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**A Global Tectonic Activity Map
With Orbital Photographic Supplement**

Paul D. Lowman Jr.

JANUARY 1981

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771



TM 82073

A GLOBAL TECTONIC ACTIVITY MAP
WITH ORBITAL PHOTOGRAPHIC SUPPLEMENT

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GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland

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**A GLOBAL TECTONIC ACTIVITY MAP
WITH ORBITAL PHOTOGRAPHIC SUPPLEMENT**

ABSTRACT

A three-part map, showing equatorial and polar regions, has been compiled showing tectonic and volcanic activity of the past one million years, including the present. Features shown include actively-spreading ridges, spreading rates, major active faults, subduction zones, well-defined plates, and volcanic areas active within the past one million years. Activity within this period has been inferred from seismicity (instrumental and historic), physiography, and published literature. The tectonic activity map has been used for planning global geodetic programs of satellite laser ranging and very long base line interferometry, and for geologic education. It illustrates several aspects and problems of global tectonic and volcanic activity not shown on conventional plate maps: the large areas of crustal deformation not susceptible to treatment as parts of rigid plates, the wide occurrence of volcanoes on the upper blocks of continent-continent convergence zones, areas of little-known vulcanism and tectonism, intraplate rifts, and the bilateral across-strike symmetry of young fold belts.

A supplemental collection of representative orbital photographs is included, showing major tectonic and volcanic features active within the last one million years. Areas covered include parts of North and South America, Europe, Africa, southern Asia, and selected oceanic islands.

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A GLOBAL TECTONIC ACTIVITY MAP WITH ORBITAL PHOTOGRAPHIC SUPPLEMENT

INTRODUCTION

Plate tectonic theory is based on essentially four elements: rigid spherical plates, spreading centers, subduction zones, and transform faults. The theory in this original form has been strikingly successful in describing oceanic and active margin geology, and has been shown by Minster et al. (1974) and others to have predictive capability. However, the question remains of how well plate tectonic theory describes and explains global geology as a whole, especially continental geology.

The question has become acute with the development of ultra-precise geodetic techniques, using satellite laser ranging and very long baseline interferometry (VLBI), which permit the direct measurement of plate motion and deformation over intercontinental distances (Lowman, 1976b). To plan such measurements, and to interpret satellite geophysical data (Kaula, 1972), a realistic representation of present global tectonic and volcanic activity is required. Existing plate maps are both generalized and eclectic, being intended to illustrate a particular theory, and do not show continental geology in any detail (Morgan, 1968; Dewey, 1972; LePichon et al., 1973). Furthermore, even the most recent such maps (e.g., Condie, 1976) are out-dated in that they do not include findings from orbital photography such as those of Lathram (1972), Molnar and Tapponnier (1978), Ni and York (1978), and others. For these reasons, I undertook the preparation of a global tectonic and volcanic activity map covering the last one million years, for use in geodetic experiments and geophysical data interpretation. Early versions of this map have appeared elsewhere (Lowman and Frey, 1979; NASA, 1979; Lowman et al., 1979). This paper presents a substantially revised version, accompanied by the seismicity maps on which it is largely based, and with complete documentation of sources.

DATA SOURCES AND COMPILATION METHODS

The primary topographic base map chosen was the National Geographic Society's 1975 "The Physical World," (Figure 1), reproduced here with the Society's permission. This map is an artist's rendition of global physiography detailed enough to permit delineation of many tectonic features, such as oceanic ridges and trenches, directly from it. The Van der Grinten projection used, though neither equal-area nor conformal, has several useful characteristics. Most important is the fact that it is possible to show the entire surface of the Earth if desirable, which cannot be done with the commonly-used Mercator projection. Coverage of the main map presented here was actually restricted in latitude, with polar regions being shown on separate orthographic projections. "The Floor of the Oceans," a Mercator projection published by the American Geographic Society (1974) and based on the well-known maps by Bruce Heezen and Marie Tharp, was used in drawing specific details not shown by the National Geographic Society map.

Any global map of this sort must obviously draw on an extremely large number of sources; those used here are listed in the bibliography, though not all are referred to in the manuscript. The location and shape of any given tectonic features as finally drawn generally represent a composite of or a compromise among the various data sources. However, the primary datum for

active tectonic features was the distribution of seismicity as compiled by the National Oceanographic and Atmospheric Administration (NOAA). A digital data tape supplied by NOAA was used, with the aid of a computer program for the Van der Grinten projection developed by O'Keefe and Greenberg (1977), to plot four maps of global seismicity (Hutchinson and Lowman, 1979), centered on the equator and the poles (Figures 2, 3, 4, and 5). To supplement the data tape, which covers only a ten-year period, other seismicity maps, such as the Gutenberg and Richter (1949) compilation, and seismic risk maps were used.

Orbital photographs, from the Gemini, Apollo, and Landsat programs, were frequently consulted to determine, from sharpness of physiography, whether volcanic and tectonic features in poorly-mapped areas had been active within approximately the last one million years. A representative selection of these is included as a separate photographic supplement following the map and related figures.

MAP UNITS

The choice of map units was governed by several factors. First, it was desired to strike a balance between purely objective features and those largely interpretive. Complete objectivity would produce little more than a topographic map, whereas interpretive maps are beset by subjective bias and are soon out-dated by changing concepts. Accordingly, the features chosen for map units were those whose nature (though not necessarily their origin) seems clearly revealed by geological or geophysical evidence. A second factor involved is cartographic simplicity. Maps with a large number of units, though extremely informative, require considerable study for understanding, and their complexity may obscure significant patterns. A final factor governing choice of map units is simply the degree of detail that can be shown at the scale chosen, which restricts the choice to major features that are inherently well-defined (e.g., large strike-slip faults) or lend themselves to cartographic generalization.

The map units finally decided upon are pragmatic ones and may not meet the usual requirements of a classification scheme. For example, the category "normal fault" would appear to fit into the equivalent category "major active fault." The criteria for each unit are described in the following section.

Active Ridges

Active ridges were drawn on the basis of physiography and seismicity. Where the relation between ridges and continental rifts seems reasonably clear, the latter were shown as extensions of the ridges. Oceanic fracture zones, prominent on most maps, were omitted since they are essentially inactive, a characteristic explained by Wilson's transform fault concept. Plate motion values for the ridges (total spreading rates) were taken from the "Datum" column of Table 1 in Minster and Jordan (1978). These were determined by them from magnetic anomalies 2 and 2', and thus are averages for about 3 million years. Spreading directions were drawn parallel to the nearest transform fault, or where necessary perpendicular to the ridge axis. They are not from the Minster-Jordan table, and should be considered diagrammatic only.

Major Active Faults

This category is a broad one. Most of the faults shown here are strike-slip, but the category includes some normal and reverse faults as well, such as those marking the Front Range of the Rocky Mountains. It also includes major fractures whose nature and degree of activity (within the past one million years) is uncertain. The Rocky Mountain trench furnishes a good example; it has only low-level seismicity and there is no agreement on the nature of displacement along it. Yet it seems closely related to major active faults in Alaska, and is the most conspicuous single fracture in North America, being visible from several thousand miles altitude (Lowman, 1972).

Normal Faults

Features included in this category are those with well-documented histories of dip slip reflecting regional tension or uplift not obviously related to the mid-ocean ridge system and, obviously, excluding the rifts on the oceanic ridges themselves for cartographic simplicity. Examples are the Basin and Range province (shown without hachures because of the density of faulting) and the Shansi graben system in China. Widths of a few were slightly exaggerated on the map for clarity.

Reverse Faults

Subduction zones and overthrust belts are essentially reverse faults or fault zones, though frequently associated with fold belts, and there are some places such as Burma where one grades into the other. Accordingly, these features were shown with the same symbol, a convention also followed by Hamilton (1979). It was not practical at this scale to show continental fold belts, such as the Zagros Mountains, explicitly.

It can be argued (e.g., Gutenberg and Richter, 1949, p. 97) that present seismicity in the Alpine fold belt is not related to the Alpine folding. If this were true, it would be incorrect to show these structures on the map, since that would imply that orogeny is still continuing. However, seismic risk maps, based on historic earthquakes, show clearly that seismicity closely follows the trends of the Cenozoic overthrusts and folds. Geodetic measurements also suggest that these structures are still active, and Pavoni (1971) concluded that "in principle recent horizontal movements may be regarded as being in direct continuation and development of late Cenozoic movements" though basing his review largely on strike-slip faults.

There are some areas shown as active overthrusts that are not delineated by seismic activity on the maps, such as the southern boundary of the Atlas Mountains. However, the historical record demonstrates that such features are active. For example, an earthquake in 1960 leveled the city of Agadir, although the NOAA epicenter tape shows only one event in this area in the 1965-1975 period.

Volcanoes

Volcanic fields of the central eruptive type make up most of this category, although a few, notably Tibet and Iceland, are partly fissure eruptions. The oceanic ridges could, as with rifts, be included here inasmuch as they are frequently the sites of recent basaltic eruptions. It proved

surprisingly difficult to compile volcanic areas active within the past one million years. The tabulation of active volcanoes by Gutenberg and Richter (1949) and the Catalogue of Active Volcanoes of the World by the International Association of Volcanology were good starting points, but it was obvious, from orbital photography and other lines of evidence, that such tabulations show only a small fraction of the volcanic areas with eruptions in the past million years. Accordingly, I used sources such as the Burke and Wilson (1976) hot spot map, other publications, and orbital photographs (Lowman, 1972). The primary criterion for ages less than one million years was physiography. It appears that volcanoes do not survive as recognizable land forms, at least in humid climates, for more than about a million years, and I therefore assumed that anything shown as a "volcano" on an authoritative map, such as the UNESCO geologic map of Africa, had been active within this period.

The depiction of volcanoes in Tibet merits special mention, since W. Hamilton (personal communication) has informed me that Chinese geologists doubt the existence of active vulcanism in this region. Sengor and Kidd (1979), working with samples and reports from the Sven Hedin Tibetan expeditions of the 1920s, have mapped extensive deposits of young andesites and rhyolites north of the Indus suture. The Hedin expedition reports included photographs of obviously youthful cinder cones; this, coupled with the existence of many hot springs, clearly indicates the presence of recent volcanism. However, it is stressed that the Himalayas are not a volcanic arc.

Features Not Shown

It is apparent that a number of intraplate areas, such as the Appalachians, exhibit seismic activity not reflected in the tectonic activity map. The reason for this omission is that the seismicity is not only diffuse but is frequently impossible to assign to discrete tectonic features, as discussed by Sykes (1978). Appalachian seismicity may be caused by crustal uplift and localized by very old structures (Bollinger, 1973). However, it would be misleading to imply that the Paleozoic orogeny is still continuing, so these structures have been omitted from the map. This problem of reactivation of old structures is also encountered in the Urals, the Canadian Arctic Islands, and Australia. The recent paper by Sykes (1978) analyzes this problem in detail.

A related problem is that of how to represent "passive" continental margins such as that of eastern North America. The actual amount of tectonic activity over the last one million years is quite unknown, as pointed out by Allen (1975). Furthermore, there is growing evidence of Tertiary or even Quaternary deformation along this margin and possible other Atlantic margins (Mixon and Newell, 1977; Fyfe and Leonardos, 1976), and of strong regional stress (Sbar and Sykes, 1973). These margins may not be as inactive as commonly supposed, but there is simply not enough information to warrant their inclusion on the maps presented here.

APPLICATIONS AND IMPLICATIONS

Being essentially a compilation of previously-available data, the tectonic activity map can hardly be expected to produce new discoveries. Nevertheless, it appears to be of potential value in several applications.

The most obvious such application is in the planning and interpretation of data from VLBI and satellite laser ranging experiments. As first pointed out by Lambeck (in LePichon, et al., 1973), to

measure plate movements by these techniques it is necessary to locate instrument sites a considerable distance from the plate boundaries to avoid measuring "the instantaneous deformation in localized areas." However, conventional plate maps emphasize narrow, well-defined boundaries. The North American-Pacific plate boundary, for example, is customarily shown as the San Andreas fault, yet as the tectonic activity map shows, this is actually an extremely broad zone (a fact discussed by Atwater (1970) and LePichon et al. (1973)). VLBI measurements made with radio telescopes at Goldstone and Owens Valley will not, therefore, give true indications of plate movements. Similar problems may be encountered in laser ranging experiments. The tectonic activity map has for these reasons been used for planning VLBI and laser ranging sites (Lowman et al., 1979).

The broad zones of tectonic activity illustrated by the map have major implications for regional and global crustal dynamics measurements. The most obvious of these, already implied, is that a number of existing radio telescopes usable for VLBI are not ideally situated for plate motion determination because they are within active zones (or diffuse plate boundaries). Examples include the radio astronomy observatories at Bonn, Germany; Bologna, Italy; Fairbanks, Alaska; Kashima, Japan; and possibly the Crimea, U.S.S.R. Interpretation of measurements from such sites will require extensive local surveys to assess near-by crustal movements (e.g., Lowman, et al., 1980). A further implication is that a comprehensive program of global crustal movement measurement, as contrasted with simply plate motion determination, will require a large number of sites, whether laser, mobile VLBI, or fixed VLBI. However, it may be desirable to supplement measurements with these techniques by dense arrays of retro-reflectors on the ground in broad deformation zones for use with orbiting lasers (IASOM, 1979).

The scientific implications of the tectonic activity map lie primarily in its capability to visually illustrate already-known relationships and problems.

One general problem thus illustrated is central to plate tectonic theory: the question of how much of the Earth's crustal behavior can be described by a model with "a small number of well-defined plates" (LePichon et al., 1973, p. 95). LePichon et al. point out that such models are the essence of the theory, and urge that the theory's constraints be observed, despite the obvious difficulties encountered in wide areas of "superficial deformation." They present a 12-plate model that includes, beside the large well-defined ones such as the Nazca plate, segments of the Alpine fold belt divided into small plates: Persia, Turkey, Aegea, and Adriatica. However, it is now rapidly becoming recognized that these areas cannot be validly described as micro-plates. Molnar and Tapponnier (1978) find slip-line field theory, in which Asia behaves as a plastic mass deforming in front of a rigid indenter (India), more realistic. Cummings (1976) arrived at a similar conclusion in regard to the Mojave block, which is similarly being squeezed laterally by an advancing plate. Dewey and Sengor (1979), in a study of the Aegean and surrounding regions, found plate tectonics *sensu stricto* inapplicable, referring instead to "continuum tectonics" for much of the area. Roeder (1979), in reviewing continental collisions, generalized this conclusion, calling plate models "inappropriate for explaining the variation of tectonic styles which comprises nearly all known orogenic style elements." All these interpretations were foreshadowed by McKenzie's (1969) paper in which it was pointed out that continental plates should be much more easily deformed than oceanic ones.

The tectonic activity map does not of course prove or disprove these views, but it does provide a good impression of the large areas that are not assignable to rigid plates, in North and South America, Europe, and southern Asia. These areas can be considered broad diffuse plate boundaries, but if so the map provides a much more realistic picture of their location and extent than do conventional plate maps.

The tectonic activity map illustrates, especially in the Alpine-Himalayan chain, the bilateral symmetry of folded mountain belts, expressed as matching overthrust zones of opposite polarity. Although this symmetry is well-known (Holmes, 1965; Van Bemmelen, 1960; Roeder, 1973; Bally, 1975), few global plate maps show it and most recent treatments of the origin of folded mountains neglect it. A discussion of this characteristic would be beyond the scope of this paper, but it may be worth pointing out that such symmetry seems more easily explained by vertical movement and resultant gravity tectonics as proposed by, for example, Cady (1972), than of the major horizontal movements assumed in plate tectonic mechanisms. A contrary view has been published by Roeder (1973).

The tectonic activity map suggests another general question concerning the Alpine fold belt: Is this immense chain, particularly the northern margin extending from the Pamir to France, as unified a structure as the map shows? Taken at face value, the tectonic activity map implies that almost the entire 7000 km length of this margin is simultaneously (in terms of geologic time) being overthrust to the north. Such unified behavior seems unlikely if the fold belt is the result of the complex horizontal movement and collision of many small plates as proposed by, for example, Dewey et al. (1973). Several explanations suggest themselves. Most obvious is the possibility that the tectonic activity map is simply over-generalized, thus producing an illusion of structural unity. Dewey's (1977) map of the Alpine fold belt, for example, is far more complex than mine. Another possible explanation is that we are seeing by chance, at this point in geologic time, a temporary coalescence of randomly-moving tectonic elements. A third possibility is suggested by Dewey's (1977) concept of continental collision as a "terminal" stage of suturing; the apparent unity of the Alpine fold belt may be a reflection of its tectonic maturity, just as mature soil profiles on a variety of rock types tend to converge.

The tectonic activity map illustrates another relationship not explained by classic plate tectonic theory, namely, the great difference in dynamic behavior between continents and ocean basins, or more precisely, between continental and oceanic crust. There is clearly far more deformation occurring within continents, a fact neglected by treatments in which the continents are simply passive riders on lithospheric plates and the continental margins incidental features that may or may not coincide with plate boundaries. Possible explanations for this evidently real continent-ocean dichotomy are discussed by McKenzie (1969), Solomon and Sleep (1974), and Jordan (1975); further discussion is beyond the scope of this paper.

The problem of intra-plate rifting is also illustrated by the tectonic activity map. The best example is the East African Rift valley system. It is not obvious how these rifts can be expanding when the continent is largely surrounded by actively spreading ridges. The reality of this problem is indicated by the fact that Minster and Jordan (1978) found it impossible to satisfactorily model Indian Ocean tectonics with rigid plates; their RM2 model indicated east-west compression across the rift valleys at over 1 cm/yr. A possible explanation easily visualized with the tectonic activity map is that the ridges themselves are moving away from Africa. However, such a mechanism is not clearly applicable to other features such as the Baikal, Rhine, Reelfoot (New Madrid), and Rio Grande rifts. It may be that rifts reflect vertical rather than horizontal stresses, as suggested by H. Cloos, Holmes, and Dewey and Burke (1974).

The tectonic map shows the surprisingly widespread occurrence of volcanoes on the upper blocks of subduction or overthrust zones in the Alpine chain from Burma to Morocco. This relationship is well-known and reasonably well-understood for the subduction zones ringing the Pacific (e.g.,

Marsh, 1976), but there is considerable uncertainty as to how magma is generated at continent-continent convergence zones. Radiogenic heat in areas of thickened crust has been suggested by Dewey and Burke (1974), referring specifically to the Tibetan plateau, but as the map shows, volcanic activity occurs in other convergence zones with much thinner crust. Frictional heating would seem to be a more generally available mechanism (Bird, 1975); a third possibility (Bird, 1978) is continental delamination following collision, exposing the crust to hot asthenospheric mantle material. A useful review of this problem has been presented by Roeder (1979).

Finally, the tectonic activity maps of the Arctic (Figure 6) and Antarctic (Figure 8) regions provide at least a new perspective on the tectonics of the polar regions, which are generally omitted from global plate maps. Several problems are easily visualized with the maps presented here. For example, it is apparent (even though coastlines, not margins, are shown) that the Arctic Ocean cannot be explained as simply the result of one episode of continental drift driven or accompanied by sea-floor spreading, a concept suggested in the Atlantic from the parallelism of continental margins and the mid-ocean ridge. The complexity of plate tectonic interpretations for this area (e.g., Herron et al., 1975) reflects this problem. At the other end of the earth, the geologic peculiarities of Antarctica are well illustrated. Particularly noticeable is the apparent absence of a subduction zone along the Pacific coast of Antarctica (between the Ross Sea and the Palmer Peninsula), as shown by the absence of seismic activity (Figure 7). The Pacific-Antarctic Ridge would appear to require such a subduction zone, and the few volcanic centers east of the Transantarctic Mountains might be explained thus. One might speculate on the presence of a Benioff zone characterized by extremely slow subduction; asymmetric spreading from the Pacific-Antarctic and other ridges surrounding the continent may also be involved.

SUMMARY AND CONCLUSIONS

Uniformitarianism, broadly interpreted, is still a basic assumption of geology, and the tectonic and volcanic activity of the present is presumably the key to understanding the geologic past. However, there has been no map produced showing such activity over a long enough time span to be reasonably representative of the "present." Conventional maps of seismic and volcanic activity generally cover only a few decades or centuries, while geologic maps cover periods of tens of millions of years or more. The tectonic activity map presented here should help to fill this cartographic gap. The one million year time span chosen does not correspond to any particular epoch, but it is long enough for the accumulation of physiographic evidence of geologic activity and short enough to be considered an instant of geologic time.

When viewed in the light of recent studies indicating the importance of continuous deformation in orogenic belts, the map can be considered a reasonably realistic assessment of how well global tectonics can be explained in terms of rigid plate interaction as required by rigorous plate tectonic theory. It is becoming clear that large areas of the crust and several major classes of structure cannot be validly treated as aggregates of micro-plates, and that the continent-ocean dichotomy may be a fundamental one, contrary to conventional plate theory. This by no means invalidates mechanisms such as sea-floor spreading, transform faulting, and subduction. But it seems clear that global tectonic and volcanic activity cannot be completely explained by such mechanisms acting on rigid plates. It is hoped that the maps presented here will lead to improved tectonic syntheses that more realistically describe and predict crustal activity.

ACKNOWLEDGMENTS

This paper, being a global compilation, rests on the work of innumerable earth scientists; the reference list must serve as a minimal acknowledgment of their efforts. I am in addition specifically grateful to the following for their help: H. V. Frey, C. A. Wood, P. J. Taylor, J. Ni, M. K. Hutchinson, A. P. Trombka, A. P. Greenberg, S. J. Gawarecki, W. Hamilton, B. D. Marsh, S. P. Meszaros, and J. A. O'Keefe, and collectively, the participants in the 1976 Penrose Conference on the Geology of Tibet. Barbara M. Christy and Gary Fitzpatrick of the Geography and Map Division, Library of Congress, provided invaluable assistance in using the Library's facilities and for advice in compiling the maps. Finally, I thank F. O. Vonbun, G. D. Mead, and B. M. Christy for reviewing the manuscript.

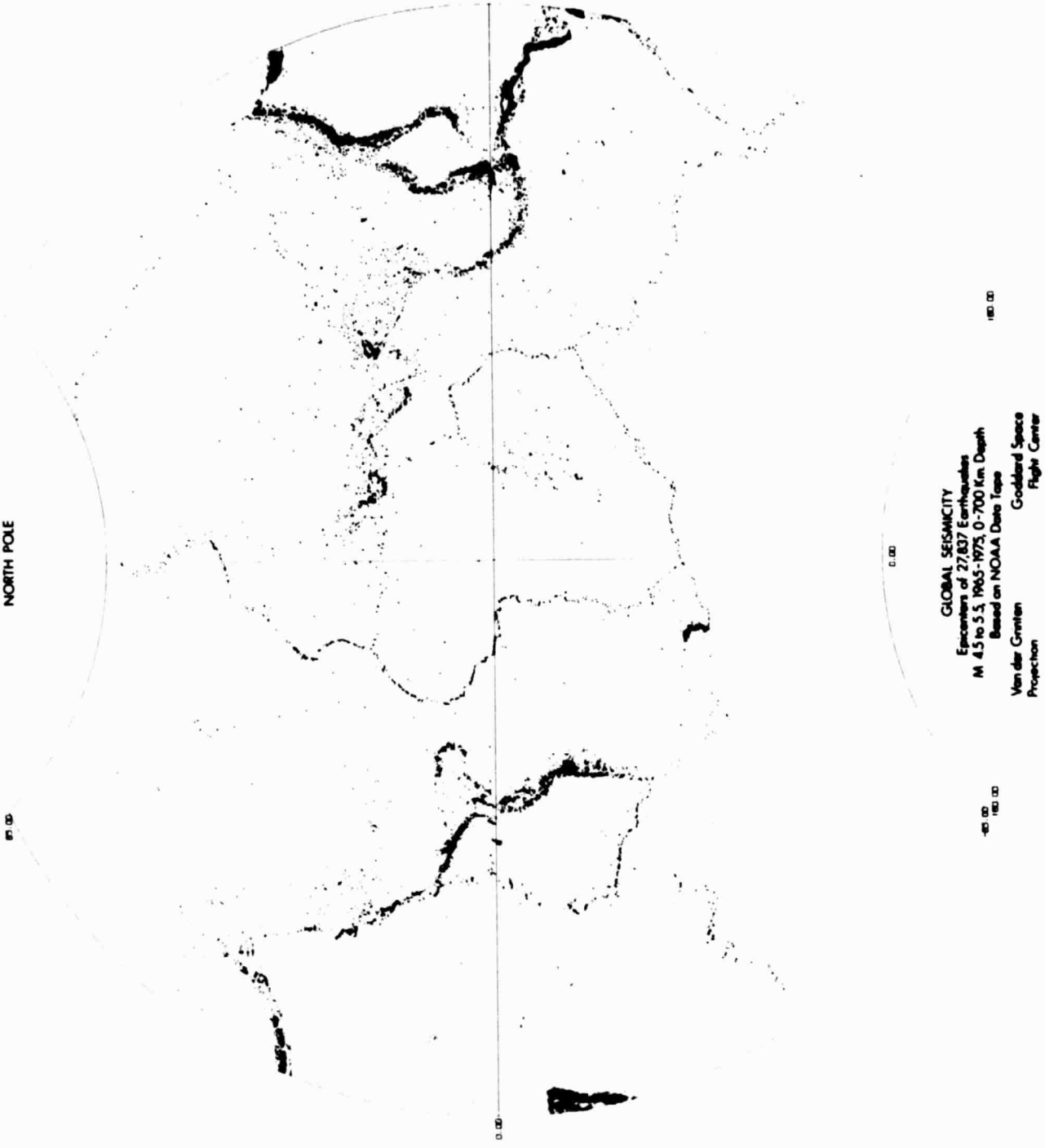


Figure 1. Global relief map. "The Physical World," used as base for the tectonic activity map.
Reproduced with permission of the National Geographic Society.

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Figure 2. Earthquake epicenters, 1965-1975, without continental outlines.

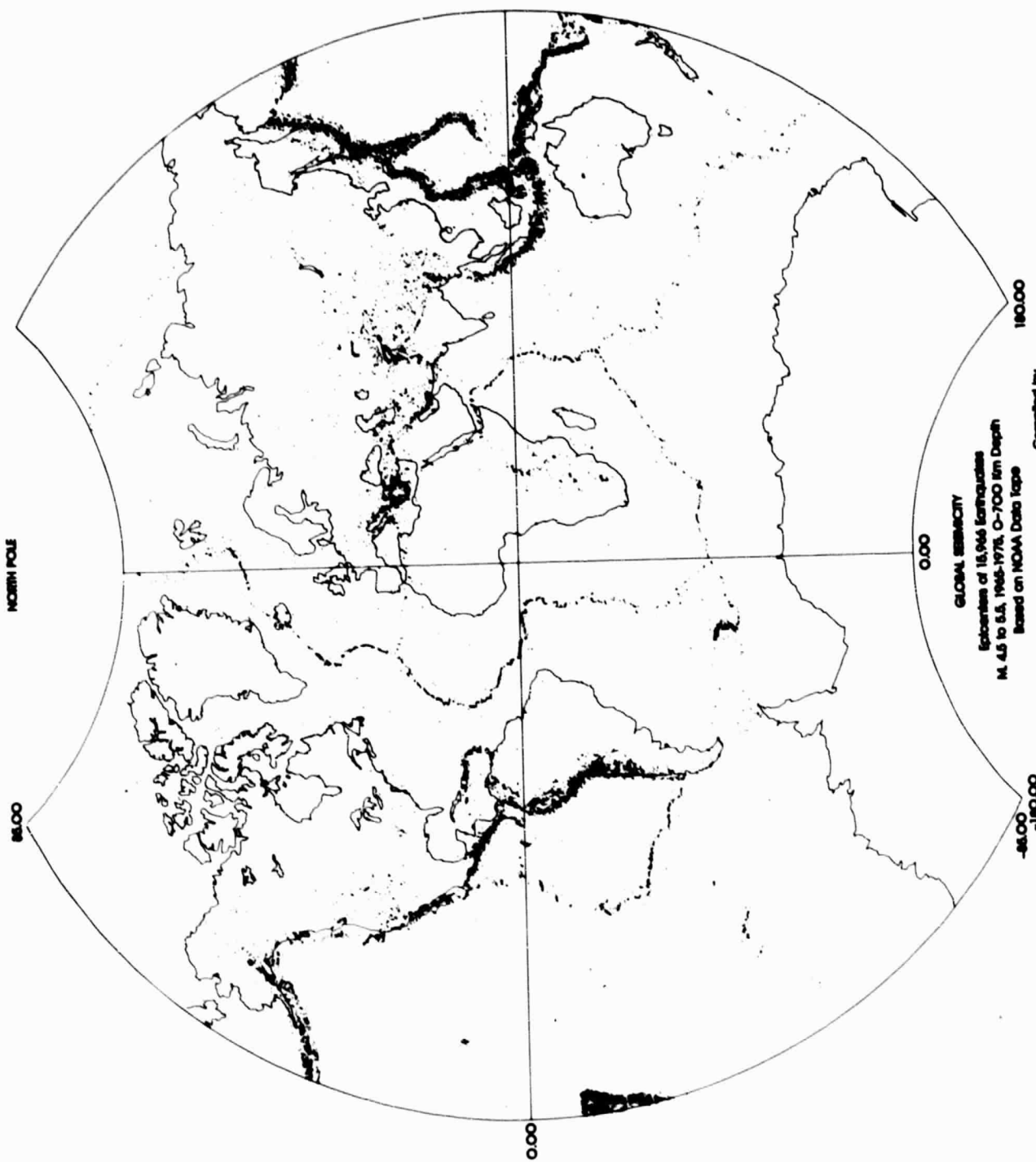
NORTH POLE



GLOBAL SEISMICITY
Epicenters of 27,837 Earthquakes
M 4.5 to 5.5, 1965-1975, 0-700 Km Depth
Based on NOAA Data Tape
Van der Grinten
Projection
Goldland Space
Flight Center

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Figure 3. Earthquake epicenters, 1965-1975, with continental outlines.



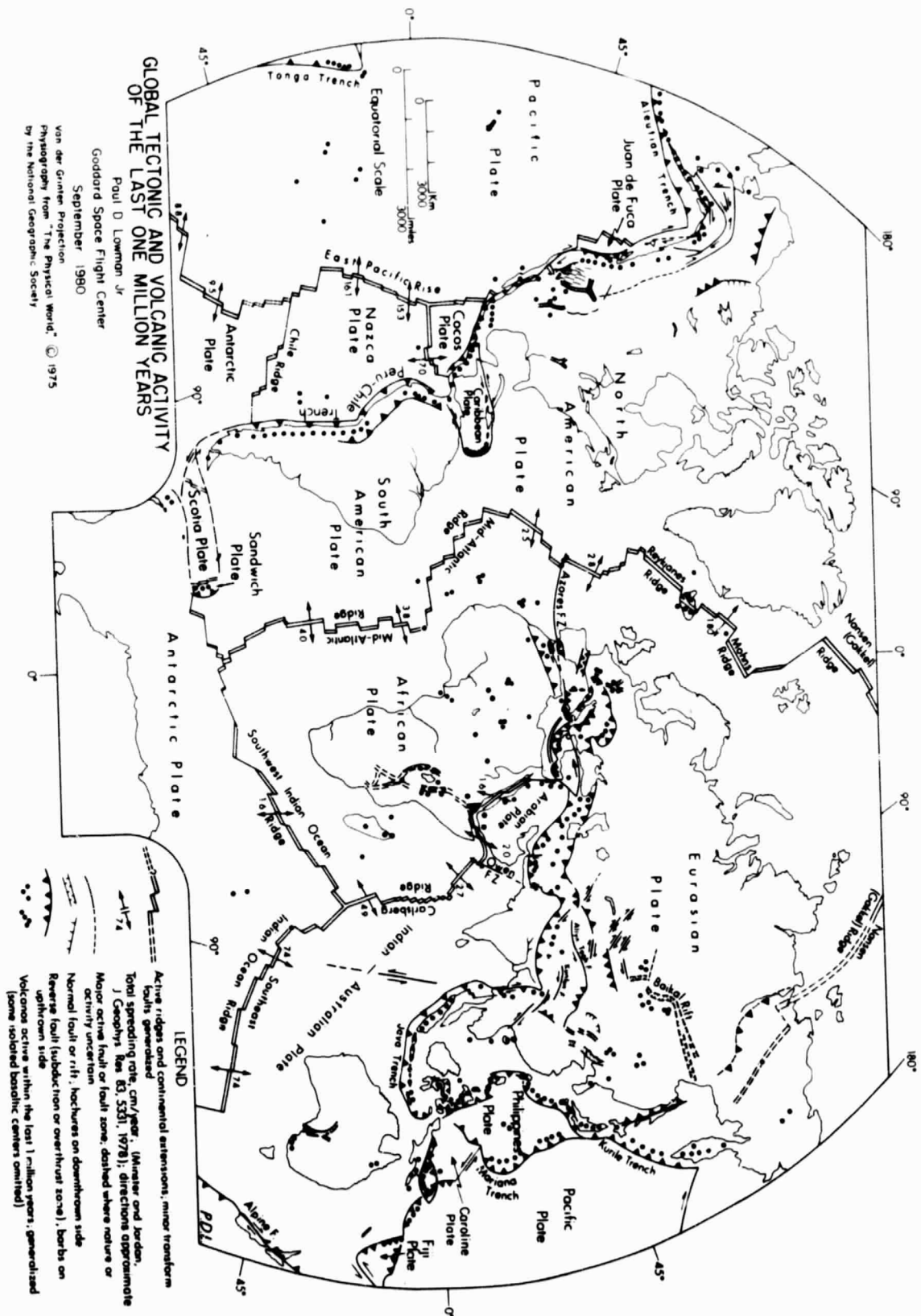
GLOBAL SEISMICITY

Epicenters of 16,944 Earthquakes
M. 4.5 to 6.5, 1968-1978, 0-700 km Depth
Based on NOAA Data Tapes

Compiled by
M. K. Hutchison
P. D. Louman
Goddard Space Flight Center

Von der Grinten
Projection

Figure 4. Tectonic activity map.



GLOBAL TECTONIC AND VOLCANIC ACTIVITY OF THE LAST ONE MILLION YEARS

Paul D. Lowman Jr.
 Goddard Space Flight Center
 September 1980
 van der Grinten Projection
 Physiography from "The Physical World," © 1975
 by the National Geographic Society

LEGEND

Active ridges and continental extensions, minor transform faults generalized

Total spreading rate, cm/year. (Minster and Jordan, J. Geophys. Res. 83, 5331, 1978); directions approximate

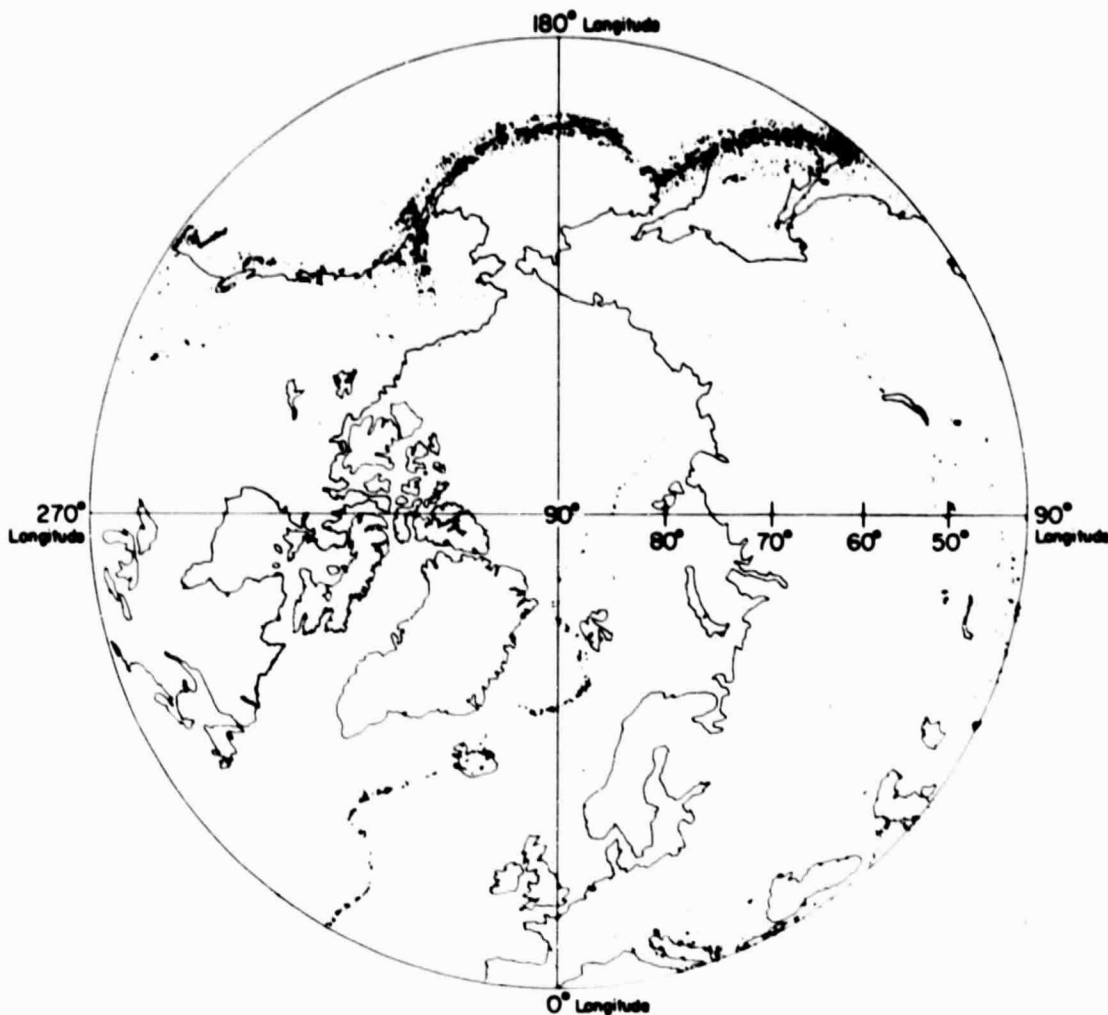
Major active fault or fault zone, dashed where nature or activity uncertain

Normal fault or rift, hachures on downthrown side

Reverse fault (subduction or overthrust zone), bars on upthrown side

Volcanoes active within the last 1 million years, generalized [some isolated basaltic centers omitted]

Figure 5. Earthquake epicenters, 1965-1975, Arctic regions.



ARCTIC SEISMICITY

Epicenters of 4,518 Earthquakes, 1965-75
M.4.5 - 6.9 (•), > 7.0 (+), 0-700 km Depth
Based on NOAA Data Tape

**Orthographic
 Projection
 40° to 80° Latitude**

Compiled 1978

Goddard Space Flight Center

Figure 6. Tectonic activity map, Arctic regions.
Continental outlines taken from earthquake epicenter map.



TECTONIC AND VOLCANIC ACTIVITY OF THE
ARCTIC REGIONS
(Last one million years)

Goddard Space Flight Center
1980

Paul D Lowman Jr

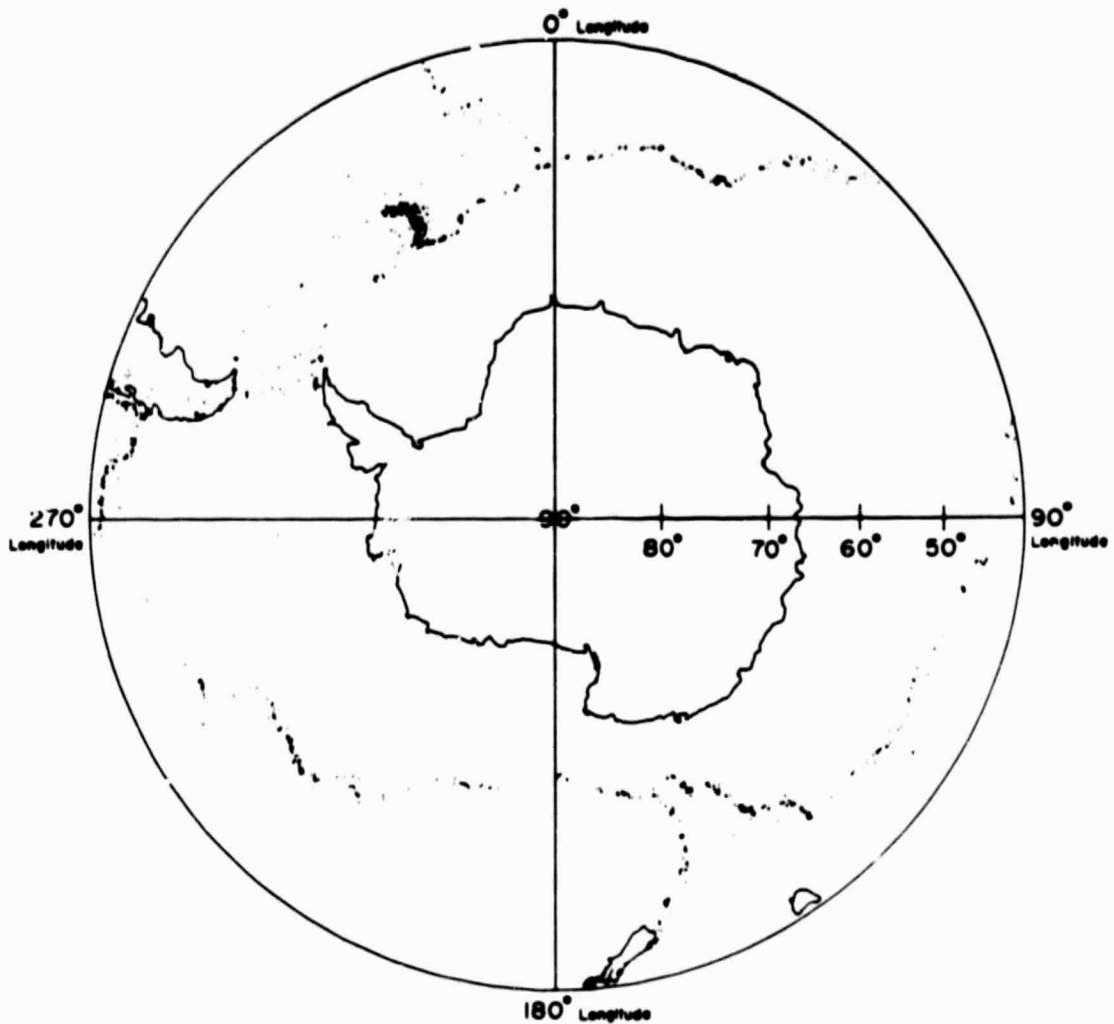
Orthographic
Projection Covering
latitudes 40° to 90° North

Polar Scale

1100 Km (110°)
680 Miles

- Active ridges and continental extensions, minor transform faults generalized
- Major active fault or fault zone, dashed where nature or activity uncertain
- Normal fault or rift, hachures on downthrown side
- Reverse fault (subduction or overthrust zone), hachures on upthrown side
- Volcanoes active within the last 1 million years, generalized (some isolated basaltic centers omitted)

Figure 7. Earthquake epicenters, 1965-1975, Antarctic regions.



ANTARCTIC SEISMICITY

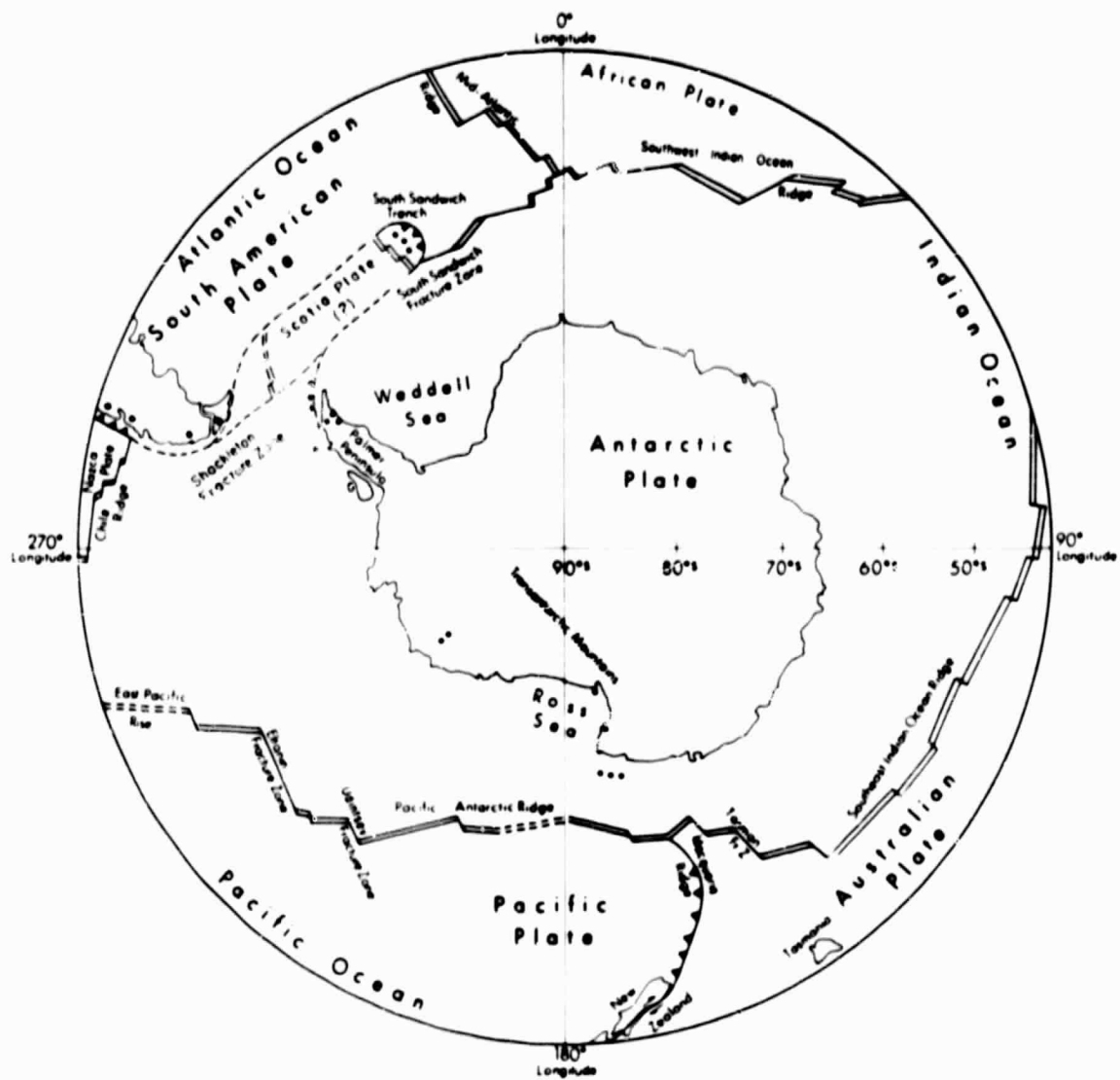
Epicenters of 1,138 Earthquakes, 1965-76
M.4.5 - 6.9 (•), > 7.0 (+), 0-700 km Depth
Based on NOAA Data Tape

**Orthographic
 Projection
 40° to 90° Latitude**

Compiled 1978

Goddard Space Flight Center

Figure 8. Tectonic activity map, Antarctic regions.
Continental outlines from earthquake epicenter map.



TECTONIC AND VOLCANIC ACTIVITY OF THE ANTARCTIC REGIONS (Last one million years)

Goddard Space Flight Center

1980

Paul D. Lowman Jr.

Orthographic Projection Covering Latitudes 40° to 90° South

Polar Scale

1100 Km (110°)

680 Miles

- Active ridges and continental extension
- Major active fault or fault zone, generalized
- Major active fault or fault zone, dashed where nature or activity uncertain
- Normal fault or rift, hachures on downthrown side
- Reverse fault (subduction or overthrust zone), hachures on upthrown side
- Volcanic active areas within the last 1 million years, generalized (some isolated basaltic centers omitted)

MAIN INFORMATION SOURCES FOR TECTONIC ACTIVITY MAP

The following list, keyed to the main reference list, gives the main literature sources for the maps. It is worth mentioning again that the representation of any given feature or area on the tectonic activity map is almost always an interpretive composite from several sources, and may differ significantly from any one of the references listed here.

North America: Atwater (1970); Bally (1975); Bollinger (1973); Cady (1972); Hinze et al. (1977); Hopkins (1963); King and Edmonston (1972); Kirkham (1977); Lathram (1972); Lowman (1972, 1976a, 1976b); Lowman et al. (1980); Marsh (1976) Muehlberger and Ritchie (1975); Prostka and Oriel (1975); Simpson and Cox (1977); Smith (1915); Smith and Christiansen (1980); Stewart (1971); Webster et al. (1979).

South America: Bally (1975); Chesser and Hamblin (1975); Candie (1976); Dalziel (1974).

Antarctica: Barker (1972); Dalziel (1974); Daumani (1964); McKenzie (1969).

Australia and New Zealand: Brown et al. (1968); McKenzie and Morgan (1968).

Africa: Burke and Wilson (1976); Holmes (1965); Lowman (1972).

Europe (incl. Mediterranean): Albany Global Tectonics Group (1978); Ben Avraham and Nur (1976); Dewey et al. (1973); Dewey et al. (1977); Dewey and Sengör (1979); Holmes (1965); Rutten (1969); Van Bemmelen (1972).

Asia (incl. Indonesian Region): Albany Global Tectonics Group (1978); Bird (1978); Bird et al. (1975); Burke et al. (1974); Churkin (1972); Gansser (1964); Hamilton (1979); Holmes (1965); LePichon et al. (1973); Lowman (1972); Molnar and Tapponnier (1977, 1978); Ni and York (1978); Powell et al. (1975); Ray and Acharyya (1976); Sengor and Kidd (1979); Swiss Reinsurance Company (1978); Tapponnier and Molnar (1977, 1979); Terman (1974); Trombka and Lowman (1979); White and Klitgord (1976).

Oceans: American Geographical Society (1974); Anderson et al. (1977); Bergh and Norton (1976); Bracey and Ogden (1972); Chesser and Hamblin (1975); Condie (1976); Dalziel (1974); Dewey (1972); Forsyth (1975); Hilde et al. (1976); Isaacks et al. (1968); Johnson and Vogt (1973); Karig (1971); Karig et al. (1978); Meyerhoff (1973); Morgan (1968); Sclater et al. (1976); Stein and Okal (1978).

PHOTOGRAPHIC SUPPLEMENT TO MAP

As previously mentioned, orbital photographs were essential to completion of the tectonic activity map, by providing information on the location, nature, and approximate age of tectonic and volcanic features in remote areas. It is therefore considered useful to provide a representative selection of these photographs, although because of the scale and generalized nature of the map, there will be only occasional correspondence between it and the pictures. Brief captions are provided; for more detailed information, the reader is referred to the appropriate publications listed. Features shown and described in the captions are, with a few specified exceptions, those meeting the criteria of volcanic or tectonic activity within the last one million years. This does not of course

imply that these features originated within the last million years, only that they exhibited actively within that period.

Photographs from manned spacecraft were generally taken from altitudes of 150 to 300 km.; Landsat images are all from about 920 km altitude. Orientation is given in the captions for hand-held oblique photos. All Landsat images are printed with north at the top. Swath width of the Landsat Multispectral Scanner is 185 km; north-south dimensions of the images are the same. For detailed discussions of Landsat and most of the images presented here, the reader is referred to Mission to Earth, NASA SP-360, (Short et al, 1976). For Gemini and Apollo photographs, Space Panorama (Lowman, 1976), The Third Planet (Lowman, 1976), and This Island Earth, NASA SP-250 (Nicks, 1970) will be useful.

Landsat images can be obtained from: EROS Data Center
Sioux Falls, South Dakota 57198
605-594-6511

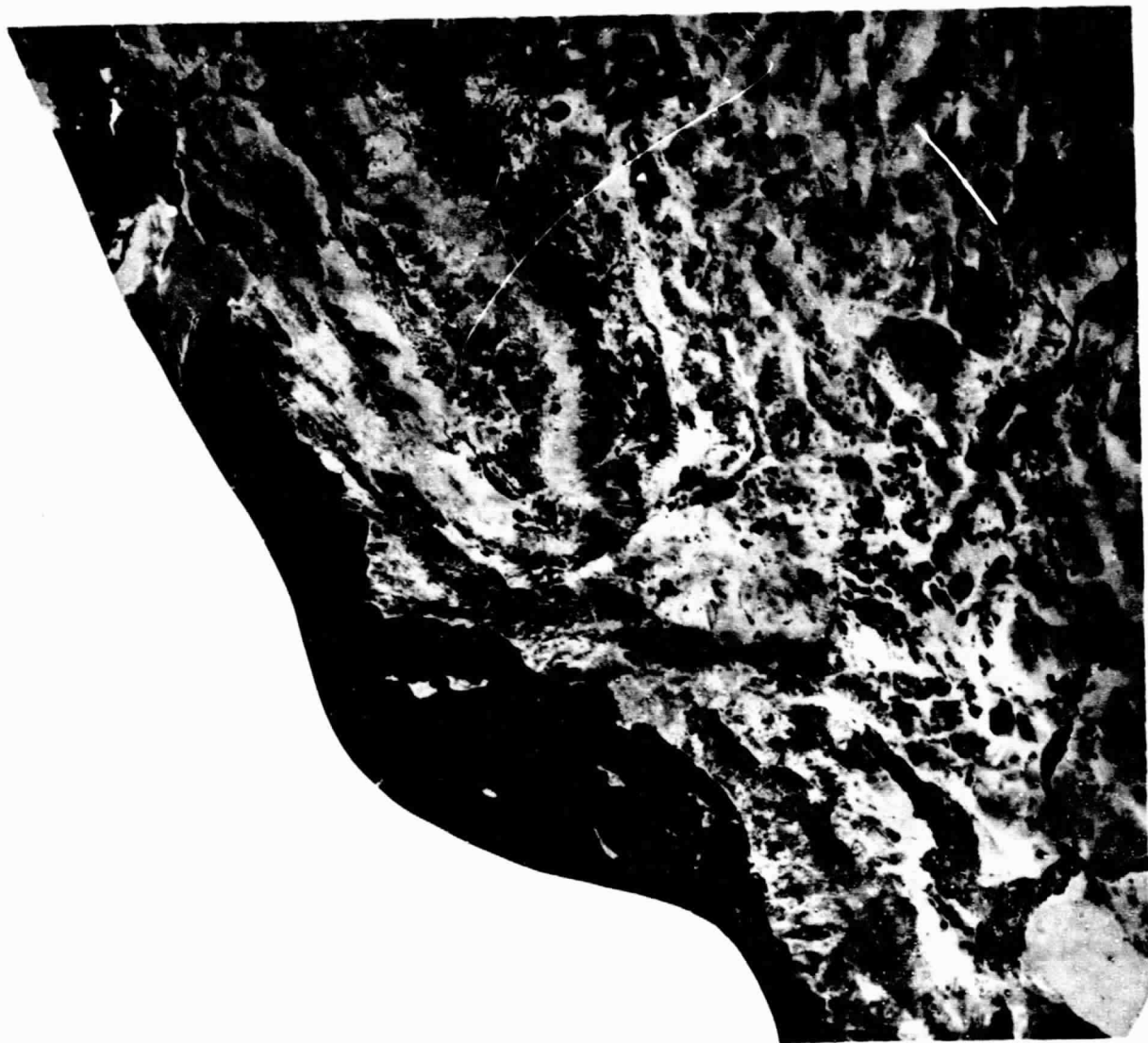
Gemini, Apollo, and Skylab photographs can be obtained from:

Technology Applications Center
University of New Mexico
Albuquerque, New Mexico 87131
505-277-3622

Aerial and selected orbital photographs can be obtained from:

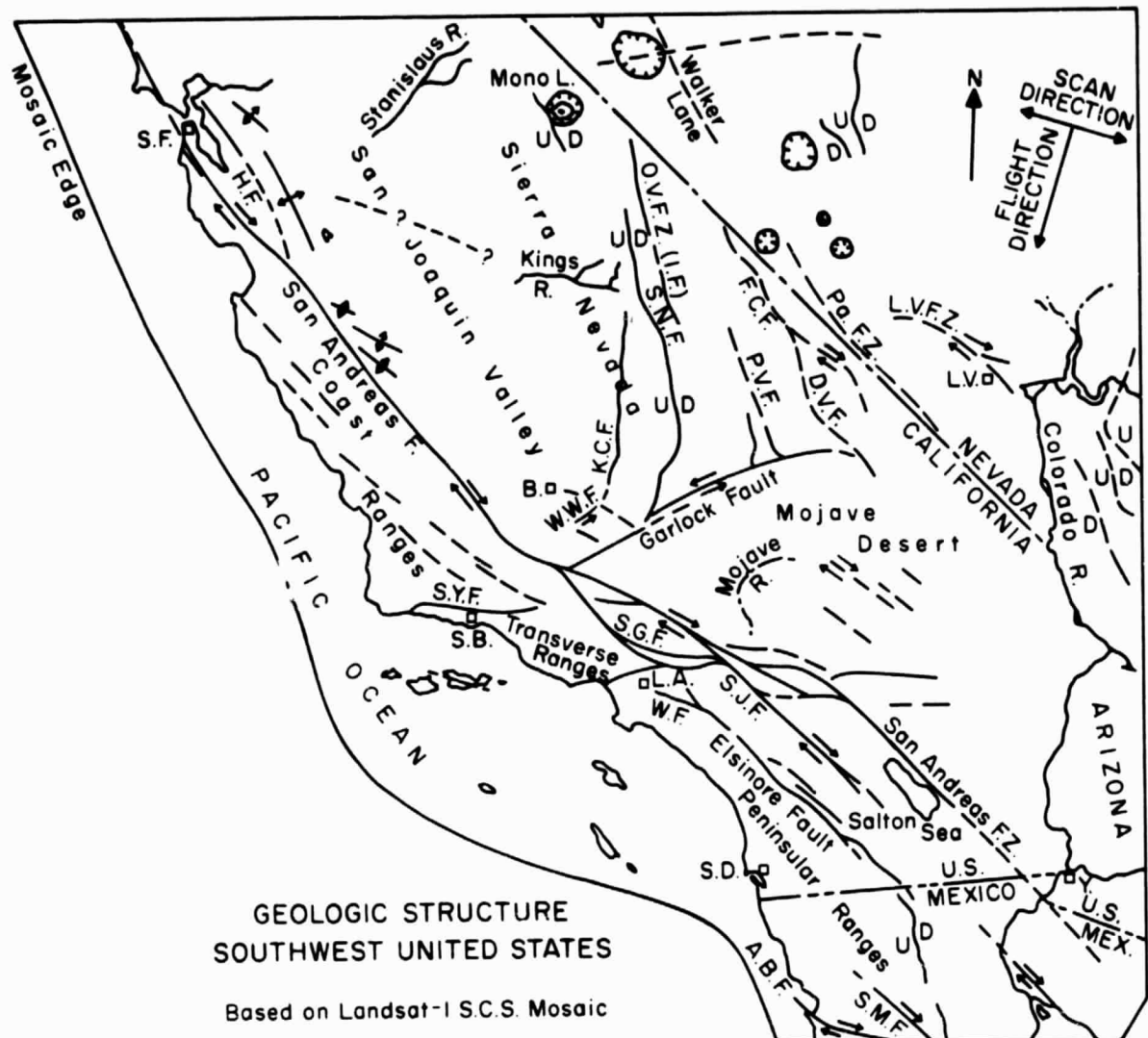
National Cartographic Information Center
U.S. Geological Survey
507 National Center
Reston, Virginia 22092
703-860-6045

Figure 1. Landsat mosaic of SW United States and parts of NW Mexico. See Fig. 2 for identification of features, and Lowman (1980) for discussion.



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Figure 2. Geologic structure of Landsat mosaic (Fig. 1).
From Lowman (1976a, 1980).



GEOLOGIC STRUCTURE SOUTHWEST UNITED STATES

Based on Landsat-1 S.C.S. Mosaic

Paul D. Lowman

Goddard Space Flight Center

January, 1976

160 Km
100 Miles

Single MSS Frame Width

Legend

- Fault (solid where confirmed, dashed where inferred)
- Anticline
- Volcanic center

Reference

1. Geologic Atlas of California
2. Tectonic Map of N America (King, 1969)
3. Rowan and Wetlaufer (1975)

Figure 3. Landsat view of southern California, showing intersection of San Andreas and Garlock faults (see Fig. 2). Triangular Mojave block (upper right) appears to be squeezed out to the east by compression in the Transverse Ranges along the bend of the San Andreas fault. Many faults beside the San Andreas and Garlock are active or potentially so. Landsat image 1090-18012.

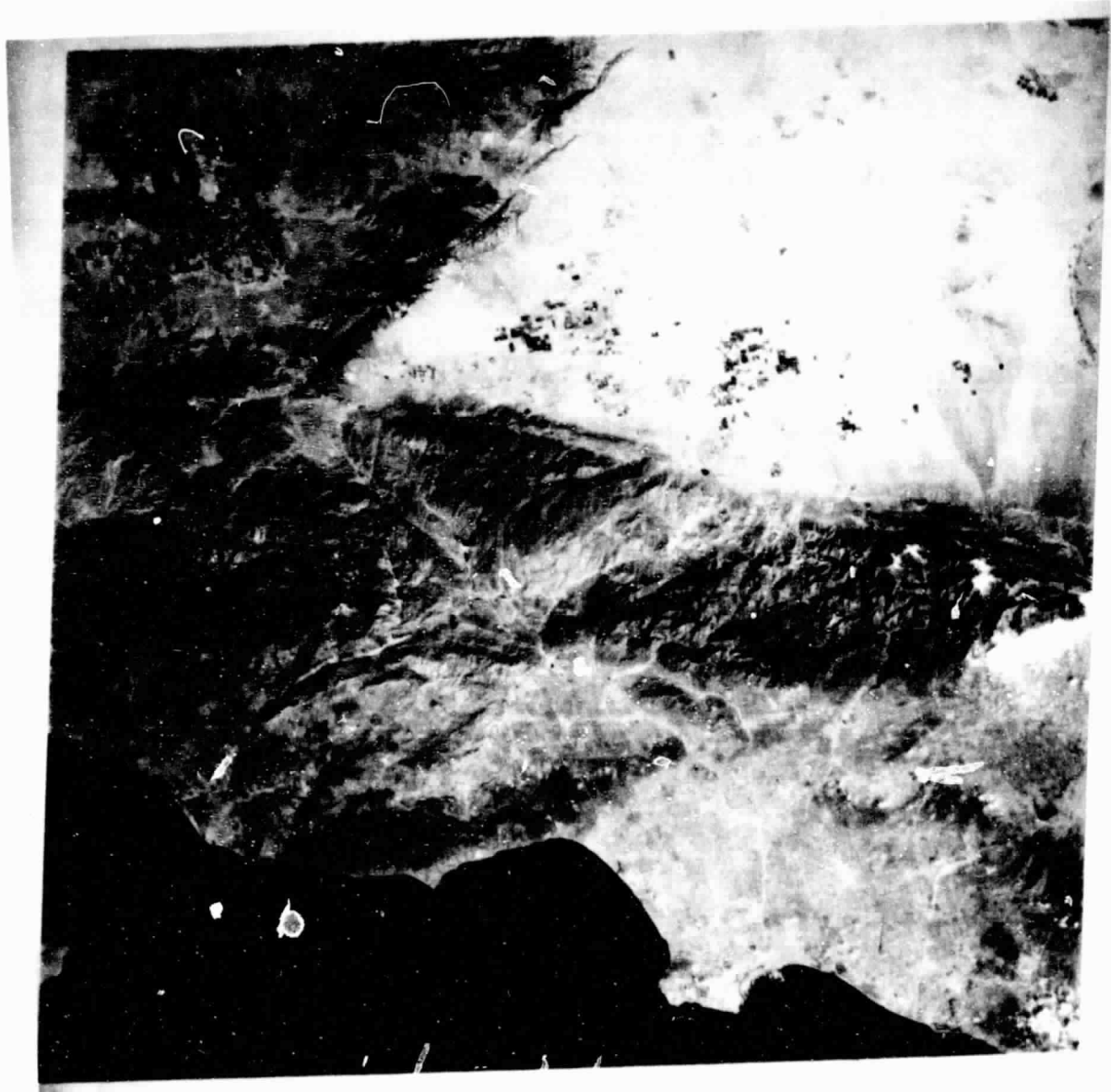
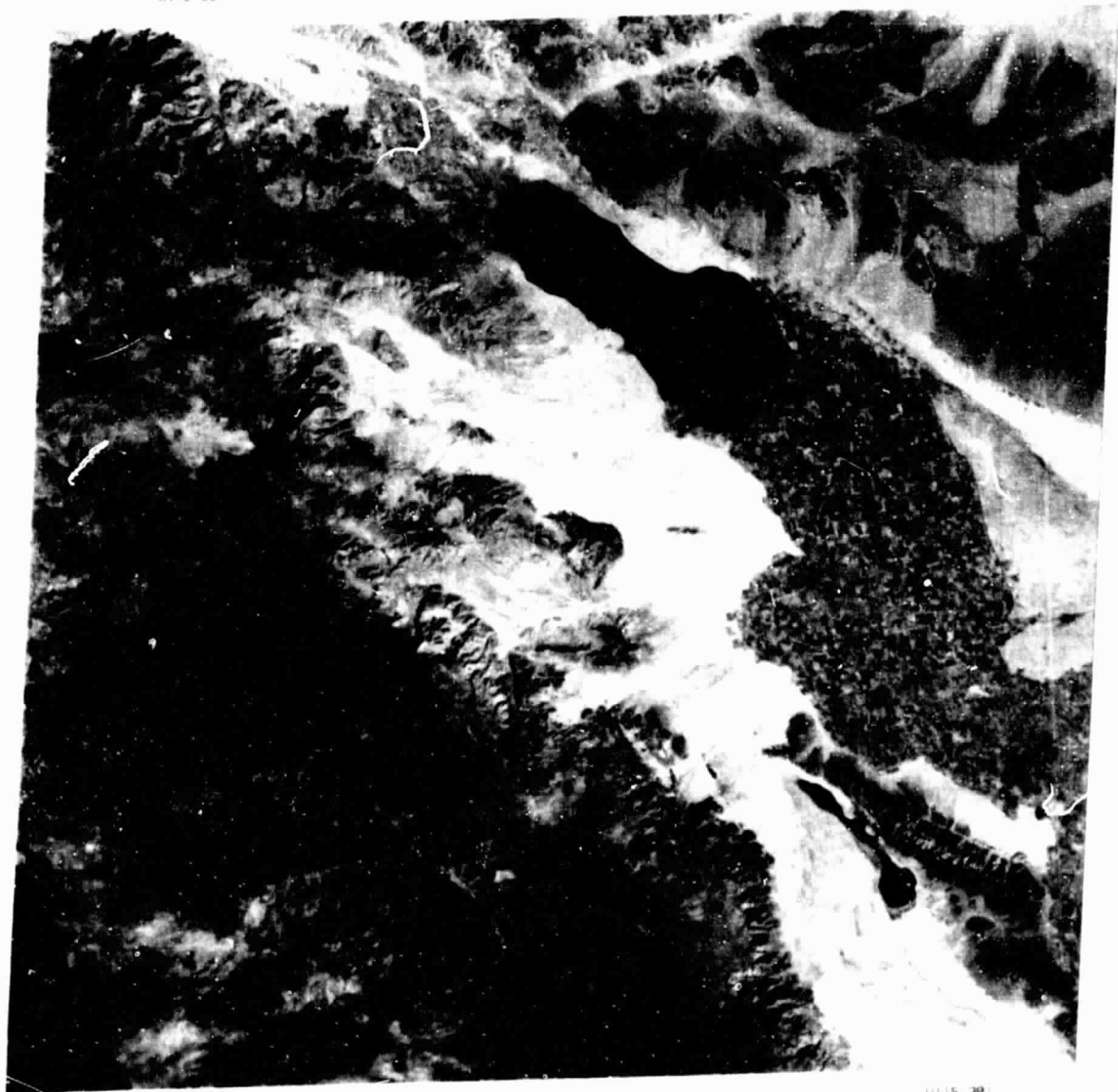


Figure 4. Landsat view of Salton trough, southern California, and adjacent Peninsular Ranges; San Diego at lower left. (See Fig. 2) Salton trough seismically active and bounded by active strike slip faults. Geothermal activity and recent vulcanism occur. Trough has been shown probably underlain by active spreading centers connecting en echelon transform faults. See Lowman (1976a, 1980) for review of regional tectonics. Landsat image 1106-17504.

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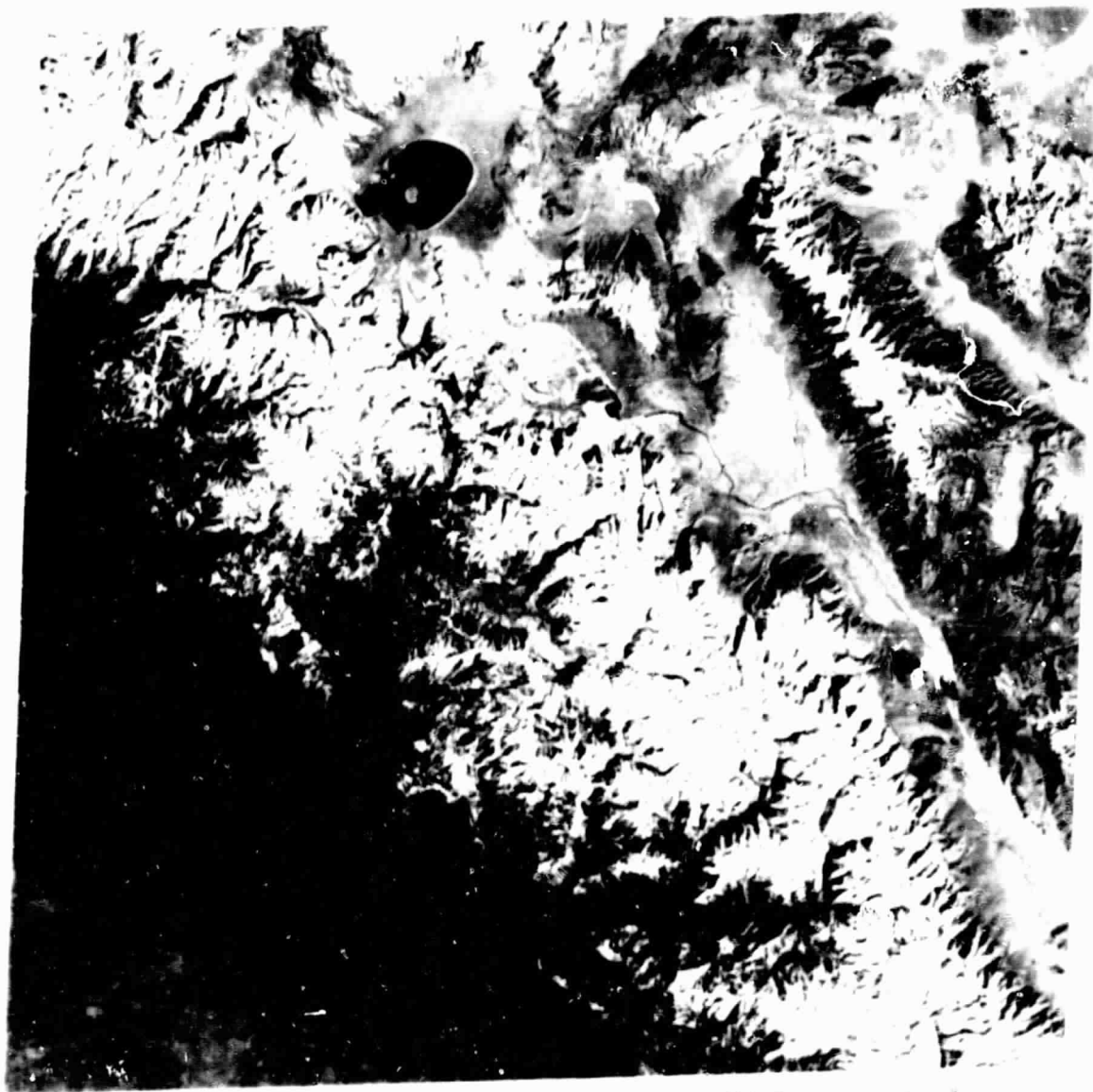
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Figure 5. Gemini 4 hand-held photo of the Sierra del Pinacate, northern Sonora, Mexico. A young volcanic field bordering the Gulf of California (lower left) with activity within the last few thousand years. Rocks chiefly basaltic. Gemini photograph S 65-34675.



Figure 6. Landsat view of Sierra Nevada, California. Picture shows normal faults bounding Sierra on northeast; Owens Valley at right. Area characterized by frequent earthquakes, occasionally strong. Mono Lake (top) and associated rhyolite domes is an area of recent vulcanism. Long Valley, just SE of Mono Lake, is also a volcanic area with activity as recent as a few hundred years ago, and is under investigation for potential geothermal energy. See Jour. Geophys. Res., v. 81, no. 5, 1976 for several papers on Long Valley caldera. Landsat image 1163-18063.



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Figure 7. Portion of Landsat mosaic prepared by U.S. Soil Conservation Service showing northwest U.S. Area includes Cascade Range, recent volcanos considered to result from magma generation in subduction zone associated with Juan de Fuca plate. Light-toned area at center is Columbia Plateau, underlain by flood basalts of Miocene age (hence not shown on tectonic activity map). Northwest-trending valleys at extreme upper right are expression of Lewis and Clark lineament, mineralized zone of low-level seismicity, shown on tectonic activity map. West end of Snake River Plain visible at extreme lower right; area of young basaltic and rhyolitic vulcanism. See G.S.A. Memoir 152, 1978, for papers on region.



Figure 8. Landsat mosaic of Great Salt Lake, Utah, and Wasatch Mountains to east. Area is the eastern margin of the Basin and Range Province, but is a north-trending belt of discrete seismicity (the intermountain seismic belt) and geophysical anomalies indicating thin crust and high heat flow. It has been considered an individual branch of the world rift system by K. L. Cook, related to the East Pacific Rise. The tectonic activity map shows it as a rift with no clear relation to the global rift system.

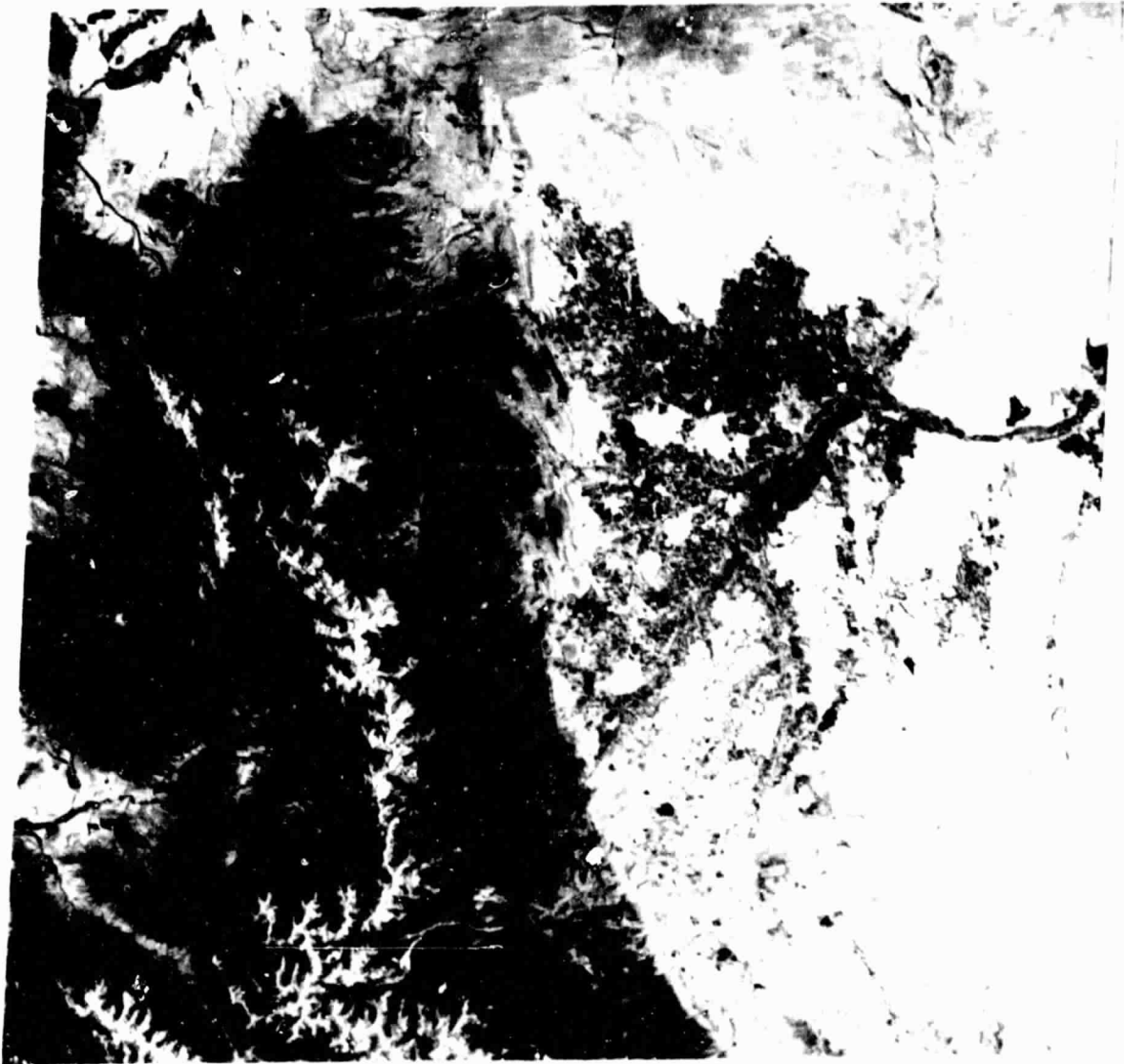


Figure 9. Apollo 9 hand-held photo looking north over the Rio Grande rift. Valles caldera at center; large volcano with associated rhyolites and ignimbrites. San Juan Mountains at upper left corner; youngest volcanics about 5 million years old, hence not shown on tectonic activity map. See Lowman, 1972, for discussion and index maps. Apollo photograph AS 9-20-3141.



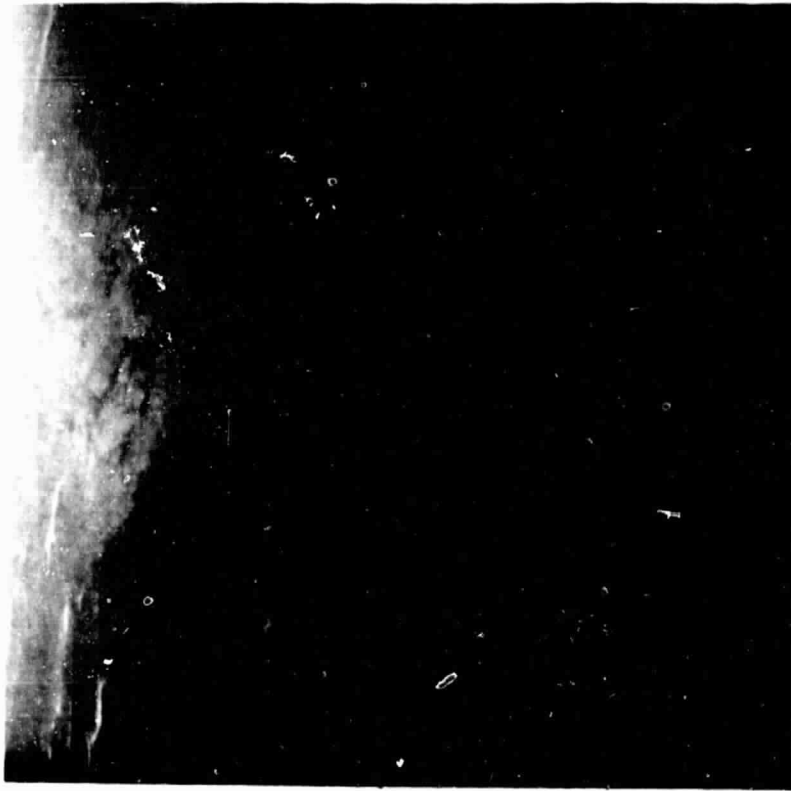
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Figure 10. Landsat image showing the Front Range, Colorado, and boundary between Rocky Mountains (left) and craton (right); Denver lower right. Light-toned mountains at left center are Continental Divide. Recently active fault on tectonic activity map in this area refers to uplift along the hogbacks marking the edge of the Front Range, not to other faults in area. Landsat image 1388-17131.

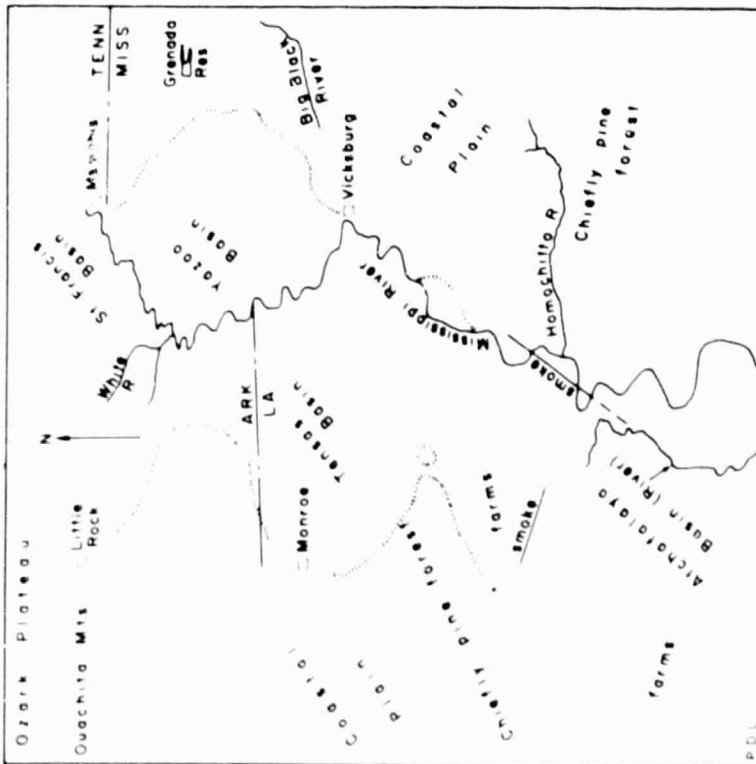


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D. S. N. F. 54. A. 21. 29. (S. 1) 5418. G. 11. N. D. 2. N. S. A. E. R. T. S. E-1388 (7/31/48)

Figure 11. Apollo 7 hand-held photo looking north over Mississippi River (mis-labeled Apollo 11 on accompanying map). New Madrid earthquake of 1811 occurred in St. Francis Basin (extreme upper right), with recurrent seismicity since. Aggrading nature of river emphasizes basically tectonic origin of Mississippi Embayment. Apollo photograph AS 7-8-1916.



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INDEX MAP

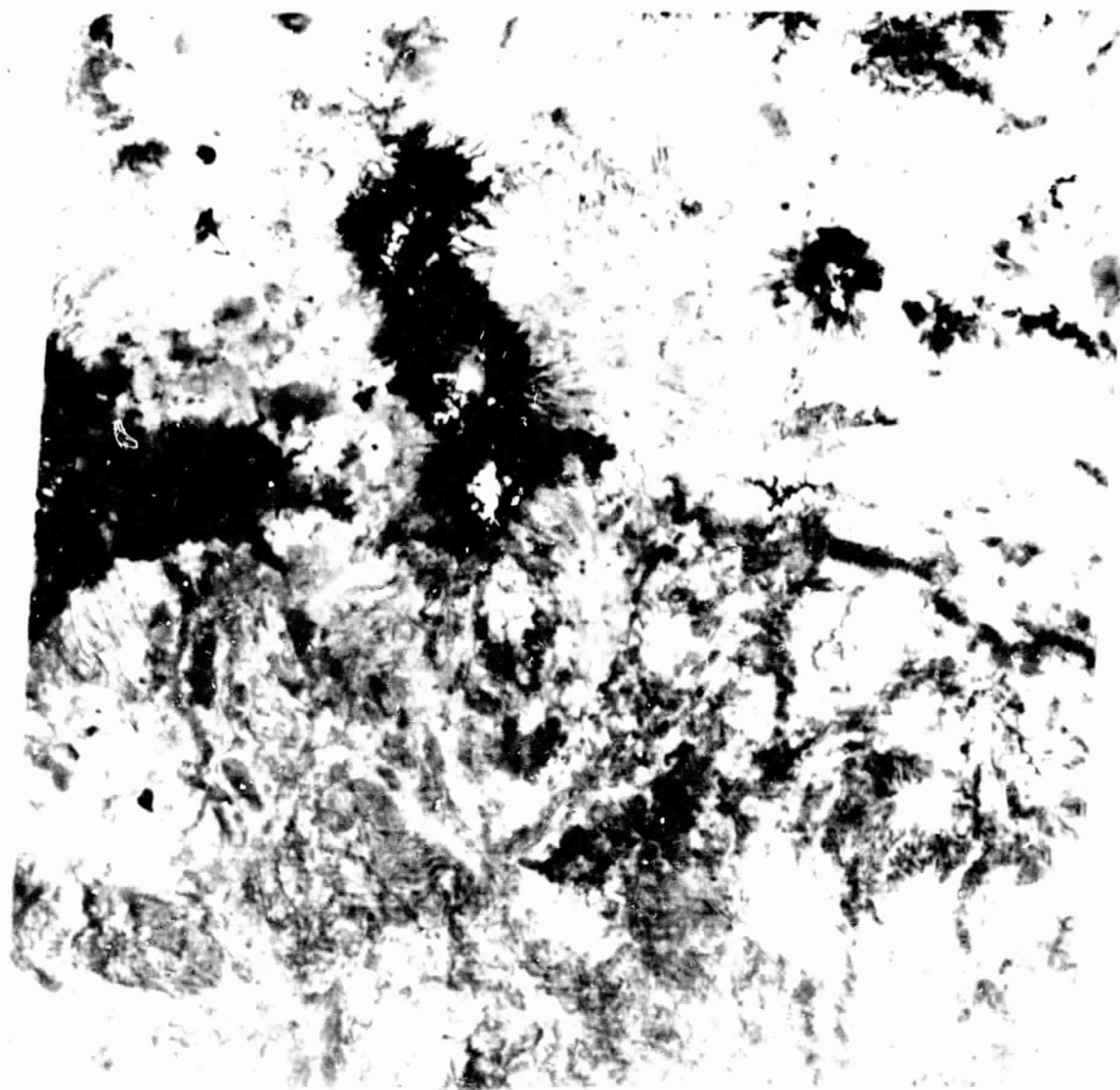
APOLLO II PHOTOGRAPH AS 7-B-1916

Note: Scale variable, Monroe - Vicksburg distance 70 miles (115 Km.)

Figure 12. Landsat mosaic prepared by U.S. Soil Conservation Service showing eastern U.S., centered on 40°N latitude, between Atlantic coast and Lake Erie (upper left). As discussed in text, area is not shown as active despite diffuse seismicity in Appalachians; picture presented for contrast with active fold belts such as the Zagros Mountains (Fig. 29). Ridges and valleys of Appalachians were formed by differential erosion after regional uplift, not directly by tectonism as in the Zagros.



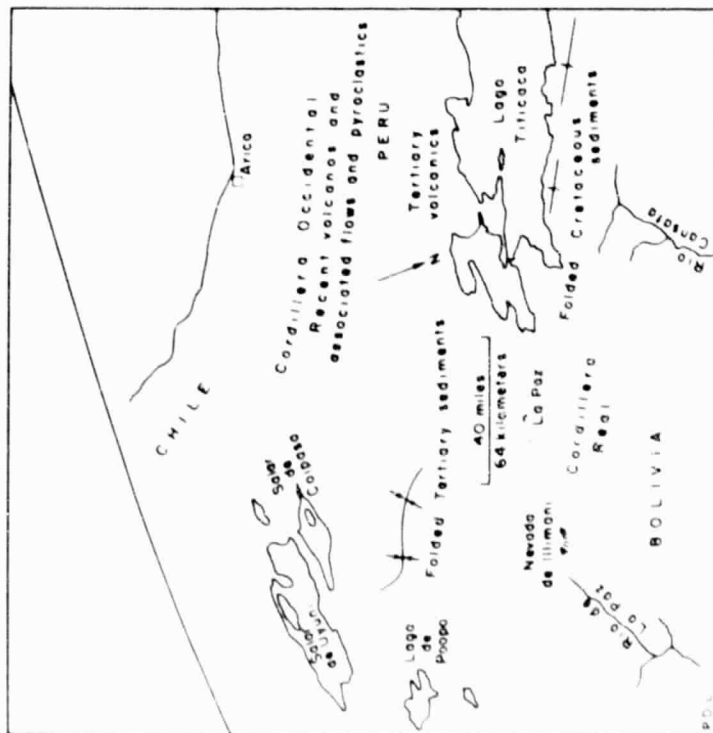
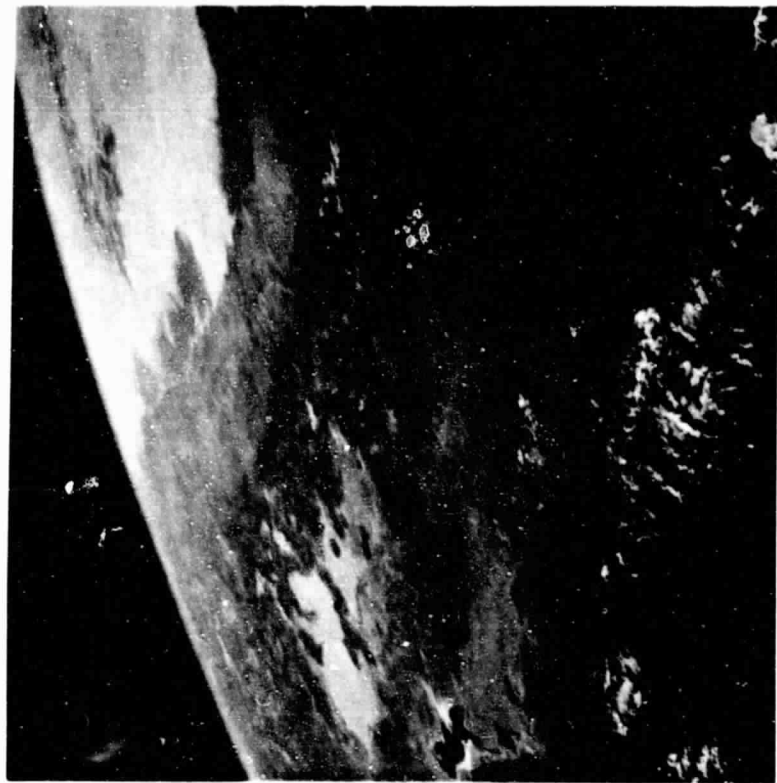
Figure 13. Landsat image of southern Mexico; Mexico, D.F., at extreme upper left. Area shown is eastern end of the Neo-Volcanic Plateau, an east-west trending belt of young and frequently-active volcanoes crossing the isthmus. Prominent northwest trending range at top center includes Popocatepetl (southern peak) and Iztaccihuatl (central peak). La Malinche, another volcano, is at upper right. Dark areas surrounding each are forested mountain slopes. Landsat image 1307-16285.



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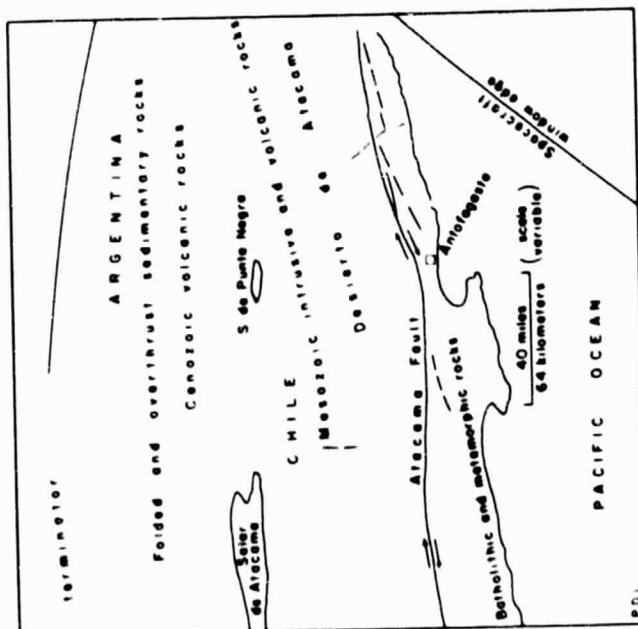
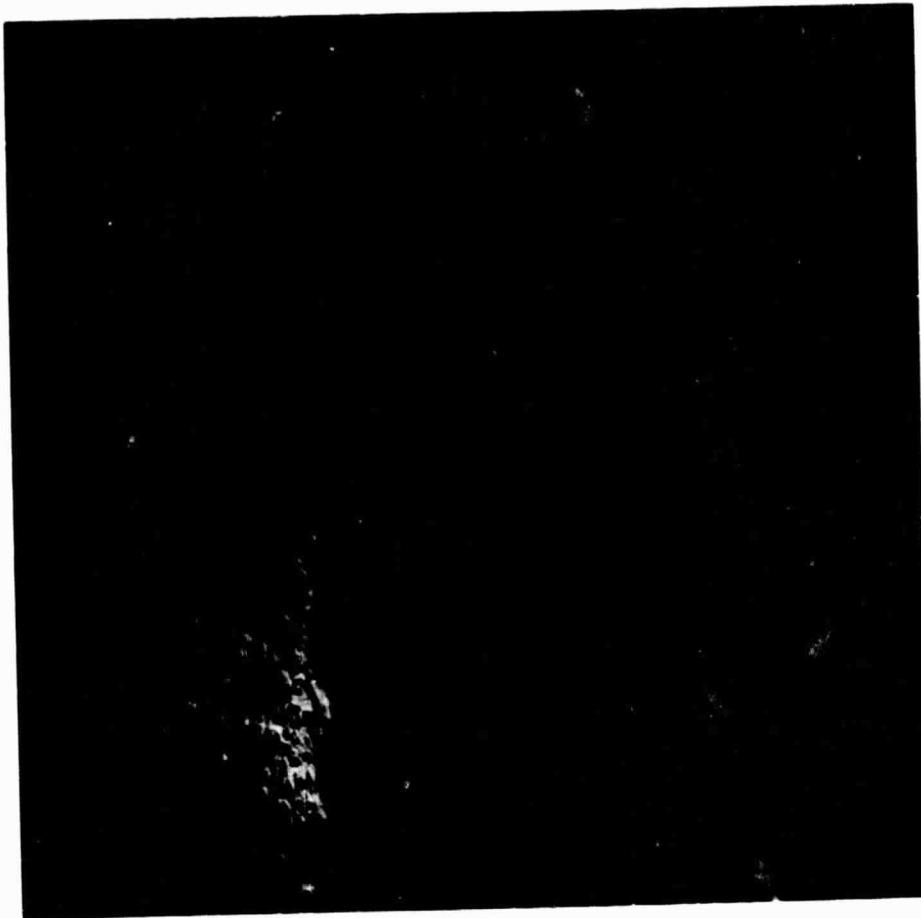
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Figure 14. Gemini 9 hand-held photo looking south over Andes. (See Lowman, 1972, for detailed discussion of photo.) Relationship of Peru-Chile Trench, arc-trench gap, and volcanic arc well shown. Subduction zone dips to east, i.e., from right to left. Gemini photograph S 66-38313.



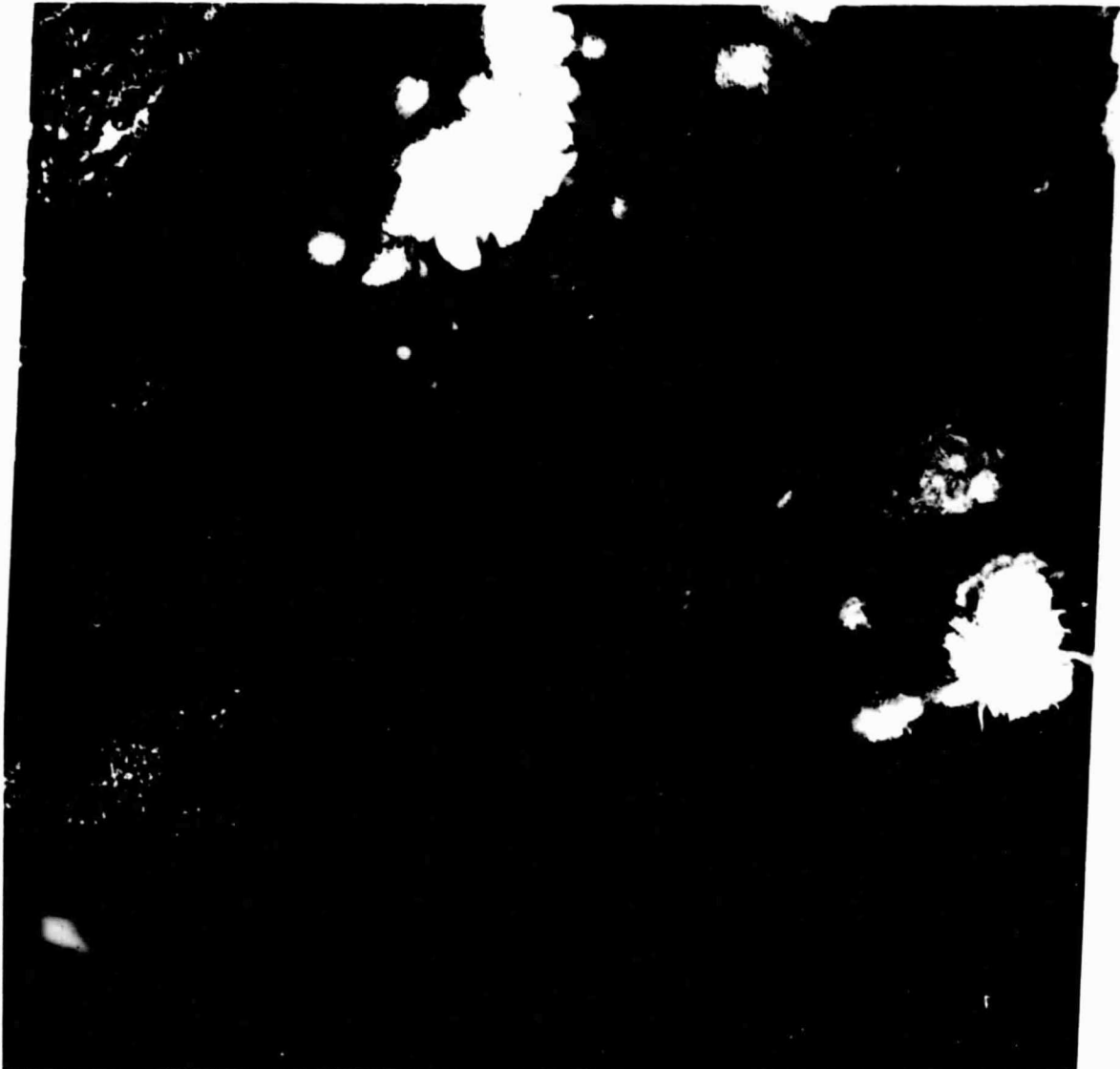
INDEX MAP
GEMINI 9 PHOTOGRAPH 5-66-38313

Figure 15. Apollo 7 hand-held photo of coast of Chile, showing area of active tectonism overlying Peru-Chile trench subduction zone. Rocks along coast are Paleozoic igneous and metamorphic rocks. Area characterized by frequent strong earthquakes. Apollo 7 photograph AS 7-7-1826.



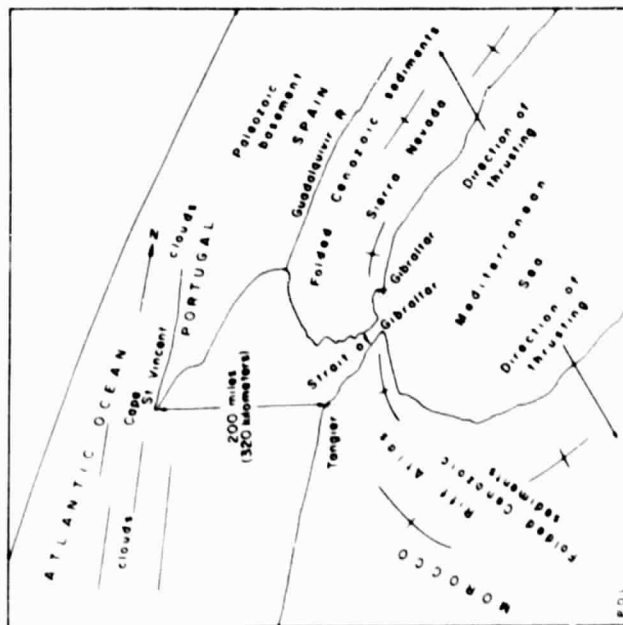
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 APOLLO 7 PHOTOGRAPH AS 7-7-1826

Figure 16. Landsat view of southern Iceland; Reykavik at lower left. Southwest-trending depressions and related features outline the extension of the Mid-Atlantic Ridge. Area is seismically and volcanic active and generally considered to be an exposed part of the Ridge. Substantial crustal extension and volcanism occurred in the northern part of Iceland in the late 1970s. See Short et al (1976), Plate 219, for discussion of this picture. Landsat image 1392-12191.



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Figure 17. Apollo 9 hand-held 70 mm photo showing continuity of structure across the Strait of Gibraltar. Folds and overthrusts of Riff Atlas (lower left) grade into similar structures in Sierra Nevada of Spain (right). Note direction of overthrusting (away from Mediterranean). See Lowman (1972) for more detailed discussion. Apollo 9 photograph AS 9-23-35;4.



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 APOLLO 9 PHOTOGRAPH AS 9-23-3514

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Figure 18. Landsat view of intersection of Rhine graben system and Alps. Rhine valley at upper right; largest city is Basle, Switzerland; Vosges Mts. at top center, Black Forest at extreme upper right, Jura Mts. at lower center. Rhine valley is south end of Rhine graben. Juras are Mesozoic sediments folded and overthrust to the northwest, largely by gravitational gliding. At extreme lower right are the Alps proper, locally the nappes of the Prealps, also overthrust to the northwest. Valley between the Juras and Prealps is the Swiss Plain, a Tertiary basin filled with coarse sediments derived from the Alps (Molasse). Landsat image 1078-09553.

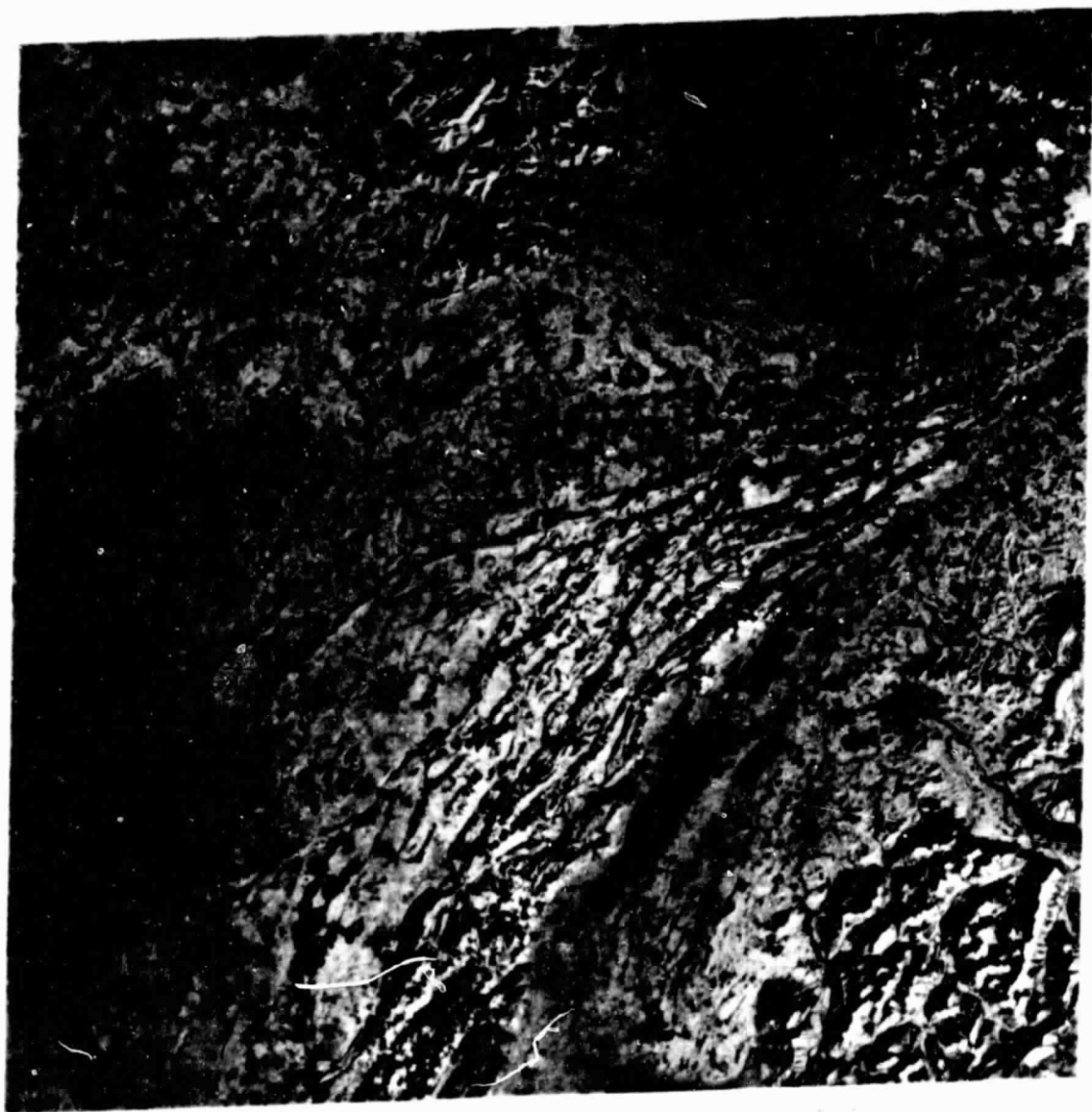


Figure 1. A photograph showing a steep, rocky slope, likely a cliff face or a steep embankment, with a prominent vertical crack or fissure running down the center. The rock surface is highly textured and appears to be composed of layered or fractured material. The lighting is dramatic, highlighting the ruggedness of the terrain.

Figure 19. Landsat view of Rome and adjacent areas. Picture shows the large calderas of the Rome district, the Sabatini and Cimino volcanoes northwest of Rome and the Latian volcano to the southeast. Although now extinct, they have been active within the past one million years. Rock types associated with them are largely ignimbrites and rhyolites. Area to northeast (upper right) in Appennines underlain by Paleozoic and Mesozoic platform carbonates, folded and overthrust to the northeast. Landsat image 1198-09232.

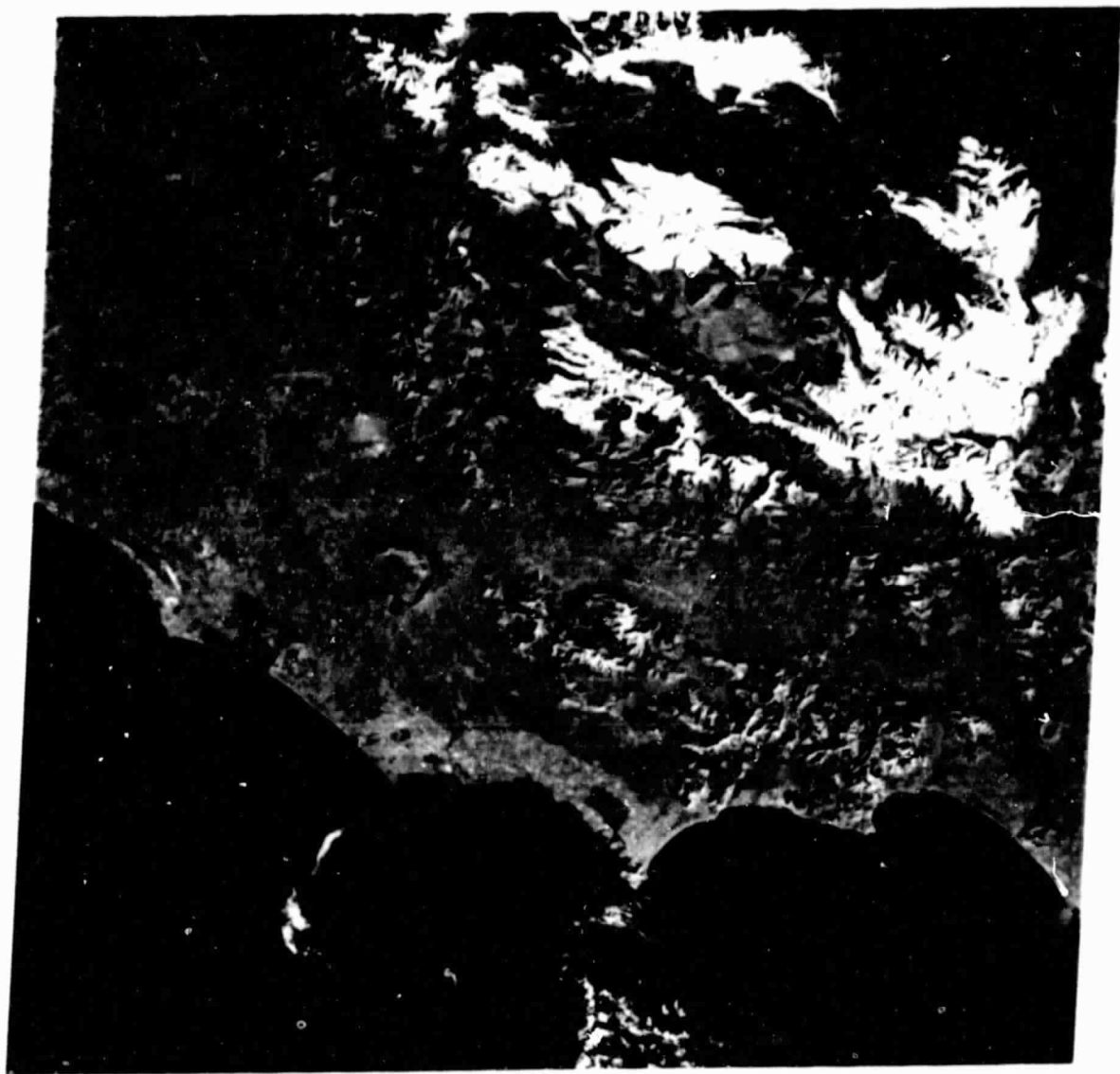
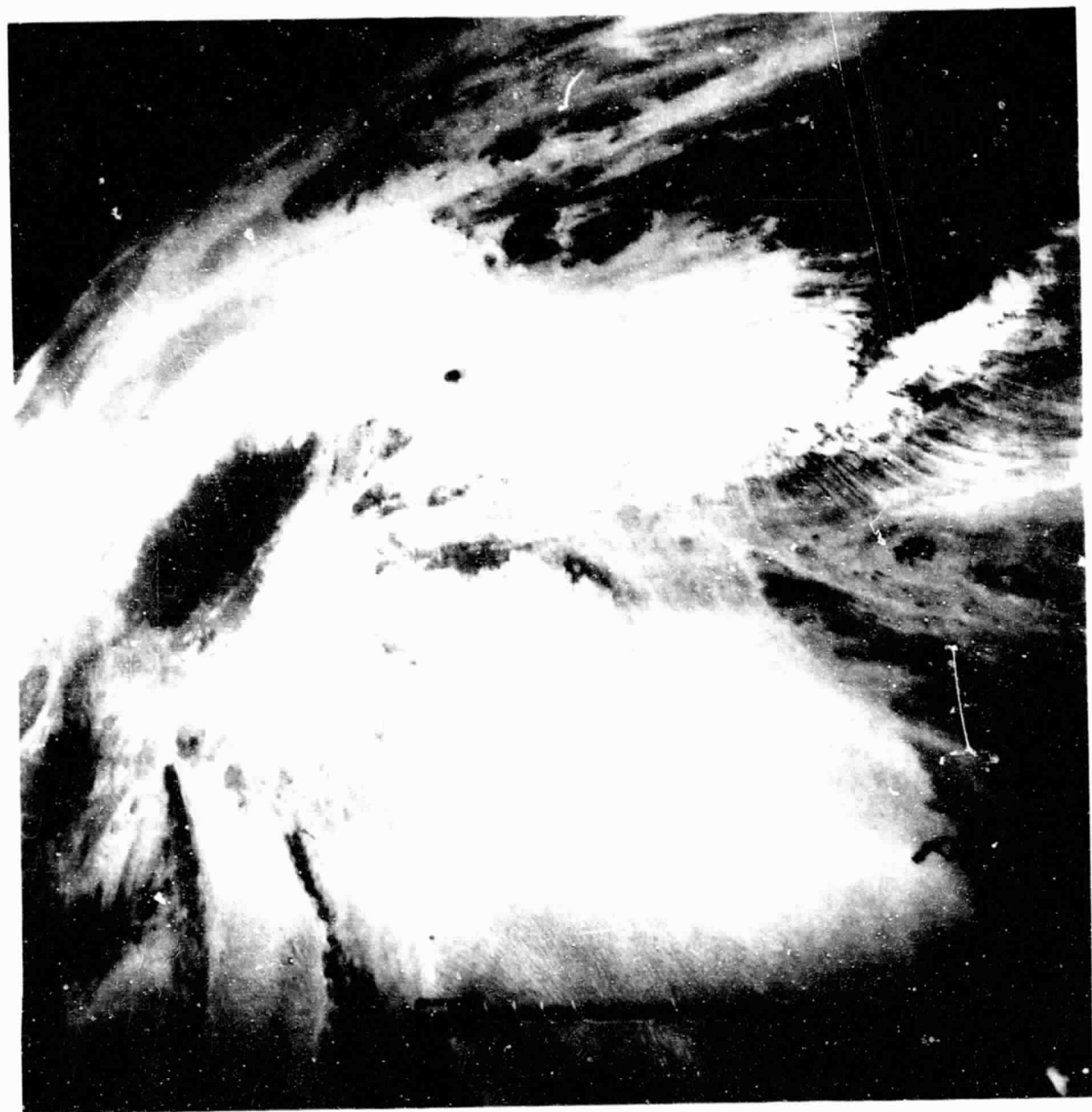


Figure 20. Skylab hand-held 35mm photo looking southeast over southern Italy: Gulf of Taranto (T) at top center, Adriatic Sea (A) at left, Naples and Vesuvius in lower right corner. Mountains in southwest half of peninsula (to right) are largely "Argille Scariose" (scaly shales) of Cenozoic age, folded and overthrust to the northeast. Area southeast of Naples was site of devastating earthquakes of November, 1980. Lower terrain to southeast (left), bounded by front of the Alpine allocthon (marked by overthrust symbols) is largely less-deformed carbonate platform deposits. White patches are towns and cities. (Reference: Carta Tettonica d'Italia, 1:1,500,000, Consiglio Nazionale Delle Ricerche, 1980).



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Figure 21. Gemini 11 hand-held photo looking northeast over North Africa toward Libya and Egypt. Dark patch at left center is Haruj al Aswad, a recent volcanic field. Tibesti Mountains at upper right are also volcanic. Light area at bottom center is Marzuk Sand Sea. Gemini 11 photograph S 66-54525.






Figure 22. Gemini 7 hand-held photo, looking to southeast over Tibesti Mountains of Libya and Chad. Calderas, associated with rhyolites and ignimbrites, are considered extinct but fresh morphology of craters and associated lava flows clearly indicates young ages (e.g. dark flow of Pic Tousside at far right). Volcanic field generally considered expression of a mantle plume. Absence of systematic age distributions indicates no movement of Africa with respect to mantle for about 25 million years (Burke and Wilson, 1972). Gemini photograph S 65-63746.

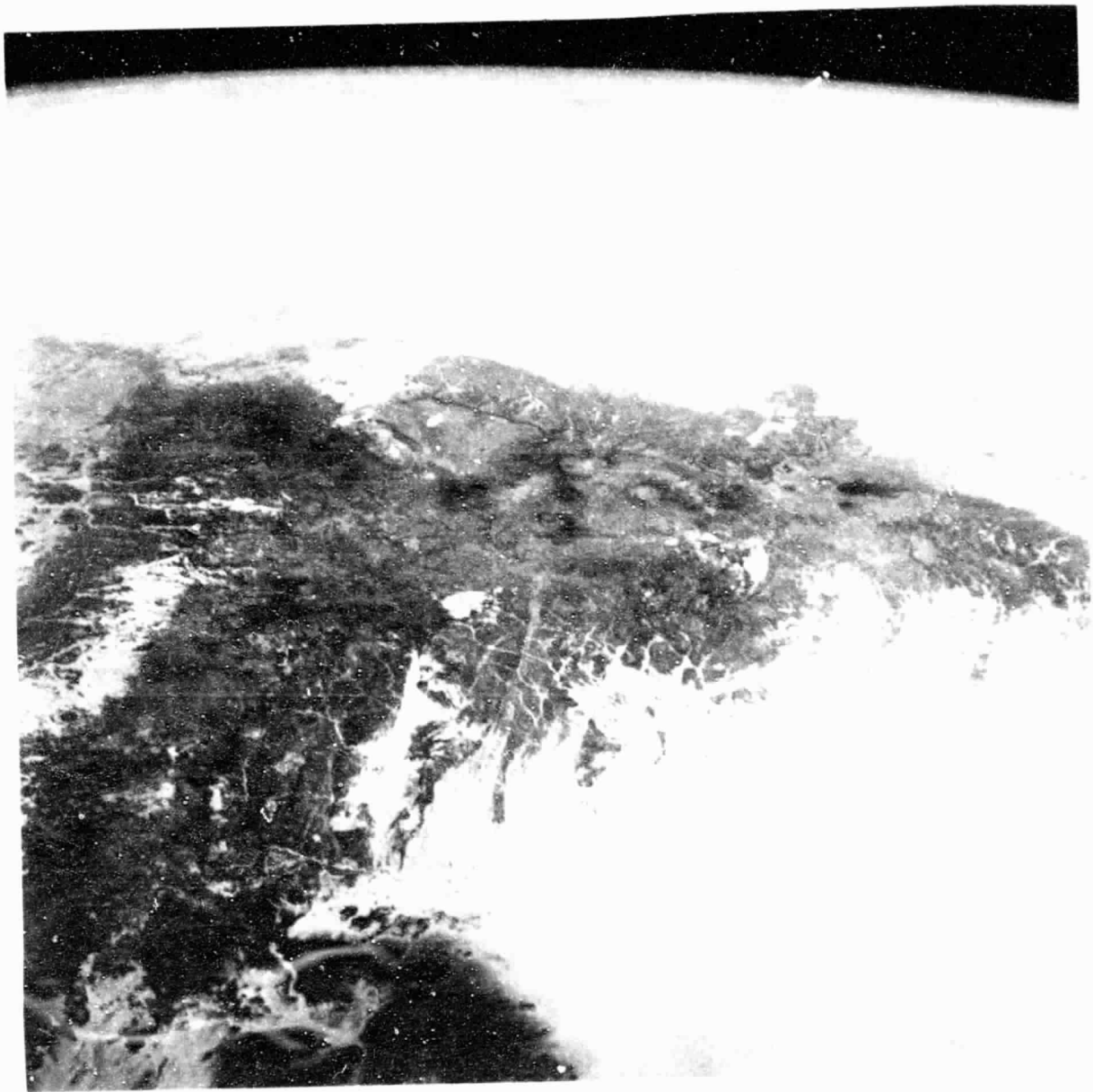


Figure 23. Apollo 9 hand-held photo of western Tibesti Mountains, showing youthful physiography of volcanoes. White-floored crater is Trou au Natron; dark flows emanate from Pic Tousside.

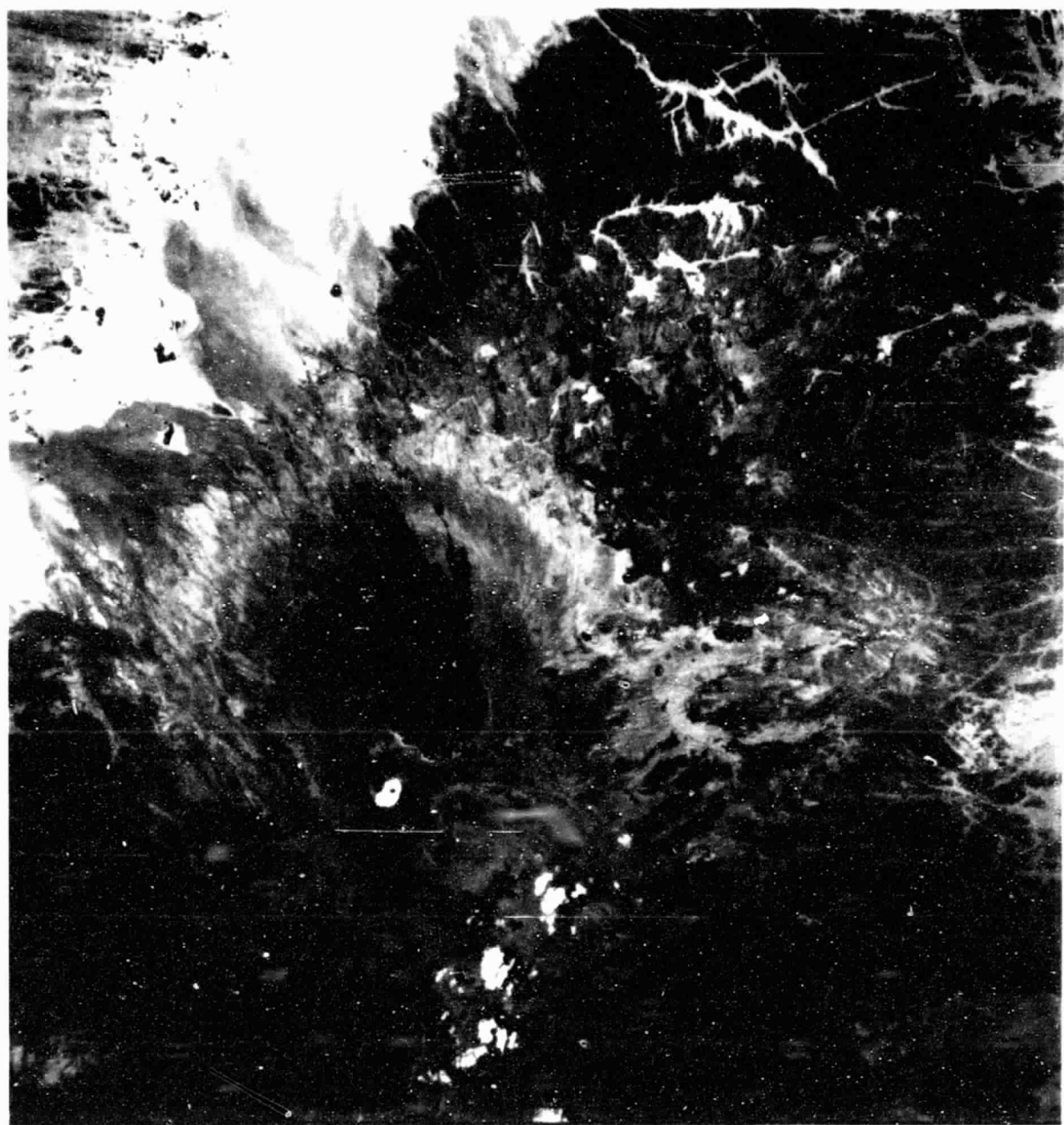
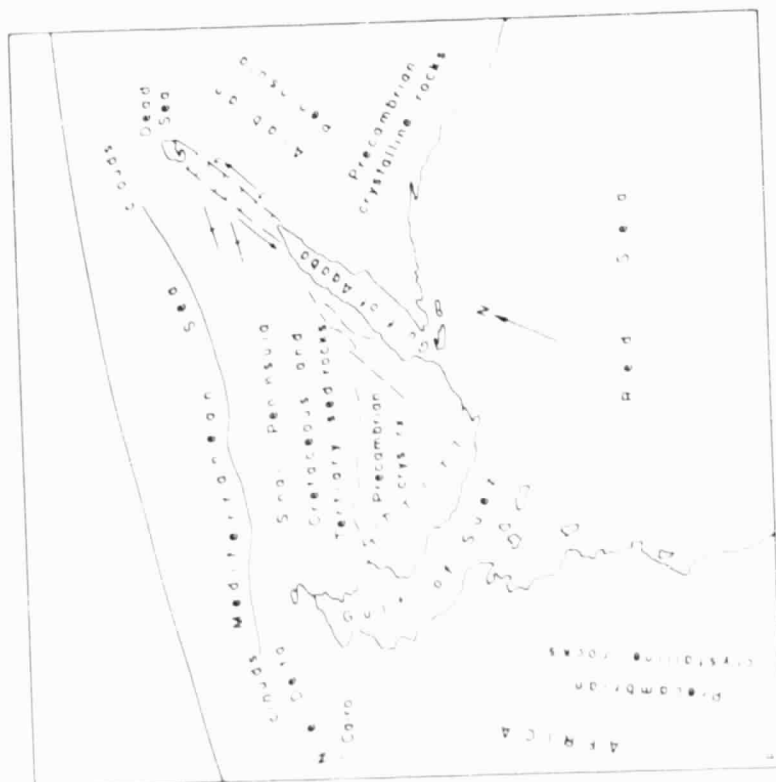
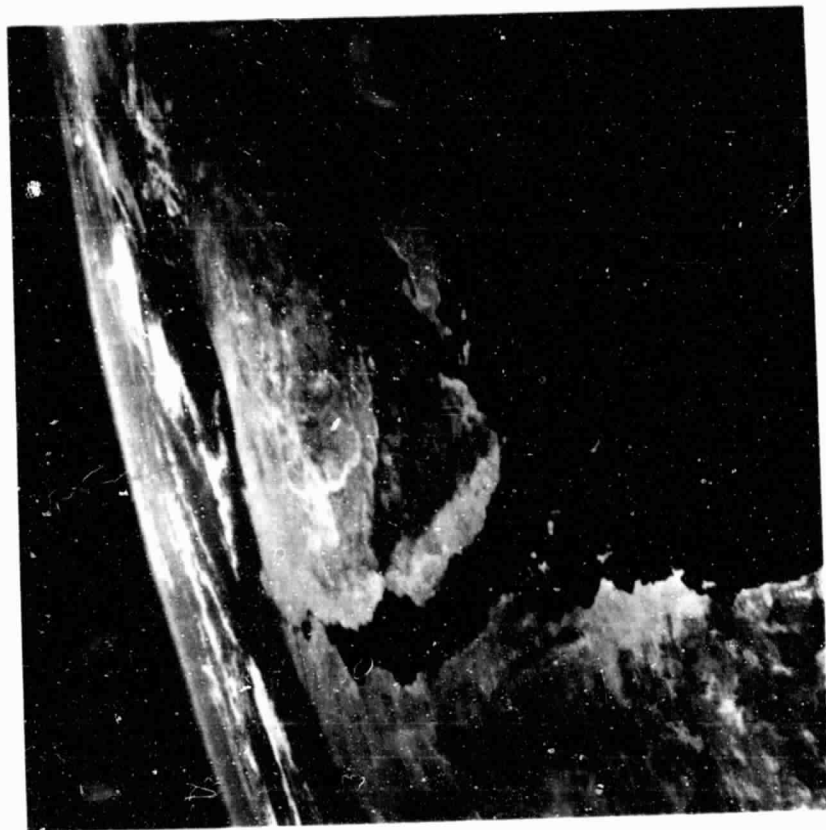


Figure 24. Apollo 7 hand-held photo looking north over Sinai Peninsula; Red Sea lower right. Region generally interpreted as a triple junction: ridge (Red Sea)-transform (Gulf of Aqaba-Dead Sea)-failed rift (Gulf of Suez). Arabian Peninsula (right) appears to be moving northeast by left-lateral slip along faults of the Gulf of Aqaba-Dead Sea "rift." For detailed discussion see Lowman (1972). Apollo 7 photograph AS 7-11-2000.

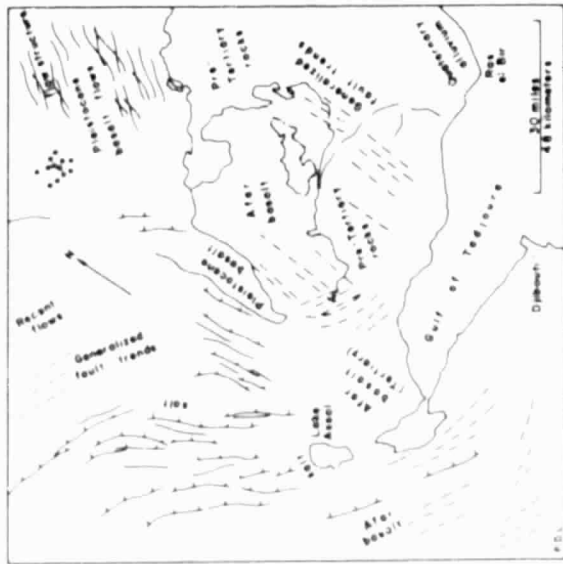


INDEX MAP
 APOLLO 7 PHOTOGRAPH AS 7-111-2000

Figure 25. Gemini 12 hand-held photo looking southeast over the Red Sea and Sinai Peninsula (lower left). Spacecraft docked to Agena; radar transponder is over Nile River, marked by dark vegetation. Photo gives good overall view of Red Sea and triple junction with Gulf of Aqaba and Gulf of Suez. Gemini 12 photograph S 66-63480.



Figure 26. Apollo 9 hand-held photo of Afar depression and Gulf of Tadjoura. Afar depression generally considered exposed sea floor, dammed off from Red Sea, on which normal faults of an actively spreading area are exposed. White areas are evaporites, dark areas of depression generally basalts. Compare with Landsat pictures of East African rift and of Iceland. Apollo 9 photograph AS 9-23-3539.



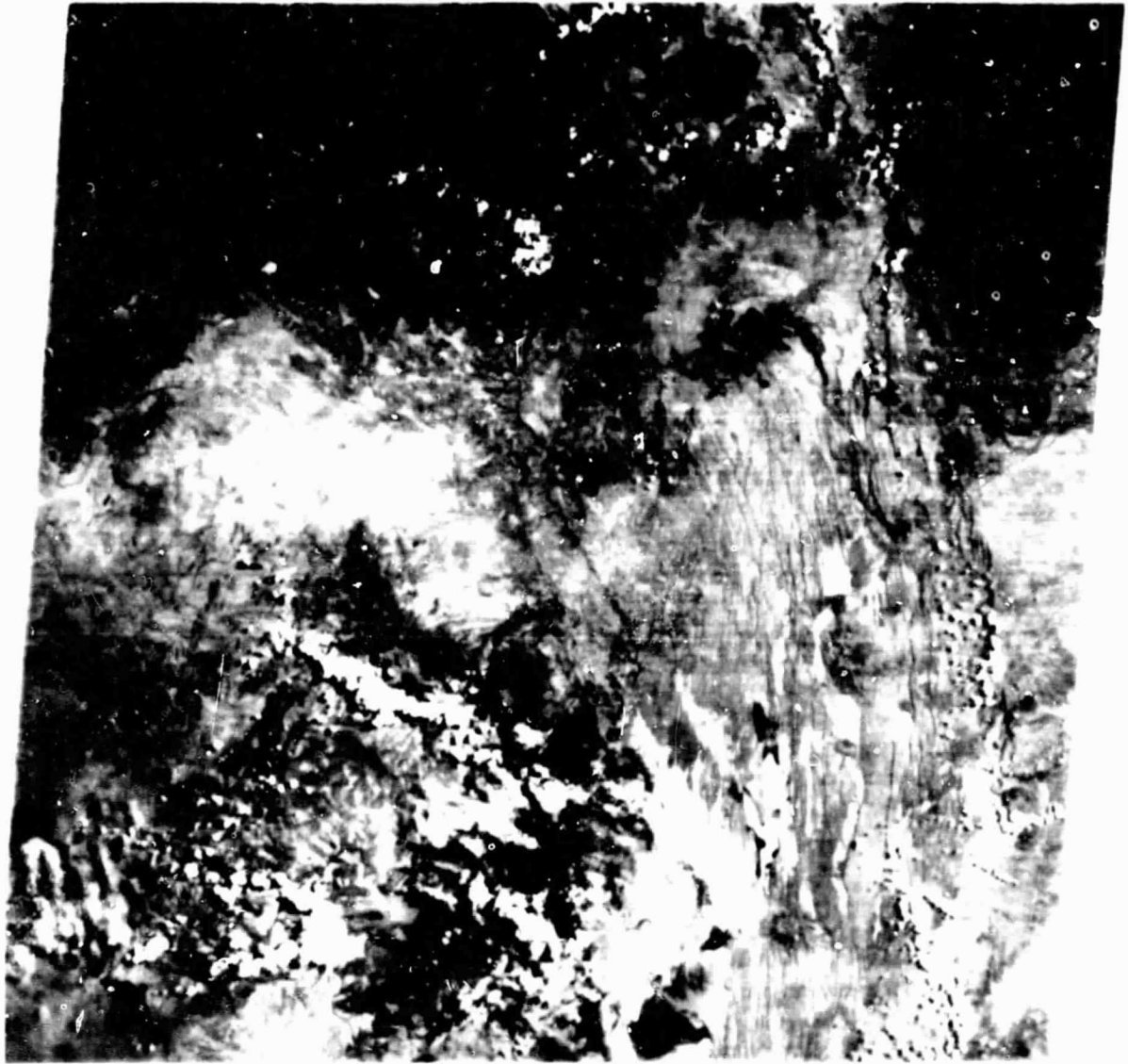
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 APOLLO 9 PHOTOGRAPH AS 9-23-3539
 Note: Only main faults shown. Features on open-dropped blocks, Capricorn, not shown completely.

Figure 27. Landsat view of southern Kenya (Nairobi at extreme right), showing East African rift system at the Equator. Large volcano at upper right, in rift, is Suswa; several others also visible. See Short et al (1976), Plate 359 for detailed discussion. Note step faults in eastern part of rift; compare with structure of Afar Depression (Fig. 26). Rift is seismically active and characterized by normal faulting. Landsat image 1048-07172.

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SECTION 40

SECTION 50



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Figure 28. Landsat view of Dead Sea and Dead Sea "rift." Valley now generally considered a transform fault regionally, along which more than 100 km of left-lateral movement has taken place. This segment has been shown by Quenell to be bounded by parallel wrench faults, opening a "rhombochasm" (S. W. Carey's term) by left-lateral slip. Landsat image 1054-07421.



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Figure 29 Apollo 7 hand-held photo of Zagros Mountains, Iran, looking to north; Qishm Island at lower right. Picture shows active orogenic area in which topography mirrors structures, with most ridges being anticlines. Dark circular features are extrusive salt domes. Area represents convergence zone between Arabian Plate and Eurasian Plate, but widespread seismicity and tectonism disqualify it from the category "microplate." See Lowman (1972) for map and discussion. Apollo 7 photograph AS 7-15-1615.

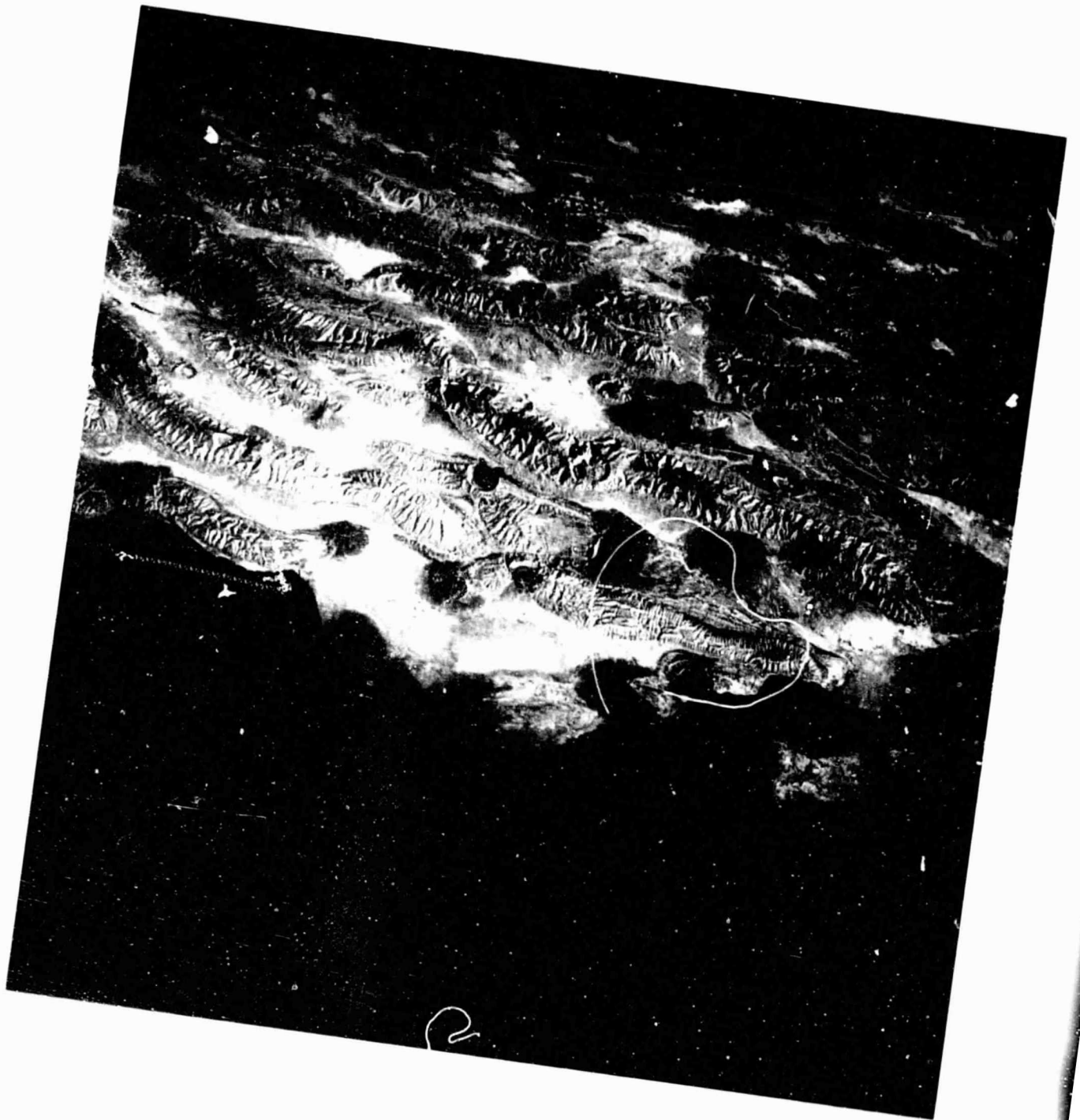


Figure 30. Gemini 12 hand-held photo looking east over the Strait of Hormuz, with Oman at right and southeast Iran and Pakistan at left. East-trending mountains at left center are the Makran Range, considered an overthrust, probably underlain by a north-dipping subduction zone. Ridges at lower left are part of Zagros Mts., divided from Makran Range by wrench faults of the Oman Line (term proposed by A. Gansser). Dark rocks of the Oman Range (right) are chiefly ophiolites, thought to have been obducted. Gemini 12 photograph S 66-63486.



Figure 31. Gemini 5 hand-held photo of southeast Iran; city of Kerman in valley at left. Picture shows intensely folded strata of Zagros Mountains, cut by major fault on east. Area underlain by salt; note white salt glacier at top center. Linear features at lower right are yardangs of the Dasht-i-Lut. Area is highly active seismically. Gemini 5 photograph S-65-45647.

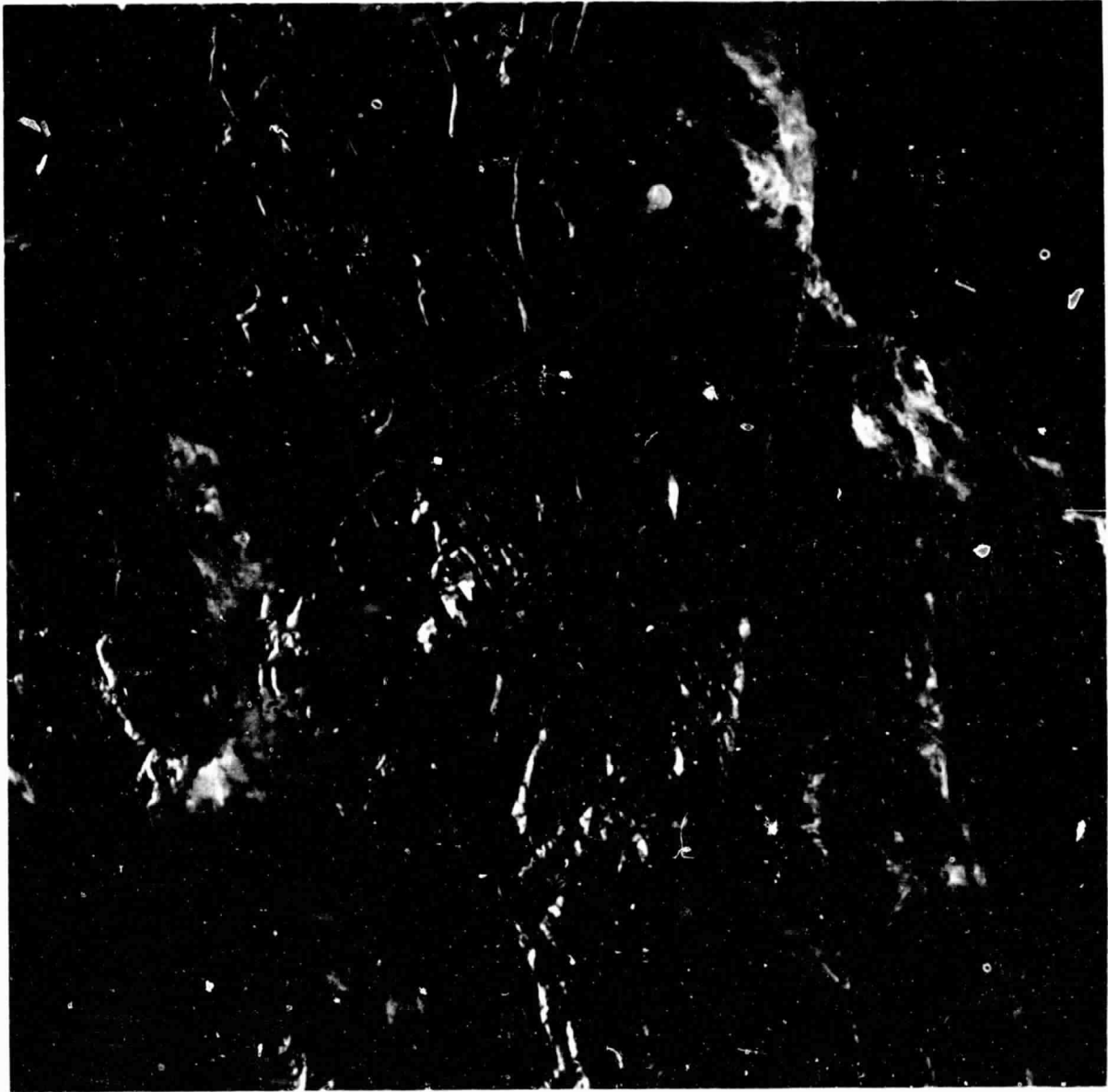


Figure 32. Apollo 7 hand-held photo showing northern India. Rivers in foreground are part of the Ganges system. Area generally considered to represent site of underthrusting of Asia by India, with the Himalayas (upper left) being the thrust. Foreground is Ganges Alluvial Plain, underlain by up to 8 km of sediment derived largely from Himalayas. Apollo 7 photograph AS 7-11-1980



Figure 33. Landsat view of Tien Shan, China, vicinity of E78°, N40°, showing folds and overthrusts. Tarim Basin to south. Note prominent overthrust at lower left, bounded by left-lateral tear faults. Landsat image 1206-05000.

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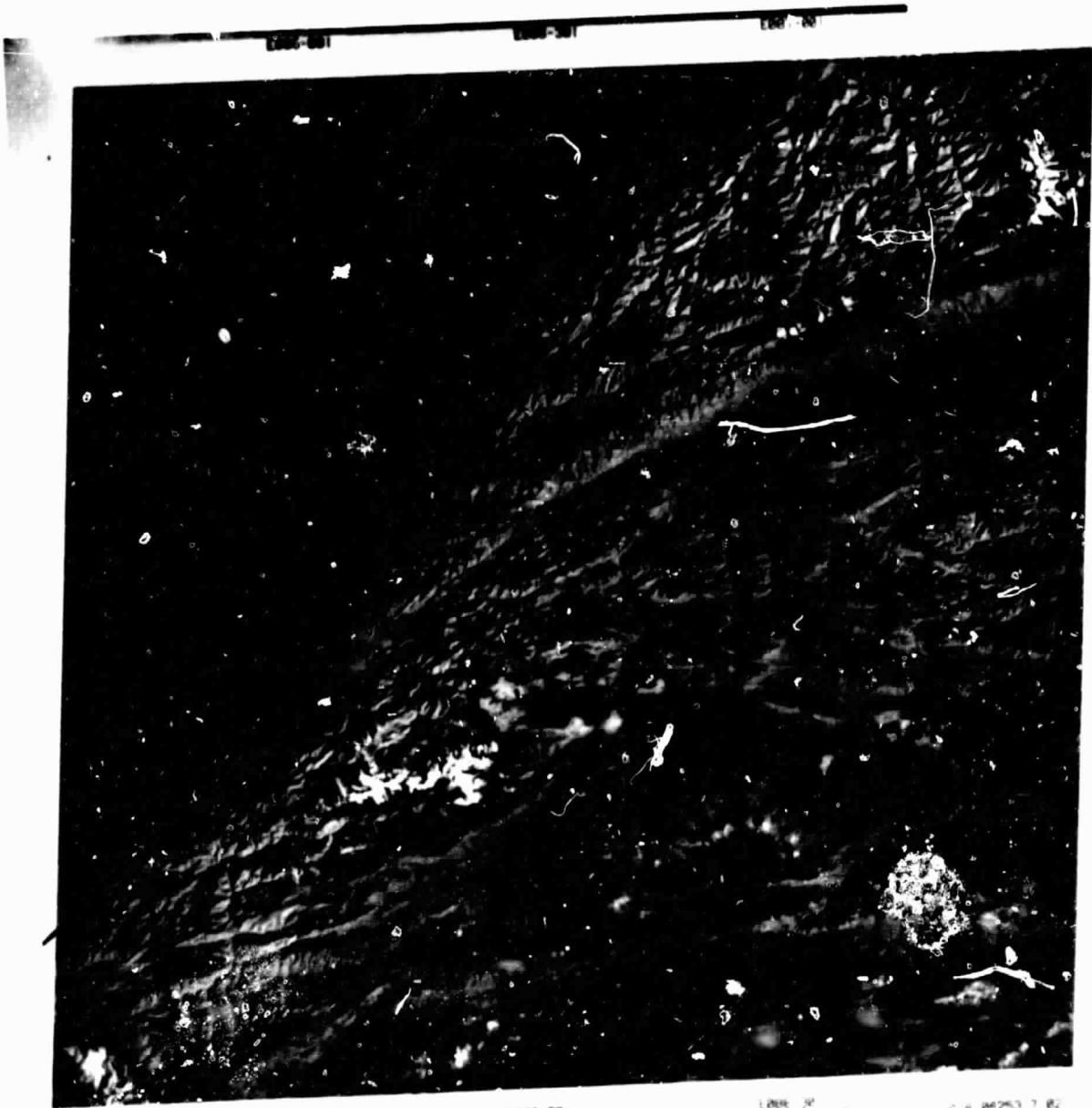
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Figure 34. Landsat view of western part of Altyn Tagh fault, western China. Fault trace indicated by arrows; sense of motion left-lateral. See Molnar and Tapponnier (1975) for discussion. Landsat image 1074-04253.



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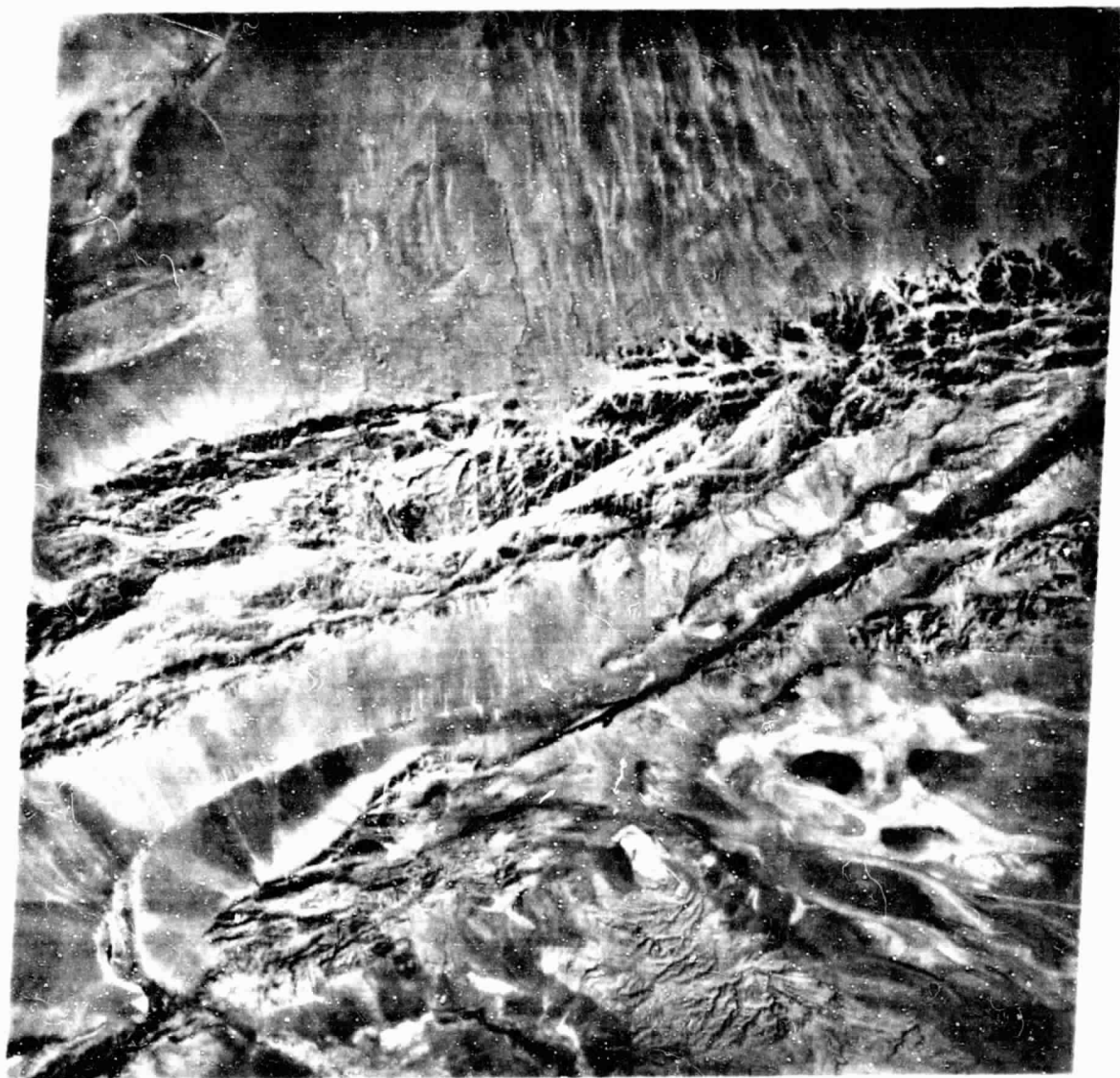
Figure 35. Landsat view of western China, vicinity of 39°N , 91°E , showing part of Altyn Tagh fault. Molnar and Tapponnier (1975) consider this "perhaps the greatest active continental strike-slip fault in the world." Fault trace shown by arrows. Tarim Basin to north. Sense of motion is left-lateral. Landsat image 1449-04062.

194 30

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Figure 36. Landsat view of Sinkiang Province, with Lake Baghrash at upper left. Area is on northeast edge of Tarin Basin. East-west trending fault at lower center shown by Molnar and Tapponnier (1975) as right-lateral, despite apparent offset of crystalline rocks. Considered by Molnar and Tapponnier to be result of east-west shearing induced by northward movement and collision of India with Asia. Landsat image 1128-04250.

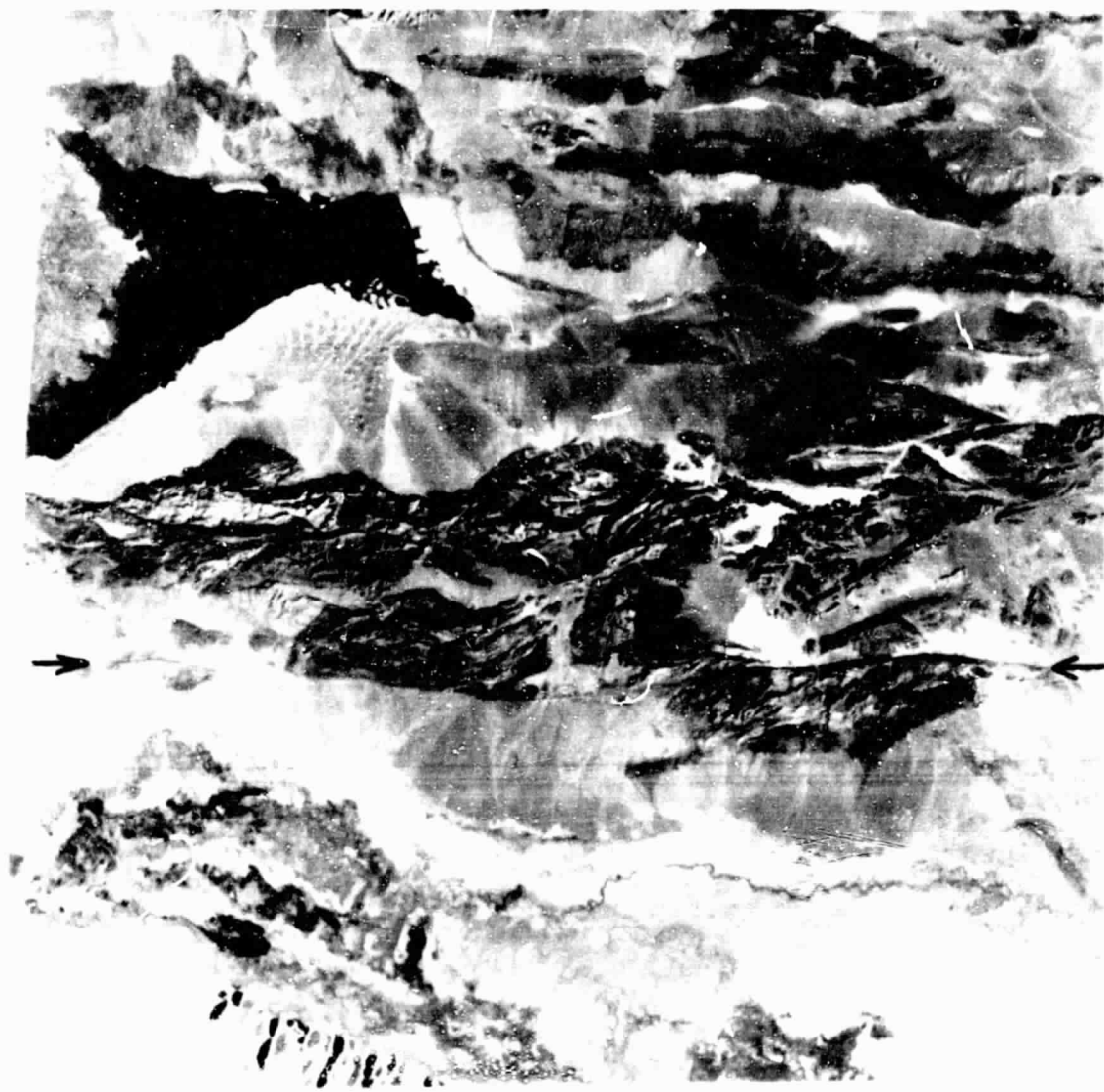


Fig. 1. A large, dark, textured rock formation, possibly a fossil or mineral specimen, with a white, irregularly shaped object resting on its surface. Two small black arrows point towards the white object from the left and right sides.

1950
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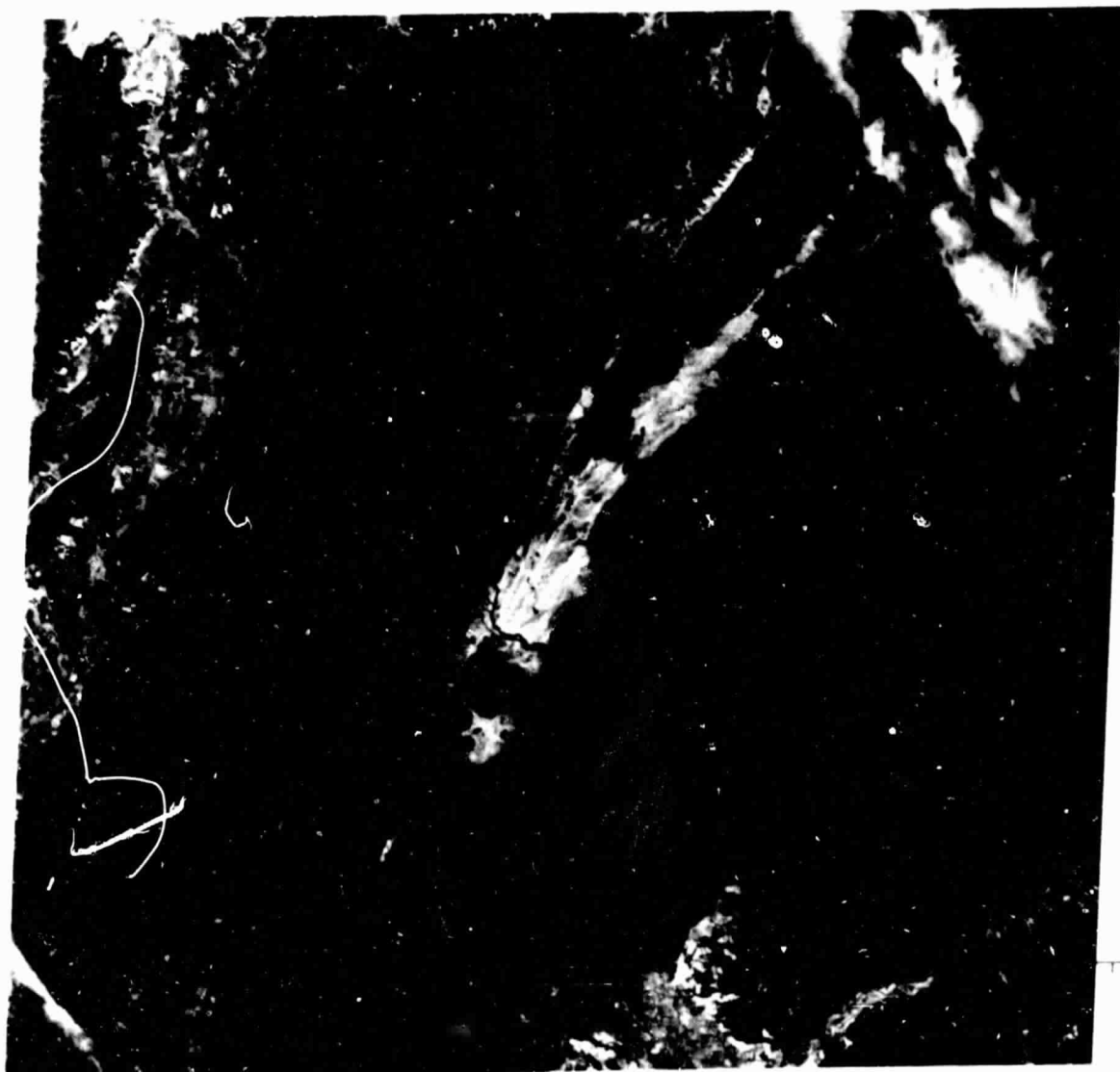
Figure 37. Nimbus I image showing northern Mongolia, Lake Koso, and southern Siberia near city of Irkutsk, U.S.S.R.; Lake Baikal at extreme. Prominent lineament running from lower right to top center is the Sayan fault (arrows). Lake Koso occupies a graben considered part of the Baikal rift system. Image shows value of seasonal coverage for rendition of geologic features. See Lowman (1972) for maps and discussion. Image taken 19 Sept. 1964.

521100



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Figure 38. Landsat view of Lake Baikal, U.S.S.R., bounded by Primorskiy Range on the west side and Ulan Burkassy Range on the east side. Lake occupies a large graben undergoing active extension, with strong seismicity and fault plane solutions (Molnar and Tapponier, 1975) indicating normal faulting. Strong earthquake in 1861 killed 1300 people. See Short et al (1976) for more detailed discussion. Landsat image 2150-03123.



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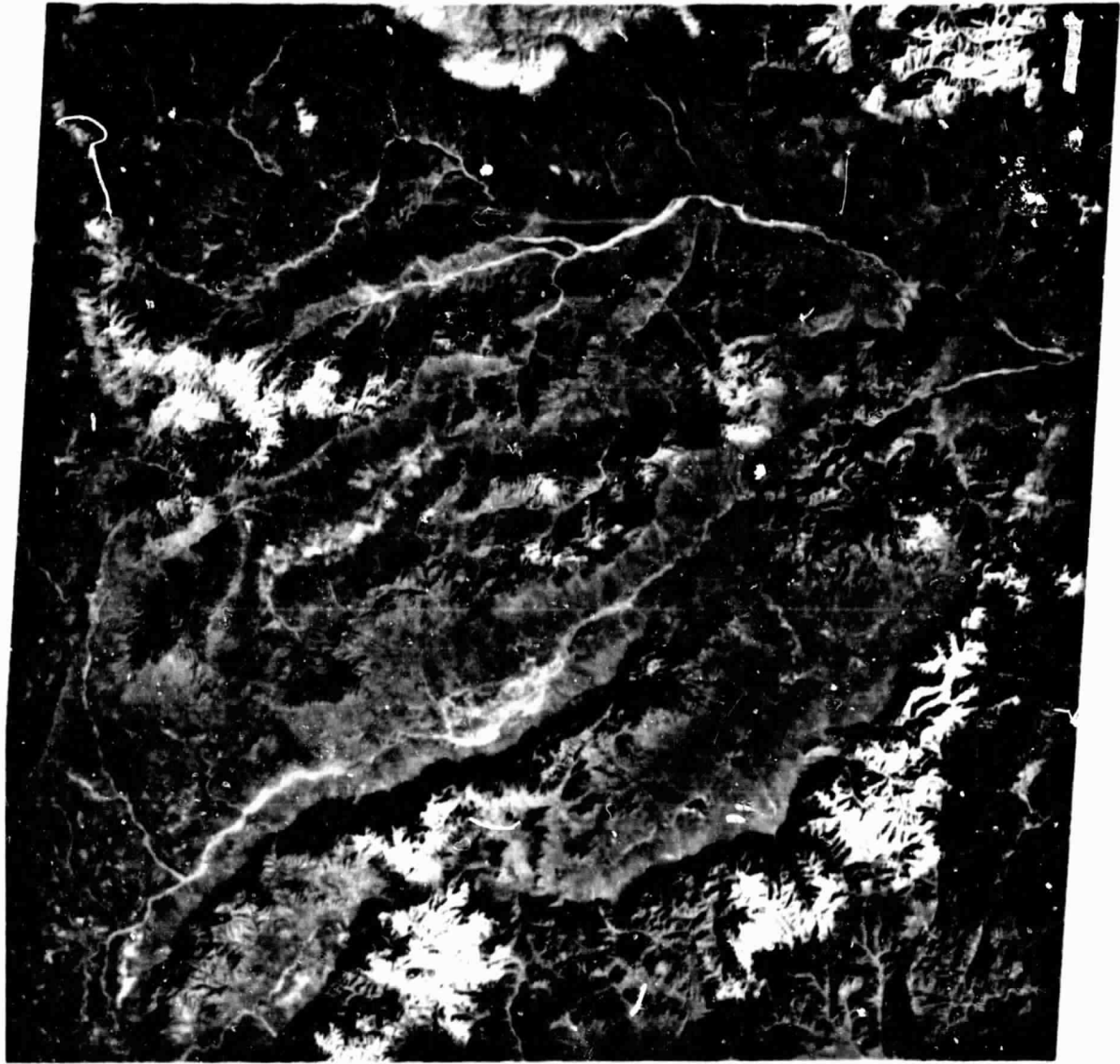
Figure 39. Landsat view of northern portion of Shansi graben system, about 150 km west of Peking. Mountains are part of the Great Khingan Range, a complex of Precambrian metamorphics and younger sedimentary and igneous rocks. Area is undergoing active crustal extension, as shown by normal faults bounding valleys. Landsat image 1523-02331.

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Figure 40. Landsat view of northern China, with city of Pingyang at lower center. Area shown is part of Shansi graben system, a series of active faults responsible for numerous devastating earthquakes. Area underlain by extensive loess deposits, indicated by intricate dendritic drainage pattern. Landsat image 1524-02400.

E111-001

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E112-001

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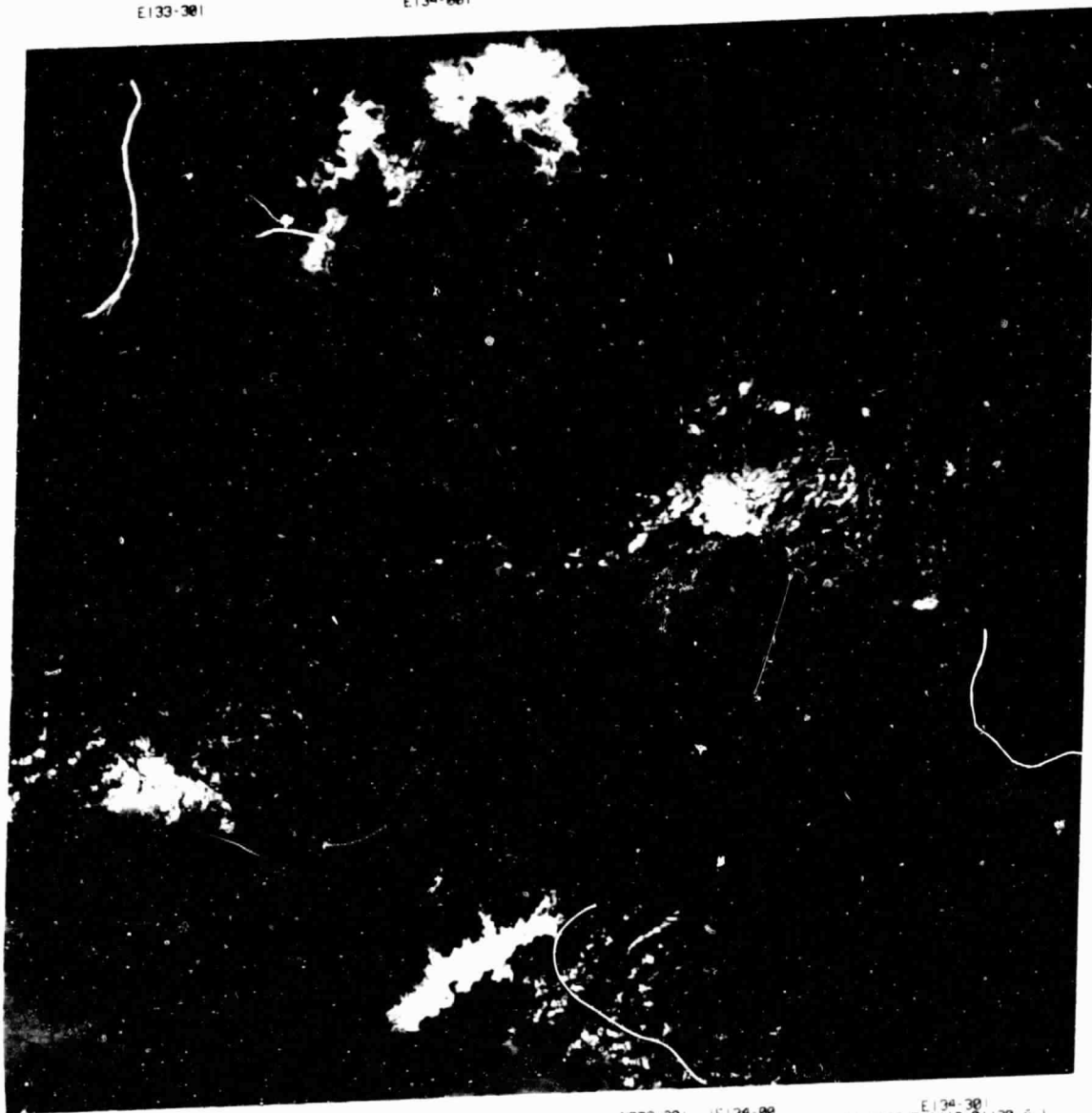
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Figure 41. Landsat view of Shikoku, Japan, Inland Sea, and part of Honshu (upper half of picture). Prominent fault crossing Shikoku from lower left to upper right is the Median Tectonic Line, separating the high pressure Sanbagawa metamorphic belt to the southeast from the lower pressure Ryoke-Abukuma metamorphic belt to the northwest. Isolated mountain range just northwest of main fault is also part of Sanbagawa belt. Sanbagawa belt is characterized by glaucophane schists and few igneous rocks, Ryoke-Abukuma belt by Cretaceous granitic intrusions (Myashiro, *J. Petrol.*, 2,277,1961). Landsat image 1112-01120.

E133-301

E134-001

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Figure 42. Landsat view of Alpine fault, South Island, New Zealand. Fault is known to be recently active (right-lateral slip) on basis of displaced stream terraces, although not displaying a clear pattern of seismic activity. Except for absence of seismicity, the Alpine fault resembles the San Andreas fault and the Median Tectonic Line of Japan in having major lateral movement and in separating paired metamorphic belts. Area shown here has high-pressure metamorphic rocks to the east. Landsat image 1503-21421.

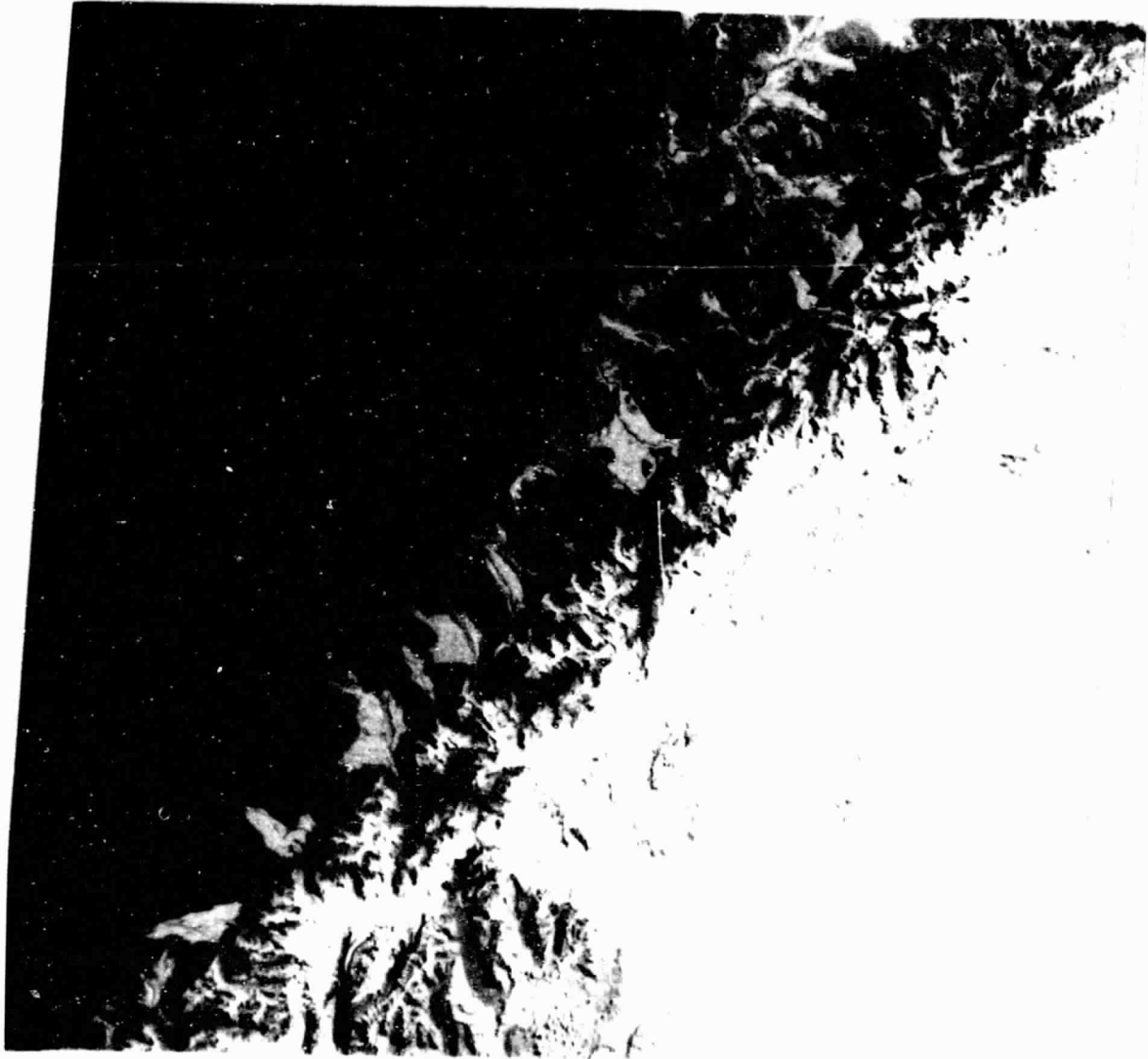
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