacial streams or variations in seasonal lakes studies for extended periods from space.

The sedimentological processes associated with most glacial landform developments could also be examined and comparative space photography of both mountain and continental glacial environments correlated with climatic effects or variations in sediment removal by glacio-fluvial processes. Continuous surveys of glacial sedimentation could lead to establishing additional environmental criteria for studying, for example, reported (H. R. Wanless, personal communication, 1966) tillites of the Paleozoic Age in the Southern Hemisphere.

A wide variety of glacial landforms can be recognized from orbital altitudes, e.g., glacially-dammed or moraine-dammed lakes detected from Mercury photographs over the highlands of Tibet. Monitoring climatically-dependent hydrological changes in such bodies could provide a qualitative indicator of variations in glacial mass budgets. The worldwide effects of Pleistocene glaciation and corresponding marine fluctuations could also be better appreciated following orbital high-resolution inventory of glacial terraces, relict permafrost patterns, and drowned stream valleys along the continental coastal margins.

Better maps of the distribution of Pleistocene marine shorelines and terraces appear possible using available photographic sensors. Eustatic changes in sea levels resulting from worldwide glaciation have left behind traces of beaches and wave-cut terraces which have yet to be surveyed and correlated on a worldwide scale. Glacio-sedimentological research at Antarctic sites can be especially useful for studying sedimentation in the vicinity of a relatively well-studied continental glacial source. Abundant scientific data currently exists as well as many international scientific stations to which orbital sensing could offer general support.

Another direction of applied space photographic research might be worldwide examination of periglacial areas including surveys of variations in the distribution of stone rings and stone polygons correlated with the extent of permafrost. Scientific data gained by correlating infrared imagery and space photography would be an effective means of analyzing periglacial sedimentation. Techniques to study periglacial areas photographically, as outlined by SAGER (1951) in a study of permanently frozen ground, are applicable to orbital studies of modern glacial environment as well.

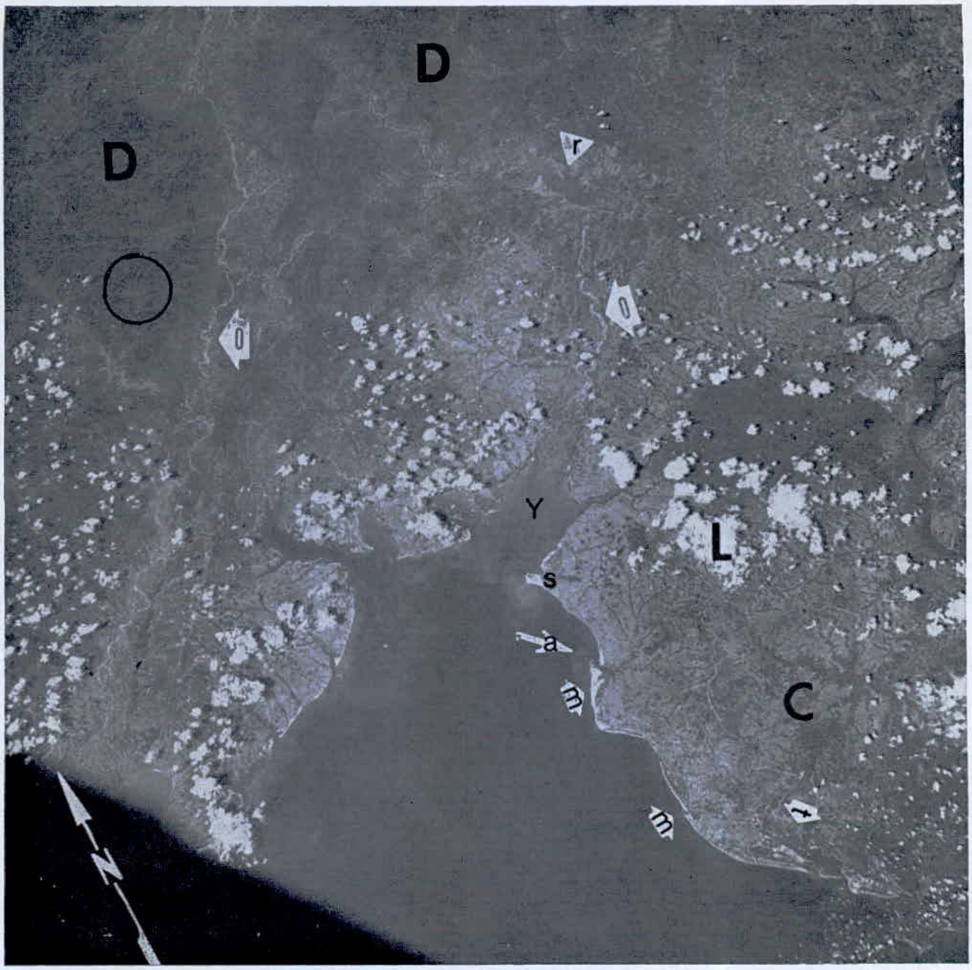


Fig.15. Gemini V photograph (S65-45731) over the Luichow Peninsula (*L*) and Kwantung–Kwangsi Provinces, China, showing dendritic primary through tertiary drainage systems discharging large volumes of sediment into the Gulf of Tonkin; exposed floodplain areas cannot be differentiated from sediment-laden (e. g., zero arrows) rivers, indicating the need for increased photographic resolution. Coastal estuaries, scattered lakes, and a large natural reservoir storage area (*r*) can be easily detected. Fluvial sediment discharges form coalescing plumes and choke Yang-Kan Harbor (*Y*); supplies of fluvial sediments are later reworked and contribute to the formation of barrier beaches and spits in marine coastal areas. Spits and barrier beaches are locally backed by tidal marshes (*m*) into which fresh water streams discharge sediment. Tidal flats (*t*) were exposed following tidal retreat at the time of this photography; tidal drift of river-supplied sediments to the south-southwest occurs. Rectangular shaped spit (*s*) built by northwesterly longshore sediments drift has presumably been truncated by strong tidal currents and possibly severe weather effects; rip current sediment mixing is tentatively identified at (*a*). Zones of intense cultivation (e. g., area *C*) are dark toned; dark grey-toned forests in highland regions (e. g., area *D*) may have been timbered (circled) in places. The difficulty of collecting useful fluvial environmental detail with existing space photography, other than in coastal areas, is well exemplified.

Fluvial environment

Fluvial landforms and environmental phenomena analagous to those of interest for orbital photographic analysis have been tabulated by LEUDER (1959, p.132) and supporting fluvial sedimentological data by ALLEN (1966).

The analysis of existing Gemini imagery shows that with improved photographic system resolution and frequent (comparative) coverage, space photographs can provide the basis for quickly analyzing sedimentation in large drainage basins. Both perennial and intermittent watercourses are detectable from existing space photographs, although only large fluvial features, e.g., channel bars and major floodplain features, can readily be analyzed from Gemini photography (Fig.15). Because the fluvial environment contains numerous subenvironments and sedimentary features that cannot be imaged synoptically, the judicious use of aerial photography is recommended to increase the information content of space photographic coverage.

Although space photographs have limitations for fluvial environment interpretation, river (sediment) effluents can readily be recognized as tonally-anomalous plumes (Fig.16). Seasonal inventory of such changing fluvial discharges reflecting fluctuations in sediment load could be correlated with the development of large-scale channel features, significant changes in channel pattern, or variations in rates of delta growth. Fluctuations of fluvial sediment discharges into coastal marine waters might also be related to beach or bar development and major changes in regional coastal morphology. Where streams discharge into large fresh or salt water bodies, mean directions of movement of high contrast sediment plumes can be easily determined despite low angles of solar illumination (Fig.11) or rough surface water conditions (Fig.17).

Fluvial sedimentological response to changing seasonal rates of lateral cutting, and backswamp sedimentation during periods of flooding, could be inferred from repetitious space coverage over major river systems. That the floodplains of the Mississippi or Nile rivers some times exceed10 miles in width is enough reason to examine synoptic space overview as a tool for summarily analyzing river sedimentation. Of equal sedimentological value would be an analysis of braided streams, particularly the relationship between channel bar orientation or changes in response to fluctuating sediment loads.

Long-term space summaries of stream density variations, and environmentally (e.g., sediment distribution) or seasonally dependent factors (e.g., flooding) influencing the fluvial cycle, can also prove the basis for understanding rhythmic fluvial deposits such as those described by ALLEN (1966) in Devonian sediments of Britain. Synoptic evaluation of the permanency of fluvial channel bars or natural levees can provide sedimentologists with a basis for statistically relating their distribution and abundance in the geological record. Such understanding (by frequent inventory) of the orientation patterns of modern fluvial channel features can also establish paleogeographic criteria to be applied in studying the geological record. Understanding the sedimentary

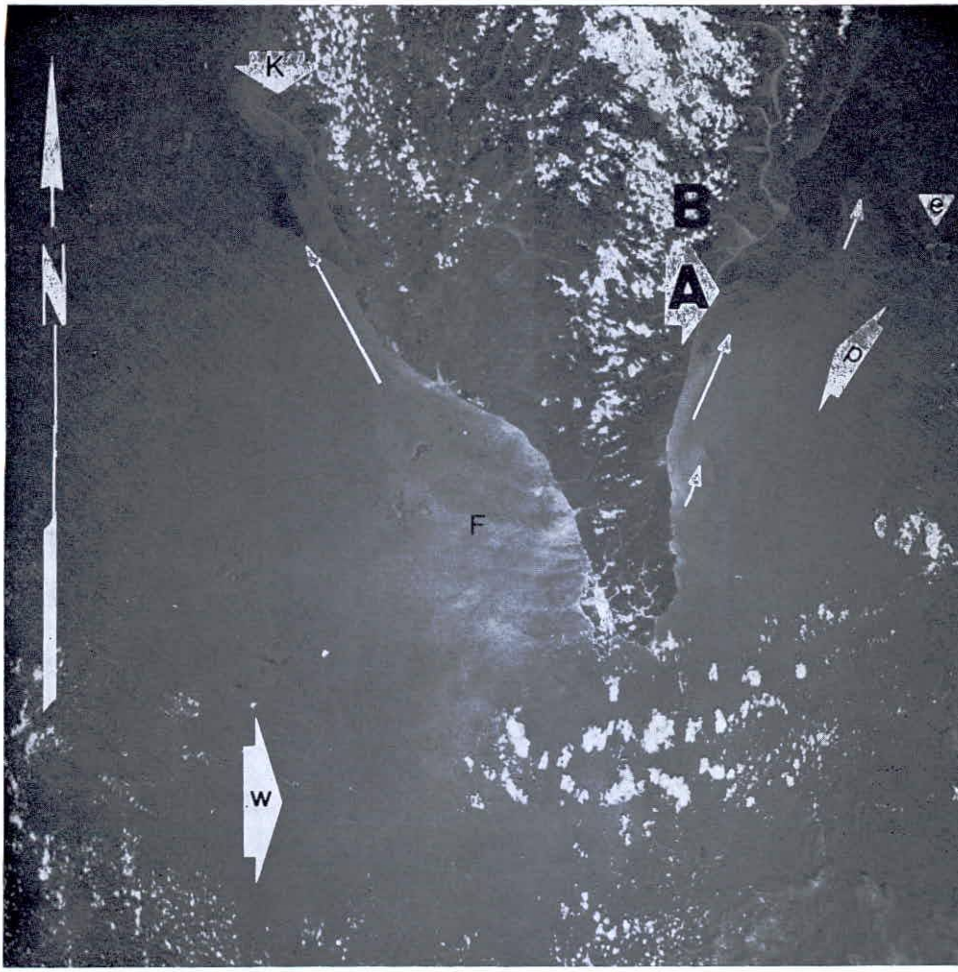


Fig.16. Gemini X photograph (S66-45868) over the partly cloud-covered southern half of Formosa, near Kaohsuing City (*K*), showing the intermixing (*F*) of small coastal fluvial sediment plumes disrupted by marine swell and currents in the Formosa Strait. Direction of sediment drift is indicated by arrows. Shallow water areas, tidal flats (*A*), marine current patterns, broad wave swell (*w*) patterns (*p*), and sediment-laden eddies (*e*) near islands can be identified. Sea surface roughness is revealed by reflective patterns towards the middle-third of the photograph; dark-toned areas in upper-third are probably due to upwelling. Wave refraction patterns are well marked on the southwestern side of Formosa. Braided stream channels possibly containing stabilized (vegetated) channel bars (islands) occur east of (*B*).

mechanisms behind the distribution and orientation of such permeable bodies has obvious advantanges for petroleum exploration.

Closely related to the arid environment are fluvial mechanisms having an influence on the development of alluvial fans for which large natural laboratories (Fig.18) are readily available. The Los Angeles Basin, for example, is an alluviated plain, but it has undergone such extensive cultural and economic development that

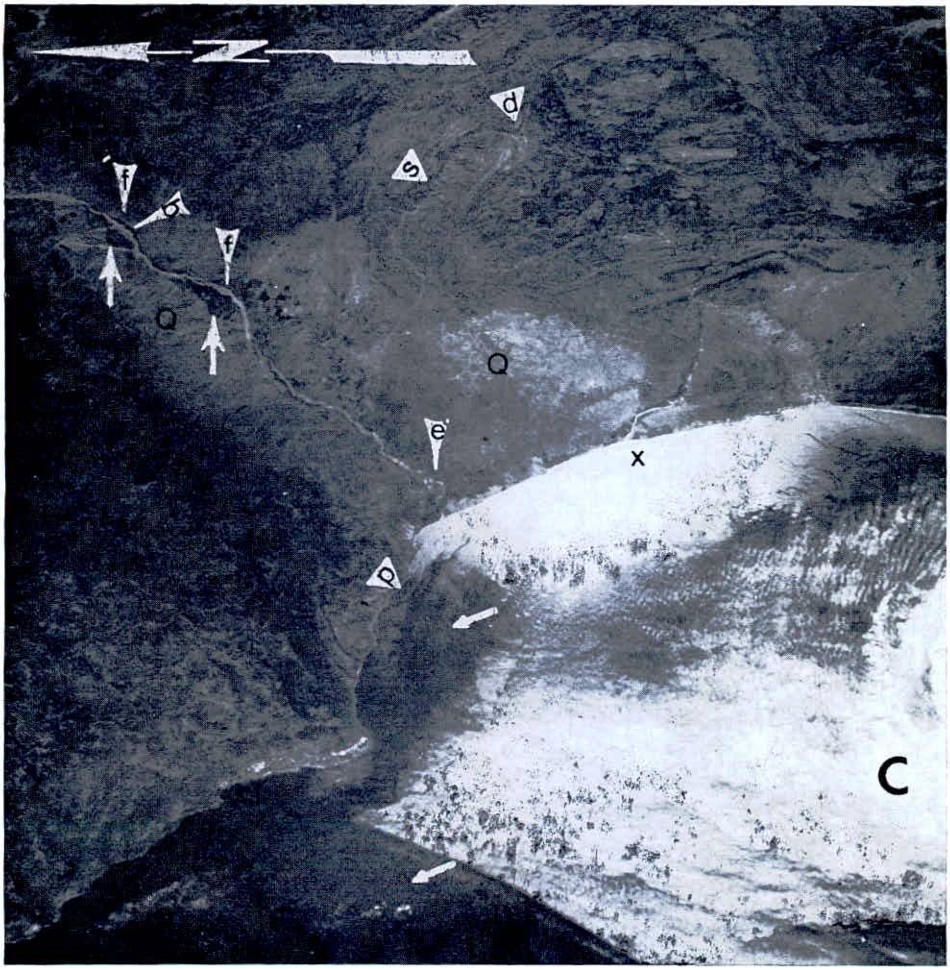


Fig.17. Gemini V photograph (S65-45644) of Cape Rhir (*R*), Morocco, viewing east over Sous River. Highly folded zone south of the Sous River is composed of Lower Paleozoic rocks which are an extension of the Grand Atlas Mountains of North Africa and contain scattered igneous intrusives; pale grey-toned sediments (*Q*) flanking the river are Quaternary sands and dunes. Streams in the area are often structurally controlled, e. g., at (*s*). The edge of an Atlantic cyclonic storm pattern (*C*) has created rough water conditions (arrows) but not obliterated the fluvial effluent pattern (*p*). Clouds and sun glare have, however, made possible sediment discharges at (*x*) impossible to detect. Dense vegetation (barbed arrows) along the river is imaged in dark tones, contrasting with broad sandy floodplain deposits (*f*) and, barely perceptible, braided channel bars (*b*). Photography at this scale (1 : 7,000,000) would be on only marginal use in recording other than major channel fluctuations, e. g., probably abandoned channel at (*e*), although stream density or factors influencing the fluvial cycle, e. g., stream piracy at (*d*), could be mapped. Large channel bars exceeding two miles in length, have been recognized in Gemini photographs of the Nile River and with frequent observation could be evaluated against broad changes in the river's sedimentation.

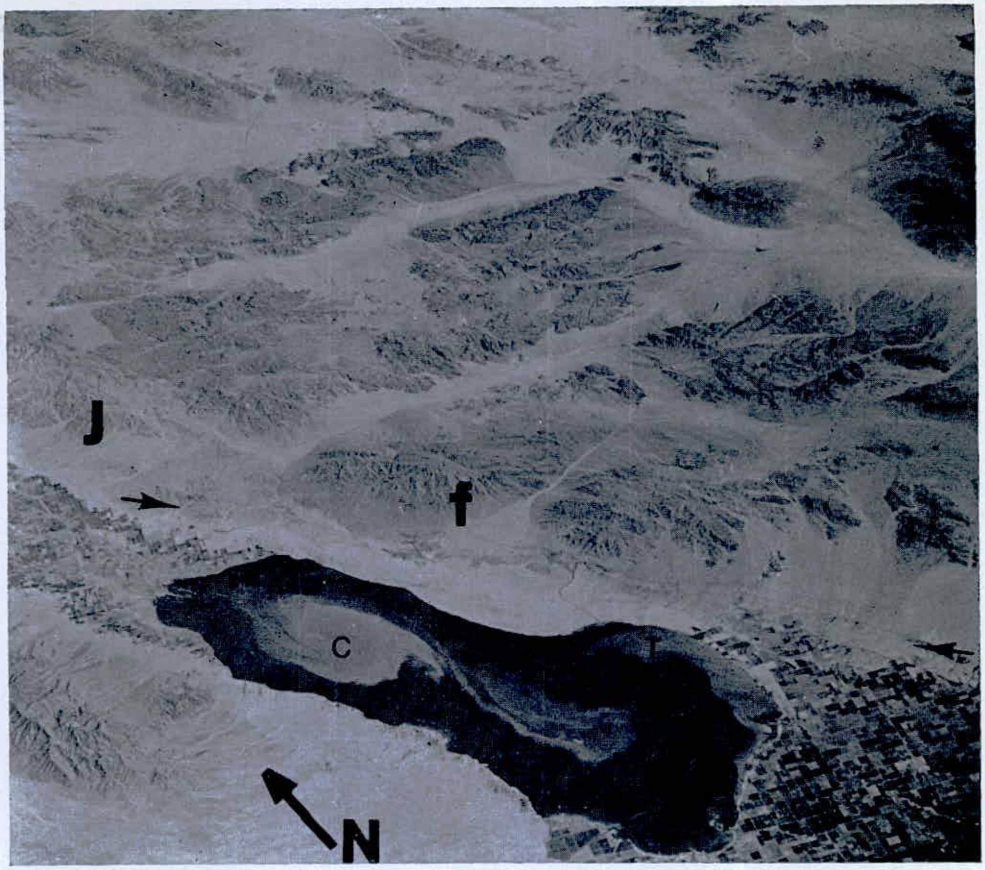


Fig.18. Gemini V photographic (S65-45748) enlargement showing the Salton Sea, and dense agricultural patterns of the Imperial Valley, California with Joshua Tree National Monument (*J*) to the northeast. Area is composed predominantly of Pre-Franciscan granites and metasediments and probably Cambrian acid intrusives infilled by Quaternary alluvium; an alluvial fan (*f*) fronts on a fault (between arrows) which is a probably part of the San Andreas system. The contact of the fan front with alluvium in Imperial Valley can be easily mapped and with additional comparative coverage, fan growth could be estimated quite accurately. Changes in the lake shoreline could be similarly evaluated. Circulation pattern (*C*), in the Salton Sea is tonally similar to turbid waters (*T*) to the southeast and appear strongly influenced by bottom topography judging from regional hydrographic maps.

its value as a natural test site for space photographic analysis is limited. The generally remote alluvial fans of the Basin and Range Province of the United States would, however, be useful for orbital survey of changing fluvial channel density related to alluvial sedimentation or rates of alluvial fan development.

The importance of fluvial planation during the development of graded pediment surfaces has been discussed at length in geological literature (THORNBURY, 1958, pp.286–290). The study of alluvial fans using space photography can likewise lead to quantitative estimates of the importance of fluvial processes versus sheetflood erosion

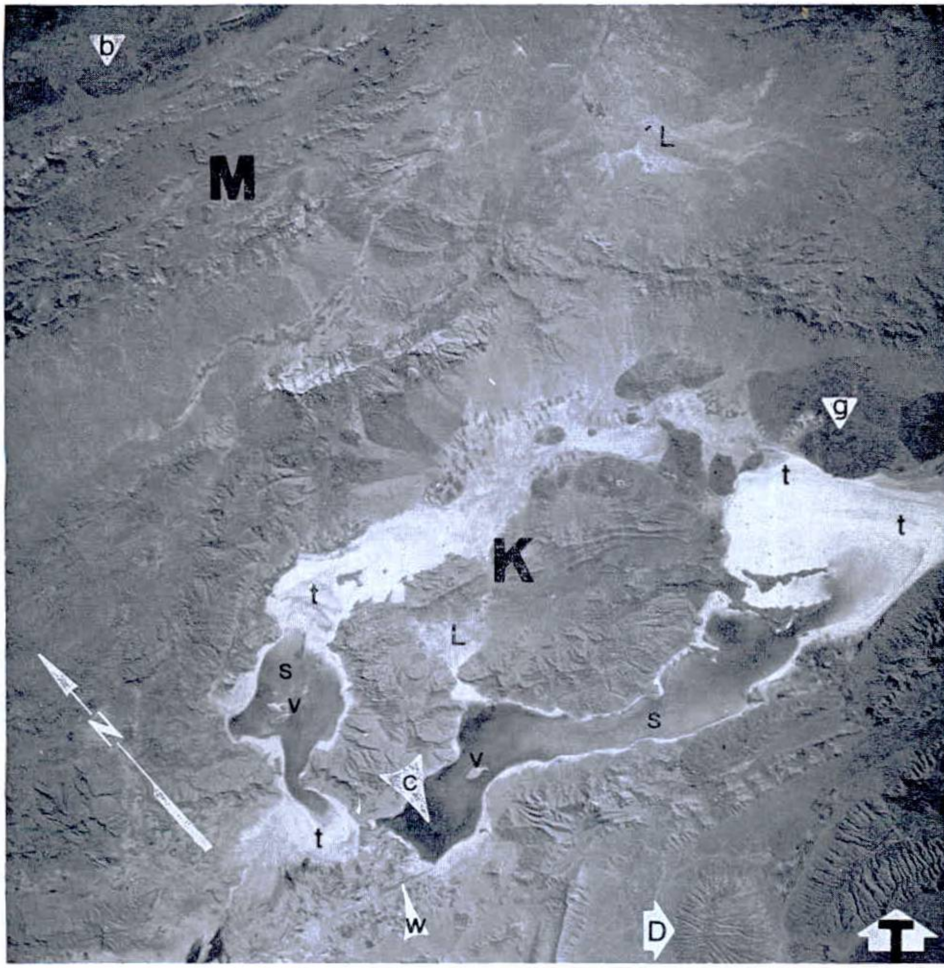


Fig.19. Gemini V photograph (S65-45720), east of Shiraz, Iran, showing salt lakes, salt flats and saline depressions (*L*); area covered is approximately 5,000 sq. miles. A major northerly thrust zone extends approximately east–west across the area and undifferentiated Mesozoic (*M*) sedimentary rocks, Cretaceous basalt (*b*) flows and greenstone (*g*), Cretaceous sediments (*K*) and Oligocene–Miocene (*T*) sediments are overlapped by Quaternary sediments. A dome-like structure occurs at (*D*), and faults are common throughout the area. Shallow water saline shoals (*s*), and bars (*v*), as well as circulation patterns (*c*) in relatively deep water resulting from the introduction of small quantities of turbid fresh water (*w*) are evident; saline strands (*t*) indicate seasonally high rates of evaporation thereby increasing brine accumulations and causing progressive lake retreat. The alluvial fan and evaporite interfaces are well defined in this photograph suggesting that fluctuating lake levels and rates of clastic sedimentation can be readily mapped from such imagery once comparative coverage is obtained. Varying shades of blue provide a means for estimating relative lake depth and volumetric (seasonal) changes in lake water.

and back-weathering in pediment formation. While large pediment surfaces are usually well defined on available space photography, contacts between pediments and mountain fronts may be obscured in places by sediments (Fig.19). Available space photographic systems can also provide cartographic data from which rates of pediment formation and distribution of sediment on pediments can be measured. Understanding modern patterns of pediment sedimentation is potentially valuable to sedimentologists interested in defining the depositional history of thick conglomerate and sandstone sequences along ancient tectonic fronts.

Lacustrine environment

The lacustrine environment includes both fresh and salt water lakes which can be speedily analyzed using space photographs. Lake hydrodynamics, genesis, and sedimentology can be studied as well. Linear to curvilinear traces of ancient and modern lake strand lines can be useful in studying seasonal or climatic changes. Seasonal fluctuations of lake levels or lacustrine currents with corresponding changes in sediment dispersal patterns can also be detected by distinctive plume-like to "whirlpool" patterns. Frequent observations of shallow lakes at moderate-to-high ($> 60°$) angles of solar illumination can be used to analyze sediment distribution related to lake basin size, geometry, and infilling. Infrared scanners and color infrared film in support of photographic records seem promising for orbital studies of lacustrine sediment distribution versus winter ice distribution or summer biota.

Annual observations of large lakes can probably cast light on seasonal rhythms by explaining varves, banded iron deposits, or similar "annual" deposits. Phenomena that might ultimately prove to be rhythmic in character and suggestive of density-controlled circulation patterns have been identified from space photography of the Salton Sea (Fig.18). These phenomena went undetected on previous photo-mosaics. The author suggests that fresh sediment-laden effluents resulting from irrigation in the Imperial Valley of California at times upset a subaqueous density balance and contribute to the circulation patterns observed.

Changes in the size of saline lake basins (Fig.19) and the distribution of evaporite sediments (Fig.20) can be directly measured using orbital photographs, and probably correlated with climatic variations, sediment supply, and regional runoff effects (Fig.12). Synoptic analysis of saline lakes can provide a basis for better understanding environments of evaporite deposition. Moreover, studies of seasonal and clastic influxes provide useful data for studying similar evaporite-clastic sequences in the geological record.

Cave environment

Useful data on cave environment cannot be collected photographically from orbital altitudes and only with difficulty using aerial methods. However, cave systems might be mapped where vegetative anomalies were detected. Space photography, although not available over known cave areas, does promise a means for future qualitative evaluation of seasonal fluctuations in fluvial sediment volume as transported into cave systems and probably rates of karst development in limestone terrains. As noted previously, however, present space photographic resolutions are

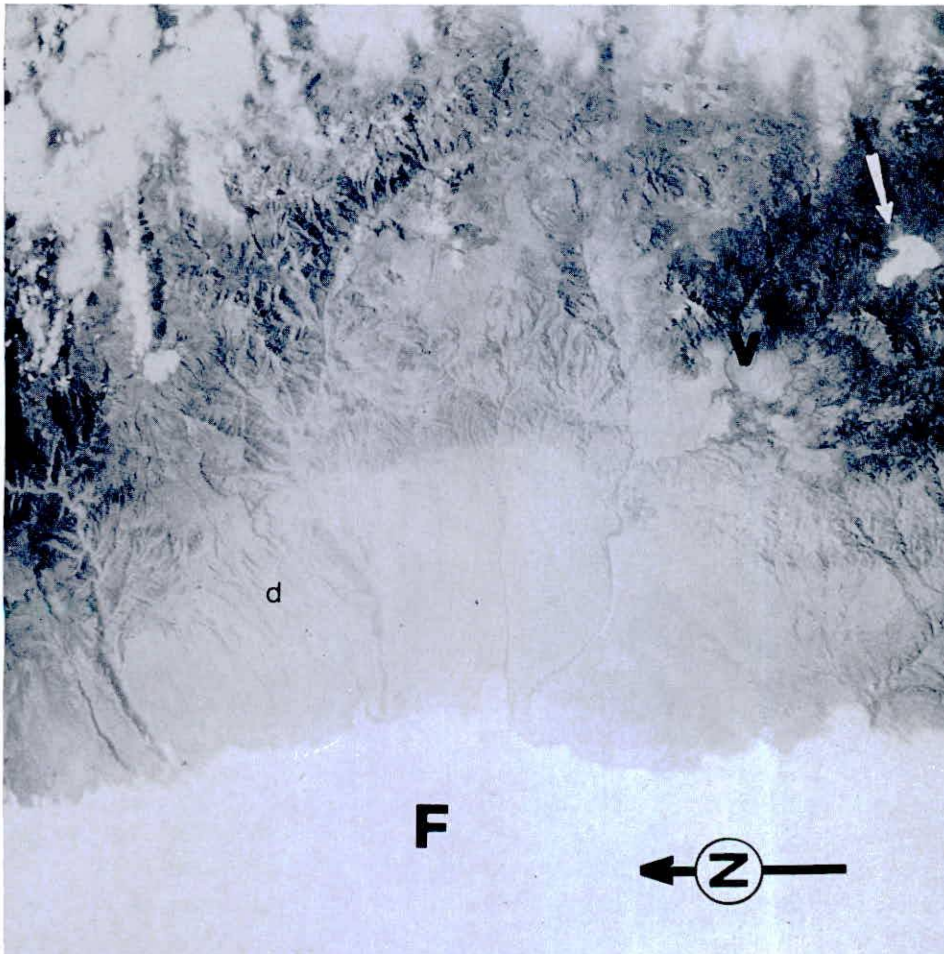


Fig.20. Gemini XI photographs (S66-54832) over southern Peru (Arequipa, Ayacucho and Ica States) showing cloud-covered Andes Mountains and dense coastal fog (*F*). The use of an alternative sensor e. g., radar, to support photographic records would be recommended under such conditions of limited visibility. Pediment surfaces throughout this region are geologically young, and veneered with sediments. The area shown contains thick Tertiary sediments overlying igneous volcanic and acid intrusives, the former deeply dissected in some areas (*d*). Laguna de Salinas, a dry saline lake is identified (arrow), not far from a volcanic cone (*v*).

largely inadequate for studying fluvial sedimentation. Further, the orbital collection of useful cave sedimentological data without high-resolution systems cannot be predicted with certainty.

Although not possible now, cave systems in densely vegetated humid areas might someday be mapped by sufficiently sensitive radars. In the absence of dense vegetation, infrared sensors may also useful in mapping shallow cave networks provided emissivity variations between caves and terrain not underlain by caves can be recorded.

Paludal environment

The paludal environment as described here includes marshes associated with the fluvial, marine coastal and lacustrine environments. A review of existing literature suggests that salt and tidal marshes (Fig.15) have often been critically examined by sedimentologists along with the nearshore marine environment, but that sedimentation in fresh water marshes still requires additional study. Orbital views of major marsh areas yield large quantities of synoptic data without the dense sampling grids normally necessary before extrapolating environmental generalizations. Large numbers of samples are especially important for marsh studies as sedimentary patterns may be obscured by dense vegetation and sampling limited in inundated areas that may be difficult or even impossible to traverse.

KNIGHT's (1934) discussions of variations in salt marsh sedimentation and the importance of plants in trapping lagoonal sediment appear generally applicable to fresh water marshes as well. Color and infrared films can be effectively used from space to evaluate paludal sediment vegetation patterns as suggested by SCHNEIDER (1966) for conventional aerial surveys. Space photographic color anomalies are indicative of depth variations in shallow bodies of standing water, subaerial sediment saturation, or extent of organic accumulation, based on surveys by the author of the coastal marsh environment. Color variations have also been correlated with marsh grasses or mangrove trees in some areas (Fig.21). Color space photographs supported by orbital infrared imagery similar to that used by FISCHER et al. (1966) in detecting submarine fresh water springs might also be used to detect thermal anomalies between vegetation and sediment-laden marsh water. Marine paludal and fluvial relationships deserve special attention because of environmental parallelism with coal deposits in the geological record. Satellite photography can probably be used to monitor marine incursions and seasonal variations in fluvial sedimentation in the modern marsh environment. The data will yield a better understanding of the genesis of discontinuous coal deposits or cyclical deposition such as that associated with Paleozoic coal measures. Similarly, environmental data could also be collected pertinent to understanding stratified pairs of lignitic coals interbedded with marine deposits in the western United States, which are suggestive of oscillating marine transgressions and regressions. The overlap of fresh water sediments by apparently oscillating marine deposition might also be studied with respect to cyclothems.

High-resolution orbital photography could also provide qualitative data concerning the relative significance of allochthonous vegetative contributions to coal deposits in the geological record. Also, space surveillance of the fluvial–marine interface could serve as a basis for interpreting organic accumulations in the deltaic marsh environments.

Marine environment

Frequent analysis of the shallow marine environment (Fig.21) and nearshore

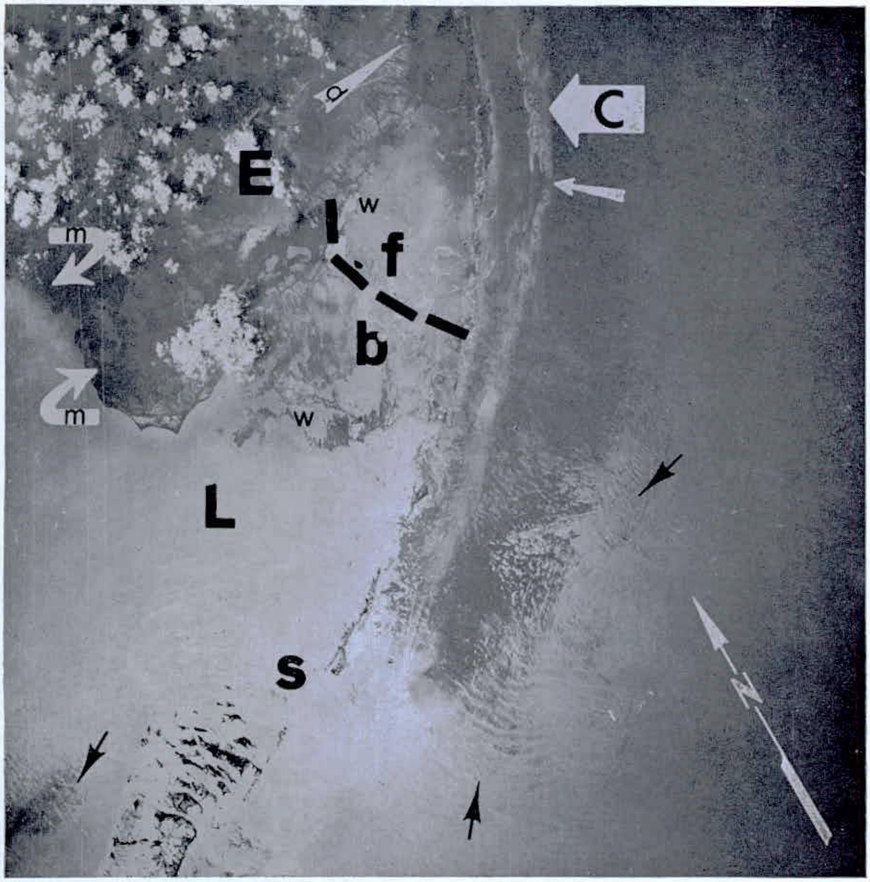


Fig.21. Gemini IV photograph (S65-34766) over Ponce de Leon (*L*) Bay, Cape Sable, Florida, and Everglades (*E*) National Park in an area underlain by Quaternary marine limestones. Sunspot (*s*) has accentuated long period marine swell (e.g., black arrows); this effect if reproduced in other areas can provide a means of examining sea state in relation to variations in nearshore marine sedimentation. Original space photograph contains colors useful for broadly differentiating drainage features (*d*), coastal marshes (*f* and *b*), mangrove swamps (e.g., *m*) vegetated and non-vegetated shoals, and shallow water areas (*w*) with interspersed grasses (?) and subaerial sediments. Irregular tidal estuaries and channels interface with fluvial marshlands. Frequent coverage of such areas can provide the basis for analyzing changing sedimentary environments in response to tidal fluctuations or reginal marine incursions and shed light on cyclical deposits in the geological record. The broad differentiation and analysis of changing environmental boundaries between predominantly fresh-water (*f*) and salt-water marshes (*b*) seems feasible using such photography. Light-toned linear (*C*) which parallels the coast is the subaqueous trace of an active coral reef; reef boundaries and channels (barbed arrow) can be readily delineated.

processes is one of the most promising sedimentological applications of space photography. Marine sediments constitute a major portion of the geological record and space photographs showing marine transportation mechanisms and sediment circulation patterns provide a basis for analysing similar processes in ancient marine environments. Orbital studies of the response of marine sedimentation to diastrophism would be equally useful. HOLLINGSWORTH (1962) suggested that diastrophic mechanisms are too often the basis for marine stratigraphic interpretation and that climatic changes may be more significant. Frequent climate observations from orbiting meteorological satellites can also help sedimentologists in evaluating modern sedimentological responses to present-day climatic phenomena.

Cylical patterns recognized throughout the geological record have been explained as the products of both meteorological and tectonic forces (WELLS, 1960) in a variety of sedimentary environments. ALLEN (1964), described six fluvial cycles in the Lower Old Red Sandstone, whereas DUFF and WALTON (1962) suggested marine sedimentological and diastrophic controls for rhythmic patterns in the East Pennine coalfield. DE RAAF et al. (1965) discussed geological rhythms as the products of a wide range of environments from deep basins to marine shorelines fronted by deltas.

Space photographic reconnaissance enables the systematic analysis of marine sediment distribution associated with supratidal incursions (Fig.21). Such analysis may ultimately contribute to explaining Carboniferous rhythms throughout the world. The author also suggests that widespread marine advances accountable to glacial fluctuations (WANLESS and SHEPARD, 1936) can be evaluated by the long-term, repetitious collection of orbital data over continental glacial sites correlated with worldwide marine responses at selected test sites.

Space photographs reveal useful sedimentological data about continental shelf areas. The break between the continental shelf and the continental slope has been tentatively identified along the African and Gulf coasts with sediment patterns suggestive of submarine canyons or submarine escarpments. K. O. Emery (personal communication, 1964) outlined marine sediment and biological sampling problems on the continental shelf. The careful selection of sampling sites from orbital photographs in areas of detectable sedimentary changes could reduce the number of samples taken and increase the cost-effectiveness of data collection. Also economical in both manpower, cost, and data yield would be systematic space reconnaissance of worldwide nearshore continental areas as the basis for selective (detailed) surface sampling activities in predetermined regions of significant physiological or sedimentological change.

The transportation of fluvial sediments to submarine canyons might also be studied in offshore areas, e.g., California, where sediments normally deposited in beach areas are carried into deep water via submarine canyon channels. Besides evaluating seaward sediment migration, patterns of longshore sediment movement could be quickly monitored and compared with mean wave direction or available sources of sediment supply. Sedimentologists interested in turbidity currents in the geological record might use space photographs to study zones where submarine slides originate. Although space photography cannot be used to locate deep water turbidity slides or mean current vectors, turbid shallow water plumes or sites where such slides begin might be detected.

Color space photography lacking special filtration has proved useful in studying submarine sedimentation and penetrated marine waters to a depth of several meters

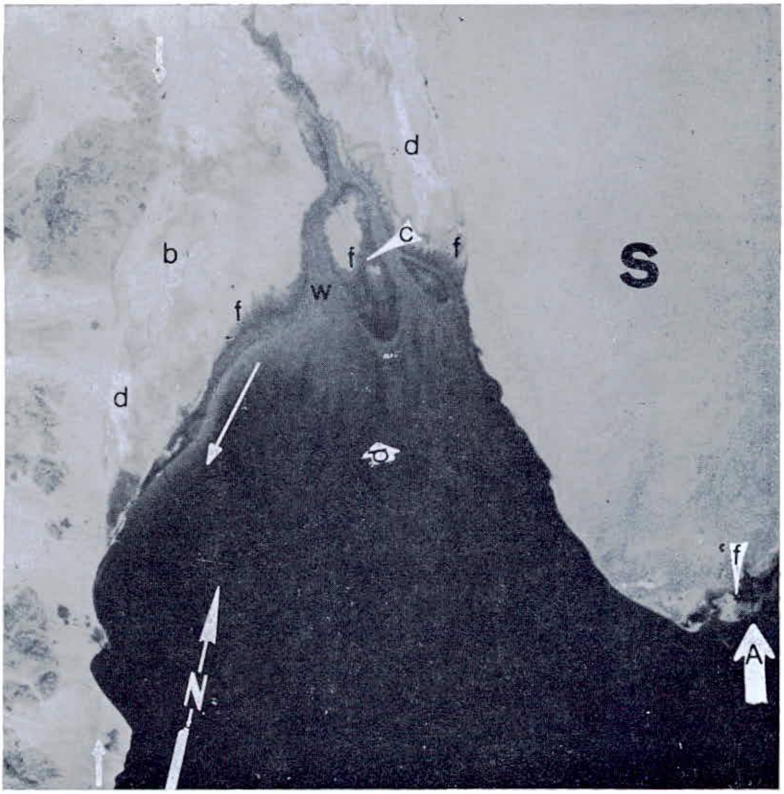


Fig.22. Gemini IV photograph (S65-34673) over the Colorado River delta and Gulf of California showing Bahia de Adair (*A*) and sand dunes in the Sonora Desert (*S*). A fault trace (between arrows) partly buried by Quaternary sediments parallels an area composed of Mesozoic acid intrusives and Tertiary volcanics. Area was photographed during a moderately-low tidal period judging from dark-toned tidal flats (*f*), exposed tidal channel (*c*) and relatively shallow water shoals (*w*) near the delta mouth. Light-toned Quaternary saline depressions (*d*) and stream beds (*b*) are seasonally subjected to flooding. Dark tonal areas contrasting with sediment plumes (*p*) closely correspond to variations in bottom topography on existing bathymetric charts; longshore sediment drift (arrow) parallels exposed subaerial tidal flats.

(Fig.22). Effective penetration appears to depend on a lack of sea surface roughness, high angle of solar illumination, and natural water transparency. Applying indirect interpretation clues, including divergent or convergent wave refraction patterns, may prove useful in locating submerged marine sedimentary features from space photographs, although only long-period wave swell has thus far been detected.

Orbital photography is also valuable for studying dynamic marine processes and their responses to changing sedimentological, or meteorological phenomena including winds, tides and current. Color infrared photography (Fig.23) appears especially useful for highlighting coastal landforms and sediments in areas despite thick coastal haze or regional industrial smog. Particularly amenable to photo-

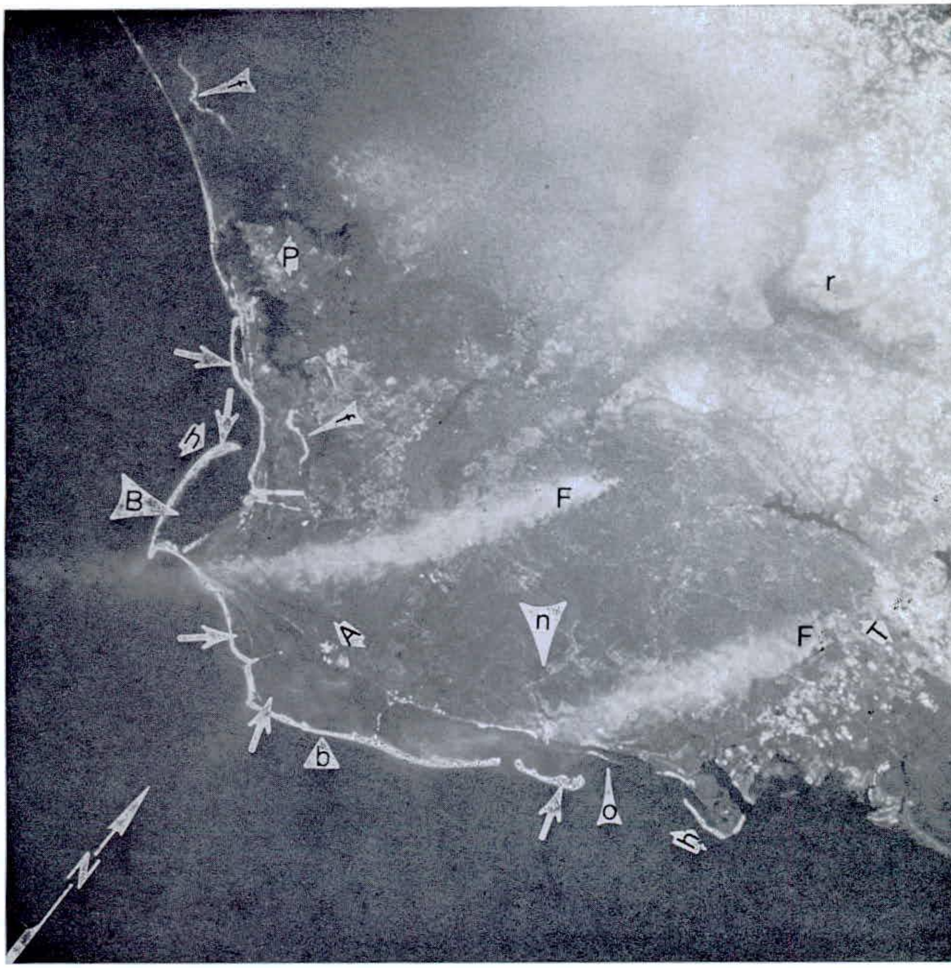


Fig.23. Gemini VII infrared ektachrome photograph (S65-64053) over the Gulf coastal towns of Apalachicola (*A*), Panama City (*P*) and Tallahassee (*T*), Florida, including such cultural features as a road network (*n*) and reservoir area (*r*). Fluvial bars (*f*), and dark-toned swamplands have been imaged; barrier beaches (*b*) and spits (*h*) are well delineated, although shallow offshore bars (*o*) are obscured by smoke plumes originating from forest fires (*F*). Color differences on original space photographs correspond to the 10–15 fathom bathymetric line on the southern edge of St. Joseph Bay (*B*). Of particular sedimentological value is the high contrast nearshore marine sediment record, and detailing of zones of saturation and (quartz–carbonate?) sandy subaerial deposits (barbed arrows). Repeated orbital observations of such coastal areas using color infrared instead of color film would permit speedy inventory of morphological changes which could be correlated to rates of sediment distribution. Color infrared film appears a useful tool for analyzing coastal sediments judging from this photograph.

graphic study is the distribution of nearshore marine sediments and sediment dispersal effects on beach nearshore and offshore bar, tidal bar and spit development. Nearshore marine transportation processes (Fig.24 and 25), including longshore marine current

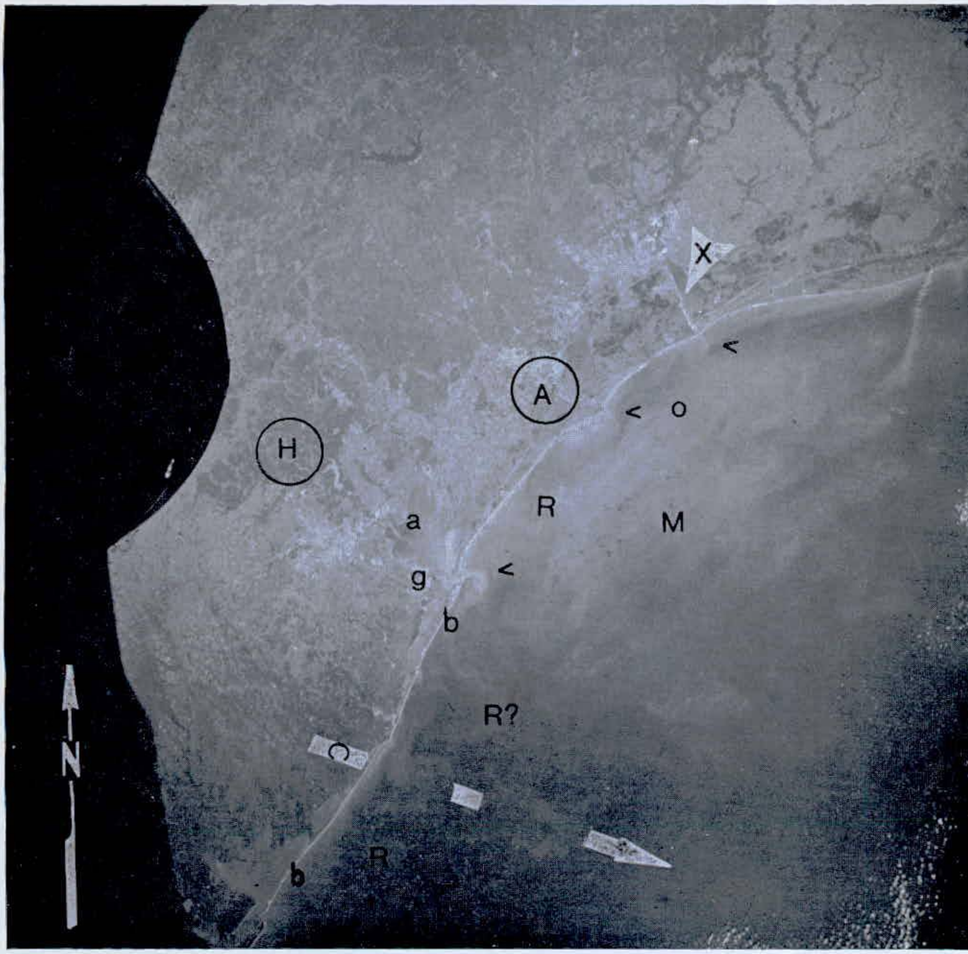


Fig.24. Gemini XII photograph (S66-63064) over the Gulf Coast showing the Port Arthur (*A*) and Houston (*H*) areas. Barrier beaches (*b*) and coastal spits extend for approximately 100 miles along the coast while well-defined sediments plumes (arrow points) mark outlet channels. Rip currents (*R*), a zone of complex sediment mixing (*M*) and a major seaward-moving distributary current (*C*, broken arrow) of potential value in disposing of urban pollutants can be detected. The western margin of dark-toned area (right) approximates the 30 fathom line along which the coastal shelf falls off rapidly (eastwards) into the Gulf of Mexico and over which sediments are carried into deep water. An offshore bar is probably developing at (*o*). Fluvial sediments carried from bay areas and through tidal inlets can be used to estimate marine longshore current directions, e.g., sediment plumes curve in a downcurrent direction. Regional haze (and probable slight photographic overexposure) limit analysis of sedimentological processes in bay regions, although tonal variations (*a*) suggest local bathymetry. A causeway (arrow *X*) divides Lake Calcasieu into two parts, and provides barriers contributing to lake infilling and marshy conditions on the west; a similar situation occurs in Galveston Bay where causeway (*g*) is beginning to isolate the lagoonal area and deflect some seaward-moving sediment into the backwater area.

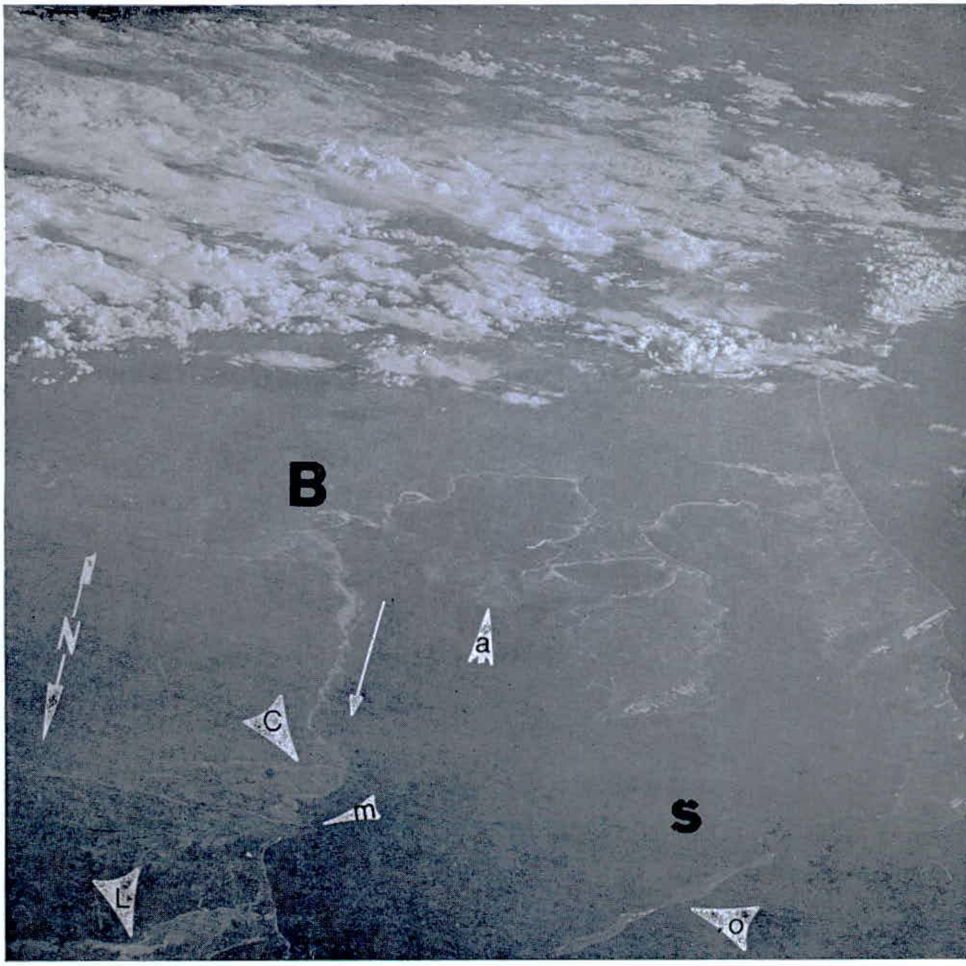


Fig.25. Gemini IV photography (S65-63136) over Western Australia, viewing southeast over Shark Bay (*S*) and the NASA Carnarvon (*C*) Space Tracking Station. Bottom of photograph traces an area 100 miles long and average photograph scale is 1 : 10,000,000. Maps of the area suggest that the embayment formed following a marine transgression into a pre-existing dune landscape resulting in linear bayheads along the coast; offshore islands (*o*) are composed of dune sands and sediments probably transported seawards from the river delta mouth (*m*) and intermittently from streams in area (*B*). Seasonal flooding results in the shallow filling of saltwater lakes (*L*) and marshes which are short-lived due to high regional evaporation rates. Shallow water carbonate and clastic quartz shoals and barrier ridges cut by tidal channels occur near Faure Island (*a*), and limit marine circulation; hypersaline lagoons behind these shoals reportedly contain stromatolitic structures and algal mats. Changes in shoreline geometry in this area could be mapped sequentially over an extended period, and sedimentation in hypersaline lagoons monitored along with changing coastal physiography.

drift (Fig.26), rip currents and tidal sediment patterns lee of barrier beaches, can be analyzed from existing space photographs. Sequential orbital coverage of coastal areas provides quantitative data concerning the shoreward transgression of barrier beaches and seasonal erosional changes. Studies by the author show that Gemini

Fig.26. Gemini V photograph (S65-45736) over the Nile River delta, Alexandria (*E*) area and Western Desert showing dense agricultural patterns, scattered small settlements (light-toned points) and road networks in the delta area. Coastal area shown is approximately 90 miles long, and average image scale is 1 : 2,000,000. Textured sand and gravel beach area (*Q*) with well-defined strand lines and coastal dunes (*s*) adjoins sand plain with irregular dunes (area *D*); textural (white line) boundary approximates the Quaternary–Miocene/Pliocene marine sediment contact. Nearshore areas (and area *A*) contain sealevel saline depressions (*d*) in approximate linear arrangements. Predominantly eastward moving longshore currents (arrow) disrupted by nearshore (rip ?) currents (*R*) have built spits (arrows). Irregular sediment mixing patterns are evident in bay area, annotated (*c*). Brown haze on color original left of area (*Q*) is dust moving westwards into the Mediterranean Sea

photographs can be used to analyze tidal, littoral current, and rip current effects on marine landforms. Rates of nearshore sediment drift can also be estimated by periodic measuration of changing nearshore spits or bars using area/volume determinations.

Gemini photography further suggests that useful data concerning tidal flat

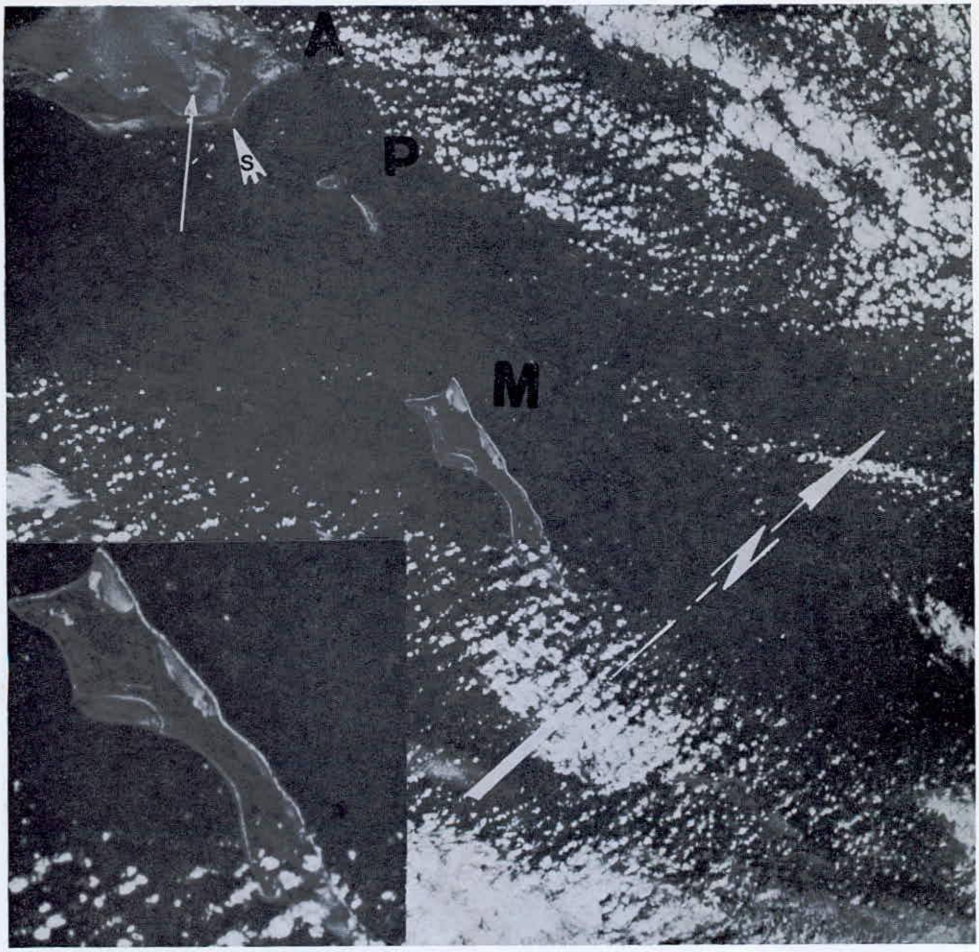


Fig.27. Gemini VII photography (S65-63858) over the Bahama Islands, showing Mayaguana (*M*) Island (see inset; enlarged 3.8 × over 70 mm original), Plana Cay (*P*) and Acklins (*A*) Island. Vegetated reef islands (dark-toned), "barrier rims" and shelf lagoon shoals (light-toned) can be mapped from this photograph. Sunlight penetrating clear waters in this region reflects from lagoonal carbonate (oolitic?) sands, and give an indication of relative depth; nearby carbonate shoals and subaqueous variations of bottom relief account for blue-white color variations around Acklins Island and suggest the presence of a sand ridge (arrow). Sediments transported southwards along the eastern edge of Acklins Island have built a small spit at (*s*). Enlargement of such high quality space photography is possible for detailed environmental studies, e.g., in areas studied less intensively than, for example, Andros Island to the west; photograph quality deteriorates rapidly with enlargement towards the edges of space photographs. Where extensive field information is available, the space photographic record serves as a base upon which scattered data concerning environmental phenomena can be synthesized.

sedimentation (Fig.22) can be collected through timely surveillance in conjunction with tidal changes. Sediment movement over estuarine flats due to tidal changes could be broadly studied and relationships established between tidal advance (retreat), marine sedimentation, and the freshwater/saltwater interface. Color pattern

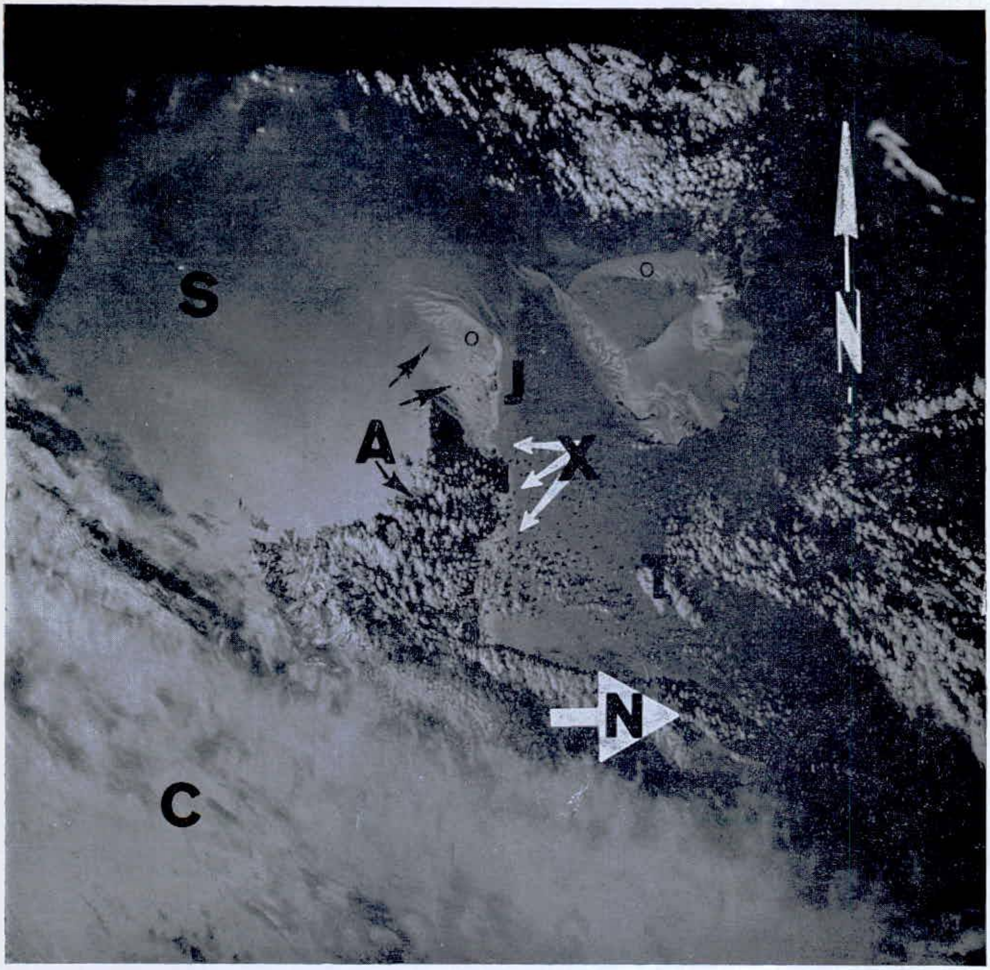


Fig.28. Gemini VII photograph (S65-63825) viewing south over the Bahama Islands and Tongue of Ocean (*T*) encompassing Andros Island (*A*, cloud-covered) and New Providence Island (*N*). Dense cloud bank (*C*) obscures the southwestern part of Great Bahama Bank, although shallow carbonate sediment mixing on the Andros Platform (*S*) can be recognized; tonal variations in area (*S*) are partly controlled by bottom relief. There appears to be no immediate means to differentiate carbonate sediment faces using such photography, although zones of oolitic sand can be determined where bottom ripples occur, e.g., areas (*o*). Small barrier and patch reefs reportedly growing along the edge of the outer platform (*X*) cannot readily be detected, although small (linear) tidal channels (arrows) west of Joulters Cays (*J*) can be recognized.

variations, including characteristically deranged drainage patterns useful in identifying tidal flats and the intertidal area, can be readily recognized on space photographs.

Modern environments of carbonate sedimentation have been well documented

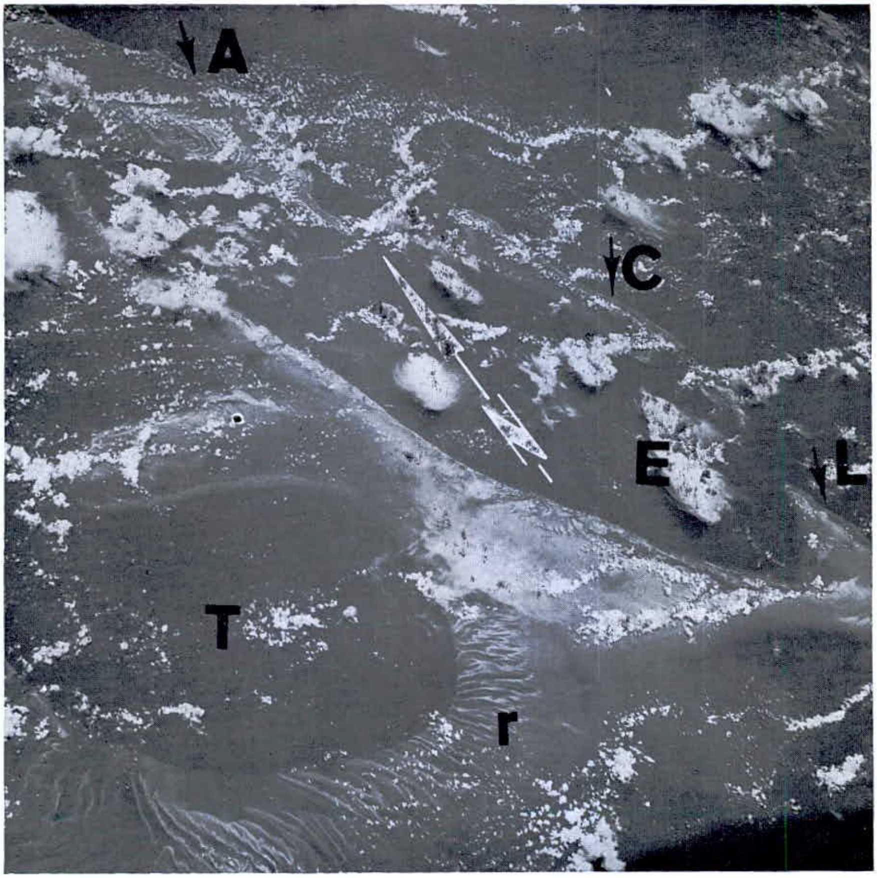


Fig.29. Gemini VII photograph over Great Bahama Banks, Tongue of Ocean (*T*), Exuma Sound (*E*) and Cat (*C*), Eleuthera (*A*) and Long (*L*) Islands showing shoal areas. Vegetated islands (dark-toned) contrast with flanking coloidal sediment suspensions and sand shoals in shelf areas. Giant transverse bottom ripples (*r*) on light-toned bank are covered by 20–30 ft. of water, while Tongue of Ocean is over 4,000 ft. deep; dark blue tones indicative of deep water are well displayed on the original space color photograph. Sunlight reflecting from the carbonate bottom in shallow water areas accentuates bottom relief and indicates that space coverage can be used to measure changes in submarine features and the rates they occur.

in geological literature. Space systems promise to expand the existing data base by surveying carbonate depositional environments (Fig.27) and carbonate sediment distribution. Variations in carbonate sediment dispersal (Fig.28) associated with seasonal, tidal, or severe weather (hurricane) effects can probably be monitored along with subaqueous carbonate shoals subjected to normal wave and current agitation. Space photographs of the Bahamas show submarine depositional features including well-known giant bottom ripples (Fig.29).

Organic reef complexes are also amenable to space photographic study (Fig.21). Reef distribution, limited to approximately 30° north and south latitude of the equator, parallels the latitude coverage of low-latitude Gemini photography, Pacific coral atolls have also been identified from Gemini photographs. The resolution of the Gemini photographs, however, limits the collection of sedimentological data because only coralline atoll boundaries or color indicators of depth variations can be immediately detected. A particularly suitable target for study by high-resolution space photographic systems is the Great Barrier Reef of Australia.

A worldwide study of the reef environment would permit long term studies of marine current effects on reef distribution and also assist sedimentologists in evaluating sedimentary processes affecting reef growth. Simultaneous infrared systems can best be used to provide information on near-reef ocean temperatures. Sedimentation within the reef lagoons has been extensively studied (NEWELL, 1959), although changing patterns of suspended carbonate sediment distribution coincident with variations in reef distribution or reef geometry over long periods can be best conducted by continuing orbital surveillance. Whether windborne (aeolian) sedimentation has a negative effect on reef growth rates, e.g., in the Persian Gulf, might likewise be determined, provided the distribution of seasonally persistent dust storms were adequately mapped. Color tones have proved especially helpful over the Bahamas for indicating depth variations and traces of the submerged margins of island platforms. Selected photographic enlargements suggest that obvious color anomalies, including milky carbonate-laden current turbidity, can speed identification of shoals or similar submerged features in shelf lagoons. Tonal contrasts between forereef and backreef sedimentation may be sufficiently well marked to assist in locating coastal (fringing) reefs (Fig.11).

The sedimentological history of the reef complex can also be elucidated by frequent mapping of reef fronts, lagoons, and surge channels that provide exits for lagoonal carbonate debris (Fig.30). Space photographs can also prove valuable for studying sedimentation in reef-barred basins with limited saltwater inflow/outflow, thus better defining the environmental history of such basins in the geological past.

Delta environment

Usable Gemini photographs have been obtained of delta areas, although sedimentological data can at times be obscured by intense agricultural development (Fig.26 and 31). Frequent orbital coverage over such areas as the Nile River delta can provide a basis for determining periods of maximum delta growth. Space photographs often constitute the most current maps of deltaic islands and channels, which are constantly changing shape, size and location in response to changing sedimentation. Submarine tidal and marine current sedimentation beyond the seaward edge of the delta can also be recognized by color pattern variations (Fig.32) and seasonally inventoried. Gemini imagery of the Colorado River delta shows current dispersal of suspended sediments imaged as buff-colored plumes that contrast with bathymetrically-related aqua to blue tones of the marine environment.

Inherent in studies of delta sedimentation is the ability to evaluate the interaction

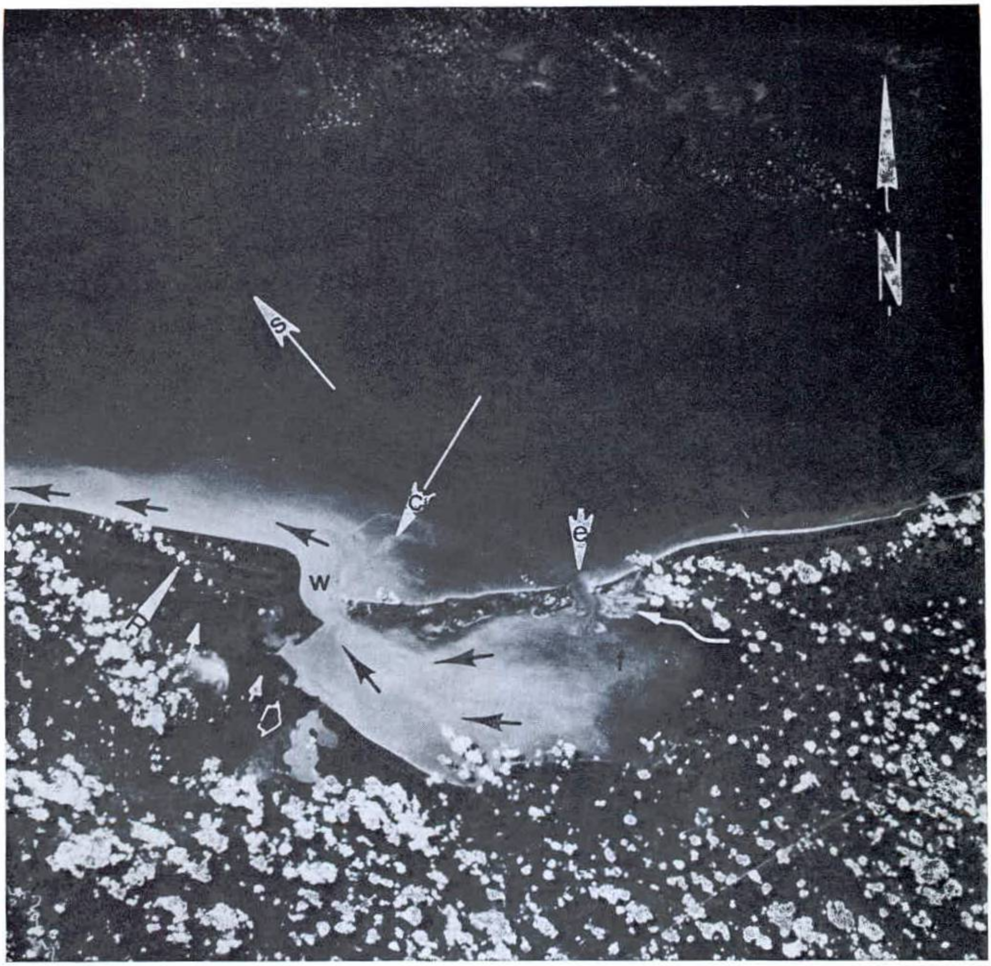


Fig.30. Gemini V photograph (S65-45765) over Laguna de Terminos, Campeche, Mexico, in a cloud-covered area of Quaternary fluvial and coastal marshes with possible zone of fresh water outflow at (*f*). Beach ridges can be seen at (*R*). Scattered dark-toned mangrove stands (white arrows, lower left; see also Fig.21) occur in zones of brackish water in close proximity to fresh water streams draining marshlands and mudflats (e.g., hollow arrow). Lagoonal carbonate sediment mixing, westward longshore current drift (*c*) and major seaward-sediment movement (arrow *s*) emphasize the value of space photographs for studying nearshore marine sedimentation. Major directions of current movement are indicated by black arrows. Turbid currents carry colloidal sediment westwards, following lagoonal circulation, through a tidal channel (*w*); a second inlet (*e*) backed by a sand bar and flanked by shoals (serpentine arrow; note deranged tidal channel pattern) is probably a tidal surge channel.

between delta sediment load, changes in prevailing winds or severe weather, and the buildup of offshore bars. The orientation of offshore shoals might also be correlated over extended periods with existing offshore currents influencing sediment dispersal and changes of deltaic sediment load (Fig.33). Deltaic sedimentation effects on marine

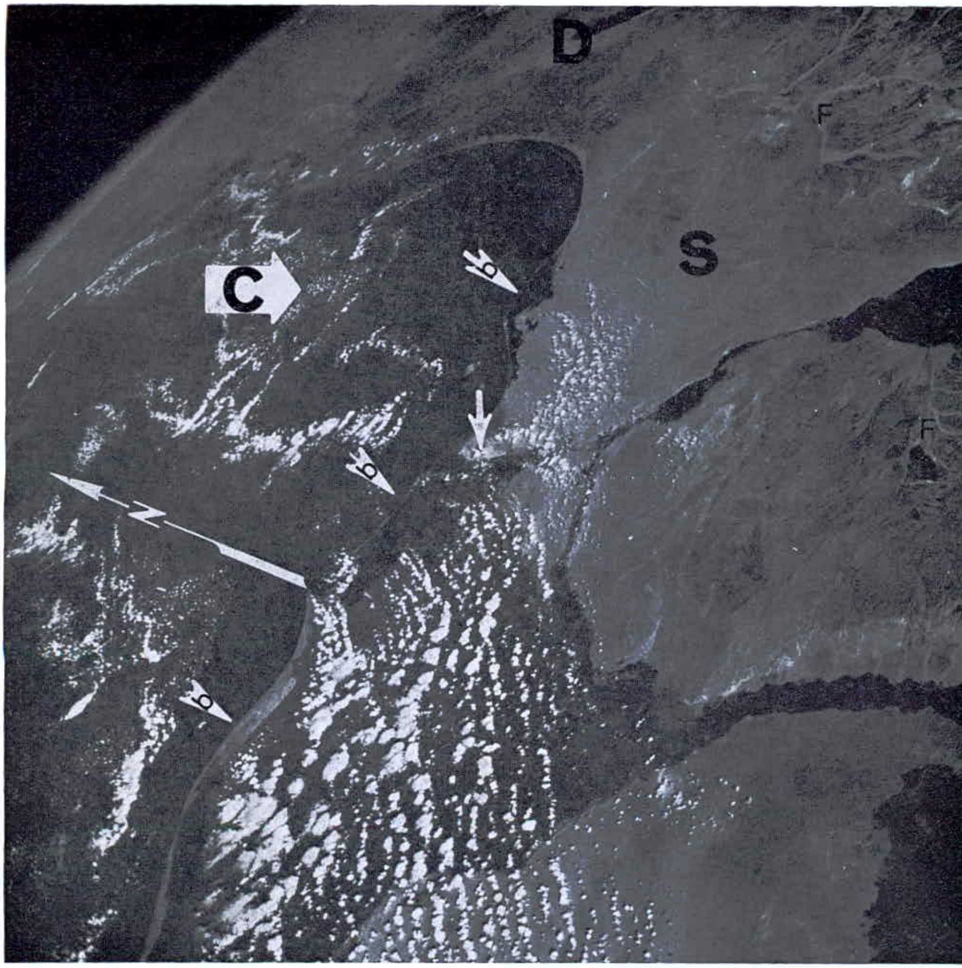


Fig.31. Gemini VII photography (S65-63849) over cloud-covered Nile delta (ref. Fig.26) and Island of Cyprus (*C*), Suez Canal (barbed arrow), Sinai Peninsula (*S*), Dead Sea (*D*), and Syria, Jordan and Lebanon, viewing north toward the horizon. Barrier beaches (*b*) are backed by Pliocene–Quaternary sands and dunes, Lower Tertiary sediments, and intermittant fluvial valleys (*F*) choked with sand. The fan-like shape of the Nile delta (100 miles wide along coast) is plainly visible, because of dense agricultural development which is imaged in dark blue on the original color photograph; lagoonal areas and marshlands behind barrier islands are difficult to delineate excepting by tones somewhat darker than agricultural areas. Such wide area coverage would be of initial cartographic value in mapping the delta environment, although less useful for detecting all but major shoreline changes and evidence of delta growth. The probable trace of continental shelf is discernible by blue tonal contrasts on original color photography.

beach deposits and other littoral physiographic features (Fig.25), might likewise lead to locating petroliferous porous sand deposits in the geological record formed under similar environmental conditions (WOBBER, 1967a). Periodic photography of delta growth rates correlated with marine tidal changes might be especially suitable studies

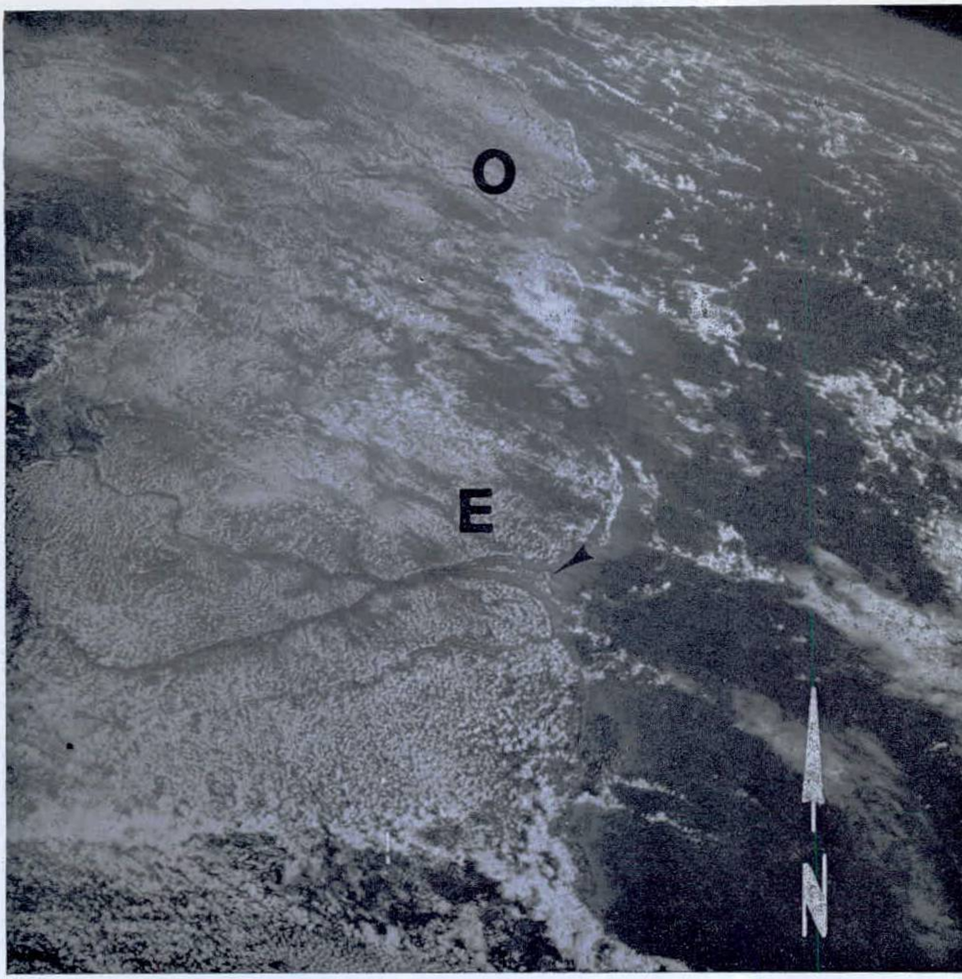


Fig.32. Gemini X photograph (S66-46054) over eastern South America (Guyana, Venezuela, Surinam and Trinidad) showing coastal sediment distribution at the mouths of the Orinoco (*O*) and Essequibo (*E*) Rivers; dense cloud cover over rainforest is typical of this area and contrasts with thin haze over river channels. Coastal area is backed by marine marshes (dark tones). Light-toned sediment drift, generally northward, and dark-toned deep water areas can readily be identified. Vegetated channel islands are visible at the mouth of the Essequibo River (arrow). Photograph is illustrative of the difficulty of collecting useful data photographically in tropical areas because of atmospheric limitations.

for near-future Apollo manned space missions because of the relative ease with which deltas can be visually detected at the terrestrial–marine interface.

THE FUTURE—SEDIMENTOLOGY AND SPACE

The abundance of valuable sedimentological data available from future orbiting earth survey systems is suggested by analysis of Gemini photography. A variety of

Fig.33. Gemini V photograph (S65-45768) over the Yangtse (*Y*) River delta and city of Shanghai (arrow), viewing west over turbid water plumes extending several miles into the East China Sea. Offshore bars, shoals and islands (e.g., area *A*) are continually changed in shape and size due to shifting offshore sedimentation and variation in distributary currents. This photograph constitutes a means of updating maps in delta areas where island lifetimes may be limited. Based on a review of hydrographic data, tonal variations in nearshore areas are due to changing turbid water density rather than changing depth.

remote sensor systems can yield data concerning marine water temperature, ground moisture and vegetation distribution in parallel with color space photography. With extraterrestrial exploration, sedimentologists may be called on to interpret erosional, transportational, or depositional processes on other planets—data initially collected by remote sensors. Experience gained from studying currently available remote sensor records can establish the degree of confidence necessary for extraterrestrial analyses in the absence of field data.

Space surveillance of modern sedimentary environments can likewise have broad international economic advantages. For example, adequate warning of approaching dust storms or projected directions of dune migration can permit early corrective engineering control. Offshore bar or reef development related to navigational safety or coastal engineering planning, as well as studies of the rates of sediment accumulation in reservoirs that extend the life of large dams, also have considerable economic overtones. In areas of commercial fishing activity, knowledge of the distribution and movement of sediment on the continental shelf as affecting fish migration or reproduction and movement of pollutants harmful to shellfish may also prove promising. Space photography of sediment patterns in the Gulf of California compared with bathymetric maps show a marked correlation and suggest broad opportunities for speeding mapping in the paludal and lacustrine environments. For natural resources development, space photography would be an especially effective means of synoptic mapping, and locating heavy metal concentrations by the study of nearshore marine distributory currents on continental shelves of the world.

A significant but largely unrecognized benefit of space photography is its use for developing improved sedimentological and ecological sampling programs. By using available space photography, samples could be collected at selective marine or terrestrial sites predetermined to warrant increased sampling density. For example, a program concerned with the distribution of heavy minerals or sediments could obviously benefit from samplnig site selections that consider existing distributary currents. Sampling programs based on space photographs can therefore produce increasingly significant ground data regardless of the sedimentologist's interest in otherwise using space photography. Selective, purposeful sample collection sites ensure that data are obtained where needed and provide the basis for more than a "hit and miss" sampling program. Detailed consideration of this application of space photography is included in WOBBER (1967b).

It is important that sedimentologists be aware of the technological opportunities offered by space photographic environmental studies, and that they develop the necessary experience and confidence to make maximum use of orbital remote sensor records. Data permitting the deeper understanding of modern environments are now available, as this paper suggests, but they have been largely untapped.

CONCLUSIONS

Geologists in cooperation with space systems engineers are best able to specify sedimentological problems to be addressed by orbital sensors, but they must first gain experience in analying available space imagery. The advantages of orbital remote sensing include synoptic overview, the potential for frequent (seasonal) worldwide coverage, and a data collection capability in otherwise inaccessible areas or under hostile environmental conditions. Available Gemini photographs are suggestive of space photographic capabilities for environmental analysis but were collected under operational constraints. Technical developments forthcoming from aircraft and experimental orbital programs can greatly improve the quality of data collected.

Color Gemini photographs are generally useful for environmental studies and mapping gross lithology, geological structure, and regional hydrology. Dynamic aeolian, lacustrine, deltaic and marine processes can be identified along with the land forms they produce, although high resolution orbital systems and/or supporting color conventional aerial photography is required for an in depth appraisal of the fluvial environment.

Space photography is particularly useful for evaluating marine erosional, depositional and distributary processes and for surveying beach geometry and coastal marine sedimentation. Color photographic anomalies are indicative of relative depth and pıovide data concerning subaqueous topography and turbidity. Repetitive coverage of marine carbonate environments provide a mapping base for expanding baseline data in such areas as the Bahamas, and for examining seasonal fluctuations affecting coral reef distribution and growth.

Changing delta growth rates in response to changes in fluvial sedimentation or erosional variations in drainage basins can likely be observed with additional coverage. Abundant environmental data in arid areas, e.g., the evolution of alluvial fans, dune fields, and playas can also be collected. Frequent and prolonged observations of sedimentary environments offer new opportunites for better understanding processes leading to sedimentary rhythms, including cyclical sedimentation in the Coal Measures throughout the world, and generally expanding the environmental data base in support of research in the geological record.

Extensive and as yet untapped quantities of sedimentological data are available from existing color space photography. Radar and infrared sensors can be used to supplement the information content of orbital photography especially where climatic limitations prevent the exploitation of the visible portion of the spectrum. Future opportunities for the rapid orbital collection of information concerning sedimentary environments and processes necessitate that sedimentologists now exploit existing space records and critically evaluate the potential contribution of orbital observations to the geosciences.

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