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GEOLOGIC MAPPING
STRUCTURAL ANALYSIS
MINERAL RESOURCES of
SOUTH AMERICA

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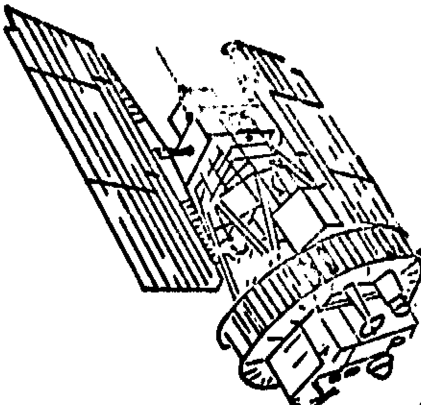

(E76-10459) EVALUATION OF LANDSAT-1 IMAGE APPLICATIONS TO GEOLOGIC MAPPING, STRUCTURAL ANALYSIS AND MINERAL RESOURCE INVENTORY OF SOUTH AMERICA WITH SPECIAL EMPHASIS ON THE ANDES MOUNTAIN REGION (Geological Survey) G3/43

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by

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EVALUATION OF LANDSAT-1 IMAGE APPLICATIONS TO GEOLOGIC MAPPING, STRUCTURAL ANALYSIS AND MINERAL RESOURCE INVENTORY OF SOUTH AMERICA WITH SPECIAL EMPHASIS ON THE ANDES MOUNTAIN REGION

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16. Abstract

Linear features of over 1,000,000 km^2 of the Guyana Shield and the Andes of Peru, Bolivia, Chile and Argentina were mapped using 1:1,000,000-scale mosaics of Landsat images. The association between linear features and the distribution of known mineral resources was demonstrated and resulted in the discovery of new copper showings in Bolivia. Possible iron deposits in Argentina, and a new Tertiary basin of interest for petroleum exploration in southern Chile still await field confirmation.

Landsat-1 images were also found useful in mapping hydrologic basins and identifying potential ground-water sources in the deserts of northern Chile and the altiplano of southwestern Bolivia. It was also found useful in mapping major rock types in arid regions and structural features in tropical jungles of Bolivia.

A nucleous of Landsat-1 data users was established in each of the principal geological mapping agencies in Venezuela, Colombia, Peru, Bolivia, Chile, Argentina and Brazil with whom an interchange of information became operational. Follow-on joint efforts are under development which will utilize the full capabilities of the Landsat system.

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1.0 Summary

1.1 Objective: This experiment was designed to evaluate the application of Landsat data to geologic mapping and mineral resource inventory and exploration in the Precambrian Shields and Andes Mountains in cooperation with national geological survey geologists of South America. The purpose of this arrangement was to build local expertise in the use of the data and provide a means for field checking interpretations. Demonstration models and methods of interpretation were investigated and are presented.

1.2 Scope of Work: Landsat images processed as 70 mm film chips and 23 x 23 cm positive film transparencies (in 3 sets) were supplied by NASA to the Principal Investigator who in turn sent sets of pertinent images to each of seven in-country investigators. Interpretation was done using light tables and magnifying lenses as the principal tools, and a diazochrome processor to make color composites at contact scale (1:1,000,000). Each investigator worked independently, later comparing results with the Principal Investigator. Mosaics covering 4 x 6 degrees latitude and longitude were constructed for three areas where sufficient cloud-free images were obtained. Examples of the La Paz, Copiapo and Tucuman mosaics are included in this report as demonstration products from which interpretation maps of lineaments are derived and to which metallogenic maps and other types of compilations can be compared. Such comparisons are used to identify promising areas for field investigations and exploration.

1.3 Conclusions: Landsat images were found to be ideal for geologic study of large remote areas of South America. The flexibility of scale from 1:3.6 M to 1:250,000 or larger, the adequate resolution (80 m) and broad multispectral range are important additions to geophysical techniques, never before available to geologists on a systematic basis. It was found that all bands contributed useful information. Band 4 was best for studying variations in water bodies such as Lake Titicaca; band 5 was used to define vegetation areas in arid regions; bands 6 and 7 were used most extensively in both tropical jungle and desert mountain regions for delineation of water bodies and interpretation of geologic linears. Three mosaics, using band 6 images, were constructed of Andean test areas using the UTM coordinate system. Hopefully they will serve as models and provide impetus for local projects to continue a mosaic program.

Field investigations in Bolivia, based on interpretations of linear features of the La Paz mosaic, resulted in the discovery of mineralized fault breccia defined as a lineament in the Totora Formation of Tertiary age. This sandstone formation is the host rock of the well-known disseminated copper deposit of Corocoro. The discovery of malachite veinlets surrounding fragments of chalcocite, a major copper-bearing mineral, has led to the development of a detailed sampling program along the lineament, known to extend for 20 km. The Geological Survey of Bolivia (GEOBOL) is now conducting field surveys along this feature.

Interpretation of the Copiapo mosaic has defined major linear features extending north and south of the largest copper producing mines (El Salvador and Portrerillos) of the area suggesting areas where prospecting may be worthwhile. South of Antofagasta de la Sierra, Argentina, three anomalously dark areas suggestive of iron-absorption in the near-infrared region of the spectrum have been identified and should be field inspected for the possibility of iron deposits.

Careful mapping of open areas in largely cloud covered scenes of Magallanes Province, Chile, by Dr. Eduardo Gonzalez of Punta Arenas, Chile, has defined a new Tertiary basin that may be a potential oil source for the Chilean Nacional Petroleum Co. (ENAP).

1.4 Recommendations: Special effort, under the Landsat-2 experiment, should be made to provide complete cloud-free coverage of the South American continent. This will be especially difficult in the Colombian and Ecuadorian Andes and the lake and fiord country of southern Chile and Argentina. When the data base is complete, subsequent data will then make it possible to map changes that take place in these remote areas.

More color composite images and mosaics should be prepared for important resource areas of the continent. Efforts should be made to develop local capabilities in these arts.

Interest in the use of Data Collection Platforms is growing rapidly as South American scientists become aware of their operational capabilities, especially in the fields of hydrology and power generation. Full support should be given to disseminate information on the equipment, techniques and results of DCS data use. We should learn about the limits of the system using existing receiver antenna systems in order to determine where platforms can be used, where additional receivers may be required and which extant tracking stations might be modified to increase the capability of Landsat around the world. A roving platform is being sent to Bolivia, under the auspices of IAGS, to Dr. Brockmann for tests at a minimum of six sites representing different geographic and terrain types throughout the country. If these tests are successful, it is proposed that the roving platform be sent to Chile for additional testing southward down the coast and crest of the Andes.

Additional evaluation of extant data using computer compatible tapes (CCT's) on Image 100 and other interactive computer systems should be undertaken to evaluate the full capabilities of Landsat to provide geologic, land use and hydrologic information by computer processing methods. Dr. Carlos Brockmann, for example, suggests that this method could be especially useful in delineating surface variations in the distribution of various types of evaporites in the salar deposits of the Bolivian Altiplano and the Atacama Desert. Because of high reflectance and lack of contrast, this task is very difficult by optical means.

2.0 Introduction and Program Description

Mineral resources, after food in importance, are basic nonrenewable commodities on which the world population depends for its progress and well being. As population has grown and known reserves of these natural resources are used, it has become increasingly more difficult to search for and find new deposits which can be developed and exploited. Ways that such deposits can be identified are: 1) by developing new tools for exploration, and 2) by looking for extensions of known deposits in well-known areas. Current trends are to extend these searches into the lesser-known regions of the continents and into the seas. One of the areas of the world which still shows great promise for future mineral resource development is the vast continent of South America.

Although mining has been a great source of commercial enterprise in South America for centuries, the introduction of modern geophysical tools has been relatively recent and successful. Airborne aeromagnetic techniques were introduced in Chile, for example, about 1960 and resulted in the discovery of several significant iron deposits. Radar imaging systems were first used in the Darien area of Panama and Colombia in 1968 and led to its extensive use in the Amazon and Orinoco basins of Brazil and Venezuela in the early 1970's. These data are still being evaluated and used operationally, but the total value of their contribution to the economies of the countries involved is still being evaluated and may not be fully appreciated for decades.

The launch of Landsat-1 (formerly called ERTS-1) on July 23, 1972, and the subsequent collection of over 100,000 multispectral images of the Earth's surface has provided the world scientific community with a new tool enabling small-scale, systematic and repetitive observation of natural and manmade phenomena over large areas. The unique data, representing four bands of the visible and near-infrared spectrum, can be provided in film or paper format at scales ranging from 1:3,369,000 to 1:250,000 or on computer compatible tapes which, when processed, can be used at scales as large as 1:25,000 in digital output form. Each picture element (pixel) covers approximately .4 hectare on the ground and provides an accurate record of reflectance of the Earth's surface at approximately 09:30 on the day of overflight. These observations can be repeated every 18 days, assuming no cloud cover. Relatively constant sun angle is obtained in equatorial regions but seasonal variations provide significant changes in surface textures and tones in temperate and polar regions. Where overlap of adjacent images is sufficient, the area common to both may be viewed in stereographic form.

At the time experiment proposals were submitted to NASA, prior to the launch of Landsat-1, it was uncertain how many South American geologists were sufficiently aware of the proposed satellite or whether they would know how to go about participating in this world-wide scientific experiment. Because of the author's long standing interest in the geology and ore deposits of South America, this experiment was designed to make Landsat data available to each national geological mapping agency that had expressed or would, in my estimation, express sufficient interest in working with the data.

Letters of endorsement of the proposal were requested from the geological agencies of each country and submitted to NASA. The areas selected for study were selected primarily by the author, in some cases, after consultation with various local participants.

Landsat data, requested from NASA for each of the proposed areas, were received by the principal investigator and redistributed to the participants. Interpretive results and ideas developed during the interpretation process were exchanged largely by mail or by personal contact at meetings and lectures in the countries involved. Training courses conducted at Ft. Clayton, Canal Zone, by the Inter American Geodetic Survey under the sponsorship of the EROS Program and once by USAID also served as a medium of exchange. It can be stated that this form of scientific exchange, while not a substitute for classroom teaching or shoulder-to-shoulder field and laboratory work, can be very useful in furthering the technological development of geologic agencies in Latin America.

The project began in January 1973 when data was first received from NASA and theoretically ended with the failure of the Landsat-1 tape recorder in the spring of 1974. This failure prohibited the taking of data over South America except through the Brazilian reception station at Cuiaba.

Interpretation and manipulation of the data into mosaic format, however, will continue after completion of this report because it is very clear much more can be done with the data that has not yet been explored. For example, a number of new interpretation devices such as the Image 100, have been developed which employ the use of computer compatible tapes (CCT's). Use of CCT's and the LARSYS Computer Programs of Purdue University and other computer techniques should be tested more adequately for their potential applications to geological problems. Other automated or optical enhancement techniques must be tested as the state-of-the-art develops.

3.0 Acknowledgments

The author (principal investigator) wishes to take this opportunity to thank his foreign counterparts for their participation in this experimental project. They are listed individually by country and agency below. Contributions of various kinds were also made by my colleagues, Kenneth Segerstrom, George Stoertz, and George Ericksen and are identified in the report and references where appropriate. Of special help were Stuart Marsh and William Kowalik, graduate student assistants who worked with me during the summers of 1973 and 1974, respectively. The Kowalik contributions are included in the report although they have not yet been evaluated in-country by our counterparts. Copies of this report will be distributed to them for comment simultaneously with distribution to NASA.

<u>List of Counterpart Investigators:</u>

Argentina	Dr. Eduardo Methol, Secc. de Fotogeologia	Buenos Aires
Bolivia	Dr. Carlos Brockmann, GEOBOL	La Paz
Brazil	Berilo Langer, Projeto RADAM	Rio de Janeiro
Chile	Dr. Jose Corvalan, Inst. de Investigaciones Geologicas Jaoquin Sanchez Gabriel Perez Agustin Gutierrez	Santiago
	Dr. Eduardo Gonzalez, ENAP	Punta Arenas
Colombia	Ing. Taissir Kassem, INGEOMINAS	Bogota
Peru	Dr. Jose Pomalaza, Instituto Geofisico Dr. Jose Lizarraga, ONERN	Lima
Venezuela	Ing. Luis A. Gonzalez S., Secc. de Geologia Min. de Minas y Hidrocarburos	Caracas

4.0 Scientific Objectives of this Investigation

The objectives of this investigation were:

4.1 To evaluate the applications of Landsat-1 data in improving knowledge of the geology and structural relationships to mineral resources in selected areas of the Andes and other key areas of South America.

4.2 To develop a cadre of South American geologists experienced in the use of Landsat-1 data in the countries selected for study.

4.3 To develop demonstration models of interpretive materials that can be used as standards, or develop points of departure from which uniform interpretive mapping standards can be established.

4.4 Compare seasonal variations of images and identify the significance of the variants.

4.5 Long range goal: Construct orthoimage mosaics of South America and develop interpretive overlays that will serve as a guide to future work and contribute to revision of the Tectonic Map and Metallogenic Map of South America.

5.0 Methods and Approach

Twelve areas of the Andes and the Guyana and Brazilian Shields known to be producers of mineral resources or holding high promise for resource discovery were selected for study (Fig. 1). Each area covers four degrees of latitude by six degrees of longitude (major units of the UTM coordinate system) or approximately 276,000 square kilometers.

Data in the form of 9 x 9 inch positive transparencies (3 sets) and 70 mm positive transparencies (1 set) were sent to the author by the NASA Data Processing Facility (NDPF). Of these, 1 set of 9 x 9 and 70 mm transparencies were retained for the use of the author, 1 set of 9 x 9's was sent to the in-country cooperating investigator and 1 set was sent to U. S. collaborators. Data was received for all areas except 5, 6 and 8 in Brazil which were dropped from the project due to agreements made between NASA and the Brazilian Space Agency (INPE). As was expected, data for areas 1-4 in the equatorial region and area 12 in the Magallanes areas of southern Chile were largely cloud covered (see Inventory, Part 13.0). Areas 7 (La Paz) was the first area to have sufficient cloud free data to construct a preliminary orthoimage mosaic. Areas 9 (Copiapo), 10 (Tucuman) and 11 (Mendoza-Santiago) followed.

Each of the investigators conducted their studies independently and sent their products and evaluations to the author (principal investigator). During the course of the experiment there was much

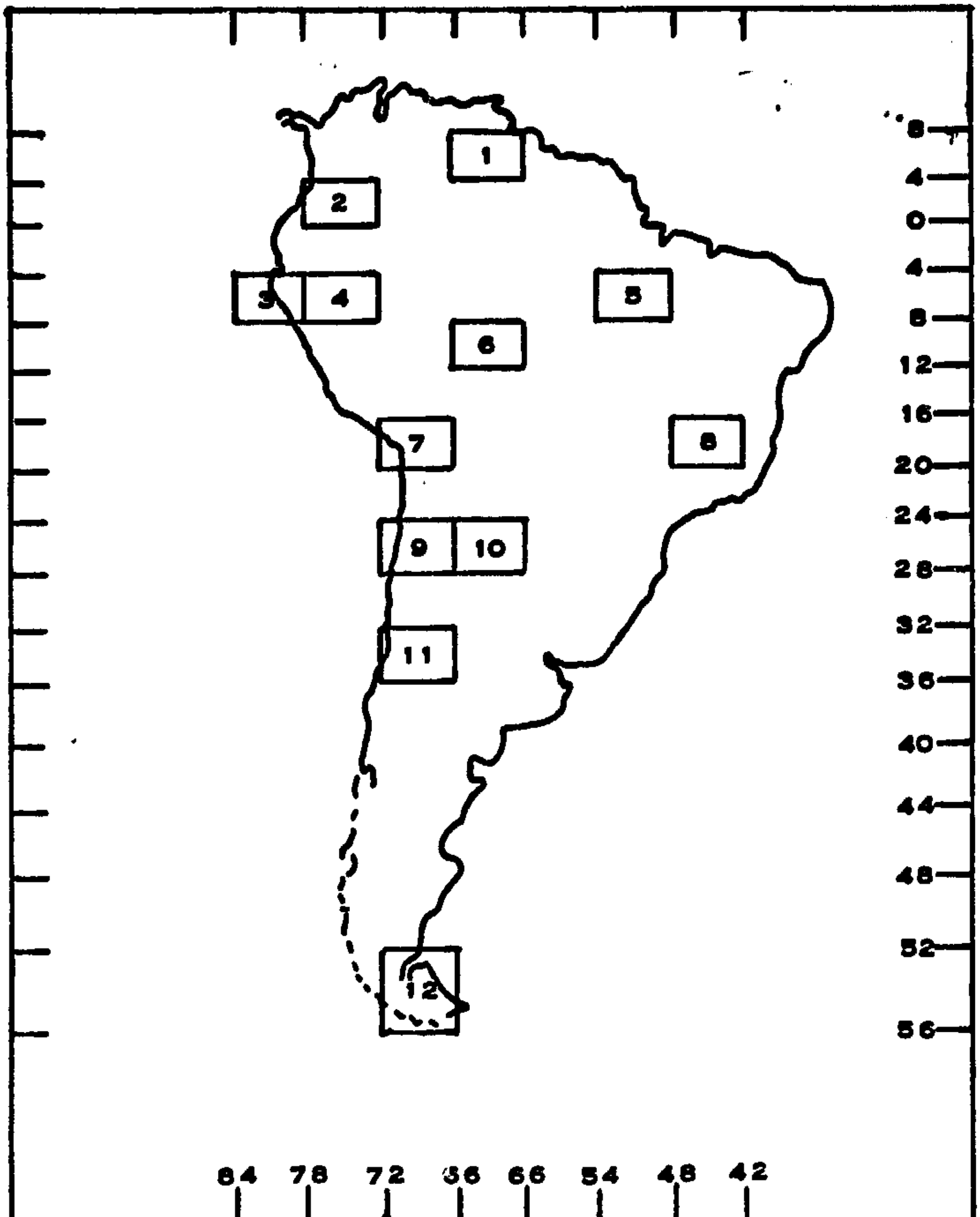


Fig. 1. Index map of South America showing areas selected for study, 1) Guyana Shield, Venezuela; 2) South Central Colombia; 3,4) Northern Peru; 5) Araqua, Brazil; 6) Porto Velho, Brazil; 7) La Paz, Bolivia, Chile, Peru; 8) Belo Horizonte, Brazil; 9) Copiapo, Chile; 10) Tucuman, Argentina; 11) Santiago, Chile - Mendoza, Argentina; 12) Magallanes, Chile, Argentina

interchange by mail and on several occasions the author was able to visit in-country investigators as part of official business trips in conjunction with attendance at international meetings in which remote sensing was discussed. Training courses offered by the Inter American Geodetic Survey (IAGS), in the Canal Zone, supported by EROS and USAID, and in which the author participated, served also as a medium of information exchange and demonstration. On occasions some of the in-country collaborators visited the U. S. for conferences. While this type of interchange does not substitute for day-to-day contact, this development approach was satisfactory in most cases, because most of the participating geologists were already trained in standard photointerpretation techniques.

The main purpose of the experiment was to determine the value of Landsat images and the various spectral bands in mapping lineaments (faults, fractures) and other structures (strike of regionally outcropping strata, folds) that might be significant in the occurrence of mineral deposits. Lineaments are here defined as alignments of straight courses of rivers and streams, depressions, cliffs and ridges, or surface tone variations. The term linear feature here includes both lineaments, regional lines of strike, and spurious artificial and cultural features (Gold, et al, 1974). At the 1:1,000,000 scale it was determined that all linear features 10 km or more in length which are not obviously of cultural origin would be mapped. Other surface features such as unusual rock types (e.g., light toned extrusive or intrusive rocks) or forms (e.g., volcanic cones or craters) were also noted because of their general association with deposits of economic value and their importance in the structural and tectonic history of the Andes.

Overlaps of individual scenes and mosaics were compared with existing maps (U. S. Air Force Operational Navigational Charts) of the various countries to determine their relative accuracy. Great variations were found. For example, Stoertz and Carter (1973) found that salar deposits of the Andes were poorly located or inaccurately portrayed on the Operational Navigation Charts. Some volcanoes were either not shown or mislocated. On the other hand, major lineaments in southern Peru corresponded precisely with major mineralized fault zones cutting the Peruvian mineral belt as shown on the Metallogenic Map of Peru (1:1,000,000) (Carter, 1974a).

6.0 Instrumentation

Geologic interpretation of single images and, later, mosaics was conducted by standard photointerpretation techniques using light table and enlargement lenses as the principal instruments. Color composites made by General Electric Company's Space Division Photographic Engineering Laboratory, Cromaline dye composites made by the USGS Special Mapping Center, and diazochrome diapositives were made in our own analysis laboratory and evaluated as interpretation aids. An I^2S (International Imaging Systems) color additive viewer and Spatial Data Density Analyzer were also tested. A digitizer and IBM-360-65 were used for some areas to analyze the orientation versus length and frequency distribution of linear features using computer programs developed at the Pennsylvania State University and the NASA Goddard Space Flight Center (GSFC) (See discussion of Area 1, p. 16). Samples of these products are included in this report.

7.0 Products and Evaluation

Area 1 - Venezuela

The area lies between 4 and 8 degrees North latitude and 60 and 66 degrees West longitude, covering southeastern Venezuela, western Guyana and a small portion of the upper Rio Branco basin of northern Brazil. The east-west trending Sierra Pacaraima forms a natural barrier on the south and most of the rivers in the area drain to the north or west into the Orinoco.

The area was chosen because a large part of it lies in the State of Bolivar and the Amazonas Territory of Venezuela, a large, relatively unexplored region of great interest to the Venezuelan government for future exploration and development. Part of the area was recently surveyed by a side-looking airborne radar imaging system and is currently the subject of intensive study. It was believed that our study would support these on-going efforts and that they, in turn, would provide a basis for evaluating our work.

The area is underlain by the Guyana Shield and the eastward trending northern Andes lie along the coast to the north. It has been extensively explored in the north and the highly productive Cerro Bolivar iron deposits are a result of that exploration. Manganese, aluminum, titanium and tungsten also occur in this area. In the south, which is sparsely settled and poorly developed, prospectors have reported the occurrence of precious (gold, diamonds) and semi-precious minerals.

Paved and unpaved roads extend from the Orinoco Valley on the north to the south in the eastern part of the area. Access to the rest of the area is largely by bush plane and helicopter or river boats and canoes. Rainfall ranges from 1400-4000 mm or greater per year in the region, and the climate is typical of the tropical rain forest regions of the world. Some of the higher elevations, however, are more temperate.

Our first work with Landsat-1 data was the study of individual images that were relatively cloud free. Image 1174-14091 (Fig. 2) of the Rio Ventuari region in the southwest part of the area clearly indicated that band 7 images were most useful in defining the drainage system and identifying linear features and rock types in this tropical region. Color composite images made by the diazochrome process helped identify cleared and burned areas relating to indigenous communities and distinguished them from open natural savannahs in the jungle. Figure 3 is a drainage overlay of the area, and Figure 4 is an interpretation of lineaments within the Rio Ventuari area.

On conclusion of the data collection phase, it was found that 5 images were sufficiently cloud free for analysis; 3 were fair, and 6 were poor for mosaicking purposes. No data were available for a small area in the northwest and a larger area in the northeast, and therefore construction of a formal mosaic was not undertaken. A preliminary mosaic (Figure 5) of adjacent prints was used to make overlay maps of drainage, general rock types, and linear features.

Figure 2. Landsat-1 image (1174-14091-7) of the Rio Ventuari area of the Amazonas Territory, Venezuela. Areas burned for clearing at A, Precambrian sedimentary strata at B, massive metasedimentary (gneiss?) or intrusive igneous rock outcropping at C. A few of the well expressed lineaments in the area are marked by arrows at each end.

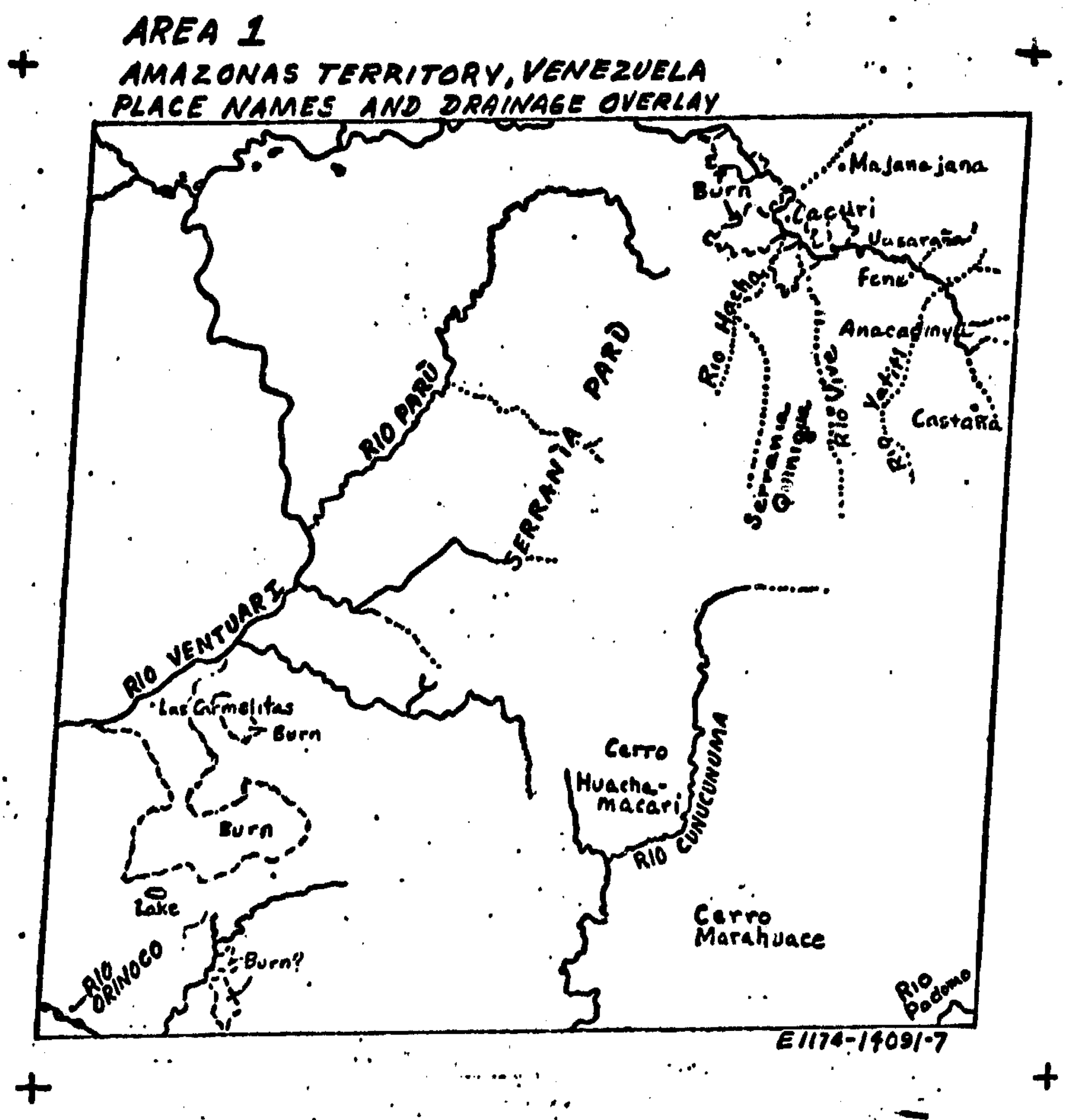
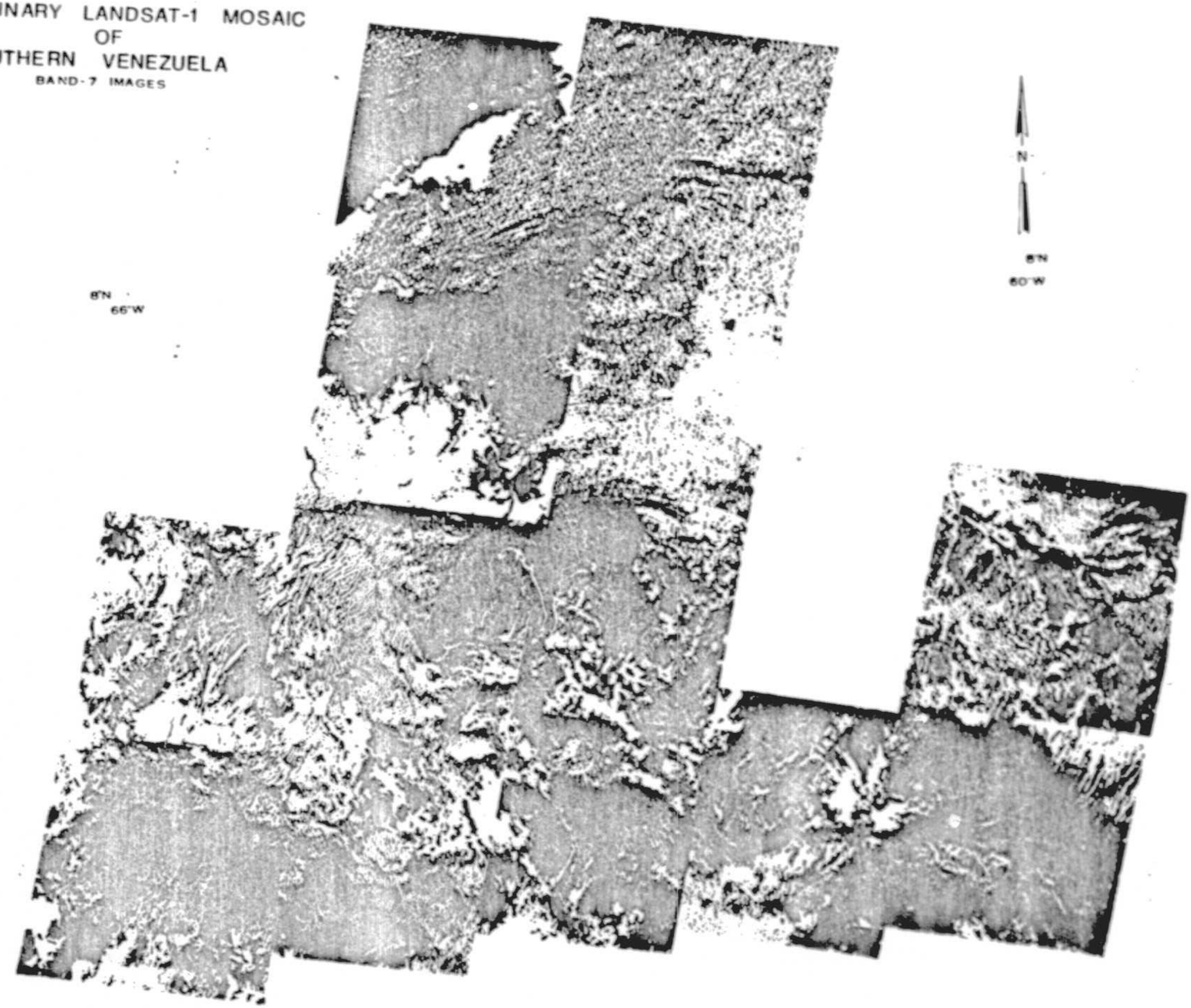


Figure 3. Drainage overlay of Rio Ventuari area, Venezuela. This area is also covered by the southwesternmost section of Figures 5, 6, 7, and 11.

Figure 4. Lineament interpretation by W.D. Carter of Rio Ventuari area.

PRELIMINARY LANDSAT-1 MOSAIC
OF
SOUTHERN VENEZUELA
BAND-7 IMAGES



Surface Water Overlay: The surface water overlay of Area 1 (Figure 6) shows that a rectangular drainage pattern with general NW and NE trends predominates on a regional scale with local deviations where strongly affected by structure. For example, sharp bends in streams occur frequently and many streams follow anomalous courses (e.g., the Mazaruni River on the eastern side of the area and the Rio Paragua near the center; see Figure 6 at points A and B). Comparison of the drainage with that shown on the Operational Navigation Chart L-27 indicates that serious revision of the published map is in order.

Geology: An interpretive overlay of the geology (Figure 7) was compiled largely from geomorphic study of infrared (band 7) images. Standard diazo color composites were useful in areas where vegetation patterns appear to reflect the underlying geology. Principles used in interpretation of large-scale aerial photographs (Ray, 1960) were applied to the Landsat imagery after considering the effect of viewing terrane at Landsat's much smaller scale.

Six broad photogeologic rock types were identified in this study. Two sedimentary units of Precambrian plateau strata and Precambrian intrusive igneous rocks, extrusive igneous rocks, metamorphic rocks, and Quaternary alluvium were defined. The igneous and metamorphic terranes are identified and separated somewhat tenuously. The sedimentary units and structures are much more easily discerned, and are mapped with confidence. Fold axes and dipping beds in these units are denoted by standard map symbols. Contacts between units defined here are dashed where uncertain.

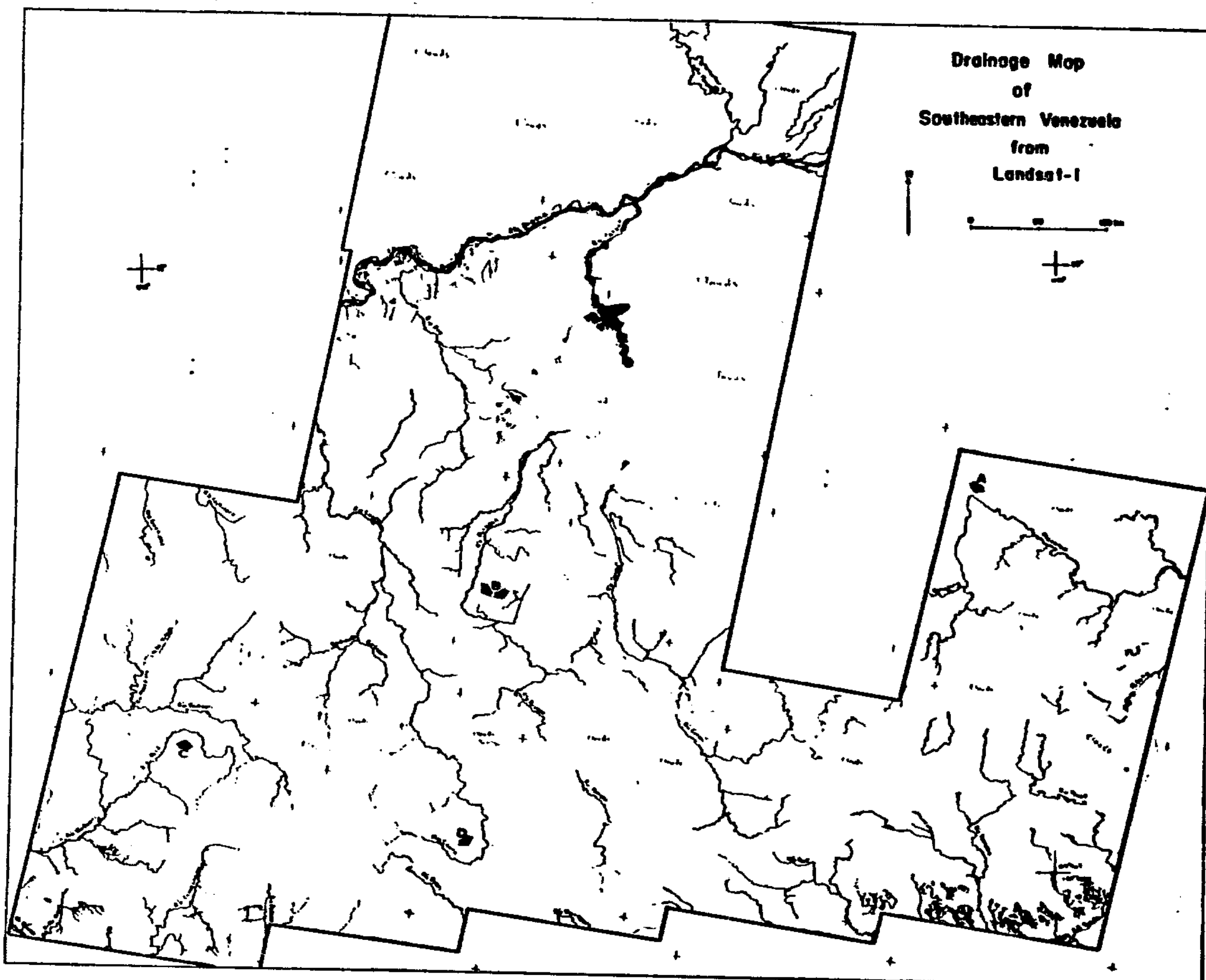


Figure 6. Drainage Map of Southeastern Venezuela from Landsat-1.

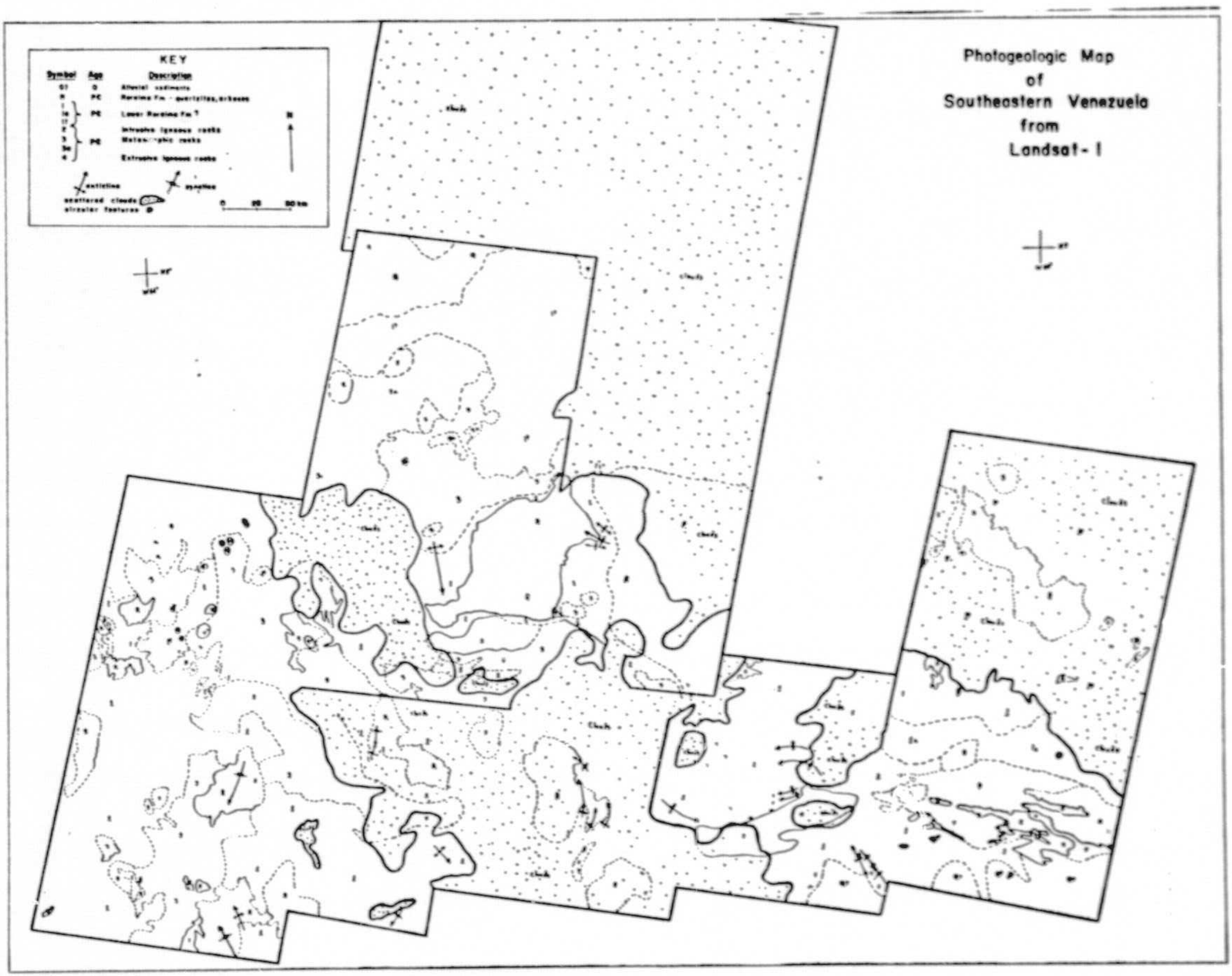


Figure 7 Photogeologic Map of Southeastern Venezuela from Landsat-1.

The Atlas of Venezuela (1969) geologic map (pp. 126-127) (scale 1:3,500,000) and the Geologic Map of South America (scale 1:5,000,000) were used as references for the geologic overlay. The interpreter had no prior field knowledge of the area. The more detailed map in the Atlas of Venezuela separates the area considered here into 8 units: 1) Quaternary, 2) Precambrian Plateau Strata, 3) Precambrian undifferentiated igneous and metamorphic rocks, 4) Precambrian low rank metamorphic rocks, 5) Precambrian high rank metamorphic rocks, 6) Precambrian acidic intrusives, 7) Precambrian basic intrusives, 8) Precambrian acidic extrusives. A large part of the region is mapped as undifferentiated igneous and metamorphic rock (3). This region has been tentatively separated here into igenous and metamorphic units.

The uppermost sedimentary plateau strata are readily mapped due to their topographic expression (Figure 8, areas at A). The plateau strata are Precambrian quartzites and sandy arkoses of the Roraima Formation (unit R). The Roraima Formation forms steep sided plateaus (relief up to 1000 M) with a different vegetation pattern than that of the igneous and metamorphic rocks of the underlying Guyana Shield (Figure 8). Several obvious cliff and bench forming units within the Roraima Formation (Figure 8) were not differentiated here.

A sedimentary unit underlying the main plateau forming strata of photogeologic unit R forms low relief topography compared to the overlying elevated plateaus and represents the lower Roraima Formation. Fold structures are expressed in this unit (photogeologic map symbol 1, see Figure 7) despite the tropical climate and heavy rain forest cover. Seven anticlines and four synclines are defined in unit 1 (e.g., Figure 7 and 8). Ten other broad anticlinal and synclinal warps are identified in

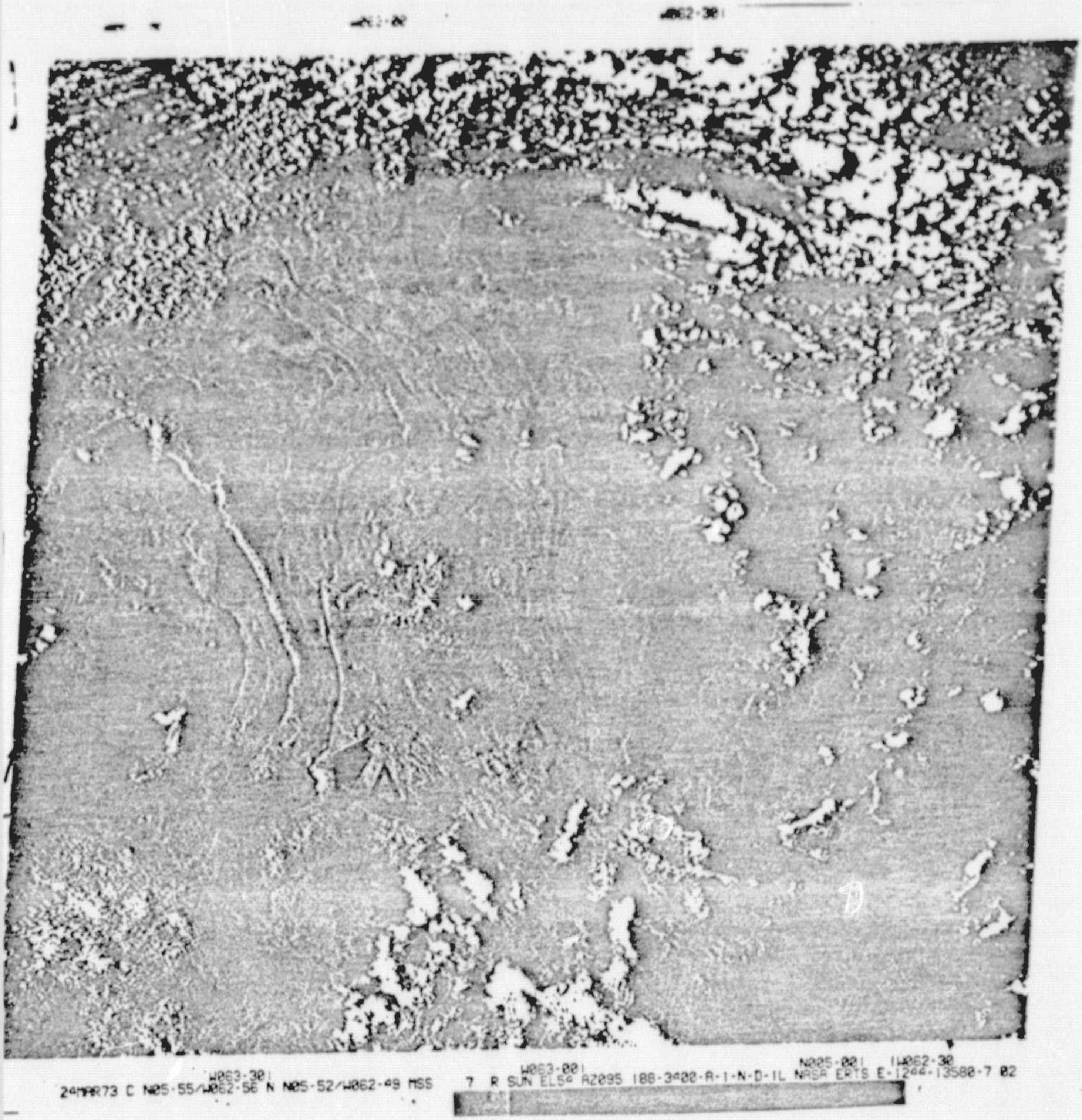


Figure 8. Landsat-1 image (1244-13580-7) covering the areas of Auyan Tepuy and Serrania Pararena in Southeastern Venezuela. Arrows at A point to steep sided plateaus underlain by the resistant quartzites and sandy arkoses of the Precambrian Roraima Formation. Note folds at point B in sedimentary unit 1 between the high plateaus. Several well expressed lineaments, possibly the surface expressions of faults, are marked at each end by arrows.

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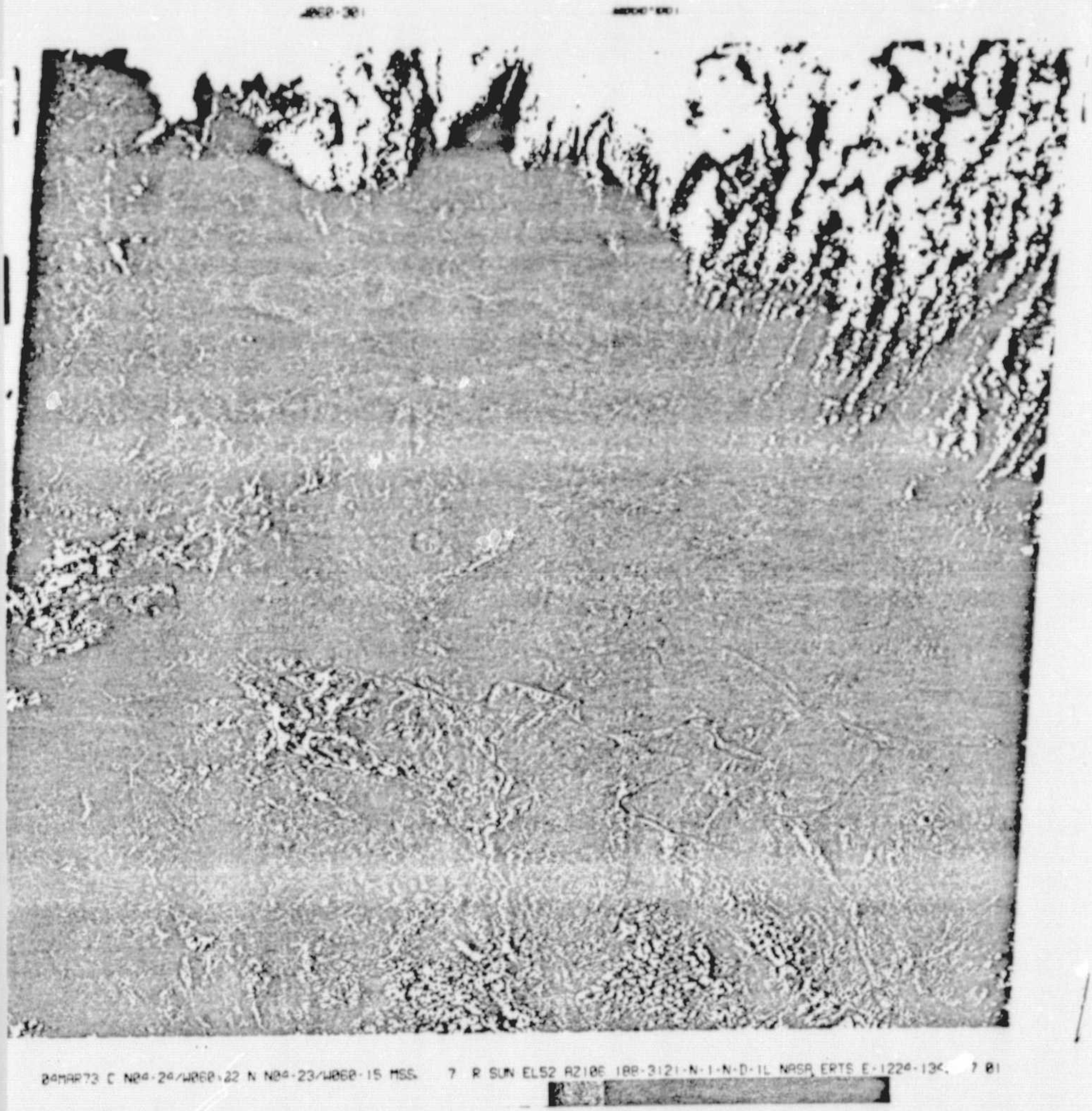

Figure 9. Tilted and dissected strata striking nearly East-West between A-A' are cut by a major left-lateral strike slip fault at the bend in the outcrop belt nearer A'. Intrusive igneous rock outcrops in areas B. Extrusive igneous (volcanic) rock is present at C. Note curvilinear patterns suggestive of flow within area C. Patchy "snakeskin" pattern formed in Quaternary unit at D. A few well expressed lineaments are marked by arrows.

the overlying plateau strata. None of these structures appear on the geologic or tectonic maps of Venezuela (Atlas of Venezuela, 1969, pp. 124-127). The stream pattern further suggests the presence of broad fold structures (e.g., the Rios Paru and Caura at C and D in Figure 6).

Two subtypes of unit 1 have been differentiated (unit 1? and unit 1a). Unit 1? designates areas of even tone and low relief largely underlying scattered clouds on the imagery. The unit 1a subtype (Figure 9, between points A-A) appears to be tilted and dissected rocks oriented with the major fold axis trending nearly East-West. A fault with about 4 km of left lateral displacement appears to cut these strata (Figure 9 near A).

Unit 2 denotes probable areas of intrusive igneous rocks as defined by coarse drainage, greater relief, and rounded geomorphic forms (Figure 9, area B).

Areas of probable metamorphic rocks (Unit 3) are marked by the absence of rounded mountain forms and lack of a dense intersecting lineament pattern. A prominent single direction of linear features, possibly foliation is taken to suggest metamorphic rocks (Figure 10, point A). Unit 3A is a subtype of metamorphic rock showing higher relief than the remainder of Unit 3, and according to the Atlas of Venezuela (pp. 26-27) it is an area of granulite facies of metamorphic rock.

Unit 4 defines areas of probable volcanic extrusive rock. An area is defined on scene 1174-14084 (Figure 10, area B). Neither geologic map shows the presence of such volcanic rock in the area so the identification as volcanic is questionable. Several circular features of unknown origin 5-10 km in diameter are marked on the photogeologic map (Figure 7) by a circle with a 'v?' inside. Several of these circular features occur in this questioned area of volcanic rock (Figure 10 near points C). Unit 4 volcanic rocks have also been mapped in scene 1224-13465 (Deposito, Figure 9). The central zone of this area has a flow texture with curvilinear patterns of minor linear features within it (Figure 9, points C). The published geologic maps support the interpretation of the area as extrusive volcanic terrane.

Probable Quaternary deposits (Unit Q?) have low relief and occur in low lying areas with a patchy "snakeskin" pattern of vegetated areas interspersed with clear areas suggesting an interlocking network of braided stream channels (Figure 9, points D).

The relative stratigraphic position or age of the photogeologic units from youngest to oldest is as follows: (Q?), (R), (1, 1a, 1?), (2, 3, 3a, 4). Units included within the same set of parentheses have not been distinguished by age.

The value of these geologic observations in Area 1 has not yet been analyzed by our Venezuelan counterpart geologists. Copies of this report will be sent to Venezuela for evaluation.

Lineaments: A total of 2220 linear features greater than 10 km and averaging 17.8 km in length were identified in Area 1 (Figure 11). Several of the many well-expressed lineaments in the area are marked by arrows on Figures 8, 9, and 10. The well-expressed lineaments may be faults, none of which appear on the tectonic or geologic maps in the Atlas of Venezuela (1969).

The end points of the linear features of Figure 11 were digitized and recorded on magnetic tape and subsequently punched on computer cards. An IBM 360-65 was used with Fortran IV programs Transform and Azmap developed by Podwysocki (Podwysocki and Lowman, 1974) to summarize the

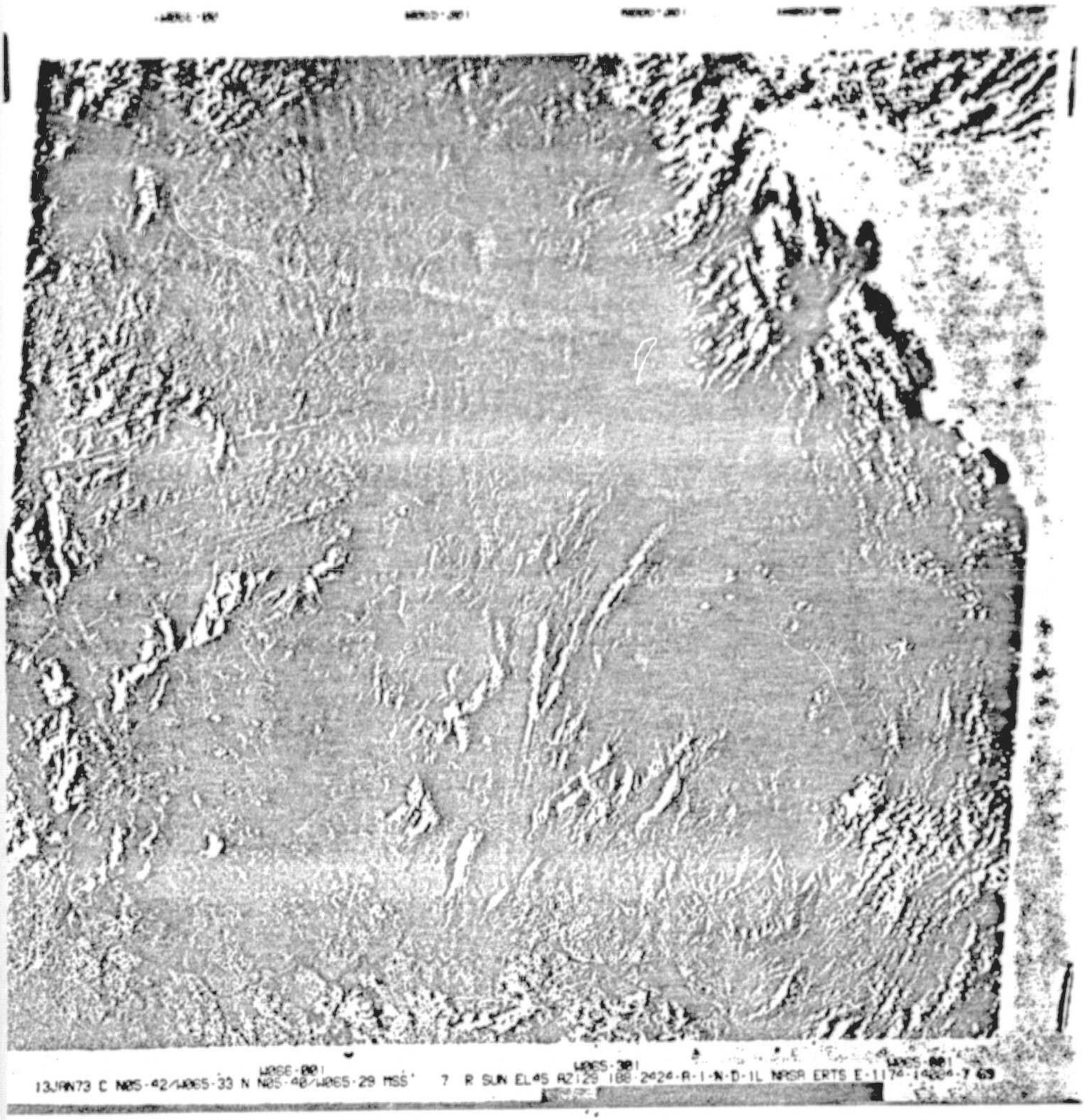

Figure 10. Landsat-1 image (1174-14084-7) covering the Maigualida Mountains. Possible metamorphic terrane at A, possible volcanic terrane at B, and circular features at C. Note several well expressed lineaments marked by arrows.

Figure 12 Lineament Map of Southeastern Venezuela from Landsat-1.

data. These programs permit easy manipulation of the data and print histograms of lineament length and frequency versus orientation. Figure 12 outlines the program flow chart.

Figure 13 presents the length and frequency orientation histograms of the lineaments interpreted in Area 1. Minor peaks occur at N15E, N60-80E, and N53W. Many other peaks of nearly similar height are present indicating a complex overall pattern.

A distinct trough between N65-75W corresponds well with the N70W average sun azimuth over the region. Lineaments appear to be effectively masked parallel and within about 5 degrees of the sun azimuth despite the relatively large sun elevation angles (40-50 degrees). Scan lines trending N80W may have introduced false lineaments parallel to that direction as major troughs exist on either side of that direction (Figure 13).

Similar histograms were prepared for each 1 x 1 degree sector within the area. These histograms indicated that preferred orientations are present within sectors which are masked when the area is considered as a whole. For example, the sector of Cerro Bolivar shows that the longest and most numerous lineaments trend N60-70E, with a second peak at N20-25W. South of the Serra Pacaraima in the headwaters of the Rio Branco, Brazil, the dominant trends and frequencies are N75-85E and N10-15W. These orientations suggest the presence of a pattern of lineament sets nearly at right angles. Further analysis of these lineament patterns is planned.

A comparative time study was undertaken to evaluate hand measuring vs. machine aided digitization of lineament data. It was found that about 20 hrs. were required to complete the overlay by manual measuring

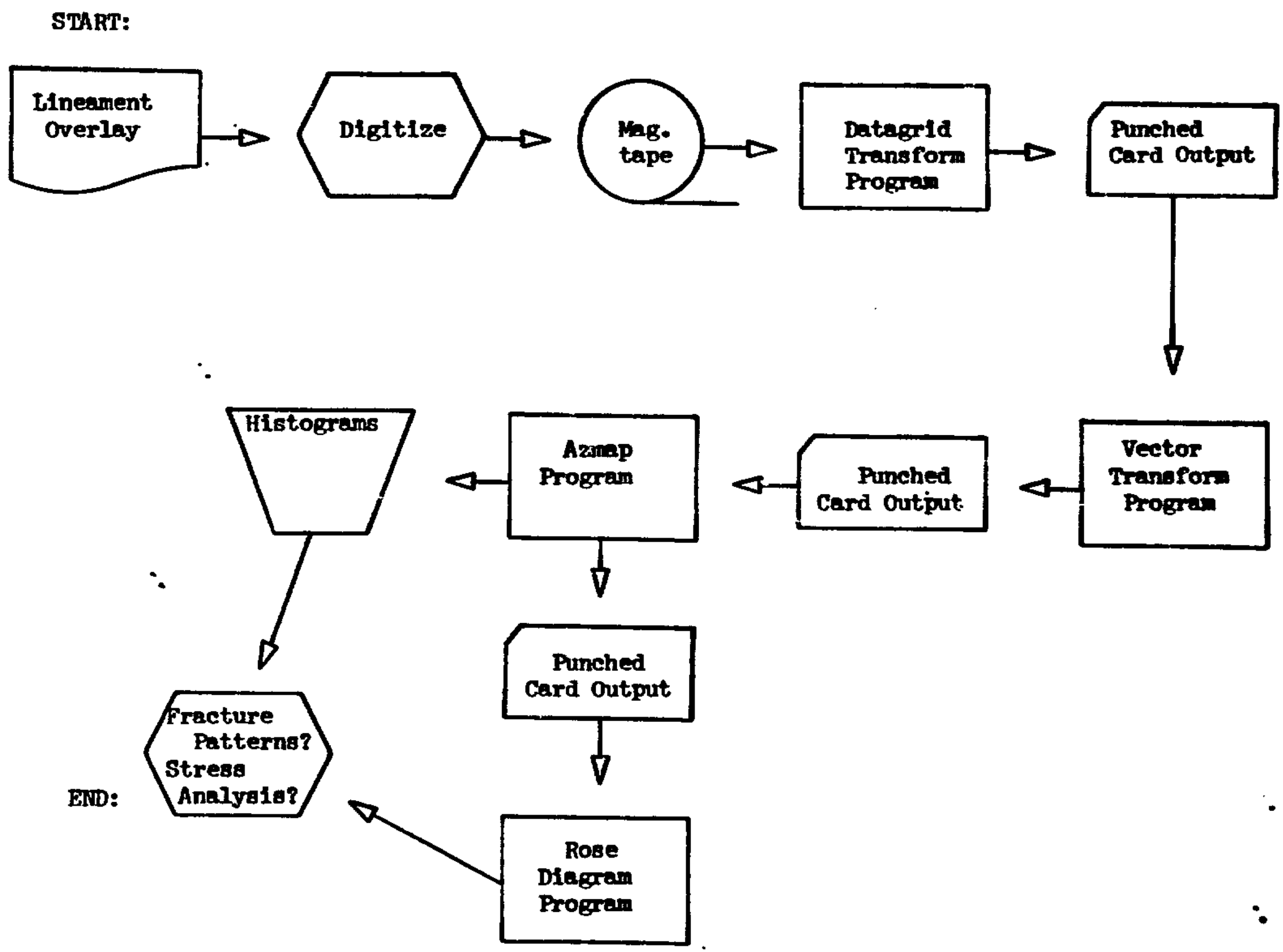

Figure 12. Program Flow Chart for Analysis of Lineament Orientations

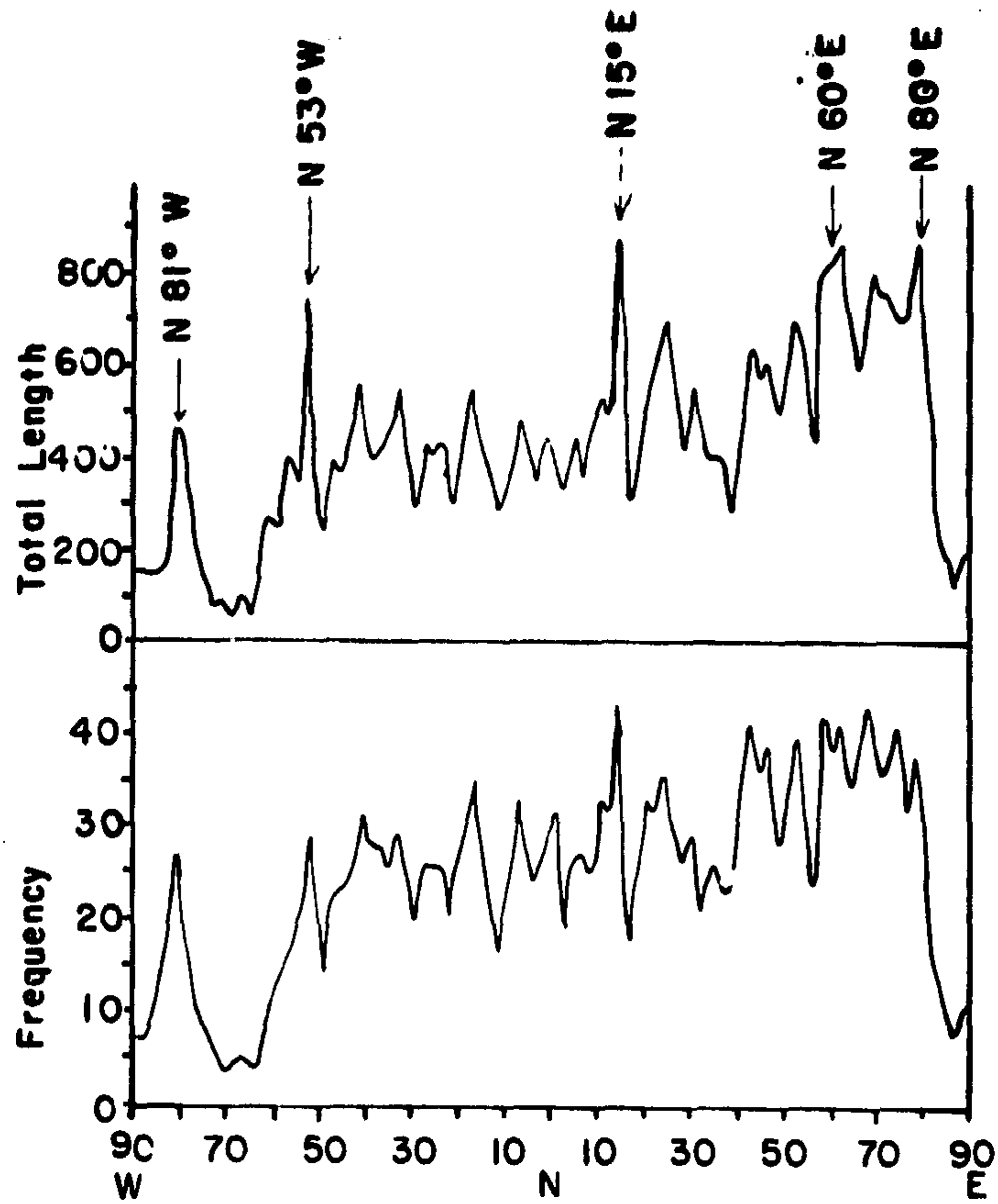

Figure 13. Orientations of lineaments summarized by total length and frequency into 2 degree wide classes. Lineaments are those of Area 1 (Figure 11). Summarization of orientations of lineaments within small blocks of the entire area indicates that preferred directions are locally present which are masked in this whole area summary (see text).

and recording (about 107 lineaments/hr.) whereas the same 2100 lineaments were digitized in four hours. The machine aided digitizing was five times faster and produced data in a much more flexible form. Subsequent use of the computer programs on the digitized data provide rapid and varied means of summarizing the lineament orientations.

Area 2 - Colombia

This area lies between the Equator and lat. 4° N. and long. 72° and 78° W. and is one of the most difficult areas in the world to photograph. Only ten images were acquired over the area between January and March 1973, and of these seven had 50% cloud cover or more. The best image, 1196-14325, of the Rio Guaviare area, about 270 km southeast of Bogota, has only 5% cloud cover and was considered adequate for color compositing by the cromaline dye process (Figure 14). The work was done by Alden Warren of the USGS Special Mapping Center.

This image covers the eastern foothills and plains of the Andes in the Rio Guaviare Basin, a western tributary to the Orinoco River. The towns of Puerto La Concordia and San Jose del Guaviare can be seen in the lower left at the junction of the Ariari with the Guaviare. Highland plains have been cleared for cattle raising in the west, where gray-toned burn scars are numerous. These burns probably represent recent clearings for planting and grazing. Bluish smoke plumes indicate that some areas may be actively burning. On the east, the continuous red areas show that tropical vegetation provides a uniform surface cover over much of the area.

The Carte Geologique de L'Ameriqué du Sud shows that the area has not been mapped in detail. The area is almost entirely underlain by undifferentiated Cenozoic rocks. A small outlier of Cretaceous and

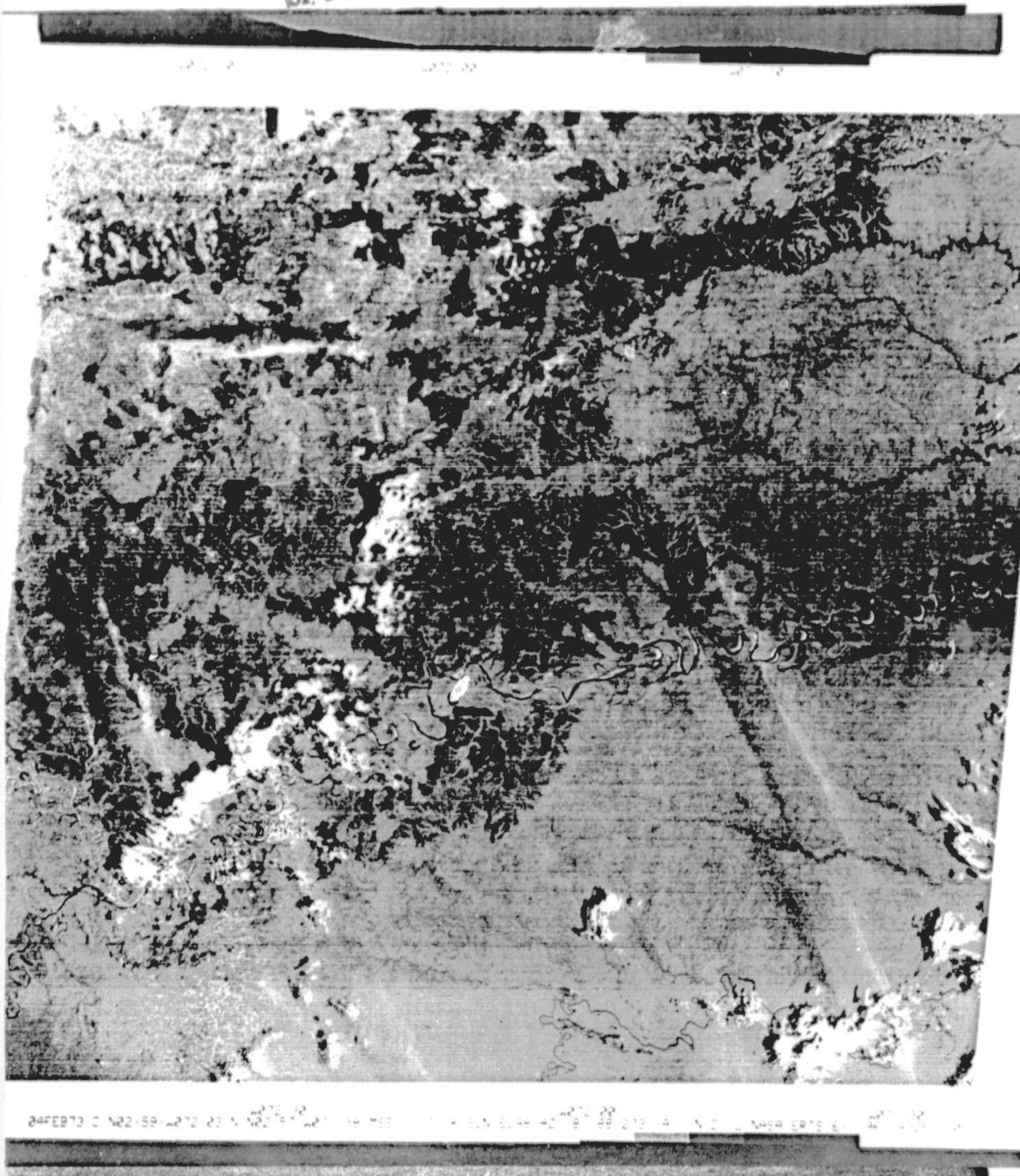

Figure 14. Color composite image of the Rio Guaviare area, Colombia, made by the cromaline dye process and reproduced by color Xerox. (E1196-14325)

Precambrian rocks is shown just south of San Jose del Guaviari, extending in a southeasterly direction. Part of it may be exposed in the scene underlying the gray-toned red vegetation in the lower left corner of the image.

The meandering pattern of the rivers in the scene indicates that the total surface of the area is generally flat (Figure 14). The dendritic pattern of vegetation displayed along the eastern margin of the cleared areas indicates that the cleared areas may be a highland plain of terrace.

The few linear features mapped are mainly relatively straight stream courses. They trend N35-65°E and S45-75°E. The two offset, northwest trending linear features in the lower right appear to be shadows of thin vapor trails left by aircraft.

Little else was done in this area because of the lack of adequate data. Two other images of fair to good quality (1196-14332 Miraflores, and 1179-14382 Calamar) will be analyzed in the future under the Landsat-2 follow-on experiment.

Area 3 - Sechura Desert and North Central Peru

The area, comprising two contiguous 4 x 6 degree quadrangles, lies between lat. 4-8°S and long. 72-84°W. It comprises a strip across northern Peru that includes the coastal Sechura Desert, the northern Andes and westernmost extent of the Amazon in the vicinity of Iquitos. Most of the area is sparsely settled, remote and less developed. There is, however, great promise of mineral and energy resources in this region. Best known are the extensive phosphate deposits of the Sechura Desert. More recently petroleum deposits have been discovered on the eastern flank of the Andes in the upper Amazon.

Of 12 images acquired for Area 3, seven covered parts of the Pacific Ocean. Of the remaining five images covering land areas, three had cloud cover of less than 50%. Data, therefore, were insufficient for mosaicking of Landsat images in this area. A cursory examination of the best images was made and only one was considered to be of sufficient quality to mention in this report. Image 1237-15043, dated 17 March 1973, known as Bahia de Sechura, (not shown) provides an example of the extreme aridity of the northern Peruvian coast and the general location of phosphate deposits.

Area 4 - Northeast Peru and Westernmost Brazil

Area 4 lies east of Area 3 between lat 4°-8° S. and long 72°-78°W. It covers the eastern flank of the Andes and headwaters of the Amazon Basin. Much of the area is being actively explored for petroleum as well as mineral resources.

Like Area 3, it is difficult to acquire cloud-free data. Eleven images were obtained and, of these, only two had less than 50% cloud cover. Image 1195-14291 of the Iquitos area (not shown) provides a typical example of the terrain that comprises the western Amazon Basin. Because of the lack of data in this area, however, it was decided to concentrate our efforts in other areas.

Area 5 - North Central Brazil (Araguia)

This area lies between lat 4°-8° S. and long 48°-54° W. in northeast Brazil on the south side of the Amazon Basin. It was selected to support the Radam Project of Brazil, a multidisciplinary program to inventory the Amazon Basin by analysis of side-looking airborne radar images. For reasons never explained, data were not received for this area.

Area 6 - West Central Brazil (Porto Velho)

The Porto Velho area lies between lat 8°-12° S. and long 60°-66° W. on the southwestern margin of the Amazon Basin. It was selected, as Area 5, to support and supplement the Radam Project of Brazil. No data, however, was received for this area.

Area 7 - Peru-Chile-Bolivia Border (La Paz)

This area lies between lat 16°-20° S. and long 66°-72° W. and covers southern Peru, northern Chile and western Bolivia from Lago Titicaca on the north to Salar de Uyuni on the south. It was selected for study because it covers one of the major "bends" of the Andes and is famous for its copper, tin and tungsten deposits. It was believed that here there would be a high probability of being able to determine the relationship of lineaments to the distribution of various types of ore deposits.

Because of the relatively arid climate throughout much of the year, 56 images were acquired within or bordering the area. Of these, 22 had cloud cover of 50% or greater and 17 had 10% or less. It was the first area in which sufficient coverage became available to compile a mosaic of Landsat images. The La Paz mosaic (fig. 2, app. A) compiled by the Special Mapping Center of the U. S. Geological Survey's Topographic Division, was produced from 1:1,000,000 scale positive band 6 transparencies and distributed to in-country cooperating investigators for evaluation and interpretation. Band 6 images were chosen because of their near infrared characteristics and because bands 4, 5, and 7 were being used to make diazochrome color composites by the investigators. An accuracy evaluation of the mosaic was made by the USGS Topographic Division which found that north to south measurements of points were within 100 meters of their true location, but that east to west measurements had a maximum error of 1300 meters. On the mosaic, at a scale of 1:1,000,000, this means that some points may be located slightly more than 1 mm east or west of their true position. It is believed, therefore, that the mosaic, laid from the World Aeronautical Chart (ONC-P26) as a base, is reasonably accurate and certainly more detailed than the existing maps of the area.

Linear features on the mosaic were compiled on an overlay map. The interpretation was then compared to interpretations done by cooperating investigators to develop a map of relative confidence of interpretation. Using published and unpublished mineral deposit location maps, the writer then developed a revised metallogenic map as an overlay map. This was supplemented by a seismic hazard map compiled from computerized earthquake epicenter information from the files of the U. S. Geological Survey. These maps and their geological significance are described in the Appendix (Carter, 1974).

A most interesting result of this study is detection of a high concentration of lineaments that bound and define the Chile-Peru porphyry copper belt. The belt ranges from 20-40 km wide and has been traced for 500 km across the La Paz mosaic area. Several linements within the belt correlate well with faults on published maps derived from earlier field work by local geologists. The lineaments and their intersections may serve as guides for future exploration within the belt. The belt is known to extend intermittently to the south at least as far as the El Teniente mine in central Chile and to as far north as central Colombia. The potential for the discovery of new deposits within it is considered high.

Also of significance are the transverse lineaments that cross the Andes in NE and roughly E-W directions. Of these, perhaps the most significant is that which extends from south of Cochabamba, Bolivia, in a westerly direction, through the Desaguadero River Valley, the region of Toquepala and the coast near Punta Yerba Buena between Mollendo and Ilo, a total length of 600 kilometers (Figure 15). Because the Desaguadero River Valley is sharply deflected along the lineament to the east from its generally southeast direction from Lake Titicaca to Lake Poopo, the lineament is referred to as the "Desaguadero Lineament." It is expressed physiographically as straight valleys, stream beds and, in places, as marked changes in surface tone in Quaternary and Recent rocks and soils.

A similar "geotectonic line" known as the Santa Cruz-Arica line was postulated by Pontus Ljunggren (1962) to explain the mineralogic differences in the Bolivian tin belt which occupies the eastern part of the La Paz Mosaic (Carter, 1974). Ljunggren noted that the northern part of the belt was narrow, closely associated with granitic rocks high in elevation and exposed at the surface; and that the mineralogy consisted of a single phase of high temperature minerals. The southern group of deposits, he noted, are more wide spread, associated with granitic rocks that are lower in elevation or not exposed, and consisted of two phases of generally lower temperature minerals. The "Desaguadero lineament" separates these two mineral subprovinces near Ljunggren's "geotectonic line" (Figure 16). Perhaps comparative studies of the mineralogy of the porphyry copper deposits north and south of the Toquepala region will reveal similar differences in mineralogy and temperature of ore genesis.

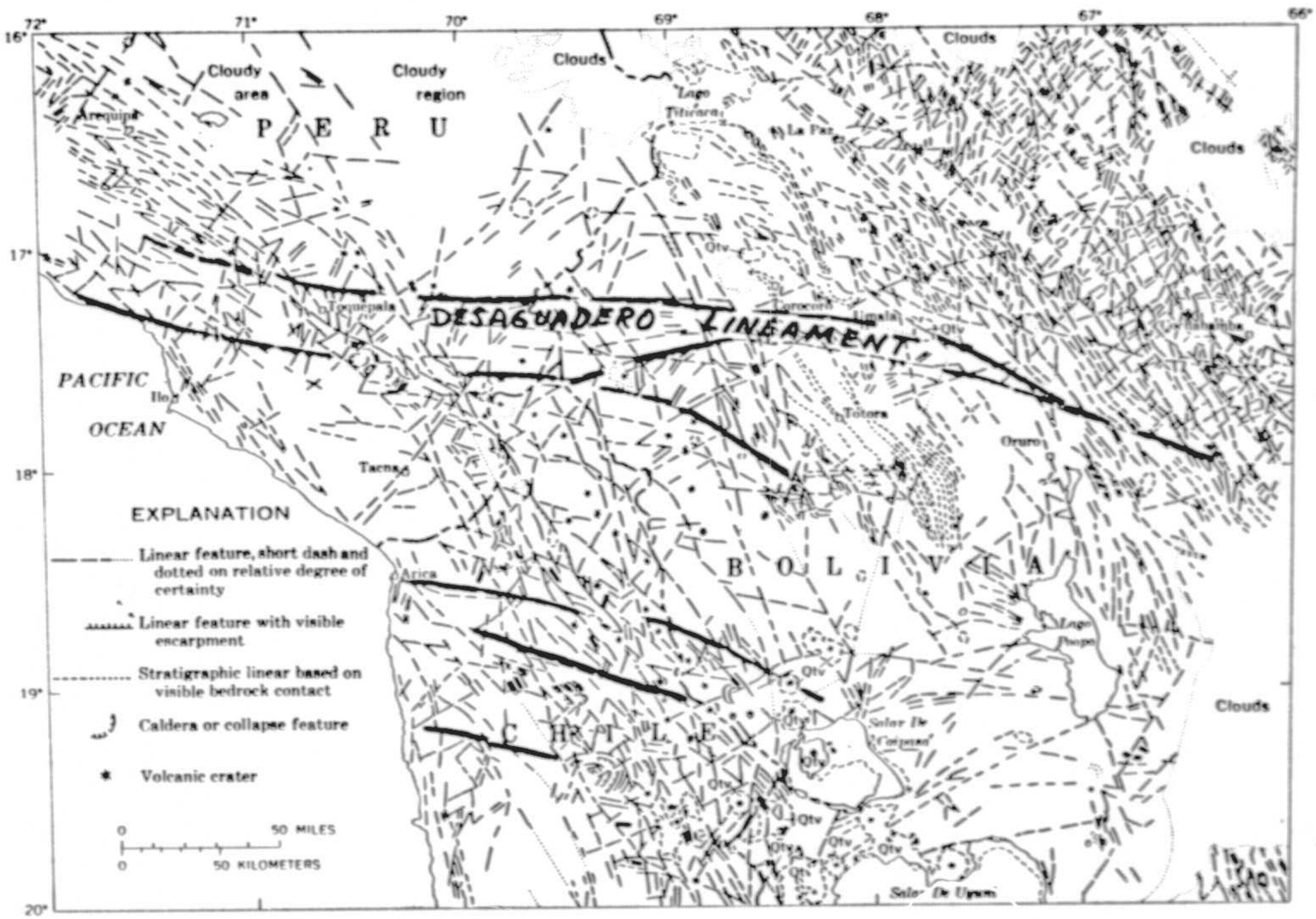

Figure 15. Linear features of the La Paz Mosaic. Short dashes are linear outcrop belts of sedimentary rocks, longer dashes are crosscutting linear features. The Desaguadero lineament is well expressed in the terrain as seen from Landsat.

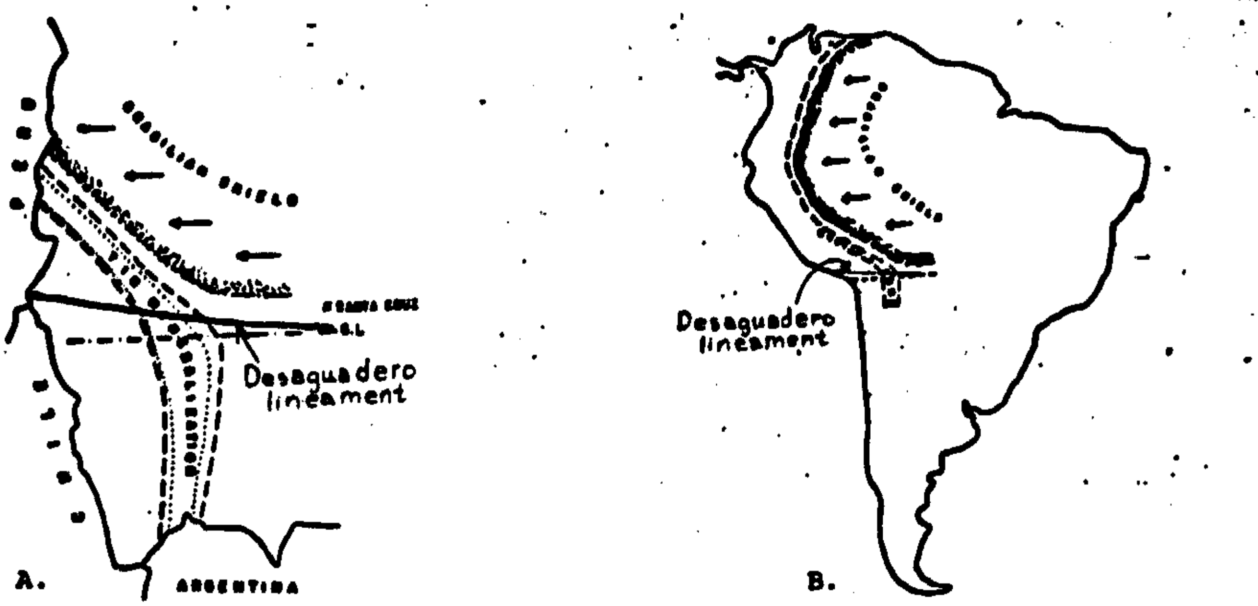

Figure 16. Illustrations from Ljunggren (1962) showing the postulated Santa Cruz-Arica geotectonic line in relation to the Bolivian tin belt and the Brazilian Shield. The location of the Desaguadero lineament is shown in both A and B.

The linear features identified on the La Paz Mosaic are currently being field checked in several areas of Bolivia by the Mineral Resources Division of the Geological Service of Bolivia (GEOBOL). In July 1974, when the writer was visiting their offices, a field geologist had just returned from the Altiplano with samples of fractured reddish-brown sandstone enriched with malachite and chalcocite, two important copper minerals. The bedrock is from the same formation that contains the famous Corocoro disseminated copper deposit. The sample had been found in the trace of a fracture system mapped as a lineament on Landsat-1 data (the La Paz Mosaic) and is known to have an extent of at least 20 km. Although the grade of mineralization is not yet known, a plan for more detailed exploration of the area has been developed and is now underway. Landsat-1 data, therefore, has served as a guide for new exploration that may have economic benefit for Bolivia.

It is hoped that the Landsat-1 mosaic and overlay maps developed in this area and elsewhere in this report will serve as models for continued studies of the Andes and other regions of South America, and that eventually enough relatively cloud-free data will become available for a mosaic of the entire continent at some smaller scale (e.g., 1:5,000,000). Analysis of systems of linear features on a continental basis will likely increase our knowledge of the structural development of the Andes and improve our understanding of plate tectonic theory.

As part of this experiment, the Salar de Coipasa image (1010-14035) (Fig. 17) was reproduced in color by the General Electric Company's Space Division Photographic Engineering Laboratory, Beltsville, Maryland.

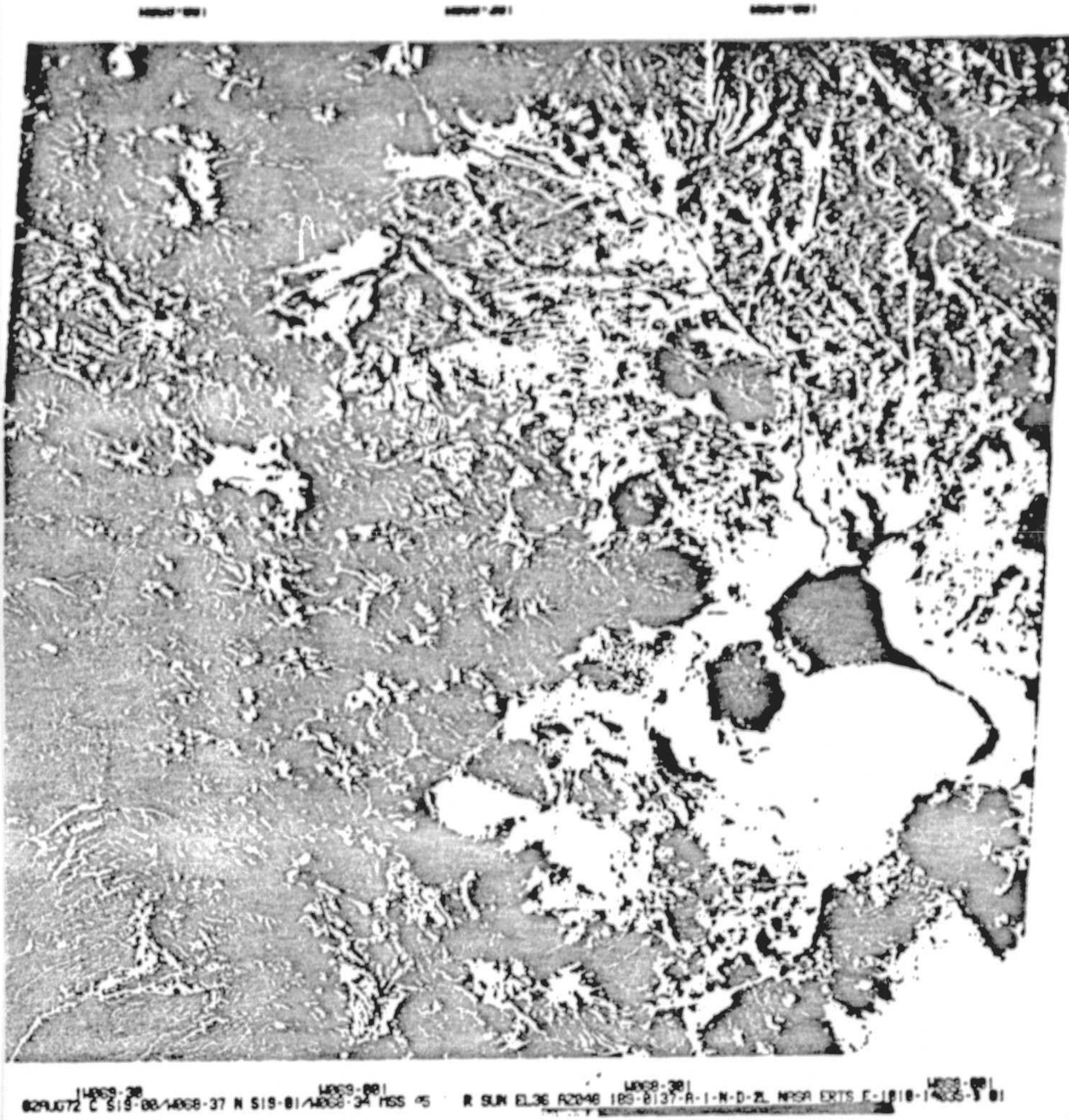

Figure 17. Color composite image of the Salar de Coipasa area, Bolivia, reproduced by color Xerox. (E1010-14035)

It served as a demonstration product for the Bolivian ERTS Project and was used as a basis for comparison with black and white images. It also served as a guide to the color lithographic map, precision processed by GSFC/NDPF and printed by the Bolivian Instituto Geografico Militar with the cooperation of the Topographic Division, U. S. Geological Survey and the Inter American Geodetic Survey. This type of international and interagency cooperation is symbolic of the cooperation that is developing around the world, as Landsat-1 data is evaluated and applied.

Area 8 - Belo Horizonte, Brazil

The Belo Horizonte quadrangle lies between 16°-20° South latitude 42°-48° West longitude and is well known for its production and extensive reserves of itabirite iron ores. It has been extensively mapped by USGS and Brazilian geologists and was selected for study because of the abundance of published detailed geologic information that could provide support to the investigation. Unfortunately, no data was received for this area.

Area 9 - North-central Chile (Taltal-Copiapo)/Area 10 - Tucuman, Argentina

The Copiapo quadrangle lies between 24°-28° South latitude and 66°-72° West longitude in north-central Chile. It is a major mineral producing area in which iron, copper, gold, silver, and mercury have contributed significantly to the country's economy for centuries. The area has been well mapped by Chilean and USGS geologists and published reports are available. Notable among these are the detailed quadrangle maps of Kenneth Segerstrom of the U. S. Geological Survey, published in Chile by the Instituto de Investigaciones Geologicas. The area was

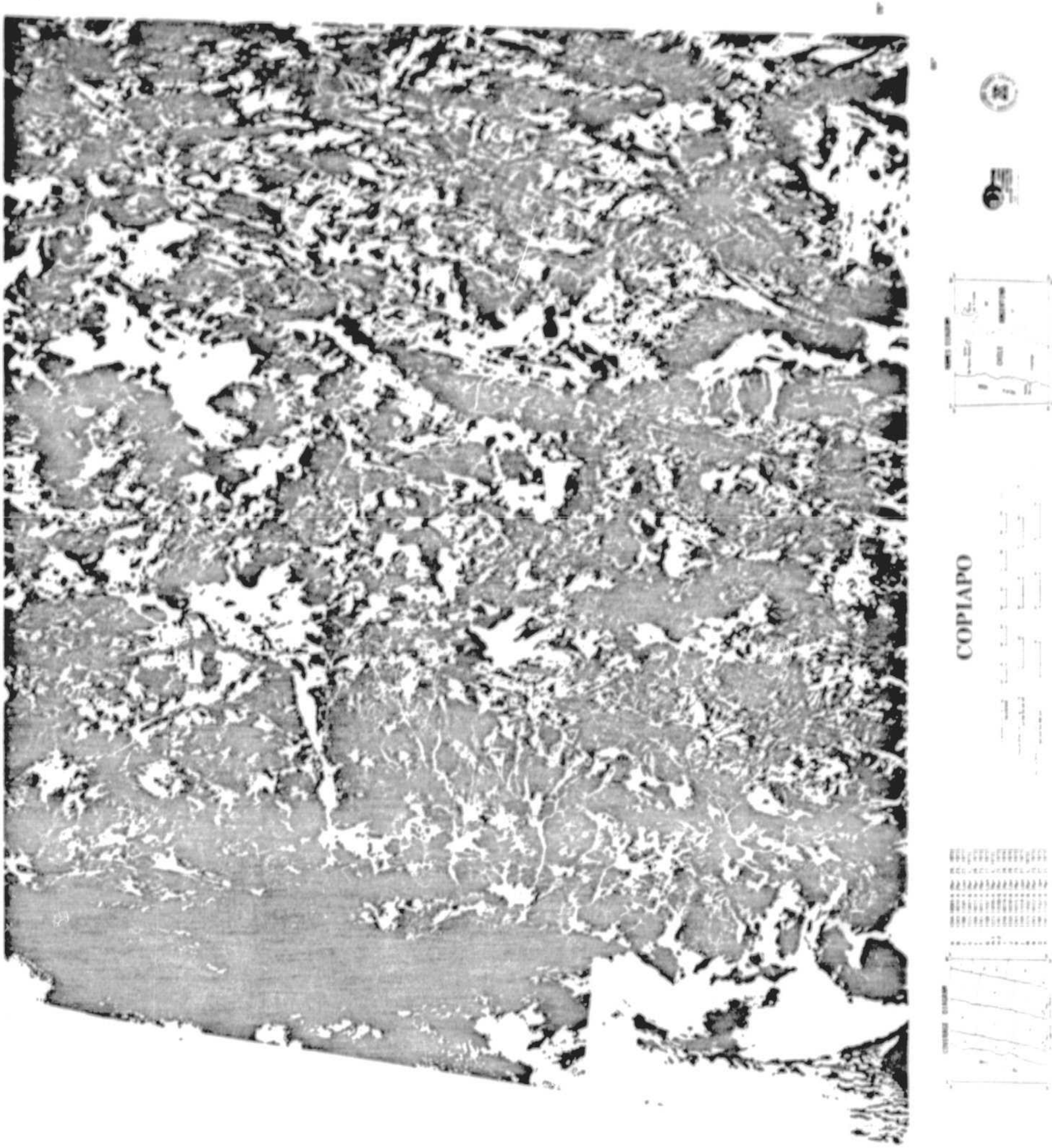

Figure 18. Landsat-1 Mosaic of the Copiapo Region, Chile and Argentina.

Figure 19. Landsat-1 Mosaic of the Tucuman Region, Argentina.

selected for study, therefore, because of its high mineral potential and the wealth of detailed information.

The Tucuman area (Area 10) lies adjacent to the east of the Copiapo area between 60°-66° West longitude. It was included in this study so that the entire width of the Andean mountain range would be covered. Of 53 images acquired by Landsat-1 for the two areas, 26 had cloud cover of over 30% and were not considered useable for the mosaicking process. Only at the end of the contract period was sufficient data acquired to compile the two Landsat-1 mosaics, Copiapo (Figure 9) and Tucuman (Figure 10). They were constructed with band 6 black and white images. The work was done by the Western Mapping Center, Topographic Division, U. S. Geological Survey, Menlo Park, California.

Interpretation of linear features was conducted by W. D. Kowalik, Pennsylvania State University, and summarized using the same procedure as was used in Venezuela (Area 1). For the Copiapo area, 3,206 linear features were identified on the mosaic supplemented by diazochrome color composites of bands 4, 5, and 7 images. The accompanying histogram (Figure 20) shows frequency peaks at N47°W, N9°S, N41°E, and N51°E. As in Area 1 of Venezuela, the presence of many subsidiary peaks indicates that the pattern is not simple. The N47°W and N41°E trends can be taken to represent a ragmatic shear pattern of fractures at nearly 9° to each other.

A peak parallel to the scan line direction of the images suggests that some of the linear features may be scan lines. A "trough" is also noted at 290° (N70°W) but is not a result of sun azimuth bias in this area (24°-28° South latitude) because the average sun azimuth is primarily northeasterly.

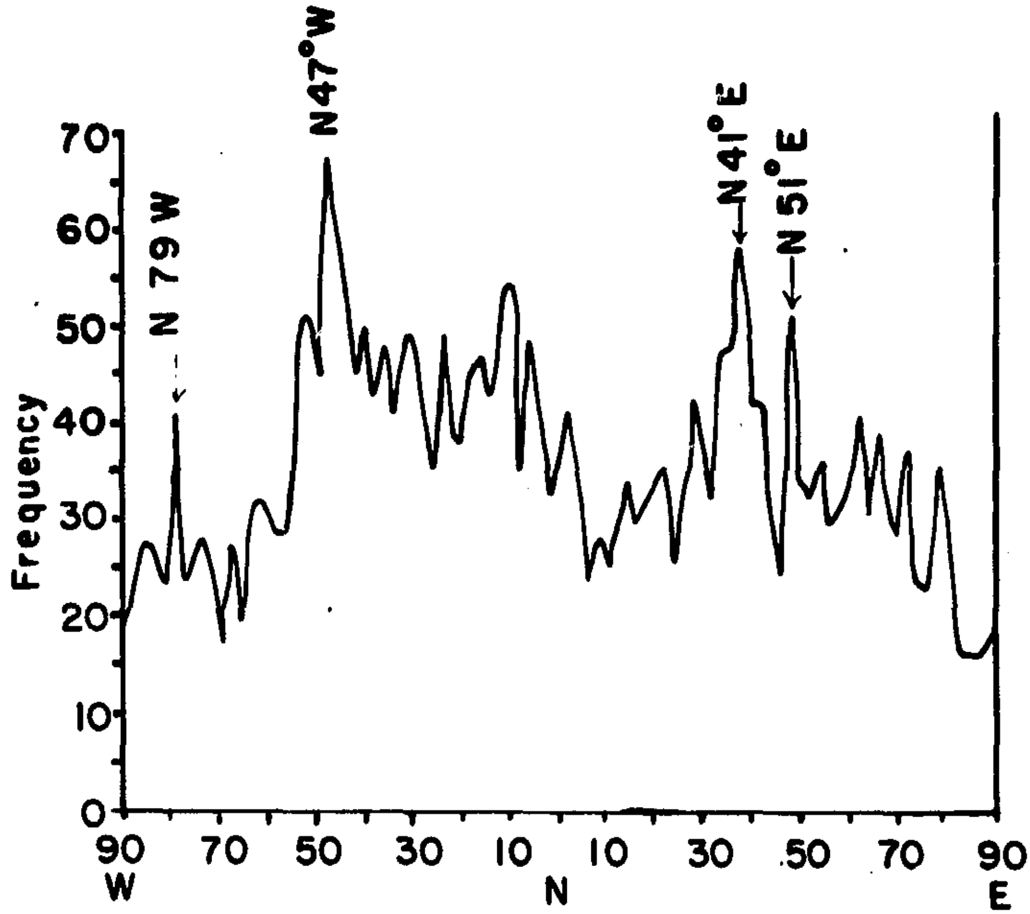

Figure 20a. Frequency of orientations summarized for lineaments of the Copiapo, Chile mosaic (Figure 17). The N47W and N41E peaks may be interpreted as elements of a regmatic shear pattern.

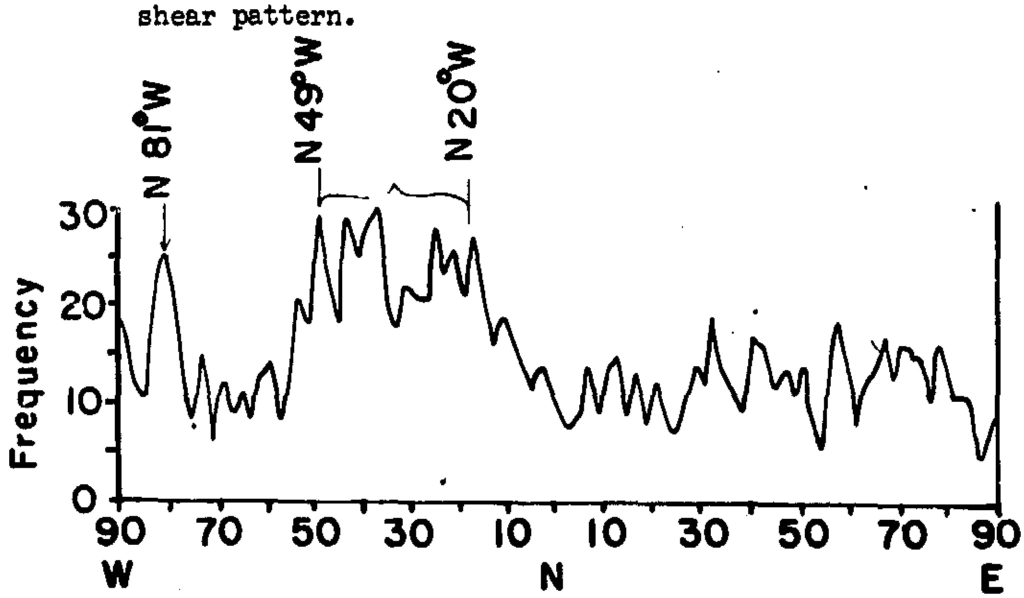

Figure 20b. Frequency of orientations summarized for lineaments of the Tucuman, Argentina mosaic (Figure 18). A northeasterly peak is lacking.

A simplified overlay showing major linear features was made by Carter on which were placed the locations and principal metallic elements of each of the known ore deposits in the mosaic area. Sources of mineral locations were the Mapa Metalogenico de Chile (1962) by the Instituto de Investigaciones Geologicas (scale 1:1,500,000) and Mapa Minero, Salta, Catamarca and Tucuman, 1966, by the Instituto Nacional de Geologia y Mineria. This product was used as a base to develop a revised metallogenic map of the area. Work is continuing to get this preliminary map into publishable form. It will soon be reviewed by Chilean and Argentine cooperators.

It is interesting to note that the two largest copper mines of the area (El Salvador and Portrerillos) lie in a crude belt along a very prominent set of north to N10E linear features extending the entire length of the mosaic. A few smaller mines lie short distances both north and south of the larger mines, but it appears that additional prospecting along the length of this trend could be worthwhile.

Also of interest are several dark bedrock areas which may be basaltic lavas. However, their extreme low reflectivity and similar shape, size, tone, and location directly south of the famed Laco iron (martite-magnetite) deposits (a distance of 250-300 km) lead to speculation that these, too, could be ferrous ultramatic deposits. These areas have been defined, using both positive and negative versions of the mosaic at the 1:1,000,000 scale. They lie south of an area known as Antofagasta de la Sierra in the drainage basins known as Río Colorado, Pirica and El Piñon between 26° and 26°30' South latitude and 67° and 67°30' West longitude. Two areas are 8-10 km long and 4-5 km wide. The southernmost is about 8 km in diameter. The existing maps of the area show that no mineral production has come from the region, nevertheless, it appears to be a favorable area for exploration. This possibility will be brought to the attention of Argentine colleagues who, hopefully, will do some field mapping and sampling in the designated areas.

Area 11 - Santiago, Chile, and Mendoza, Argentina

This area lies between 32°-36° South latitude and 66°-72° West longitude and spans the Andean Mountain Range from the coast of Chile to the Argentine pampas. The area was selected, because the area is personally known by the author and covers a wide range of ore deposits of which the Rio Blanco and El Teniente Copper Mines are most famous for their production.

Although sufficient data is now available for construction of a Landsat mosaic, it has not as yet been done. This compilation, however, will be a major first step in continuing the project under the Landsat-2 Experiment.

Several of the images were studied both by the author of this report and his assistant, Stuart E. Marsh, in the summer of 1973. It was found that band 7 images were best suited for identification of linear features in this area of extreme relief in the Andes. Mt. Aconcagua, the highest peak [6,850 m (22,834 ft.)] in the western hemisphere, lies in the north central part of the area, 135 km from the coast. Most of the terrain is extremely rugged and difficult of access. Geologic maps of much of the region are generalized and based on sparse field sampling acquired with great difficulty. Therefore, it is believed to be an area where the synoptic view from space can provide a great deal of new and valuable information.

Area 12 - Magallanes, Chile - Argentina

This area lies between 52°-56° South latitude and 66°-72° West longitude at the extreme southern end of the South American continent. It is a poorly mapped region except in the Tertiary basins, where petroleum exploration and development has been going on for more than twenty-five years by both Chile and Argentina.

Eighteen images were acquired by Landsat-1 over the region and, of these, only four had cloud cover of 30 percent or less. Of these four, three were over the South Atlantic Ocean and not useable for interpretation. In spite of the cloud problems, all images were sent to Dr. Eduardo Gonzalez, Chief Geologist of the Empresa Nacional del Petroleo de Chile (National Petroleum Co.) for analysis. By using only the small cloud free portions of the images, Dr. Gonzalez was able to compile a 1:1,000,000 scale map in the northwest part of the area near Laguna Blanca. He was able to define a new basin, believed to contain Tertiary sedimentary rocks, which he strongly believes will be worthy of exploration for petroleum resources. Although copies of the map are not yet available to be included in this report, this finding may be one of the most economically significant results of this experiment.

8.0 Significant Results:

8.1 The experiment has shown that with a small amount of introductory training, a cadre of geologists in each of the participating countries could utilize Landsat-1 data both efficiently and effectively. They greatly appreciate the synoptic view of large areas provided by Landsat-1 images which place the geology of known regions into a regional context. All have found the data beneficial in extending their knowledge from known to unmapped regions. All work to date has been done with the most rudimentary equipment and, in most cases, with black and white images at the 1:1,000,000 scale.

8.2 The discovery of copper mineralization along a lineament mapped in Area 7 (La Paz) has lent credence to the use of Landsat-1 data as a basic step in mineral exploration. The discovery has provided guidance and resulted in the development of a systematic plan for exploration which should save time and money by concentrating on predetermined targets which have been identified by analysis of Landsat-1 data.

8.3 In Area 9 (Copiapo Region), a number of lineaments have been found to be associated with the largest copper deposits of the region. These will serve as guides to new exploration. The possible identification of extensive Tertiary iron deposits in the Antofagasta de la Sierra area of Argentina should encourage exploration in that remote region of the world.

8.4 In Area 12 (Magallanes), the identification of what is believed to be a Tertiary basin from Landsat-1 data has resulted in a new area for petroleum exploration. While it will take time for field studies, geophysical surveys, and eventually drilling to confirm a new resource, the fact that the potential has been identified is important and will encourage exploration into this and other areas.

8.5 Band 7 images, as black and white transparencies, were found to be the most useful for geologic interpretation in both tropical vegetated areas and desert regions. Band 6 images (near-infrared) were used for Landsat mosaic compilation as a compromise between visible (band 5) and another part of the near-infrared (band 7) parts of the spectrum.

8.6 Color composites made by the diazochrome process, chromaline process and from color additive viewers provided additional information. Dr. Carlos Brockmann of Bolivia ran tests with his team, which indicated that information extraction increased by 50-60 percent using color composites. While color compositing methods are not yet universal, it is expected to increase as experience in the use of Landsat data grows and budgets for its operational use are obtained.

8.7 One precision processed photomap of the Salar de Coipasa region, Bolivia, was produced by cooperative efforts of GEOBOL, the Instituto Geografico Militar of Bolivia and the Inter American Geodetic Survey and U. S. Geological Survey. Because the product is excellent and conforms to accepted map accuracy standards, the Bolivian Government planned to request precision processing for all future images. It was recently discovered, however, that bulk processed images could also be produced within mapping accuracy standards, thus saving both time and money.

8.8 Mosaics of Landsat-1 data covering 4 x 6 degrees of latitude and longitude compiled at the 1:1,000,000 scale have been found to be an ideal size and format for most users. Band 6 data used on the three test examples produced to date have been satisfactory for most geologic applications. Two different groups within the Topographic Division of the U. S. Geological Survey gained experience in the preparation of the Landsat-1 mosaics and have been able to advise visiting foreign scientists on their methods.

9.0 Cost Benefit Considerations

9.1 Approximately 1,000,000 square kilometers of South America have been investigated with Landsat-1 images under this project. The experiment began January 1973 and extended through June 1974, involving three U. S. Geological Survey professional geologists on a part-time basis and two summer student assistants. Total salary costs were approximately $20,000. Mosaics were compiled for three areas at a cost of about $3,000 per mosaic. Total project costs, therefore, were about $30,000 or $.03 per km^2 for the 1-1/2 year period.

9.2 Additional and more extensive work has been done by the in-country participants, but no attempt has been made to evaluate their costs, except in Bolivia.

Recent discussions on cost/benefit analyses with Dr. Carlos Brockmann of Bolivia have identified two areas where the use of Landsat-1 data can be compared with conventional methods. Brockmann stated that in making the existing soils maps of Bolivia, a British contract team worked 8 years to produce a very generalized soils map published at a scale of 1:2,500,000 at a cost of $400,000. This cost undoubtedly included field sampling and analysis. Brockmann believes that using Landsat-1 data he can make a more detailed soils map of the country at a scale of 1:1,000,000 in two years at a cost of about $20,000, sampling costs not included. He is initiating the effort at this time and hopes to have it completed in 1976. Potential benefits in savings of time could, therefore, be estimated to be 4:1 and in dollars, approximately 20:1.

Dr. Brockmann is also a specialist in planning and designing gaslines for Yacimientos Petroliferos Fiscales de Bolivia (YPFB), the national petroleum company. His previous experience using conventional aerial methods on existing gaslines have enabled him to plan four alternative routes for a line that will connect the Santa Cruz gas field to the Bolivian border and to a Brazilian pipeline that will provide gas to markets in Sao Paulo, a total length of 1800 km. The maximum length of the Bolivian portion could be 550 km, generally following the existing railroad bed. Using Landsat-1 data, Brockmann recommends an optimum route of 517 km. He roughly calculates savings of 16 km which at current U. S. costs of approximately $150,000/km for a 26 in. line could provide savings of $2.4 M. Brockmann intends to document this more fully when the planning project is completed.

9.3 On the benefit side of the ledger we as yet have no hard figures. The knowledge gained by all participants in the experiment is difficult to quantify. Several promising areas involving potential copper, iron and petroleum resources have been identified and if any one of these possibilities becomes verified, the value could far outweigh the cost of the entire Landsat-1 experiment. Verification steps are now underway in several areas and some tentative answers should become available during the current (1975) field year.

Early cost/benefit estimates conducted by Westinghouse (1967, Table 3-1) based on interviews with U. S. Geological Survey geologists showed increases in efficiency of approximately 7 percent or at that time, approximately $7 million. These estimates are considered by the writer to be conservative one-time benefits based on one complete coverage of the conterminous United States where base map coverage is complete and most of the geology of the country has been mapped in considerable detail. The report did not consider less mapped, remote areas of the world where one-time benefits could be much larger, nor did it consider the fact that repetitive coverage could enhance our knowledge of geologic processes.

For example, Krinsley (1974) has demonstrated the seasonal dynamics of water distribution in playa lakes in Iran, and Stoertz and Ericksen (1972) have shown the distribution of playa lakes in the deserts of the central Andes. One time coverage generally shows most playas as large white masses, much like snow in reflectance in film or paper prints. The authors believe that the use of CCT's and computerized analytical tools will enable us to subdivide these bright reflectance levels and, perhaps, subdivide the playas by surface roughness and possibly mineralogic distribution. If successful, it would greatly assist the exploration for and exploitation of salts, sulfates, and nitrates within the playas.

Collins and others (1974), in conducting petroleum exploration of the Anadarko Basin, estimated that Landsat-1 can help reduce the cost of geologic exploration by 20 to 50 percent. From the work conducted on this project and associated efforts by my South American colleagues, I am inclined to agree that in well-known areas of easy access, the figure might range from 10 to 20 percent and in remote areas of difficult access, savings of 25 to 50 percent are feasible. It is interesting to note that in Bolivia, where large tracts of unmapped land are now open for leases by petroleum companies, the first action taken by the petroleum geologists is to visit Dr. Brockmann's office to see what Landsat-1 data is available to help them.

10.0 Conclusions

10.1 The data provided by Landsat-1 has far exceeded our early expectations. The synoptic view of large areas enhanced by mid-morning sun angle is ideal for geologic mapping, especially of linear, curvilinear and other geomorphic and structural features. Crude definition of rock types were made in some areas and were supported by existing geologic maps. Black and white multispectral images and mosaics and diazochrome color composites were used for most of the investigation. Band 6 and Band 7 near-infrared images were found to be most satisfactory and were used extensively.

10.2 Where repetitive coverage was available, we found that snow cover and water areas related to saline lakes were the most obvious changes that could be identified. No significant differences or relationships were noted in regard to the definition of linear features but this is probably due to the paucity of repetitive Landsat-1 data.

10.3 The scale and resolution of Landsat-1 data is ideal for broad regional geological surveys, because it is near-orthographic even in areas of great relief, such as near Mt. Aconcagua (6500 m). The scale of 1:1,000,000 is excellent for it matches the scales of many national resource maps; e.g., Peru Metallogenic Map, National Map of Bolivia, although different map projections used can produce some variation in planimetric orientation. It can also be enlarged to 1:500,000 and 1:250,000 scales in even small, unsophisticated photographic laboratories. For example, Bolivia has used the 1:250,000 scale format extensively for detailed resource and land use studies of several departments (states). For most geologic features of a regional scale, 80 m resolution is entirely adequate. Finer resolution (e.g., 40 m), however, could be useful in locating mine workings with greater accuracy, particularly in the areas where mines have little contrast with the surrounding region.

10.4 The wide range of data products that can be provided from Landsat-1 data have only been partially tested in a cursory manner under this experiment. We have not yet begun to explore, for example, the application of computer compatible tapes and density analyses of the complete spectral range of the multispectral data. Nor have we adequately explored a variety of enhancement techniques, that, each day, are becoming more sophisticated. While we have used standard methods of color compositing, we have not explored the use of color variations in rock type discrimination or change detection.

10.5 In spite of the above limitations, it is safe to say that the experiment has provided useful, much needed data to the countries involved and has successfully served as a medium of technical information exchange at minimum cost and, in places, under very difficult conditions.

10.6 The models developed under this experiment have been found to be acceptable and useful to the in-country scientists. A unified and systematic approach appears to be evolving.

10.7 Landsat-1 data has succeeded in bringing the team of international scientists involved in this experiment together for additional exchange on an independent basis.

11.0 Recommendations

11.1 This experiment has proved to be of valuable assistance to the developing nations of South America and it is recommended that it be continued as a Landsat-2 follow-on experiment and extended to countries that are not yet involved.

11.2 Landsat-2 coverage should be extended to the remaining regions of the South American continent that have not yet been covered. Special effort in programming satellite coverage will be required for the cloud covered regions of the Colombian and Ecuadorian Andes and the southern third of Chile.

11.3 A band 6 or 7 mosaic of the South American continent should be constructed to provide a total overview of the region, when sufficient data becomes available. It is recommended that it be done on an international basis in the 4 x 6 degree format using the Universal Transverse Mercator projection and grid system and at a scale of 1:1,000,000. Hopefully, this will be done by the in-country agencies on a national basis using local resources. A mechanism should be set up whereby these local compilations can be joined to make a continental mosaic at a 1:5,000,000 scale.

11.5 It is recommended that the Landsat-1 follow-on experiment for South America continue its current objectives but also include experimentation and evaluation of the use of computer compatible tapes for geologic applications. Digital enhancement of linear features, discrimination of rock types and salt types in salars, definition of alteration zones related to ore bodies in arid and tropical regions are major problems, in which some significant progress has been recently made but not fully tested on the South American continent. Demonstration products of these applications on local problems will make them more meaningful to in-country scientists.

11.6 Interest in the use of the Data Collection Platforms (DCP) to support satellite observations has become very strong in Chile, Bolivia and Peru. Studies are now underway to determine how established tracking stations at Colinas, Chile, and Ancon, Peru, might be modified to enable the use of this capability. An agreement to lend Bolivia a DCP and water level meter has been drafted to determine the southern limit of DCP reception by the Goddard Space Flight Center. The success of transmitting DCP data from Iceland to Goddard suggests that the southern limit could be as far south as Arica, Chile (20° south latitude) and perhaps even farther into the high Andes. The Bolivian experiment will test the hydrologic application of DCP's in various regions (northern tropical lowlands, central Andean foothills and southern Altiplano), where water resources are important to future development of the country. It is recommended that all necessary cooperation be given to this effort.

11.7 No modifications are recommended for Landsat-2 except that we would like to more adequately test and compare the return beam vidicon (RBV) images with those of the multispectral scanner (MSS).

11.8 The planned modifications for Landsat-C which include the increased resolution of the RBV system and the addition of the thermal channel to the MSS are endorsed as important additions to this experimental phase of satellite development.

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TECTOLINEAR INTERPRETATION OF AN ERTS-1 MOSAIC, LA PAZ AREA, SOUTHWEST BOLIVIA, SOUTHEAST PERU AND NORTHERN CHILE

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ABSTRACT

The La Paz mosaic, composed of all or parts of 22 Earth Resources Technology Satellite (ERTS-1), infrared, band 6 images (0.7-0.8 micrometers) at a scale of 1:1,000,000, has been compiled as a model designed to establish systematic mapping procedures. Such mosaics will assist regional small-scale geologic mapping and mineral resource investigations in lesser developed countries. The mosaic covers an area of 276,000 square kilometers between 16° and 20°S latitude and 56° and 72°W longitude. It is centered over one of the major bends of the Andes Mountains and spans several major mineral resource provinces.

An interpretation overlay of linear features, most of which are considered to be faults, fractures, and folds, indicate that the dominant structural trend is NNW to NW. This trend is probably due largely to orogenic forces resulting from subduction along the western margin of the South American continent. Between La Paz and the Salar de Coipasa, Bolivia, there is also a strong secondary set trending nearly E-W. These may be related to transverse movement between the northern and southern portions of the South American plate. A tertiary set of linears of lesser abundance trends NE. All of the linears are at least 5 kilometers in length, and the longest have been traced for more than 500 kilometers.

The tectolinear overlay is compared with other independent interpretations, existing geologic maps, mineral deposit and oil field location maps, and seismic epicenter maps to determine its utility as an exploration tool.

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1. Introduction

The launch of the first Earth Resources Technology Satellite (ERTS-1) in July 1972 brought earth scientists into the space age by providing the opportunity to view large areas of the world multispectrally and repetitively under nearly uniform lighting conditions. ERTS-1 orbits the Earth every 103 minutes or 14 times per day at an altitude of 920 km. The orbit is inclined about 10° to the east of the North Pole and crosses the Equator on its southern pass at approximately 09:40 a.m. local time. Due to the rotation of the Earth each successive orbit has a ground track that lies 1609.3 km or 15° west of its previous track at the Equator. It repeats its cycle of observations every 18 days.

Because of the capability of ERTS-1 to collect data on a world-wide basis, an experiment was designed to ensure that most interested national geological mapping agencies in South America had the opportunity to evaluate and apply samples of ERTS-1 data to local geological problems. The experiment established a group of investigators consisting of representatives from Argentina, Bolivia, Brazil, Chile, Colombia, Peru, and Venezuela working in cooperation with the author. Twelve areas, each 4 x 6 degrees of latitude and longitude, were selected to concentrate on principal mineral resource areas and tectonic features of the Andes and key areas of the Brazilian shield (Figure 1). This paper describes and evaluates some of the first products derived from the experiment. It is hoped that it will serve as a model for

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designing future systematic mapping activities of this type that can be undertaken either on a national basis or joint international cooperative basis. The ultimate goal is to compile a mosaic of the South American continent, and to develop products such as new tectonic and metallogenic maps that will be of value to resource development of all the nations involved.

2. ERTS Imagery

The sensor package includes three Return Beam Vidicon (RBV) television cameras, each boresighted to the nadir of the same image scene, and each filtered to a specific spectral band. Band 1 images in the green portion of the spectrum (0.475-0.575 micrometers); Band 2 is filtered to the red spectrum (0.580-0.680 micrometers) and Band 3 is in the near-infrared (0.698-0.830 micrometers). A second imaging system known as the Multispectral Scanner (MSS), consists of an oscillating mirror that scans narrow strips across the ground track. Reflected light passes from the mirror through a prism where it is split into four bands, collected through fiber optics, and converted to an electronic signal. The 4 bands are known as Band 4 (0.5 to 0.6 micrometers), Band 5 (0.6-0.7 micrometers), Band 6 (0.7-0.8 micrometers) and Band 7 (0.8-1.1 micrometers). Both systems view a ground track 185 km wide and provide 10 percent sidelap with each adjacent track at the Equator. Sidelap increases progressively toward the poles and at higher latitudes can be more than 60 percent. This sidelap has been used stereoscopically to estimate elevations to an accuracy of about

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100 m (Williams, 1974). The RBV image format is square but the MSS is rhomboid. Both produce scenes covering 34,225 km^2 (13,225 mi^2). The ground resolution of standard products is nominally 100 m. While the original images are created as 70 mm negative transparencies, they can be reproduced in a variety of enlargements and also combined to produce false-color images. Processing directly from computer compatible digital tapes permits pixel by pixel study of the data at scales as large as 1:24,000 in which each pixel represents an area of about 1 hectare. This flexibility in product provides the opportunity for each earth scientist to adapt the data to his particular needs or problem.

3. La Paz Mosaic

The La Paz Mosaic (Figure 2) was compiled at a scale of 1:1,000,000 using contact prints made from 24 x 24 cm positive transparencies of parts of 22 Band 6 images taken during 1972 and 1973. Their location, the image numbers and dates are shown as an index map and list in the lower left margin of the mosaic. The mosaic covers an area of 276,000 km^2 that lies between latitudes 16° and 20° S and longitudes 66° and 72° W. Southeastern Peru lies in the upper left, northern Chile in the south center, and southwestern Bolivia comprises the eastern half. Major water bodies include the Pacific Ocean in the southwest, the southern part of Lake Titicaca in the north-center margin; Lake Poopo and the Salars of Coipasa and Uyuni are in the south. Although the mosaic is not completely cloud free, sufficient ERTS-1 data

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became available after 1-1/2 years of satellite operation to prepare this preliminary product.

Most of the region is sparsely populated, and of difficult access. Sharp cliffs rise to elevations of 1000 m above sea level along the coast. The coastal terrain consists of high terraces composed of Tertiary and Quaternary sedimentary rocks and gently rolling hills of the Coastal Range composed of Paleozoic, Jurassic and Cretaceous igneous and sedimentary rocks. This range forms the western boundary of the Tamarugal Valley of the Atacama Desert in the south, a valley filled with thick layers of alluvium capped by significant salt deposits. East of the Tamarugal Valley the terrain rises steadily to an elevation of about 4000 m to the level of the Altiplano which, on the west, is dotted by scores of Tertiary, Quaternary, and Holocene volcanic cones and craters that mark the most recent orogenic activity of the Western Cordillera. The Altiplano consists largely of Tertiary and Quaternary rocks cropping out in a high interior basin marked by playas and lakes that lie between the Western and Eastern Cordillera. The Eastern Cordillera consists of folded Paleozoic rocks which crop out in the northeast part of the mosaic and appears as rugged terrain composed of sharp northwest-trending ridges and deeply incised valleys.

4. Tectolinear Overlay

The mosaic spans a very critical structural zone of the Andes where north-trending linear features of northern Chile and southern Bolivia swing northwesterly into Peru. The region is important for its

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mineral resources for within it are major copper, tin, and tungsten deposits as well as significant production of lead, zinc, silver, gold, and sulfur.

An overlay (Figure 3) depicting linear and curvilinear features was constructed at contact scale (1:1,000,000) to define possible structural features that could be influential in the migration of ore-bearing fluids or that could be considered potential hazards in this seismically active region. Linears such as straight segments of streams, scarplike ridges, linear changes in tone and similar features that are 10 km (10 mm on mosaic) or longer were considered to be of potential significance. Solid and long dashed lines and dotted lines were used to indicate relative degrees of certainty in interpretation. Short dashes were used to depict linear features believed to correspond to bedding plane contacts of significance. Water bodies and salars are outlined for geographic reference and volcanic centers are depicted by a radial star-shaped pattern to note their locations in relation to structural features where Quaternary to Holocene volcanic debris may mask underlying structural features.

The best known, and perhaps most outstanding, linear features are those which bear north to northwest paralleling the coast and core of the Andes. These are seen clearly, especially in the Western and Eastern Cordilleras. They appear to be largely of tensional origin and, in northern Chile, a graben-like feature, 20 km wide and 100 km long, is clearly portrayed on the western flank of the Western Cordillera.

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These structures and the concentration of volcanic activity are believed to be due to subduction of a major portion of the eastern Pacific floor, known as the NAZCA plate, eastward under the South American continent.

A lesser set of northeast-trending linears extends largely as short segments roughly perpendicular to the coast and are radial tension features as part of the arc expressed by the curved bend of the Andes in this area. They are especially abundant in the northeast quadrant of the mosaic in the more rugged and folded Eastern Cordillera.

A third set, and perhaps the most significant set recognized in this study, are a group of nearly east-west trending linear features that extend from the Peruvian Coast west of Toquepala across the Altiplano to south of Cochabamba in Bolivia. This zone appears to represent transverse or horizontal motion in which layered rocks in the area to the north have been moved eastward as much as 20 km. The westward trend of the coast north of Arica, however, suggests that major movement has been to the west through geologic time. While the significance of these features and sense of movement is not clearly understood at this time, it is felt that this zone may be a key area in unraveling the structural history of the Andes. Further field work is recommended in this area.

5. Relative Confidence Map

To evaluate this interpretation a relative confidence overlay was made in which those linear features which agreed with published sources

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were marked in red (Figure 4). Those features which were identified by both the principal investigator and one or more of the national co-investigators were marked in green. Published small-scale sources are scarce and difficult to assemble. The Metallogenic Map of Peru (scale 1:1,000,000) was ideal for comparison, however, and the few ore-bearing structural features shown on that map coincided well with those depicted on the tectolinear overlay. A separate ERTS-1 interpretive study of the volcanic and linear features by Kussmaul (1973), as part of the Bolivian ERTS Program, also showed good agreement with this interpretation for the areas of coincident coverage. Those areas in which disagreement or divergence exists are defined as areas where further study is needed.

6. Metallogenic Overlay

A composite metallogenic map overlay (Figure 5) showing the location and principal elements of known ore deposits was made from the Mapa Metalogenico de Peru (scale 1:1,000,000), Mapa Metalogenico de Chile (scale 1:1,500,000), and published records of Ahlfeld (1964) for Bolivia. The latter were later updated by Dr. Carlos Brockmann (written communication) and his ERTS Experiment Team and have been added to the existing compilation.

Superimposing the composite metallogenic map over the tectolinear interpretation enables the investigators to immediately see the close relationship of structural features to the location of ore deposits of various kinds. Most prominent are the close association of major

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copper deposits to structural linears in northern Chile (Mocha and Cerro Colorado) and southeastern Peru (Toquepala to Arequipa). This narrow band of apparently intensive structural activity appears to be a very fertile area for further detailed studies.

Small curvilinear features identified mainly along the west margin of this "active" region may be of special significance in locating ore deposits near but not exposed at the surface. A similar feature, 5.4 km (4 miles) in diameter, was found in eastern Arizona by study of an Apollo 6 photograph (Carter, Eaton and Bromfield, in preparation). The area was field checked by detailed surface mapping and geophysical surveys. Aeromagnetic highs were found on opposite sides of a gravity low suggesting an intrusive mass buried about 300 m below a surface of stratified volcanic rocks. Apparently the intrusive mass expanded the overlying caprock during its fluid phase, failed to break through to the surface and contracted during solidification leaving collapse features in the overlying bedrock. No drilling has yet been done in the area to confirm the presence or absence of ore deposits, and the area remains as a promising prospect.

The Corocoro copper mineral belt, consisting of disseminated copper is associated with fine-grained sandstone of the Totora Formation of Tertiary age. These strata are known to extend from the shores of Lake Titicaca southeastward to near Salar de Uyuni, a distance of over 300 km. South of Corocoro, near Umala, the strata appear to be offset to the west a distance of 20-40 km by a suspected transform fault identified

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by this interpretation. Offset of similar magnitude along the same structure is also suspected by offset of the tin belt which is parallel to the Corocoro copper belt and lies about 90 km to the east.

7. Seismic Hazard Overlay

A seismic hazard overlay was made from computer generated locations of seismic events recorded by the World Wide Seismic Net from 1963 through 1973. Only those events having a magnitude of 5 or greater were used because the area is so seismically active. It was believed that a plot of magnitudes of 3 and 4 in this highly active area would be too complex to be meaningful. Although generalized, the present overlay appears to outline the most active areas, and it is recommended that construction works, whether they be civil, or industrial-commercial activities, be planned with extreme caution where crossing or constructing near linear features within the areas of high seismic risk.

8. Conclusions

ERTS-1 images provide synoptic views of large areas of the Earth surface. These views are essentially orthographic and easily mosaicked at a scale of 1:1,000,000 providing image base maps of acceptable accuracy at that scale. The 4° x 6° format at this scale is convenient for interpretation work on most standard light tables.

In spite of the fact that data was collected over a 1-1/2 year period the solar illumination angle is relatively uniform so that surface tones and shadowing can be distinguished. Of the various

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spectral bands available, the near infrared bands (6 and 7) have proven to be most useful for linear interpretation, especially in forest covered regions. While vegetative cover is absent in the area described band 6 was chosen to mosaic the La Paz region because this band combines the advantages of haze penetration, evenness of tone and delineation of water bodies.

No attempt has yet been made in this study to enlarge the scale of the mosaic or individual images to 1:500,000 or 1:250,000 scales. From studies elsewhere, however, it is clear that additional geologic information can be gleaned from the same images at larger scales. This is also true of color combined images at the various scales.

Mosaics at smaller scales (e.g., 1:5,000,000) serve as a filter which removes "surface noise" (i.e., minor details) so that only major features are identified. Such mosaics have an added advantage in that a larger area can be studied in its total context.

It is recommended, however, the mosaicking in South America be continued at the 1:1,000,000 scale on the 4° x 6° grid pattern. When completed the separate parts should be photographically reduced to scales matching the Geologic Map of South America (scale 1:5,000,000).

The overlays accompanying this mosaic are merely a beginning of the varieties of information that can be derived from or correlated with ERTS-1 images. The Bolivian, Chilean and Peruvian ERTS investigation teams are also making maps showing bedrock distribution, drainage basins, geomorphology, volcanology, and soils that can have considerable application to problems related to geology in the respective countries. Time will be required to check the validity of these preliminary interpretations. This work will be reviewed largely by in-country geologists whose knowledge of local geologic conditions is fundamental to complete evaluation.

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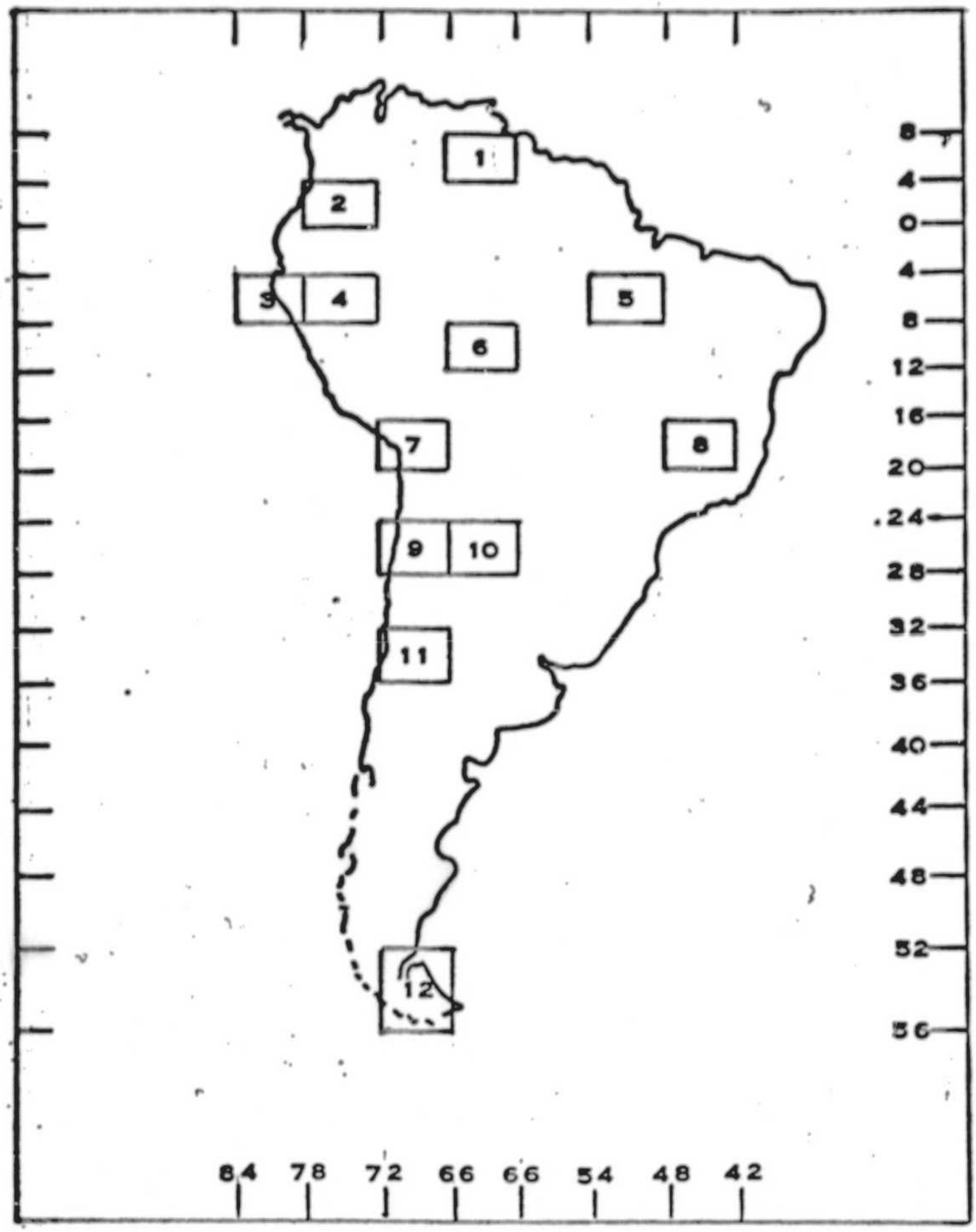

Figure 1. Index map showing location of proposed project areas and indicating the La Paz Area (7) described in this report

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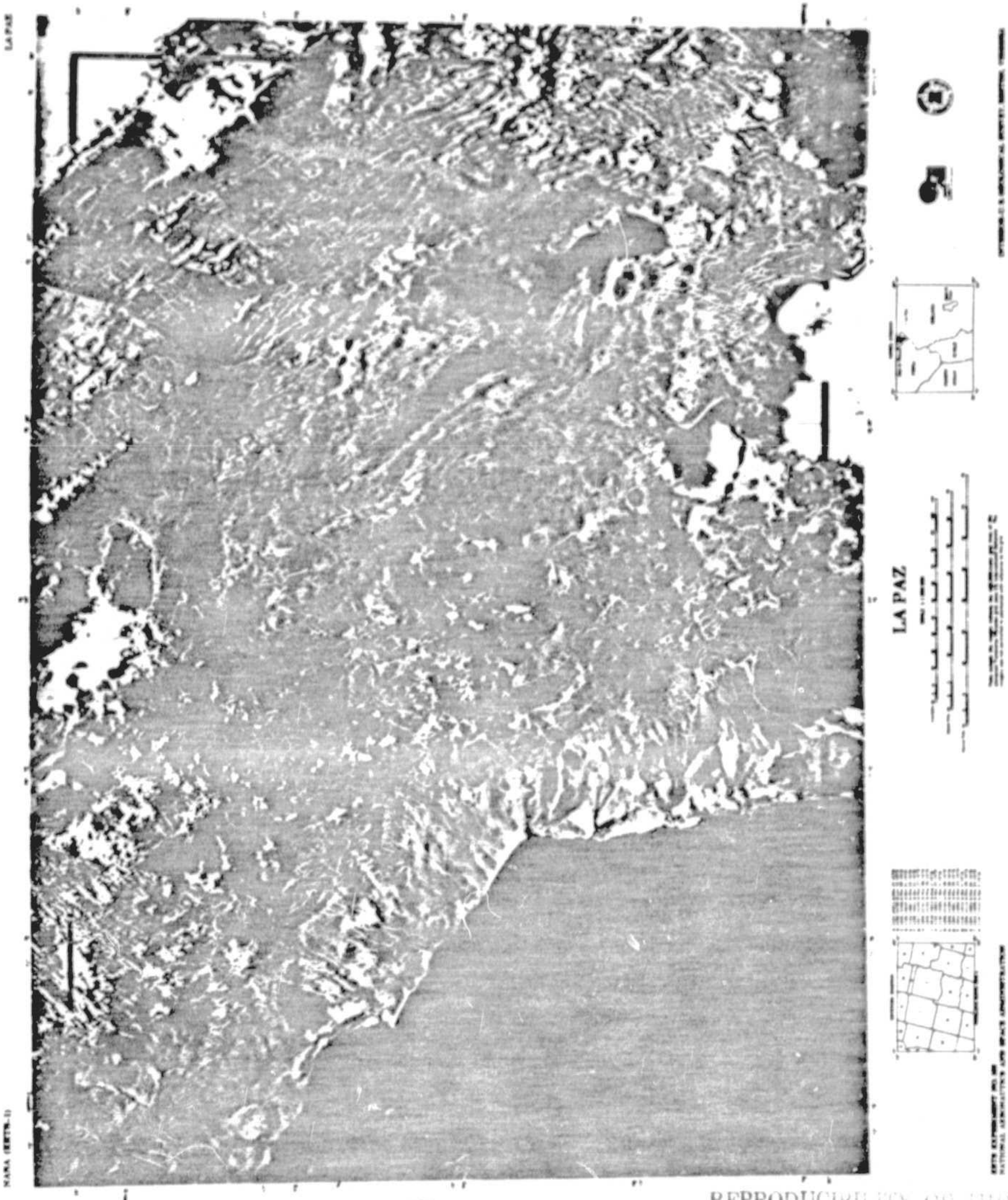

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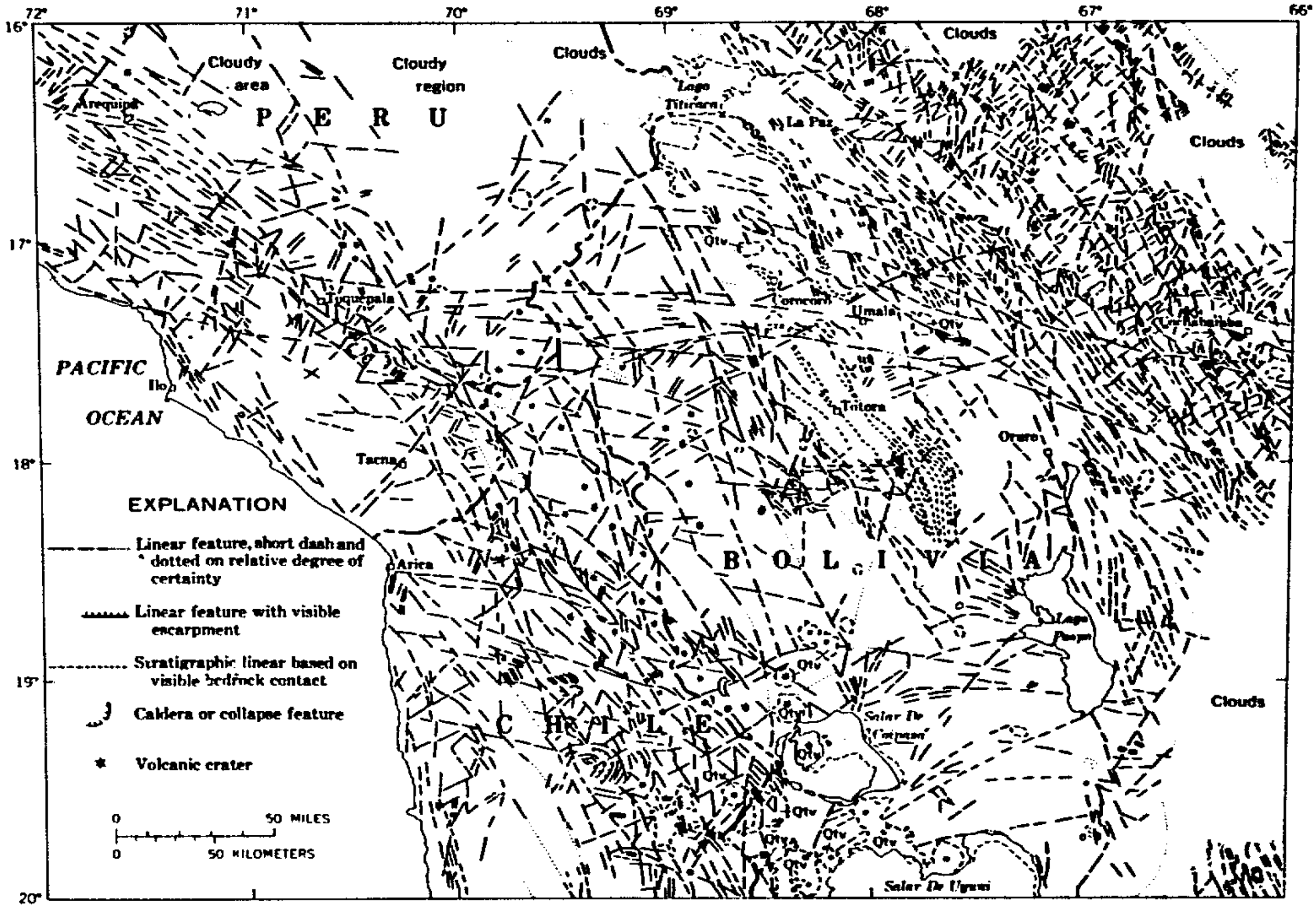
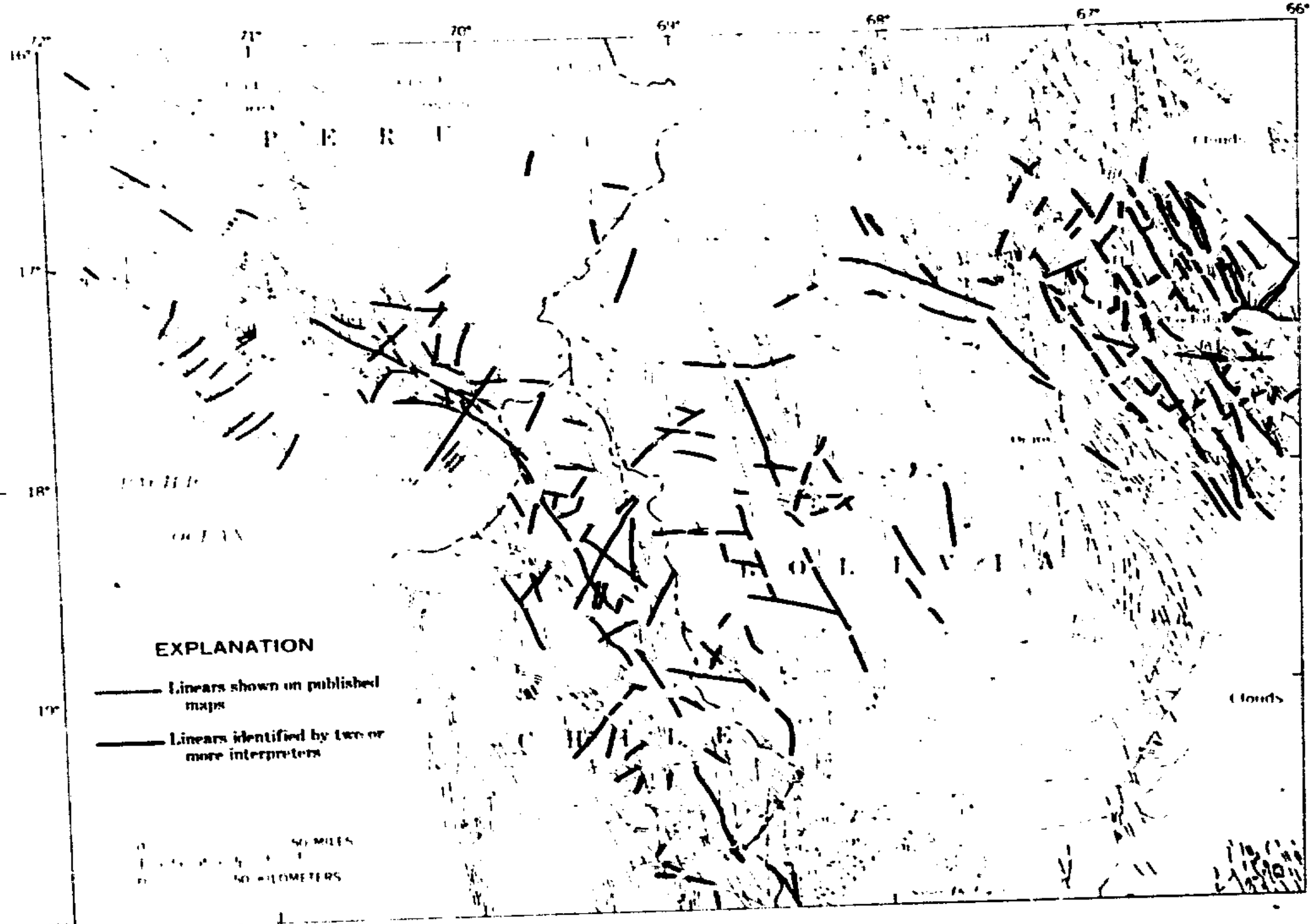
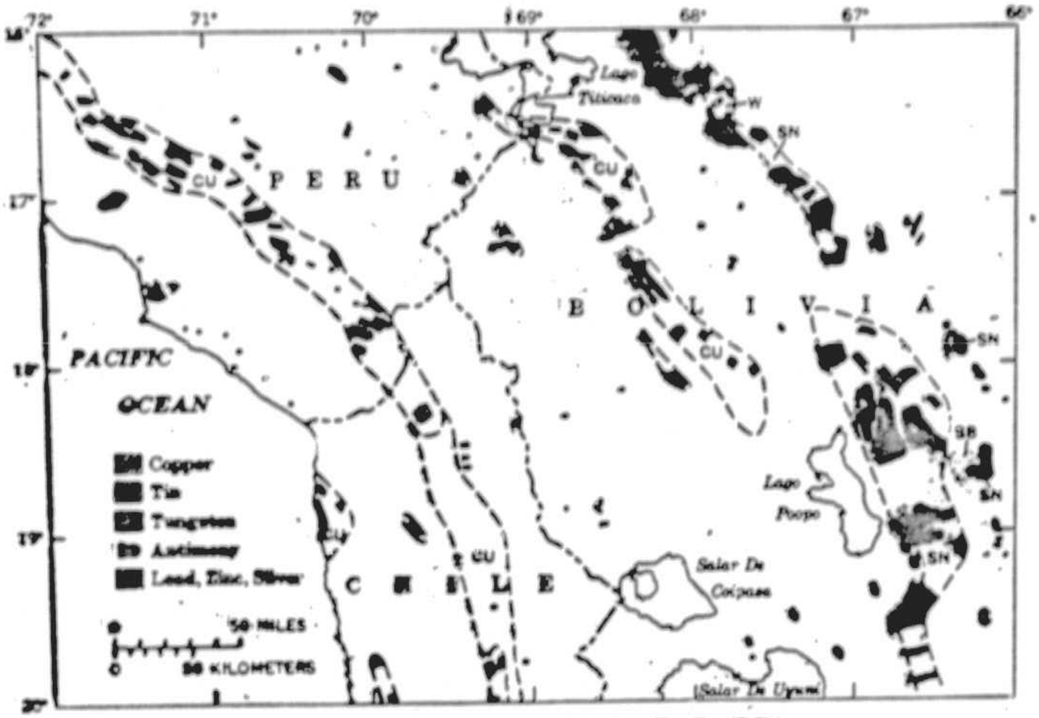


TECTOLINEAR MAP OF LA PAZ



RELATIVE CONFIDENCE MAP



METALLOGENIC MAP OF LA PAZ AREA

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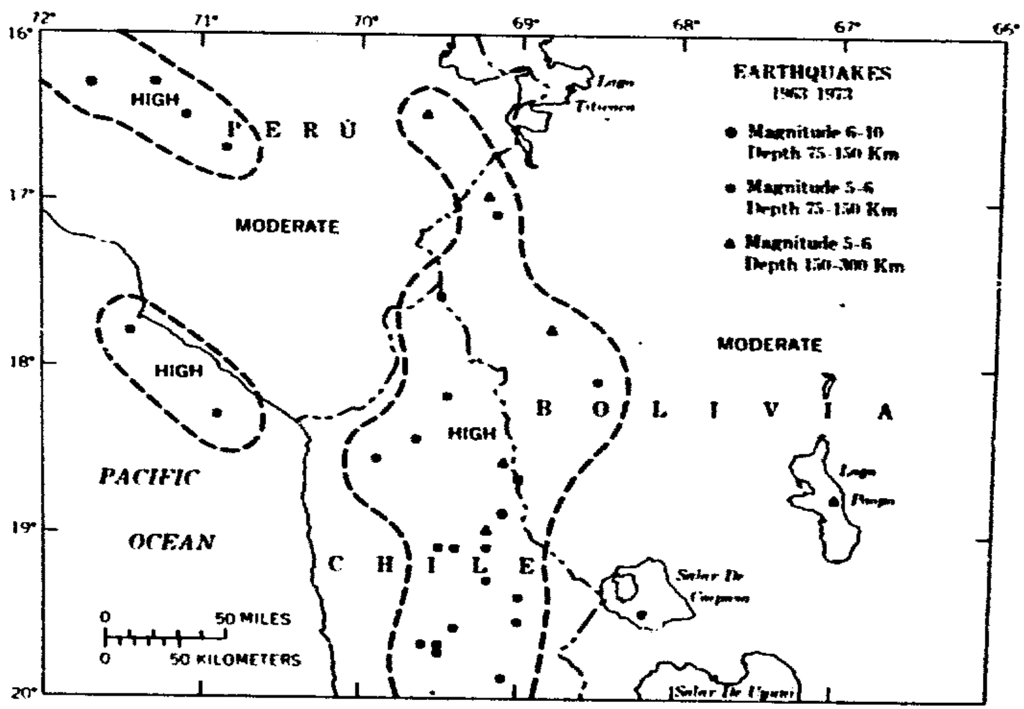

SEISMIC HAZARD MAP LA PAZ REGION

ERTS-1 Data: A Key Ingredient to Mineral and Energy Resource Exploration

by
William D. Carter
EROS Program
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Reston, Virginia

ABSTRACT

The Earth Resources Technology Satellite (ERTS-1), an experimental satellite launched by NASA on July 23, 1972, has acquired approximately 100,000 multispectral images of the earth in 2 years of operation. While the data have application to many disciplines, it is of special interest and has operational use to scientists and engineers involved in supplying the burgeoning demands for mineral and energy raw materials.

Small-scale mosaics compiled of large areas of North and South America are providing new data that will aid in refining theories of plate tectonics and metallogenesis, and contribute significantly to the selection of new exploration targets. For example, a mosaic of the conterminous United States compiled originally by U.S. Department of Agriculture Soil Conservation Service at a scale of 1:1,000,000 and reduced to 1:5,000,000 permitted the definition of major linear, curvilinear, and circular features in less than 2 days of analysis. More detailed analyses of selected regions were also conducted on mosaics compiled from images in the infrared spectrum (0.8-1.1 micrometers) at 1:1,000,000 scale by several individuals working independently. Comparison of these results helps determine the level of confidence of the interpretations. Further comparison with published geologic and geophysical maps at similar scales helps strengthen this confidence and, furthermore, defines those areas where future field study and exploration is needed.

For presentation at AIME/SME Fall Meeting, September 23-25, 1974, Acapulco, Mexico

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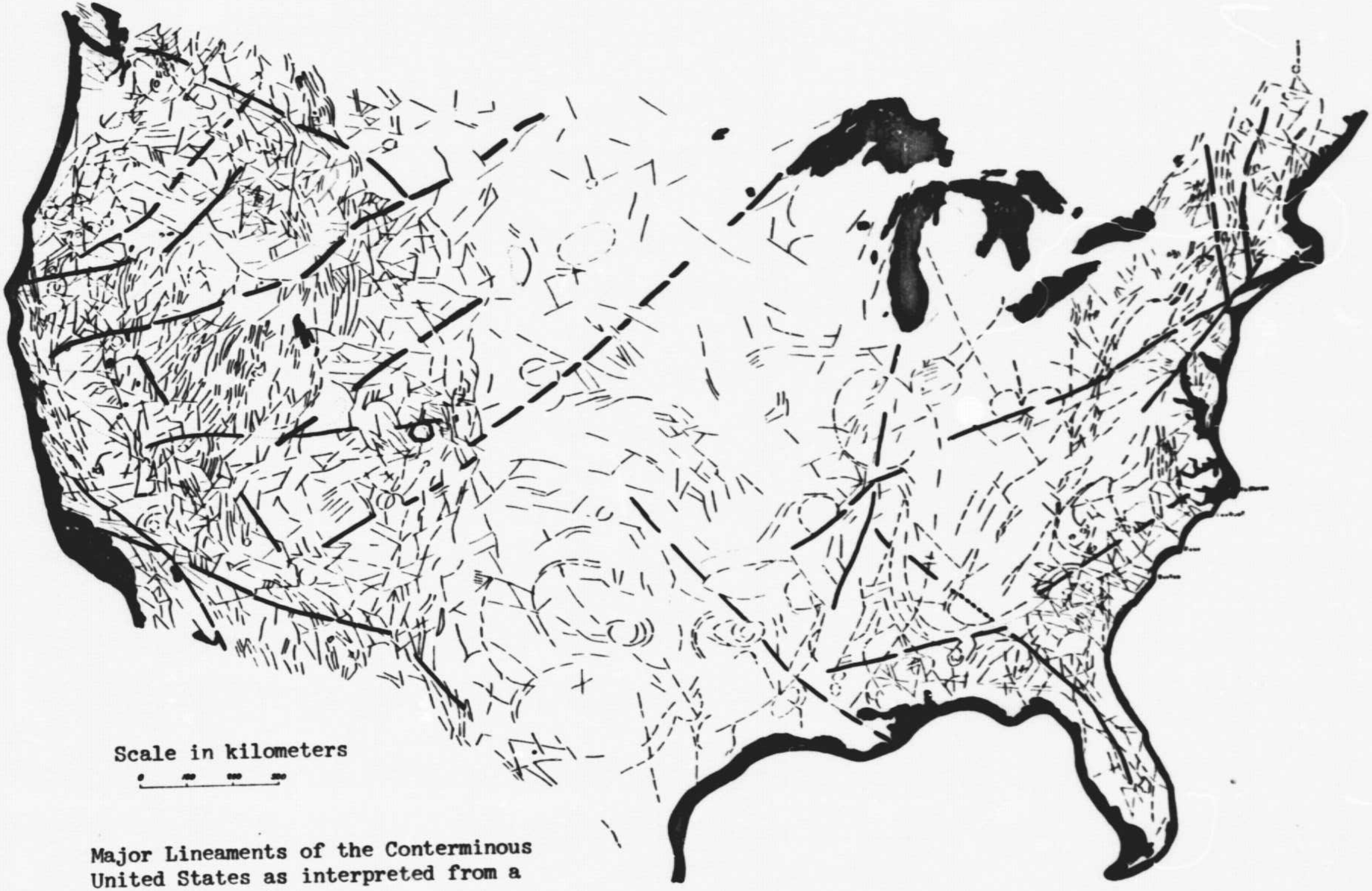
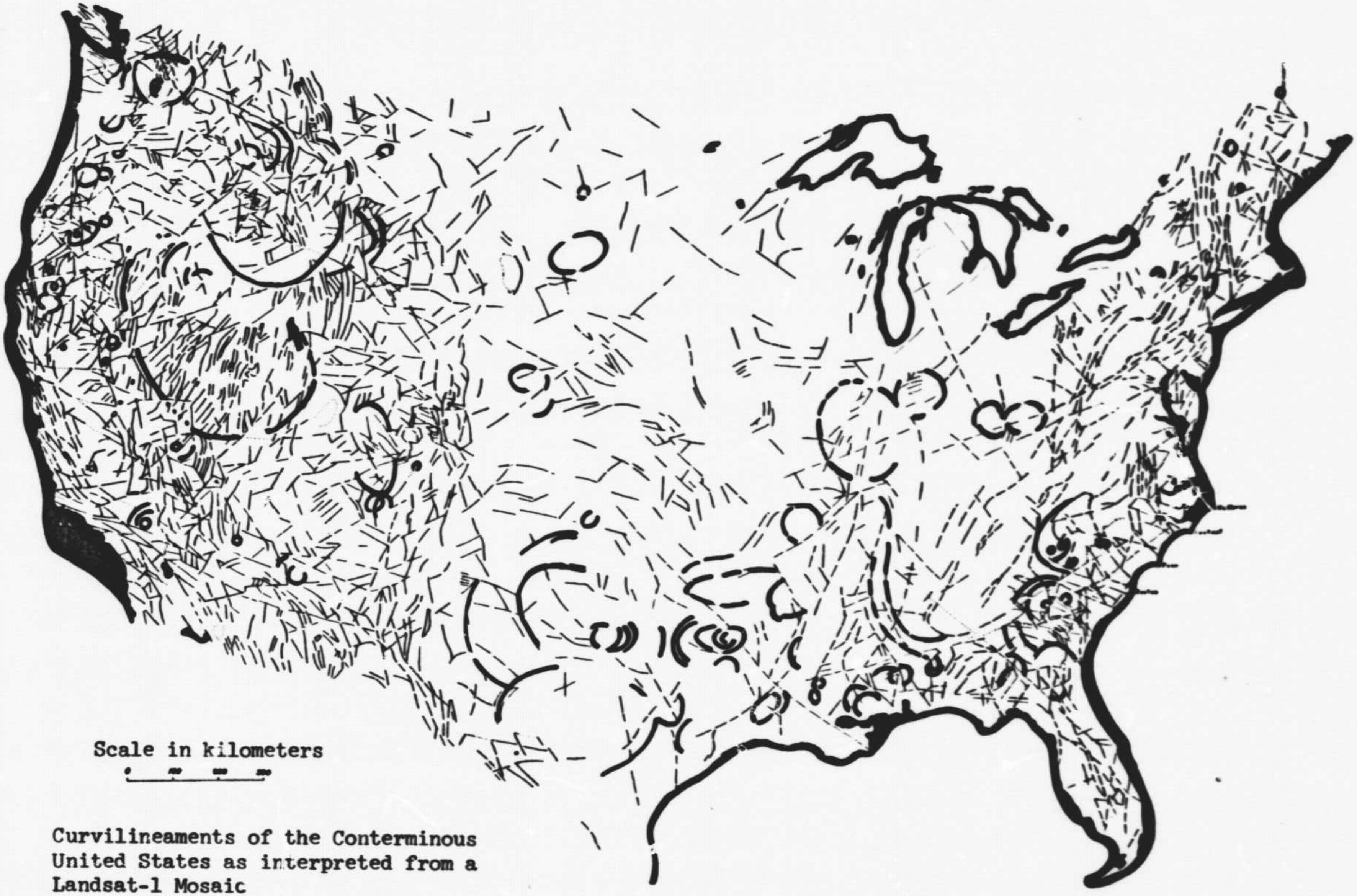


Major Lineaments of the Conterminous United States as interpreted from a Landsat-1 Mosaic



Curvilineaments of the Conterminous
United States as interpreted from a
Landsat-1 Mosaic

APPENDIX C

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EROS PROGRAM AND ERTS 1 SATELLITE APPLICATIONS TO GEOPHYSICAL PROBLEMS

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The US Department of the Interior Earth Resources Observation Systems (EROS) Program is a multi-disciplinary Department-wide effort to evaluate data from remote sensors borne by aircraft and spacecraft as they apply to operational problems and responsibilities. These problems and responsibilities range from managing large tracts of public range and forest lands, Indian reservations, wildlife refuges, national parks and recreation areas, to geologic mapping for mineral and water resource inventories and studies of the environmental impact of proposed public works projects. The EROS Program began in 1966 as a result of earlier feasibility studies conducted in cooperation with the National Aeronautics and Space Administration (NASA). It has grown in both scope and area so that it now has cooperative endeavors with many Federal, state and local agencies, universities, foreign nations and international organizations.

The Earth Resources Technology Satellite, ERTS 1, successfully launched on 23 July 1972, was designed to meet the needs of many earth resource scientists. Specifications for near-orthographic multiband images and a data relay capability were developed from recommendations provided to NASA by the Departments of Interior and Agriculture. Over 320 principal investigators are now evaluating ERTS 1 data from many regions of the globe, and of these more than 70 are geologists. The broad synoptic view provided by small-scale ERTS 1 images, under uniform lighting conditions, has enabled geologists to map lineaments and other structural features over large areas. Near-infrared images which portray vegetation in light tones and soil moisture in dark tones have reduced the problem of distinguishing structural features in some heavily vegetated regions. A limited number of repetitive satellite images acquired after leaves or snow have fallen have suggested new advantages to geological mapping. Yet to be realized is the high probability of identifying areas where anomalous snow-melt patterns may be of importance in prospecting for new sources of geothermal energy.

Experiments from aircraft employing multiband camera and optical-mechanical scanner systems have shown that reflectance minima occur both in the visible and near-infrared spectra in rocks rich in iron-bearing minerals. These minima are due to optical absorption caused by electronic transitions in the ferric and ferrous ions. Increases in near-infrared reflectance and temperature have been noted in coniferous vegetation overlying soils enriched by copper and molybdenum. Such observations have not yet been made at satellite altitudes. However, bi-band ratioing techniques using two bands (3.5--5.5 μm and 10—12.5 μm) of thermal infrared data from the Nimbus 3 satellite have enabled geologists to distinguish several rock and soil types and improve on small-scale maps of desert areas in Saudi Arabia and in Muscat and Oman. Geologic materials have been discriminated from Nimbus 3 and 4 reflectance and thermal data by computing the day-night temperature difference and maximizing the effects of thermal inertia.

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1. Introduction

Investigations of the geologic applications of remote sensors from air and space-borne platforms by the US Geological Survey began in 1964 as a small effort funded by the National Aeronautics and Space Administration (NASA). Initial results were sufficiently encouraging so that research was expanded the following year into the fields of cartography, geography and hydrology. By the end of 1966 it was determined that many applications could also be developed within other bureaus of the Department of the Interior and to this end, the Earth Resources Observations System (EROS) Program was formed. The EROS Program is a multi-discipline effort in which seven agencies of the Department have vigorously sought, obtained and evaluated photographic and line-scan data from aircraft and spacecraft as they apply to resource inventory and management responsibilities. Nimbus and TIROS weather satellite data and photography from Mercury, Gemini and Apollo manned spacecraft missions provided early experience of viewing large areas of the earth from afar. This experience helped NASA and its sister agencies design the first Earth Resources Technology Satellite (ERTS 1).

ERTS 1, launched on 23 July 1972, flies at 915 km above the earth's surface, in a circular, near-polar orbit to provide synoptic views which cover 34225 km^2. Each scene is orthographic or distortion free. A mid-morning sun angle provides shadowing of surface features of a few hundred meters in relief. Two imaging systems are employed. One is a 3-camera, high resolution (4500 line) return beam vidicon (RBV) system in which each camera records a different spectral response. Unfortunately this system operated for only a few weeks before a power failure incapacitated its tape recorder. The RBV system is temporarily shut down but may be reactivated in the future if the second system fails or appears to degrade.

The second imaging system is the multi-spectral scanning system (MSS), consisting of four detectors that operate simultaneously in the green (500 to 600 μm), red (600 – 700 μm) and two near-infrared (700 – 800 and 800 – 1000 μm) bands. All the data, in the form of radio signals, are relayed directly to the nearest NASA reception stations in Alaska, California or Maryland or stored on tape recorders until the stations are in view. Canada also has a station for direct transmission and others are being constructed or considered in Brazil, Europe and Africa.

A third system on the satellite is an S-band data relay system for monitoring ground-based data collection platforms in North and Central America. The ground-based instruments include stream and tide gages, water quality meters, snow measuring devices for hydrologic experiments; tiltmeters and seismic event counters are used in conjunction with volcano monitoring experiments. EROS Program experimenters have a total of 116 such instruments located on a large number of test sites which include major river basins and estuaries, lakes and reservoirs as well as recently active volcanoes. The data relay system has been proven to be effective for a distance of 6500 km: from Iceland where a thermistor array monitored volcanic temperature and relayed this information via ERTS 1 to the Goddard Data Reception Center at Greenbelt, Maryland. Further details of the ERTS 1 system and its products can be obtained by requesting a copy of the *ERTS Data Users' Handbook*, available on sale for $ 10.00 from the General Electric Company, Beltsville, Md.

The ERTS 1 imaging systems operate in the visible and near-infrared spectrum and sense reflected radiation from the sun. Surface reflectance varies greatly from place to place depending on the composition, reflectance and absorption characteristics of the surface materials and also on the local composition of the atmosphere and its scattering characteristics. For example, images of forested areas of the tropics and temperate zones have less contrast than arid regions because of scattering properties of atmosphere in these regions. The green and red bands appear to be equally suitable in desert or arctic regions, while the near-infrared bands provide optimum information in tropical and temperate regions because atmospheric scattering is minimized and vegetative reflectance is greatest at the longer wavelengths. In the near-infrared bands surface water absorbs light and appears black except where silt or other impurities create a scattering effect. Moisture in soils appears as dark tones of gray.

It is (i) the synoptic view of large areas under uniform illumination, (ii) the absorption and reflectance characteristics of the earth surface, and (iii) repetitive observation that make ERTS 1 an excellent addition to our geophysical tools. Let us now consider three examples of geologic and geophysical problems that have presented difficulties to earth scientists for many years.

2. Problem 1: Regional and Continental Tectonic Analysis

One of the more difficult and complex geophysical problems that geoscientists have had in the past is that of regional and continental tectonic analysis. Such studies have had to rely on the synthesis of detailed surface mapping completed on a quadrangle by quadrangle basis and pieced together subjectively by scientists interested in a broad overview. These syntheses are then correlated with geophysical data obtained by ground or airborne surveys at different map scales. While many of these analyses are excellent in areas where surface mapping and geophysical information are abundant, the compilations are subjective and often valuable information is discarded. There are many areas of the world where mapping is inadequate or non-existent and, therefore, must be studied by other methods. Views of large areas as recorded by ERTS 1 place geologic structures in their true perspective and relationships. They are, therefore, ideal for regional and continental tectonic analysis. Adequate tectonic maps are fundamental to mineral resource development because they provide a base on which to develop ideas on metallogenesis and metallogenetic provinces which, in turn, are basic keys to exploration and development.

Synoptic, multi-spectral views of the earth provided by satellite imaging systems have already provided significant new information on the geologic structure of Alaska (Fig. 1) and a revision of metallogenic hypotheses in that rugged, less well-known state [1, 2]. Fig. 2a shows the distribution of metallic ore deposits of Alaska according to concepts based on geologic mapping and synthesis prior to ERTS 1. Fig. 2b shows the revision of metallogenic provinces due to new lineament information provided by Nimbus 4, and refined with ERTS 1 data. While it will be several years before mapping and exploration in Alaska can confirm or refute these new concepts, it is important to note that the new hypothesis has narrowed or confined the targets of interest to smaller areas and has resulted in a more rational distribution pattern for some ores, e.g. mercury, considered by many to be fault-associated. This interpretation has identified areas where new work

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Fig. 1. A clear day in Alaska from Nimbus 4.

Fig. 2a. Metallogenic provinces of Alaska based on geologic and geophysical mapping.

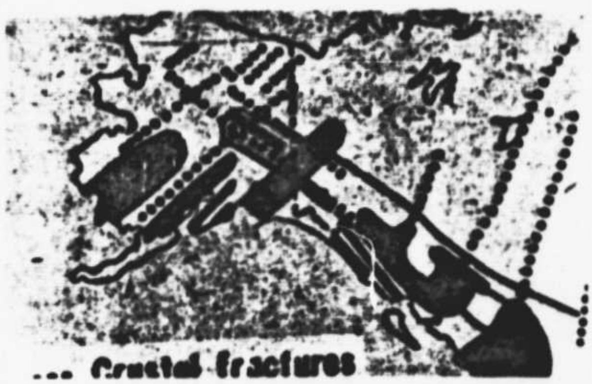

Fig. 2b. Revised metallogenic provinces of Alaska based on geologic and geophysical information combined with new information provided by interpretation of Nimbus 4 and ERTS 1 images.

should be done and should therefore reduce the time and costs of future mapping and exploration.

New views of the earth from ERTS 1 have also provided geologists with the opportunity to "see" large structures in well mapped areas that have not heretofore been defined. For example, Fig. 3 is a mosaic of ERTS 1 images of the State of Nevada where a major lineament is revealed that trends northeastward across the northern part of the state, transecting the northern end of the north-trending Basin and Range province [3]. Projection of this trend (Fig. 4) to the southwest indicates that it also marks the break between the Sierra Nevada batholith on the south and the Cascade volcanic chain on the north. If projected further to the west, it passes through the entrance (mouth) of San Francisco Bay. Here there is a suggestion that valleys, fault extensions and rock formations may be offset to the east along the north side of this projection. To the northeast, in southern Idaho, small segments of faults have been mapped along the trend. Along the trend is the Snake River downwarp, the southern limit of the Idaho volcanic field, the Island Park caldera and the geothermal areas of Yellowstone National Park. The Fromberg fault in Montana not far south of Billings may also be part

Fig. 3. ERTS 1 image mosaic of the State of Nevada.

of this trend. There is a coincidence of magnetic patterns with this lineament which suggests a tectonic and petrologic relationship.

A third aspect of tectonic mapping problem has to do with exploration for energy resources such as new geothermal and petroleum reserves. The repetitive nature of ERTS 1 permits us, for the first time, to collect data throughout the year; to map snowfall and snowmelt patterns with sufficient resolution to determine where geothermal heat sources may affect the surface. Snowmelt patterns have been recognized in areas of near-surface geothermal anomalies of Yellowstone

Park where snowfall thickness and melting rates have been used as a calorimeter by White [4].

In southern Mississippi arcuate stream drainages and vegetation patterns have been identified on ERTS 1 images that are related to known salt domes that are the sources of petroleum and possible geothermal energy in the state (Fig. 5).

Fig. 4. Generalized tectonic map of the United States showing indicated projection of the northern Nevada lineament.

Similar arcuate patterns have been identified in ERTS images south of the known salt dome region suggesting additional favorable structures for exploration. While most of the domal structures are less than 10 km in diameter, one has been defined that is 70 km in diameter. Although the significance of this feature has not yet been determined, it certainly defines an area that should be studied in greater detail by ground and airborne geophysical methods.

3. Problem 2: Volcano and Earthquake Monitoring

Active geologic phenomena such as volcanoes and earthquakes, especially those located in populated areas, present very special problems to man as he attempts to develop monitoring and predictive capabilities. On-site laboratories such as the Hawaiian Volcano Observatory have contributed much to man's under-

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standing of volcanism. New instruments such as tiltmeters and seismic event counters have been developed and tested at such sites to increase our ability to monitor the pulse of the earth.

With the flight of ERTS 1 the US Geological Survey began an experiment to monitor a large number of volcanoes that constitute part of the circum-Pacific "Ring of Fire". Sixteen volcanoes in a zone extending from Alaska to Nicaragua in Central America have been instrumented with tiltmeters, seismic event counters and thermocouples for monitoring changes in land surface, seismicity and temperature. These instruments are coupled to radio relay systems that transmit

Fig. 5. Composite ERTS 1 image of southern Mississippi showing location of suspected salt domes and a larger circular feature.

to and are relayed by ERTS 1 to receiving stations in California and Alaska. While the system was installed too late to assist in the monitoring of the Managua, Nicaragua, earthquake of 23 December 1972, it did record a number of earthquake swarms preceding the 23 February 1973 eruption of Volcan Fuego in Guatemala. Seismic event counters, installed in February 1973, were counting an average of five events a day until the number of events increased to 80 or more. Five days later Volcan Fuego erupted [5].

ERTS 1 data were used on a limited basis due to heavy cloud cover and low sun-angle in a study of the eruption of Kirkjufell on the island of Heimaey, Iceland [6]. However, the NOAA 2 weather satellite with its more frequent repeat cycle, poorer resolution and thermal imagery proved more useful in mapping the volcanic smoke plume and making quantitative measurements of radiant emission. More recent work by Williams in analysis of ERTS 1 imagery of Iceland has revealed several new sub-glacial calderas within the Vatnajökull (ice cap).

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4. Problem 3: Discrimination of Rock and Soil Types

Remote detection and discrimination of rock and soil types has been attempted from air and spacecraft during the past five years. An early attempt was made by Smedes and others [7, 8] in Yellowstone Park using the airborne multiband scanning system developed by the Willow Run Laboratories of the University of Michigan. Approximately nine generalized terrain types (rock rubble, kame terraces, etc.) were successfully mapped using four optimum bands from the twelve collected that were trained on small test plots (Fig. 6). Accuracies of over

Fig. 6. Multiband scanner image of surface terrain characteristics acquired from aircraft, Yellowstone National Park, Wyoming.

85% were obtained. Using the same bands that had been selected for the ERTS 1 satellite system the accuracy dropped a few per cent but still exceeded 80%.

Testing of a Reconofax IV thermal scanner (8 – 14 μm) [9] and, later, the same multiband scanning system using visible reflected infrared and thermal-infrared bands in the Mill Creek, Oklahoma, area [10] enabled a clear distinction to be made between limestone and dolomite, silica sandstone and granite. "Such discrimination of rock type was possible because of a combination of the inherently different albedo and thermal inertia properties of the limestones and dolomites" [9]. Pohn and others [11] have also used ratioing techniques in which day and night temperature differences in the thermal bands from Nimbus 3 and 4 satellite imaging systems are weighed against each other. They were successful in discriminating eleven rock and soil types in the Muscat and Oman area of the Arabian peninsula. Estimates of rock and soil density can be calculated by this approach. The clarity of atmosphere and lack of vegetation in this region enabled the investigators to conduct their experiment without interference from such factors. Several changes in the existing generalized geologic maps of the area were suggested by this study.

Fig. 7. Multiband camera image of oxidized breccia pipe in the Homestake Mine area, Montana. 1, blue; 2, green; 3, red; 4, near infrared.

A four-band multi-spectral aerial camera was tested from aircraft using bands and filters similar to ERTS 1 to study the effects of iron absorption in the near-infrared region [12]. An oxidized breccia pipe containing pyrite and copper ores in the Homestake Mine area in the New World mining district of the Beartooth Mountain Region in Montana was flown at moderate altitudes. The oxidized zone appeared dark on the near-infrared band while there was no marked anomaly in the visible region (Fig. 7). A similar response was recorded in the near-infrared band in data acquired over a nearby, chrome-bearing, ultramafic body (Fig. 8).

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While these deposits were relatively small in areal extent and below the resolution of the ERTS 1 system, it appears likely that larger but similar deposits can be recognized from ERTS 1. In fact, it appears that several new ultramafic bodies have been identified in color composites of ERTS 1 images in the foothills of the Sierra Nevada of California by Lathram (1973, written communication). These and

Fig. 8. Multiband camera image of chrome-bearing, ultramafic body near Homestake Mine area, Montana. 1, blue; 2, green; 3, red; 4, near infrared.

other suspected examples of iron absorption are now being field-checked. Thus far, these results are consistent with laboratory spectra for iron-rich and iron-poor minerals measured by Hunt and Salisbury [13] as shown in Fig. 9, and for selected felsic and mafic rocks as in Fig. 10 as determined by Ross, Adler and Hunt [14]. The visible and near-infrared reflectance spectra for limonite, Fig. 11, show diagnostic absorption at about 0.9 μm and 0.65 μm and a reflectance maximum at about 0.80 μm. The positions of the iron-absorption bands depend on the oxidation state and coordination of the iron bands.

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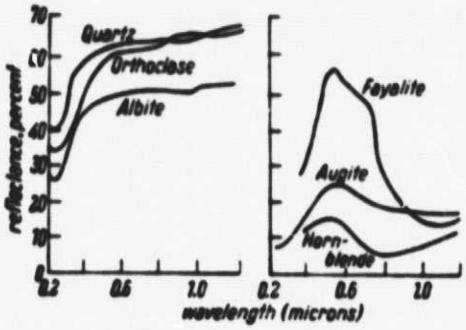

Fig. 9. Laboratory spectra of iron-rich and iron-poor minerals in the 0.2 – 1.5 μm region.

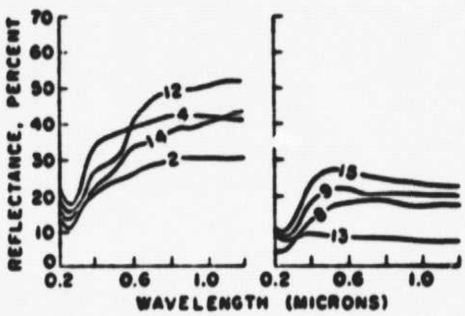

Fig. 10. Laboratory spectra of felsic and mafic rocks in the 0.2 – 1.5 μm region.

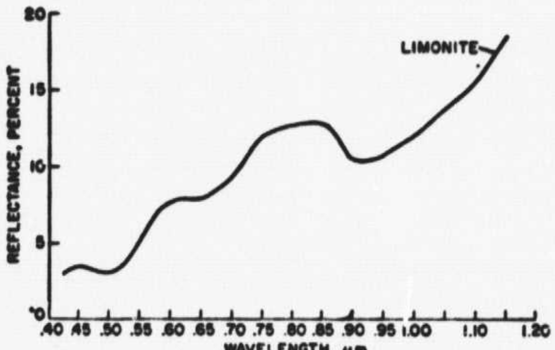

Fig. 11. Visible and near-infrared reflectance spectrum for limonite in the 0.4 – 1.2 μm region.

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5. Conclusions

Three major geophysical problems being addressed by studies of ERTS 1 data are: (i) regional and continental tectonic analysis; (ii) volcano and earthquake monitoring, and (iii) rock and soil type discrimination. At this time it can be stated that ERTS 1 imagery and data relay capability can contribute effectively to tectonic analysis and volcano monitoring on an operational basis. Modifications and additional instrumentation will be required before an earthquake monitoring system can reach the same stage and considerably more knowledge must be acquired before an operational predictive capability can be developed.

In the area of rock and soil type discrimination much more work is needed. ERTS 1 provides some of the basic ingredients required by virtue of its multispectral capability and current work is very encouraging. However, one or more thermal bands in the 10.5 – 12.5 μm range will be required to make such a mapping system more workable, especially if operated in both daytime and pre-dawn orbits. The multiband concept in which several visible, reflected infrared and thermal infrared bands will be tested over special sites during the current Skylab experiment will add to our knowledge. This experience should enable us to refine our requirements for future operational satellite systems.

Acknowledgment

Publication authorized by Director, US Geological Survey.

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