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ANALYSIS OF LANDSAT B IMAGERY AS A TOOL FOR EVALUATING, DEVELOPING, AND MANAGING THE NATURAL RESOURCES OF NEW MEXICO

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16. Abstract

The purpose of this study was to analyze Landsat B data in conjunction with data from conventional sources to provide new information for use in evaluating, developing and managing the natural resources of New Mexico. The following areas were pursued: A statewide land use and vegetation map was prepared by visual interpretation of Landsat images; geologic structure and metal deposits of the Datil-Mogollon volcanic area were investigated; computer enhanced images of the San Juan Basin region were studied for evidence of uranium and oil and gas deposits. Little success was achieved with the uranium and oil and gas studies, while roughly half the metal targets picked in the Datil-Mogollon area coincided with known areas of mineralization. The land use map produced meets the accuracy standards of the U.S. Geological Survey Topographic Division.

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PREFACE

The purpose of this investigation was to utilize data from Landsat (ERTS) along with data from other sources such as aerial photographs, manned-satellite photographs, geologic maps, and field investigations to provide new information for use in evaluating, developing, and managing the natural resources of New Mexico. The study area was the entire state of New Mexico although particular phases of the study were limited to specific areas. The study objectives as outlined in the contract were modified somewhat during the course of the investigation. Studies of earthquake zones, water erosion, and disaster assessment were deleted and a study using enhanced and ratioed images produced from Landsat computer compatible tapes as tools for uranium and petroleum exploration was added with the approval of the Technical Monitor, James Broderick. Emphasis was placed on the following phases of the study: structural and mineral exploration studies of the Datil-Mogollon volcanic area, the use of computer enhanced Landsat data as a tool for uranium exploration in the Grants uranium belt, and a study of the applicability of Landsat imagery for producing a statewide land-use, landform, and vegetative cover classification map. The results of these more detailed studies are reported in appendices. Phases of the investigation pursued in less detail are covered in the main part of the text.

During the investigation the principal investigator was changed from Karl Vonder Linden, who left the New Mexico Bureau of Mines and Mineral Resources in September, 1973, to David Tabet. Sandra Feldman of the

Technology Application Center (TAC), University of New Mexico left the study in July, 1975 and was replaced by Linda Love, also of TAC.

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INTRODUCTION

Study Objectives — The objectives of this investigation were to examine Landsat imagery of the entire state in order to determine its usefulness in the following disciplines:

Structural Survey -- This phase of the investigation was carried out over the middle Rio Grande Valley and Datil-Mogollon volcanic areas in order to delineate structural features important in understanding the tectonic and volcanic history, and factors controlling mineralization in the region.

Mineral Exploration -- This phase involved the study of contrast stretched and ratioed scenes of parts of an image of the San Juan Basin to see if surface alteration could be detected over uranium deposits. A separate part of this phase entailed using information from the Landsat structural study of the Datil-Mogollon area as an aide in understanding controls on mineralization and as a guide for picking mineral exploration target areas.

Petroleum Exploration -- The above techniques for uranium exploration were also applied to part of the San Juan Basin underlain by petroleum reservoirs to see if surface anomalies could be detected over them.

Volcano and Lithologic Surveys -- A continuation of the Landsat A (ERTS-1) study, this phase was directed at mapping individual volcanic flow units in the west-central part of the state near Mount Taylor in an attempt to increase knowledge of the Cenozoic volcanism there.

Land Use Survey and Mapping -- This study was made to examine the utility and accuracy with which Landsat data could be used in producing a land use, landform, and vegetation type map for the entire state of New Mexico. A subproject of this study involved the preparation of a separate smaller scale land use map for the city of Socorro and surrounding area using underflight aerial photography, and field survey information.

Personnel -- Listed below are the people involved in this investigation, their affiliation, and their contribution.

Name, Title (Discipline)	Affiliation	Contribution
D. E. Tabet P.I. (geology)	New Mexico State Bureau of Mines & Mineral Resources	Administration plus structure and exploration studies
M. H. Inglis Co. I. (geology)	Technology Application Center, University of New Mexico	Administration plus mineral exploration studies
S. A. Morain Co. I. (Biogeography	"	Vegetation and land use mapping
L. L. Love Co. I. (geology)	"	Mineral exploration studies
S. C. Feldman Co. I. (geology)	"	Vegetation and land use mapping
T. K. Budge Co. I. (Biogeography)	"	Vegetation and land use mapping
M. E. White Research Ass't (geography)	"	Vegetation and land use mapping and hydrology

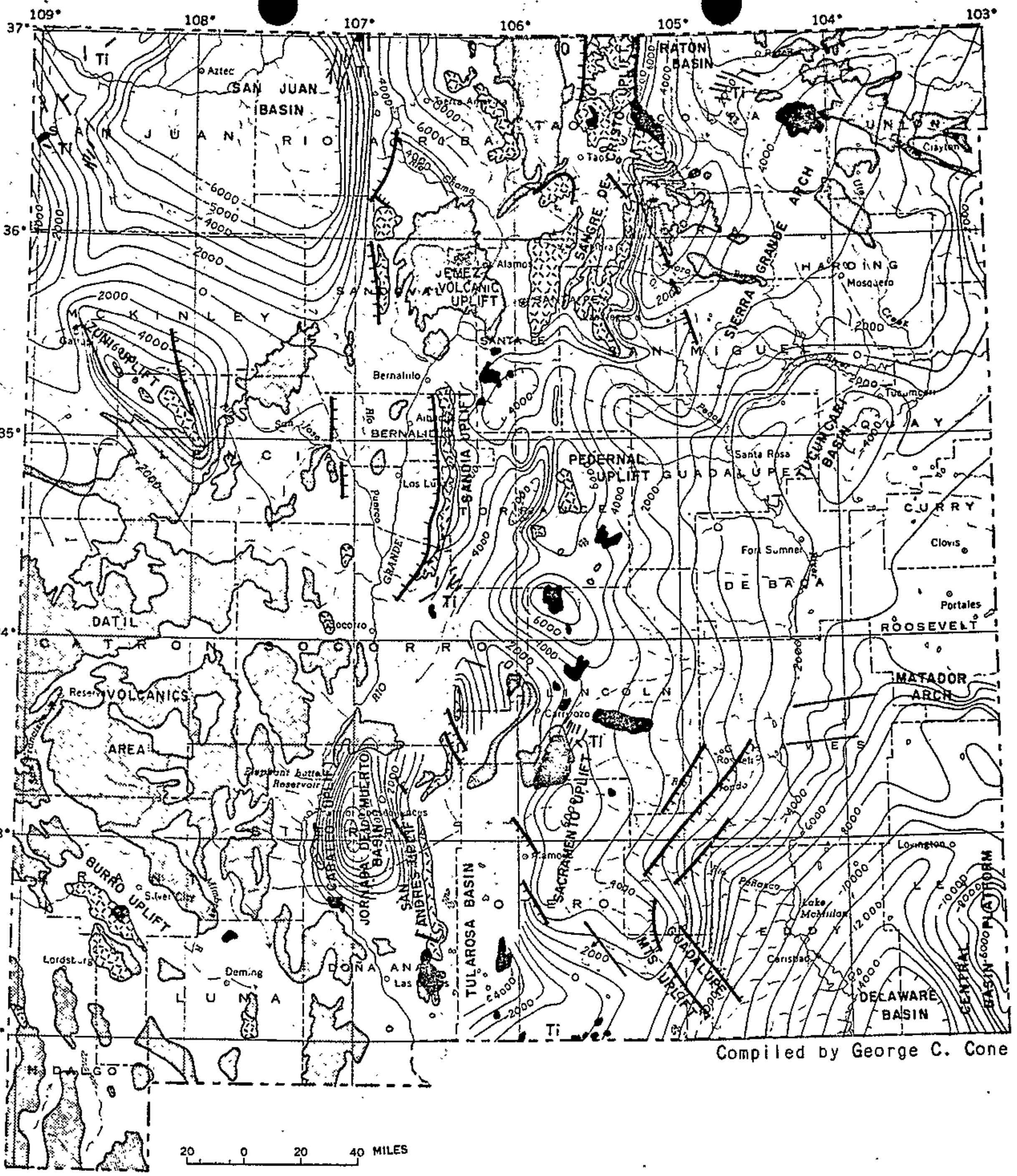
Name, Title (Discipline)	Affiliation	Contribution
A. M. Komarek Research Ass't (geography)	Technology Application Center, University of New Mexico	Vegetation and land use mapping
G. W. Wecksung Consultant (computer science)	Los Alamos Sci. Lab. Los Alamos, NM	Computer processing and statistical methods of data processing
R. W. Vogel Consultant (computer science)	"	Computer processing and statistical methods of data processing
A. D. M. Bell Consultant (geology)	School of Applied Geol. University of New So. Wales, Australia	Exploration studies

Geographic and Geologic Setting -- Every major rock type and rocks from every period of geologic time are exposed within the state of New Mexico. These rocks record a long and varied geologic history. There were times of transgression of shallow seas and times of retreat of the seas with the formation of large coal swamps or the development of vast evaporating pans. Other times saw great mountain building and episodes of volcanic activity. At still other times, erosion ate away at the mountains and deposited thick alluvial and flood plain sedimentary deposits over wide surfaces of land above sea level.

The oldest rocks in the state are Precambrian in age (0.6 to 2,000 million or more years old). Precambrian rocks form the foundation or "basement" on which subsequent sequences of rocks were layed down. These oldest rocks are principally exposed in the cores of mountain ranges such as the Burro, San Andres, Zuni, Sandia, Naciemento, and the Sangre de Cristo Mountains along the major uplifts shown on the generalized tectonic map of the state (Figure 1). North-south trending uplifts are predominant through the central portion of the state. The Precambrian rocks, originally sedimentary and igneous rocks, have been recrystallized or metamorphosed by deep burial with extreme pressures and temperatures or by intrusion of large bodies of granite to form quartzites, greenstones, and foliated schists and gneisses. No fossils are found in these rocks and they can be subdivided only on the basis of rock type or age as determined by radioactive isotope dating methods.

Paleozoic rocks, or rocks containing the earliest abundant life forms, are represented by a succession of sedimentary rocks that were deposited from 600 to 230 million years ago. These rocks are divided into systems and local formations on the basis of differing lithology and fauna. The oldest Paleozoic rocks in New Mexico, divided into the Cambrian, Ordovician, and Silurian Systems in order of decreasing age, consist mainly of limestone and dolomite along with some sandstone. Shallow seas that oscillated across the land were the environment in which these rocks formed. These rocks are preserved only in the major basins of southern and northwestern New Mexico.

Younger Paleozoic rocks of the Devonian, Mississippian, Pennsylvanian, and Permian Systems reflect many changing environments of deposition. Besides limestone, dolomite, and sandstone, these rocks include conglomerate, shale, and evaporites. The Devonian rocks are a relatively thin but widespread sheet of dark, calcareous or sandy marine



Compiled by George C. Cone

Figure 1. Generalized tectonic map of New Mexico.

EXPLANATION

Thrust fault
Sawteeth on upper plate

Normal fault
Hachures on downthrown side

Monoclinal flexure

● ——— Ti
Intrusive bodies of probable Tertiary age

Volcanic rocks of Quaternary and Tertiary age

Rocks of Precambrian age

4000
Structure contours on Precambrian surface
Contour interval 1,000 feet. Datum is sea level. Modified from Foster and Stipp, 1961

shale. The distribution of these rocks is much the same as earlier Paleozoic rocks, but slightly wider in extent.

Mississippian rocks are found throughout New Mexico at the surface or in the subsurface. The Mississippian strata consist mainly of limestone and may be as much as 1,200 feet thick.

Pennsylvanian and Permian rocks were deposited in nearly all parts of the state in widely variable environments and therefore consist of a great variety of rock types. Pennsylvanian strata are composed of limestone, gypsum, sandstone, and conglomerate. All of these rock types as well as much dolomite make up the Permian formations. In southeastern New Mexico, Permian formations include important deposits of salt and potash and the combined thickness of Pennsylvanian and Permian strata reaches 12,000 feet.

Deposits from the Mesozoic era (250 to 70 million years ago) include rocks of the Triassic, Jurassic, and Cretaceous Systems in ascending order. The seas withdrew from New Mexico at the close of Paleozoic time and thus the older Mesozoic rocks are continental in origin. Triassic rocks consisting mostly of red to maroon floodplain deposits of shale and sandstone are preserved in the northern and eastern parts of the state. Along the eastern part of the state, Triassic rocks may be up to 2000 feet thick.

Jurassic rocks are composed of a complex sequence of clastic sediments deposited in a wind blown, a stream, or a lake environment. Found only in the northern half of the state, Jurassic strata may exceed 1000 feet in thickness.

Cretaceous time saw the seas wash over New Mexico once again, and as the shoreline oscillated a complex intertonguing sequence of marine and marginal marine deposits were layed down. Lower Cretaceous rocks were deposited in a deep basin in southwestern New Mexico and are more than 15,000 feet thick. The seas that deposited Upper Cretaceous rocks encroached from the north and generally extended only as far south as the middle of the state. The Upper Cretaceous sequence consists of sandstone, siltstone, shale, and important coal deposits.

Cretaceous time represents the last encroachment of the seas across New Mexico. With the retreat of the Cretaceous seas, the region was uplifted and underwent mountain building.

Tertiary aged rocks (70 to 1 million years old) consist of shale, sandstone, some coal, and intrusive and extrusive igneous rocks. The sedimentary formations were shed off the rising mountain masses and deposited in intermontane basins. Southwestern New Mexico was an especially active volcanic area in Tertiary time.

Rocks of Quaternary age (1 million years to the present) also include sedimentary and some minor volcanic deposits. The sedimentary deposits are valley fill material made up primarily of clay, sand, and gravel as well as deposits of caliche. Most of the Quaternary sedimentary deposits are unconsolidated. The volcanic rocks consist of flows and ash falls of varied composition.

Mineral Deposits -- New Mexico has been blessed with a wealth of mineral deposits (Table 1) and mineral production makes up a major part of the

TABLE 1.

MINERAL PRODUCTION IN NEW MEXICO[1]

Released by U.S. Bureau of Mines, December 30, 1974

Mineral	1973 Quantity	1973 Value (thousands $)	1974 p/ Quantity	1974 p/ Value (thousands $)
Clays[2] .... thousand short tons ...	88	169	W	W
Coal (bituminous) .... do	9,069	31,862	9,392	41,619
Copper (recoverable content of ores, etc.) short tons	204,742	243,643	196,585	303,920
Gem stones	NA	70	NA	200
Gold (recoverable content of ores, etc.) troy ounces	13,864	1,356	15,427	2,464
Gypsum .... thousand short tons	255	1,220	157	532
Iron ore (usable) thousand long tons, gross weight	5	114	W	W
Lead (recoverable content of ores, etc.) short tons	2,556	833	2,364	1,064
Lime .... thousand short tons	44	793	58	1,697
Manganiferous ore (5 to 35 percent Mn) short tons	32,034	W	W	W
Mica, scrap .... thousand short tons	10	82	12	60
Natural gas .... million cubic feet	1,218,749	287,889	1,223,208	391,534
Natural gas liquids:				
Natural gasoline and cycle products thousand 42-gallon barrels	9,848	32,449	30,118	162,636
LP gases .... do	29,652	74,427	17,911	96,721
Peat .... thousand short tons	3	50	W	W
Perlite .... do	478	5,024	480	6,306
Petroleum (crude)–thousand 42-gallon barrels	100,986	414,041	96,416	696,334
Potassium salts .... thousand short tons	2,168	91,996	2,102	128,589
Pumice .... do	339	1,001	471	1,466
Sand and gravel .... do	10,641	15,753	7,413	10,605
Silver (recoverable content of ores, etc.) thousand troy ounces	1,111	2,843	1,195	5,628
Stone .... thousand short tons	2,830	5,894	3,539	8,359
Uranium (recoverable content U_3O_8) thousand pounds ...	9,263	60,356	9,971	104,693
Zinc (recoverable content of ores, etc.) short tons	12,327	5,094	13,784	9,897
Value of items that cannot be disclosed: Cement, clay, iron, sulfur, fluorspar (1974), molybdenum, salt, tin, vanadium and values indicated by symbol W	XX	29,631	XX	37,500
Total	XX	1,306,590	XX	2,011,824

p/ Preliminary. NA Not available. W Withheld to avoid disclosing individual company confidential data; included with "Value of items that cannot be disclosed." XX Not applicable.

[1] Production as measured by mine shipments, sales, or marketable production (including consumption by producers).

[2] Excludes fire clay; included with "Value of items that cannot be disclosed."

OIL AND GAS PRODUCTION, 1974

(Annual Report of New Mexico Oil and Gas Engineering Committee)

County and area	CRUDE OIL (barrels) Production	CRUDE OIL (barrels) Gain (+) or decline (–) from 1973	NATURAL GAS (thousands cu ft) Production	NATURAL GAS (thousands cu ft) Gain (+) or decline (–) from 1973
Chaves	1,787,622	–133,491	10,293,711	–14,401
Eddy	21,504,533	+3,464,235	229,214,339	+17,958,713
Lea	66,028,464	–5,806,427	436,930,336	+16,777,410
Roosevelt	1,372,927	–246,907	5,842,166	–1,862,112
Southeast area	90,693,546 (92%)	–2,722,590	682,280,552 (55%)	+32,859,610
McKinley	1,263,069	–410,382	2,668,041	+ 312,739
Rio Arriba	1,475,669	–140,066	174,869,865	–3,776,838
Sandoval	264,131	+ 63,723	1,288,661	+ 249,462
San Juan	4,998,550	+918,594	368,565,817	+ 488,533
Northwest area	8,001,419 (8%)	+431,869	547,392,384 (45%)	–2,726,104
State totals	98,694,965	–2,290,721	1,229,672,936	30,133,506

state's economy. Energy minerals and materials make up the bulk of the value of mineral production in the state with petroleum and natural gas at the top followed by uranium and coal. Petroleum and natural gas are recovered from basins in the southeastern and northwestern parts of the state. The San Juan Basin in northwestern New Mexico also produces large amounts of uranium and coal. Coal is also produced from the Raton Basin in the northeastern part of the state.

Industrial minerals, especially potash, perlite, and gypsum, account for another large part of the mineral wealth produced. Potash is mined in the Delaware Basin in southeastern New Mexico in the vicinity of Carlsbad. Perlite is taken from ancient, frothy volcanic domes found near Socorro, Grants, and north of Taos. Gypsum is produced at White Mesa about 40 miles northwest of Albuquerque.

Metallic mineral deposits in New Mexico occur in a broad belt extending southwesterly from the Sangre de Cristo Mountains to the southwestern corner of the state. This belt follows the general trend of the Rio Grande valley south to the vicinity of Socorro where it spreads to encompass the whole southwestern part of the state.

The metallic mineral deposits are generally associated with cooled bodies of magma or solutions derived from bodies of magma. Structural features in the earth, such as faults and fractures, have acted as channels for rising magmatic solutions or as zones of weakness along which magma has been intruded. Fracture patterns in regions of magmatic activity are therefore often important guides to locating important mineral deposits.

Present metal production is largely from open pit operations at Santa Rita and Tyrone in the southwest, and at Questa in north-central New Mexico. Copper as well as some gold, silver, and molybdenum are the metals produced from disseminated deposits associated with intrusive bodies at Santa Rita and Tyrone. At Questa, molybdenum is the major metal with the other three mentioned above in subordinate amounts. Historically, vein deposits and replacement deposits associated with veins have been important producers of lead, zinc, copper, silver, and gold in numerous districts throughout the New Mexico mineral belt. Although presently dormant, these districts and surrounding areas have potential for further mineral development.

RESULTS OF INVESTIGATION

Volcano and Lithologic Surveys -- The purpose of this study was to map the volcanic rocks in the Laguna and Bandera lava fields, Valencia County, New Mexico (Figure 2). As individual flow units within the Quaternary basalt flows had not been mapped on the Geologic Map of New Mexico (Dane and Bachman, 1965) a study was performed to examine the feasibility of using Landsat imagery in their delineation. Several scenes were examined, the best of which was taken on April 7, 1974, (E 1623-17155). An examination of aerial photographs together with Landsat imagery revealed a striking difference between the older, more weathered Laguna flows and the younger Bandera flows (Figure 3, Landsat color composite 1623-17155 showing two groups of flows). The Bandera lava field erupted from several local centers and primary flow features are preserved. Because lava tubes are present

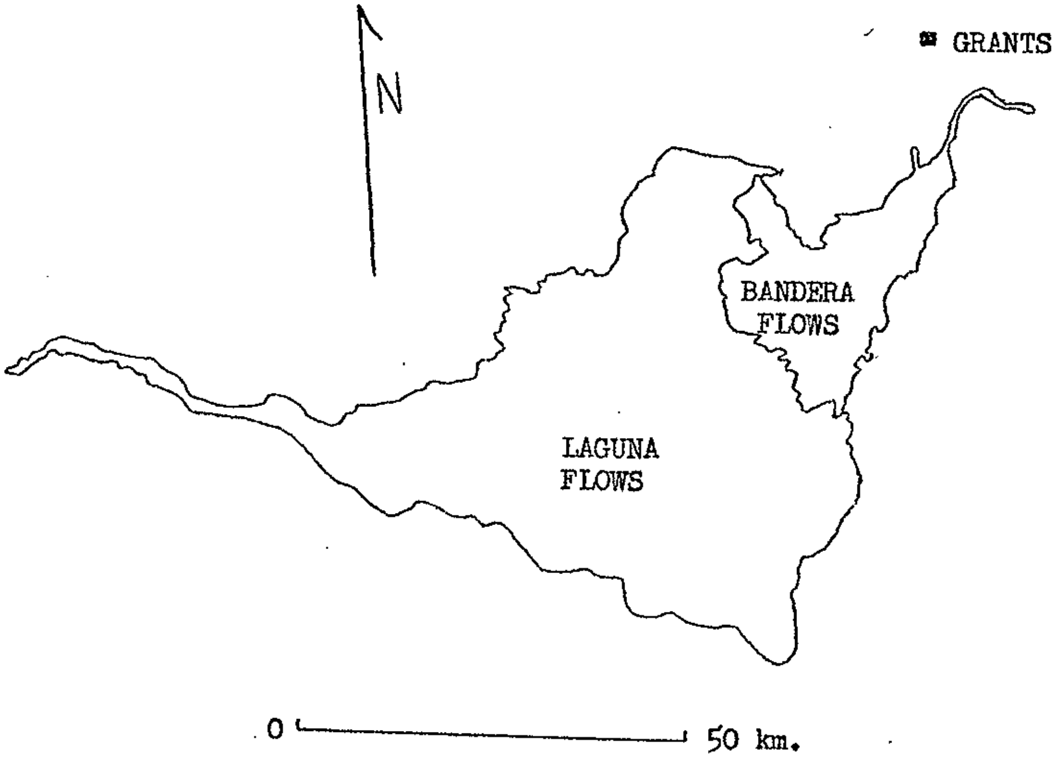


Figure 2. Sketch map of the lava fields.

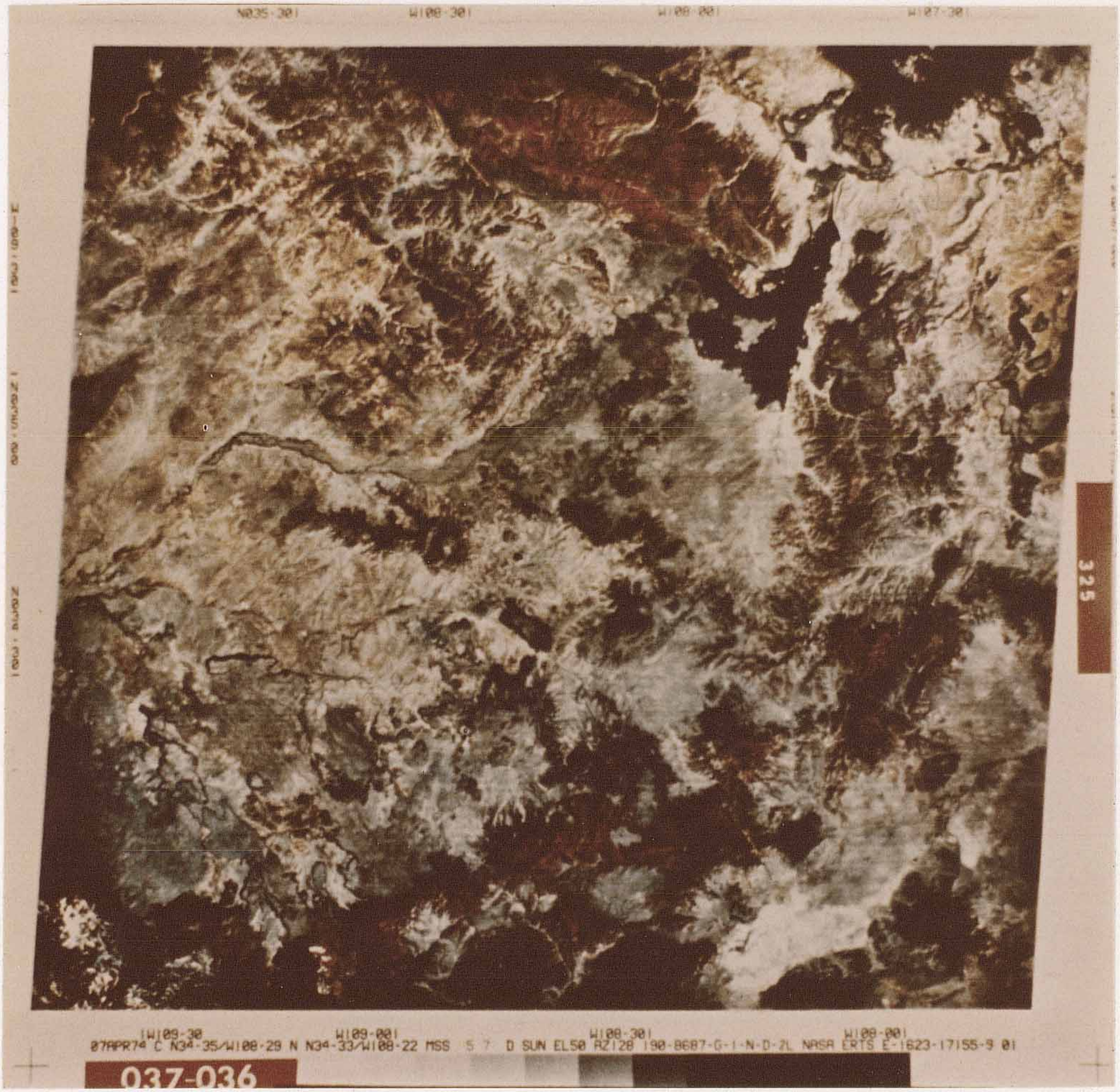


Figure 3. Landsat Color Composite of the lava fields.

in the Bandera lava field, the area is well known as a lunar analog. Several authors (Causey, 1971; and Hatheway and Herring, 1970) have done detailed mapping of individual flow units and delineation of source areas in the Bandera field. Other maps of the area were done by Thadden, Merrin, and Raup (1967) and Thadden, Santos and Raup (1967). Similar detailed mapping has not been performed in the Laguna flows. Field investigation revealed the occurrence of ponderosa pine on basalt outcrops. The stands of ponderosa are limited to those areas where basalt is exposed or where a very thin veneer of wind-deposited soil is present on top of the basalt (Figure 4). There is almost a one-to-one relationship of ponderosa pine to basalt outcrops. The vegetation on areas where basalt is not outcropping consists of scattered pinon and juniper and abundant snakeweed (Figure 5). Flow boundaries are usually scarps from 3 to 6m high and are composed of blocky boulders of basalt. The scarps are usually vegetated with ponderosa pine (Figure 6, note edge of flow in trees).

Most of the Laguna flows are covered with a buff to red wind-deposited soil. The thickness of the soil ranges from more than one meter to a wedge edge. Where present the soil completely obliterates surface features of the flows.

In general, the morphology of the Laguna flows is very subdued in comparison to the younger Bandera flows. Cinder cones have gentler slopes and generally are forested with ponderosa pine. Where the edge of a flow is a scarp of basalt boulders, ponderosa pine is usually present. Where outcrops are absent, no ponderosa is present.

Figure 4. Ponderosa pines growing on basalt outcrops.

Figure 5. Vegetation growth in areas where basalt does not crop out.

Figure 6. Flow boundary delineated by ponderosa pine.

The first analysis of the lava fields was by visual inspection of the Landsat, Skylab and low altitude aerial photographs. Although there are striking differences on the photos, these differences could not be consistently correlated to the individually mapped units of the Bandera lava fields. Color composites proved most useful in discriminating flows but only in the more recent ones. A Bausch and Lomb Zoom Transfer Scope was used during the interpretation to provide image enlargement and correlation to several of the younger Bandera units previously mapped. Negatives (scale 1:1 million) were made from the black-and-white bands 5 and 7. These were then used on an International Image Systems digicol to enhance in color the densities of the flow units. In addition, a color additive viewer was employed in the analysis. In neither case, however, was a satisfactory discrimination of the Bandera flows noted, nor was a correlation with existing mapped units observed. Within the Laguna field there was no discrimination between flow units. It is felt that delineation of lava flows within New Mexico cannot be made using the visual interpretation or visually enhanced photographic methods at the scale of the bulk processed imagery using the present spectral bands.

Hydrologic Studies -- Remote sensing, in all its types and forms, is a useful data gathering tool for hydrologic studies. Table 2 presents a synopsis of the different sensors available and their areas of application taken from the literature. The Landsat satellites are the only remote sensing system which provides temporal data in four separate bands of the electromagnetic spectrum for the same scene. This four channel scanning system enables

TABLE 2

Remote Sensor Hydrologic Resource Applications

Sensor	Snow Cover	Soil Moisture	Water Quality	Ground Water	Runoff Detection	Watershed Land Use	Resource Mapping	Sediment	Surface Water Inven.	Real Time Water Res. Data	Erosion
Radar	X	X	X	X			X				
Passive Microwave	X	X									
Thermal Infrared	X	X	X	X	X	X					
Near Infrared	X	X	X	X	X	X	X	X			
Aerial Photography	X	X	X	X	X	X	X	X	X		X
Landsat Satellites	X	X	X			X	X		X	X	X

scenes of the different bands to be contrasted and compared to one another, thereby accentuating physical features having different spectral characteristics. Digitized Landsat data allows further enhanced scene comparison by ratioing one spectral band to another. Landsat images also contain sufficient spatial resolution to meet U.S.G.S. mapping requirements at a scale of 1:250,000.

Landsat imagery was examined visually to investigate surface fluctuations and from there possibly calculate water volumes for New Mexico water bodies. This study found Landsat imagery was useful in qualitative lake level monitoring. While lake level fluctuations are detectable, the determination of surface acreages with consistent accuracy is not possible using established visual measurement techniques. It is possible that further research into this problem, probably using digital techniques, will develop a reliable means for measuring surface acreages of standing water bodies. Additional modeling studies may then provide a means for estimating water volumes using knowledge of the topography in the areas concerned.

Petroleum Exploration -- As a part of a cooperative study with the Los Alamos Scientific Laboratory (LASL) an analysis was undertaken in the spring of 1976 of contrast stretched and ratioed images produced from portions of the computer capatible tape of Landsat scene E 1425-17193 which covers the San Juan Basin. LASL personnel performed the computer enhancement on their facilities to provide the image products for analysis of whether or not surface anomalies could be detected over the Bisti oil field. Donovan (1975) has been able to detect subtle surface manifestations expressed as variations in tone, color, and geomorphology, using computer enhanced Landsat images of other oil fields. The objective of this study was to apply recently developed digital techniques (Rowan and others, 1974; Spirakis and Condit, 1975) to see if surface anomalies could be detected in New Mexico. The Bisti oil field area (Figure 7) was chosen because it is a well defined major oil field in the San Juan Basin. This study, if successful over a known oil field, could then be expanded to cover other favorable but less well known areas in the basin.

The methods of image enhancement and the enhanced image products used in this study are described in more detail in the uranium exploration study appended to this report. In brief, simple linear-ratioed images were prepared for the following contrast stretched band pairs: 5/4, 6/4, 7/4, 4/5, and 4/7 (Figure 8). Two composites of three linear-ratioed images were also prepared with the following combinations: 5/4=blue, 6/4=green, and 4/7=red, along with 4/7=blue, 6/4=green, and 7/4=red (Figure 9).

No simple correlation could be made between the area underlain by the Bisti oil field and specific areas on the enhanced images. The enhanced images did tend to show up areas, for example the reddish areas in the first composite, which correspond almost exactly with lands classified as Badland-Rockland areas by Maker, Keetch, and Anderson (1963) on their soil association map for San Juan County. In order to see if Badland-Rockland areas had any relationship to other Cretaceous oil fields in San Juan County, the soil data was plotted on the map with the boundaries of the Cretaceous oil and gas fields (Figure 7). Although not conclusive, the

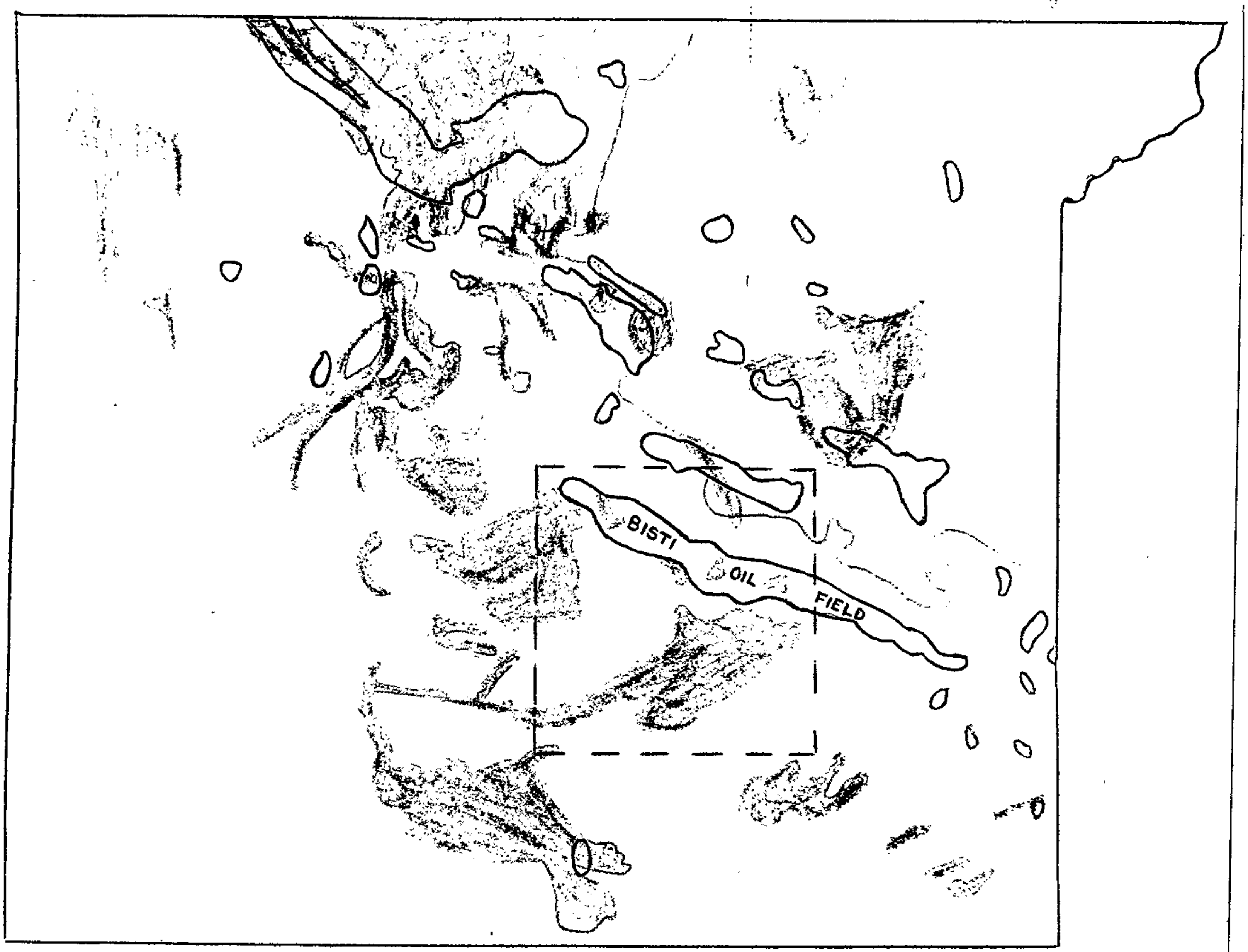
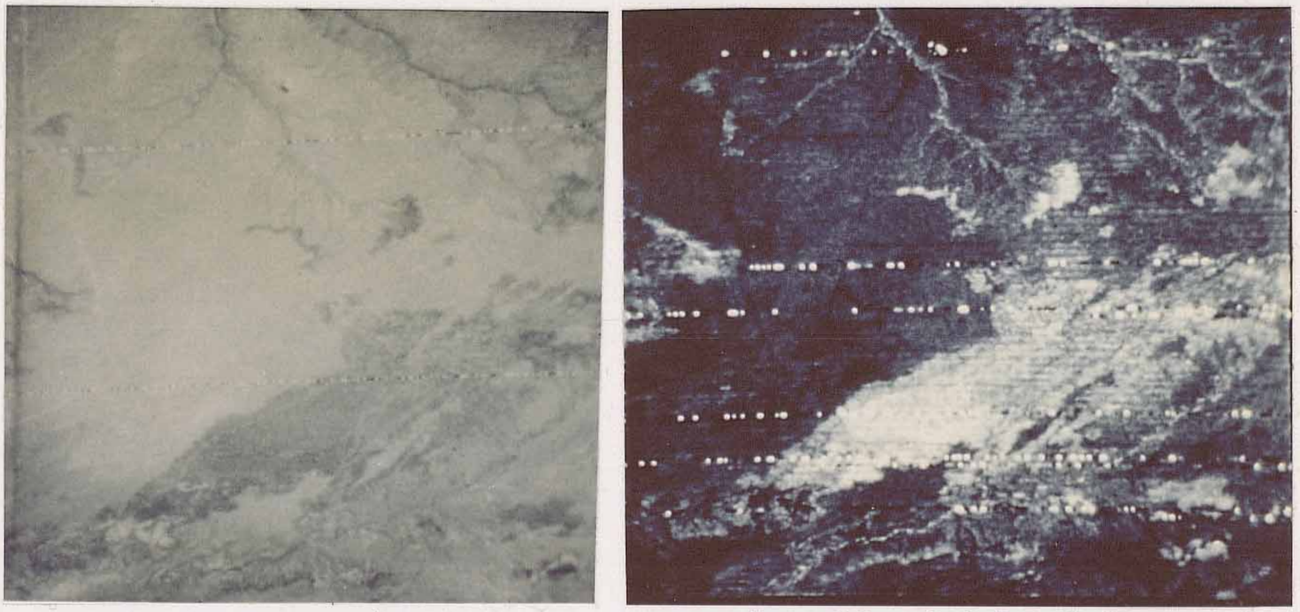


Figure 7. Oil and gas fields of San Juan County, N.M.; oil fields have a dark outline, gas fields have a light outline, and Badland-Rockland areas are shaded.



Ratio of band 6/band 4 Ratio of band 7/band 4

Ratio of band 4/band 5 Ratio of band 4/band 7

Figure 8. Linear-ratioed Landsat MSS images of the Bisti oil field study area showing (A) the Chaco compressor station, and (B) Badland-Rockland soil areas. Scale is approximately 1:362,000.

Color composite of linear-ratioed images with 4/7 in blue, 6/4 in green, and 7/4 in red.

Color composite of linear-ratioed images with 5/4 in blue, 6/4 in green, and 4/7 in red.

Figure 9. Color composites of linear-ratioed Landsat MSS images of the Bisti oil field study area. Approximate scale is 1:362,000.

overlying position or close proximity of many Badland-Rockland areas to the oil fields in San Juan County seems to suggest a possible genetic relationship between the two.

Further study could perhaps prove or disprove the relationship suggested above; however, this study only afforded a one-time look at the Bisti area. Also the lack of a hands-on computer enhancement capability limited extensive enhancement efforts. A brief two day field inspection of the test area found no particular tonal or color anomalies visible over the Bisti oil field, but the Badland-Rockland areas do have prominent geomorphic expression on the ground. They are barren or nearly barren outcrops of shale and sandstone having varied relief.

CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this investigation, to utilize data from Landsat (ERTS) and other sources to provide information useful in evaluating, developing, and managing New Mexico's natural resources, has for the most part been realized. Landsat data by itself provides much useful information, but it can be most fully utilized in combination with data from other sources.

Visual surveys of volcanic lithology and hydrology, detailed small-scale studies, proved to be the least effective ones. The spatial and spectral resolution was visually insufficient for discriminating the detail desired. Large-scale, regional surveys covering one or more images, such as the structural and mineral investigation of the Datil-Mogollon volcanic province, and the state-wide mapping of land use, landforms, and vegetation, were better suited to visual interpretation of Landsat data.

Computerized studies of Landsat digital tapes offer more complete and detailed interpretation than by visual methods since scenes can be examined pixel by pixel and enhanced in various ways. Some frustration was felt during this investigation since we lacked the hardware and software capabilities to enable us to do interpretation of Landsat in a digital mode. Therefore, we feel a complete analysis of Landsat applications was not possible.

Through a cooperative arrangement with Los Alamos Scientific Laboratory limited computer enhanced imagery was analyzed for use in uranium and petroleum exploration. Neither study provided conclusive results. Alteration associated with uranium was not identified but superior lithologic discrimination was achieved. Anomalies associated with petroleum were not found but a close association of certain landforms and soil types with oil reservoirs was noted. Further detailed computer analysis is needed to determine if the easily recognized lithology of the Morrison Formation can be subdivided into altered and unaltered areas. More analysis is needed for the Bisti oil field area to determine the exact relationship between Badland-Rockland areas and the oil fields.

Better results in the studies of volcanic lithology and hydrology would probably be possible with the more detailed areal and spectral analysis allowed by digital computer analysis. Another area where computer analysis of Landsat data may be of use is in monitoring coal strip mining and reclamation. The three inspections per year presently take one man-week per inspection trip, not including report preparation time. The addition of several proposed mines by 1980 will increase the inspection time to two man-weeks or more. If as demonstrated in other states (Anderson and others, 1975) Landsat can be used in New Mexico to classify areas of active mining, ungraded spoil, graded spoil and reclaimed areas it would produce a considerable saving of time and effort in monitoring coal strip mining activities, especially since most of the mines occur within the area covered by one image.

Considerable interest in the final results of this investigation has been indicated by various agencies contacted during the course of the investigation. The State Geologist's Office, concerned with the development of the state's energy resources, and the Governor's Energy Resources Board, have both requested copies of the papers covering the digital studies of Landsat imagery for uranium and petroleum exploration when they become available. With regard to the state land use and vegetation map, the State Planning Office is interested in using the information with its new computerized compositing mapping system. Also interested in using the map are the U. S. Forest Service, New Mexico Natural Resources Conservation Commission, the New Mexico Environmental Improvement Agency, and the New Mexico Interagency Range Commission. Finally, two active researchers of volcanics and mineral deposits of southwestern New Mexico, Chapin and Elston (pers. comm., 1976) have expressed interest in the findings of the Datil-Mogollon studies. All of this indicates that Landsat is a useful tool and can provide data for normal every-day operations for a wide range of natural resource and planning agencies. An important factor in the use of Landsat data is educating the users in how their needs can be satisfied with Landsat data. Data needs of these agencies are hard to predict, but a growing and continuing need for Landsat data will probably develop as more people and agencies learn about it and how to use it.

The nature of most of our investigation did not lend itself to analysis of costs for comparable methods. Only the land use portion of our investigation provides a good cost per acre comparison between using Landsat and aircraft imagery. Our experience shows that for studies of large areas Landsat imagery is definitely less expensive than conventional aerial photography when used in a visual mode. As illustrated in Table 3, the total costs for acquisition, visual interpretation, and preparation of vegetation and land use maps using Landsat imagery is at least one order of magnitude less expensive than that for using aircraft imagery.

None of our other studies afforded such ready cost comparative data. Landsat imagery is not simply an inexpensive substitute for previous data systems. Factors such as scale and resolution sometimes limit Landsat to use as a supplemental source, especially in detailed, small areal studies.

Table 3. Time and Approximate Costs for Producing Vegetation and Land Use Maps from Remote Sensing Images.

Task	Time and Cost Using Landsat Imagery				
New Mexico (121,666 sq.mi.)	Man Months	Cost ($)	Materials ($)	Total Cost ($)	Cost ($)/ Sq. mi.
Imagery Acquisition	--	--	600	600	@
Image Interpretation	.5	1150	300	1450	.01
Map Compilation	.5	1150	50	1200	.01
Field Checking*	2.0	4600	--	4600	.04
Drafting**	2.0	4600	150	4750	.04
	5.0	11500	1100	12600	.10

Task	Time and Cost Using Aircraft Imagery				
Socorro Area (1200 sq.mi.)	Man Months	Cost ($)	Materials ($)	Total Cost ($)	Cost ($)/ sq. mi.
Imagery Acquisition	--	--	670	670	.56
Image Interpretation	.12	200	75	200	.17
Map Compilation	.05	80	25	200	.17
Field Checking*	.25	400	--	400	.33
Drafting**	.32	400	20	400	.33
	.74	1080	790	1200	1.56

@ Less than $.005 per square mile

* Includes travel expenses and per diem

** Includes preparation of black plate, grey plate, color separation plates, text editing, map editing.

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APPENDIX A

Study of Digital Techniques as Applied to Uranium Exploration of the Grants Mineral Belt

INTRODUCTION

In the fall of 1975, the opportunity arose to participate in a cooperative venture with Los Alamos Scientific Laboratory (LASL) in the area of computer enhancement of Landsat digital tapes. LASL personnel, computing facilities, and digital tapes were used to generate images which were interpreted by New Mexico Bureau of Mines and Mineral Resources and Technology Application Center personnel.

The objective of this study was to develop and test techniques for uranium exploration with computer enhanced images of a known uranium producing area. Providing these techniques were successful, an extensive survey might then be performed over large areas of New Mexico having similar geologic conditions. Such information would reduce the cost and time needed in regional exploration. The tapes available to us which appeared to have the greatest number of possibilities for geologic interpretation cover the northwestern corner of New Mexico (Scene E-1425-17193) and north central New Mexico (Scene E-1658-17091). The northwestern corner of New Mexico is unique in that it is presently the site of production of several fuels.

The northwestern corner of New Mexico is considered to be part of the Colorado Plateau with the San Juan Basin being the major physiographic subdivision (Figure A-1). The basin is about 300 km long (north to south) and 200 km wide. Triassic rocks are exposed at the edges of the basin and Eocene strata are the youngest sedimentary rocks exposed in the interior of the basin. The basin extends northward to the San Juan Mountains in Colorado. It is bounded on the southeast by the

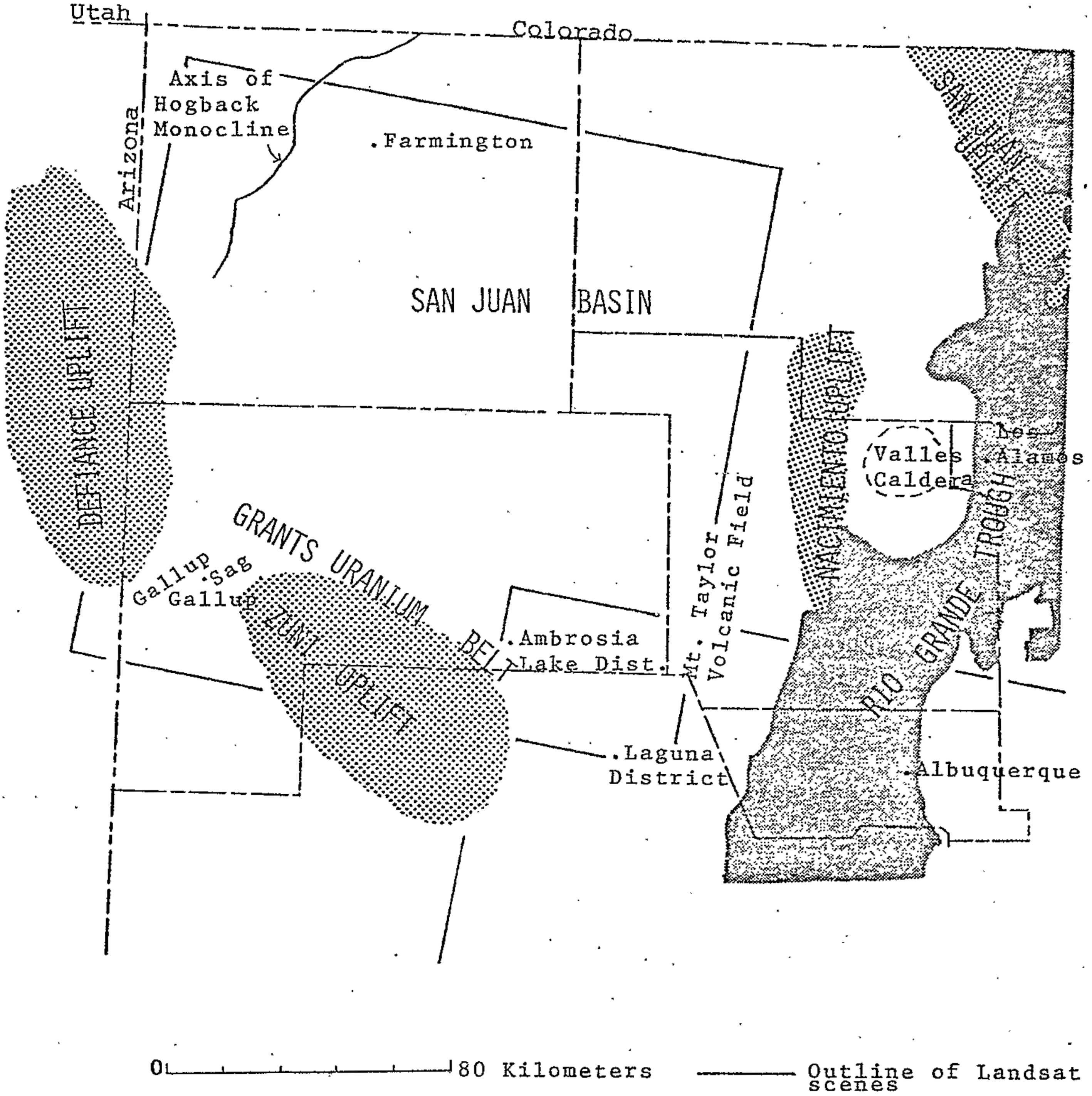


Figure A-1. Principle structural elements surrounding the San Juan Basin (from Hilpert, 1969).

Nacimiento uplift and the Mount Taylor volcanic field. The southern margin of the basin is structurally very complex with the Zuni uplift being a positive element. The Defiance uplift is a pronounced western border between the San Juan Basin and the Black Mesa Basin in Arizona (Shomaker and others, 1971).

The Triassic and Jurassic sedimentary rocks exposed at the edges of the basin are a sequence on nonmarine units, largely clastic, of eolian, stream, and lacustrine origin. The Cretaceous rocks were deposited near the margins of the widespread epeiogenic sea under conditions characterized by constantly changing shoreline positions. The resulting stratigraphic record is a jagged wedge of nonmarine sediments intertonguing to the northeast with marine sediments. They have gentle dips and have been eroded into a landscape of mesas, cuestas, canyons and dry arroyos (Shomaker and others, 1971).

The San Juan Basin gas field (Figure A-2) is the second largest producing gas field in the conterminous United States, producing considerable amounts of oil and distillate (Shomaker and others, 1971). Uranium mining is concentrated along the southern edge of the basin with the ore being produced mainly from the Jurassic sandstones. By 1974, 107,036 tons of U_3O_8 had been produced from this area (Grant, 1975). Vigorous exploration for new ore bodies continues, yielding reserve estimates of 168,000 tons of U_3O_8 at a $10/lb cut off cost (Arnold and others, 1976). Coal mining is the third largest industry in the basin with strippable reserves estimated at approximately 5,350 million short tons (Arnold and others, 1976).

The proven reserves of these three fuels make this area of New Mexico unique for testing exploration techniques. It was anticipated that techniques developed for uranium exploration by other workers would be tested and that new methods of computer enhancement would be developed.

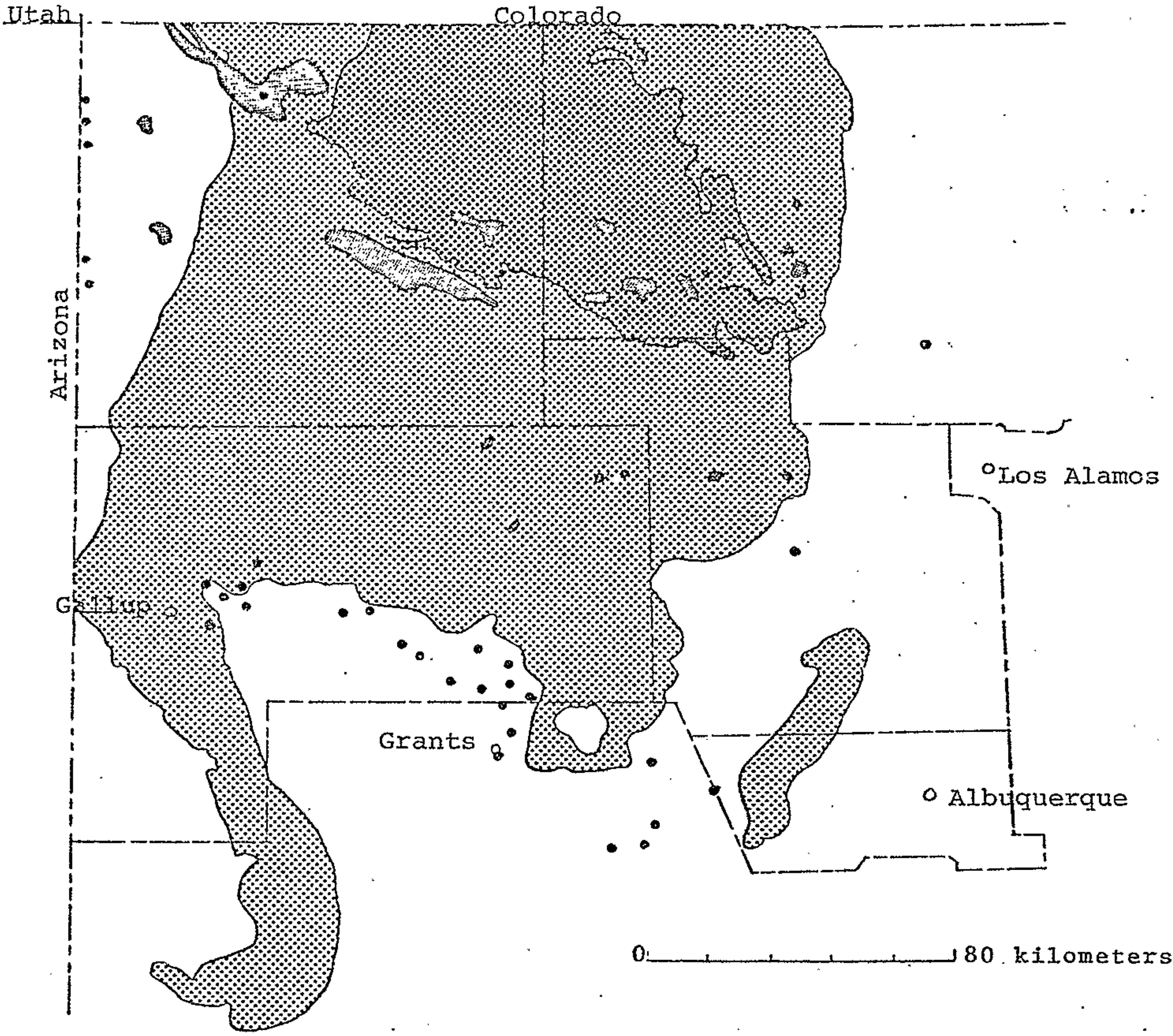


Figure A-2. Energy Resources of the San Juan Basin (from Arnold and others, 1976).

▨ Gas Field

▨ Coal Field

● Oil Field

• Uranium Production

Several authors have successfully applied enhancement of Landsat images to the identification of alteration zones associated with mineralization (Rowan and others, 1974; Merifield and others, 1974; and Houston and others, 1975). In addition, two successful attempts at using Landsat data for defining alteration associated with uranium deposits have been reported by Spirakis and Condit (1975) and Salmon and Pillars (1975). Most of these authors reported using some form of computer enhancement to produce the images used for interpretation. The ratios of MSS bands 5 and 4 are cited most often as the best ratios for identifying red beds and iron-rich alteration zones.

The most definitive work on locating alteration zones associated with uranium mineralization is a preliminary report by Spirakis and Condit (1975). By stretching and ratioing MSS data they were able to identify alteration zones near Cameron, Arizona. However, they were not able to find a unique signature for the alteration zones as bluish-gray mudstone in the target area displayed the same signature as altered rock.

In addition to interpretation of alteration zones, it was anticipated that a method of geobotanical analysis could be implemented with Landsat MSS data. This method is based on the recognition of selenium converter plant communities which indicate the presence of selenium in the soil (Rosenfeld and Beath, 1964). Cannon (1953 and 1957) successfully applied this principle in a ground-based exploration technique for uranium in northwestern New Mexico, but Kolm (1975) was not successful in using Landsat data for mapping selenium converter plant communities in Wyoming. Selenium converter plants are known to occur on soils developed on some Cretaceous rocks in the San Juan Basin and also near some outcrops of uranium mineralization in the study area.

METHODOLOGY

The basis of the uranium exploration investigation was digital image processing. Although radar, aerial photography from Skylab and low altitude aircraft photography were used for linear mapping and data correlation, the Landsat digital tapes were emphasized. Several sites in the Ambrosia Lake mining area northwest of Grants, New Mexico were selected as points of reference. The training sites delineated were 384 lines by 512 pixels and located near known producing surface and underground mines, and over an area now being intensely explored. By training on several known major producers of ore it was anticipated that a specific response could be associated with a known geologic condition.

Using the previous work in digital image processing as a guide for image enhancement, personnel at the Los Alamos Scientific Laboratory performed work on two Landsat scenes.

A number of steps were required before accurate spectral band ratios, the end product we were concerned with, could be derived. These operations consisted of: extraction of subsections of the total Landsat frame; radiometric corrections to equalize detector response; a haze correction to subtract estimated atmospheric scattering biases; and, finally, a geometric correction to facilitate image registration with a base map of the interest area. The formation of the ratios can be made either prior to, or after, the geometric correction, since both operations are of a continuous nature.

An entire Landsat frame consists of 2340 scan lines with 3228 picture elements (pixels) per line. Each pixel consists of an integer in the range from 0 to 127 for bands 4, 5 and 6 and from 0 to 63 for band 7. Thus, the standard MSS image consists of over 30 million digital numbers. Since the image covers approximately 100 nautical miles on a side and it is difficult to display the full resolution of 7.5×10^6 pixels or for that matter to even perform the numerical operations on such a large digital image, we first extracted a subsection of the data, nominally 384 lines with 512 pixels per line, which contains the area of interest. This is generally adequate since a corresponding area of 30.3 km by 29.1 km is extracted and the full resolution of the images matches the resolution of a standard television type of display.

After extraction of the four sub-images, the radiometric corrections were made. This correction was necessary since six image lines were obtained in a single scanning sweep, by six separate detectors per spectral band. These six detectors for each band do not produce the same output for a given input. However, we assume that the outputs of the detectors are linearly related for the same input, i.e. Di = ADj + B where Di is the output of detector i, Dj is the output of detector j and A and B are constants. The radiometric correction consists of choosing one detector as standard and for each other detector, estimating the A and B constants so that the two remaining detectors match. This is accomplished by calculating an average scan line for each detector from the extracted data. Five linear regressions are then performed to choose the constants so that the standard average scan line matches each other average scan line as closely as possible.

After the radiometric correction was made, we used a very simple algorithm to estimate the contribution due to the scattering of light from the atmosphere. It is known that this contribution in a given spectral band lies between 0 and the minimum of the recorded pixel values. We formed our estimate by taking one-half the minimum recorded value taken over the entire Landsat frame (not the extracted subsection). These estimates were subtracted from each pixel of the sub-image for each spectral band. Although there are more sophisticated (and costlier) techniques to estimate these spectral biases due to atmospheric noise, our technique is fairly accurate if water and cloud shadows, which result in fairly low spectral values, occur somewhere in the full Landsat image.

As a final step before ratioing we performed the geometric correction. Basically, we interpolated a new geometrically undistorted image by assigning to a pixel with coordinates (ξ,η) the value interpolated from the four pixel neighbors of the of the point (x,y) in the distorted image, where

$$x = c_{11}\xi + c_{12}\eta + c_{13} \text{ and,}$$

$$y = c_{21}\xi + c_{22}\eta + c_{23}.$$

The coefficients c_{ij} can be determined by a linear regression based on three or more control points, or they can be determined, as we have chosen, to remove nominally the skew due to rotation of the earth and to resample the data to obtain 50 meter square pixels. We decided to perform this correction before ratioing since it was easier to correct four spectral bands than to correct six ratios. The final step in the digital image processing was to form the ratios and display the ratio images. The main reason for ratioing was to remove the brightness effects due to topographic relief. After the bias due to haze is subtracted from each band, the pixel values of a spectrally homogeneous region can be modeled as a plot of points lying along a line through the origin in four-dimensional spectral space. Greater distances along this line from the origin correspond to greater brightnesses. The projection of this line into the two-dimensional space formed by a pair of spectral bands is also a line. Thus points lying on this line have the same ratio, i.e. the slope of the line, of spectral measurements. In forming a ratio image, we simply assigned the same gray level to pixels corresponding to points on the same line through the origin. It can be shown that there are three independent ratios which determine the direction of a line in the four-dimensional spectral space of Landsat. We chose to display all 12 possible ratio images (including reciprocals) although they are not independent. However, we made a color composite based on three independent ratios which in principle displays all the spectral information with brightness removed. The ratio of band 4 to band 5 is assigned to green, band 4 to band 6 is assigned to red and band 4 to band 7 is assigned to blue.

As a final note, we point out a difficulty of displaying the ratio image which can take on values from zero to infinity. Previous methods of dealing with the problem of reducing the dynamic range have consisted of taking the cube root of the ratio or perhaps the logarithm. Since we have observed that the ratio is simply the slope of a spectral signature line, we can obtain the same information by choosing the angle of inclination of the line. This corresponds to performing a non-linear contrast stretch of the ratio using the arc tangent function, i.e. we displayed θ = arc tan (x/y) instead of the ratio x/y of band x to band y. Note that if x and y are interchanged we would display $\pi/2 - \theta$ instead of θ. With this scheme our ratio images (from now on referred to as angle images) are bounded between 0 and $\pi/2$ and reciprocal ratio images become photographic negatives.

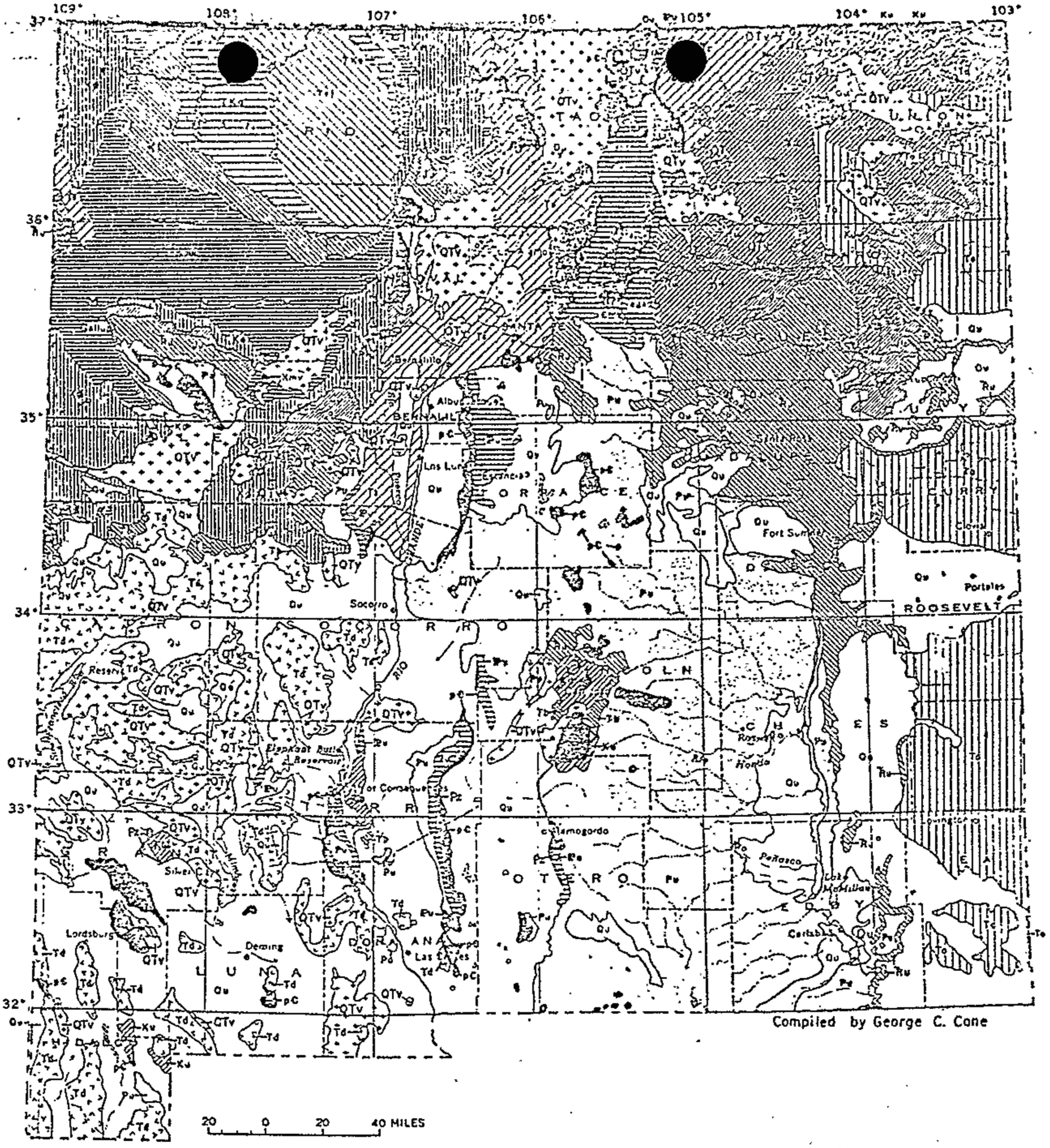
Results of the linear-ratio and angle images are discussed later in the results of the investigation.

GEOLOGY OF THE GRANTS URANIUM BELT

The Grants Uranium Belt is a west-northwest strip approximately 150 km long and 25 to 30 km wide extending from the Rio Grande Trough on the east to the Gallup Sag on the west. It is the southern edge of the San Juan Basin and crosses the northwestern extension of the Zuni Uplift as shown in Figure 1 (Kelley, 1963). Most of the following generalizations about the Grants Uranium Belt are taken from an excellent summary by Fischer (1970).

The geology of the Grants Uranium Belt (Figure A-3) is principally composed of Mesozoic sedimentary rocks of marine and nonmarine origin (Figure A-4). Most of the ore has come from the Morrison formation (Jurassic) which is primarily composed of interbedded sandstone and mudstone. Most sandstone beds are lenses 15 to 30 meters thick and several kilometers wide, and some lenses occupy narrow channels. The sandstones are well lithified and light-colored. They are primarily quartzose but may be arkosic and contain fragments of carbonized fossil wood. The mudstone beds are predominantly red or variegated and may contain considerable volcanic debris. These rocks were deposited by streams and in floodplains or lakes (Fischer, 1970). A small amount of uranium production (approximately 4%) comes from the Todilto limestone (Jurassic) (U.S. Geological Survey, 1965).

Since the time of deposition of the Morrison formation, this area has been subjected to one major and several minor episodes of deformation (Kelley, 1963). The first deformation was relatively minor, producing folds and collapse pipes in the Morrison and underlying Jurassic rocks. This episode appears to have accompanied and followed the Morrison sedimentation (Kelley, 1963).



Compiled by George C. Cone

Figure A-3. Generalized geologic map of New Mexico (from U.S.G.S., 1965).

EXPLANATION

Qu Quaternary deposits
Includes some Tertiary rocks

QTv Quaternary and Tertiary volcanic rocks

Ts Santa Fe Group
Includes some lower Quaternary rocks

To Ogalalla Formation

Td Datil Formation
and related volcanics

Tsj San Jose Formation

▨ Baca Formation
and related units

TKa Nacimiento and
Animas Formations

Tr Raton Formation

▨ Upper Cretaceous sedimentary rocks
Post-Mesaverde formations

▨ Mesaverde Group

TERTIARY

CRETACEOUS

▨ Mancos and Dakota Formations

▨ Cretaceous rocks, undivided

▨ Jurassic rocks, undivided

▨ Triassic rocks, undivided

Pu Permian rocks, undivided

▨ Pennsylvanian rocks, undivided

Pz Mississippian, Devonian, Silurian, Ordovician,
and Cambrian rocks, undivided

▨ Precambrian rocks, undivided

INTRUSIVE ROCKS

▨ Tertiary intrusive rocks
Includes some rocks of Cretaceous age

System	Age		Formation	Thickness (meters)	Character and distribution	Uranium deposits
Cretaceous	Early and Late Cretaceous		Dakota Sandstone Unconformity	5-125 1.5-38	Tan to gray, medium-grained quartz sandstone, some interbedded carbonaceous shale and local coal lenses. Local conglomerate-filled scours at base as much as 7.5 meters deep.	Scattered small deposits, generally near base and closely related to carbonaceous material. A few in Ambrosia Lake district have yielded ore.
Jurassic	Late Jurassic		Morrison Formation	0-180	Brushy Basin Member: mostly greenish-gray mudstone and local thick arkosic sandstone units. Contains Poison Canyon sandstone of economic usage near base in Ambrosia Lake district and Jackpile sandstone of economic usage at top in Laguna district. Member is 6-90 meters thick and generally thickens eastward and northward from Ambrosia Lake district.	Sandstone lenses contain many deposits. Very large deposits occur in Jackpile sandstone in Laguna district and large ones occur in Poison Canyon sandstone and other sandstone units in Ambrosia Lake district.
					Westwater Canyon Member: light-brown to gray, poorly sorted, arkosic sandstone and some interbedded gray mudstone. Intertongues with Brushy Basin Member and thins from maximum of about 90 meters in Ambrosia Lake district to less than 15 meters in the Laguna district where locally absent.	
					Recapture Member: distinctive alternating beds of gray sandstone and grayish-red siltstone or mudstone. Beds are a foot to several feet thick. Contact with Bluff Sandstone generally sharp, but intertongues with Westwater Canyon Member. Recapture is less than 15 to more than 60 meters thick.	Contains many large deposits in Ambrosia Lake district.
			Bluff Sandstone	46-120	Pale-red to pale-brown, fine- to medium-grained sandstone. Forms massive cliffs. Upper part marked by thick sets of large-scale crossbeds; lower part grades down into smaller-scale sets of crossbeds and some flat beds.	Contains no deposits.
			Summerville Formation	27-120	Alternate beds of pale-brown, thin-bedded sandstone and reddish-brown mudstone or siltstone. Sandstone beds thicken in upper part and grade into overlying Bluff Sandstone; at base grades and intertongues with Todilto.	Contains scattered deposits at base, generally where underlying Todilto Limestone is mineralized
			Todilto Limestone	0-26	Consists of upper gypsum-anhydrite member exposed only in Laguna district, 0-23 meters thick; and lower limestone member, gray, laminated in lower part and more massive, contains interbedded siltstone in upper part, 1.5-11 meters thick.	Contains (mostly in Ambrosia L Lake district)many small and some fairly large deposits in the limestone member.
			Entrada Sandstone Unconformity	46-75	Consists of upper unit, 24-75 meters thick, of reddish-orange, fine-grained sandstone with thick sets of large-scale crossbeds and a medial unit, 3-26 meters thick, of red and gray siltstone. In the Laguna district, a lower sandstone unit, 0-9 meters thick, may belong in the Entrada or may be the Wingate Sandstone. Medial unit probably unconformable on Wingate Sandstone in Ambrosia Lake district; lower sandstone unit unconformable on Chinle Formation in Laguna district.	Contains scattered small deposits at top of formation, generally where overlying Todilto Limestone is mineralized. Some have yielded ore.

Figure A-4. Partial composite columnar section in the Ambrosia Lake-Laguana area, New Mexico (from Hilpart, 1963).

The area was subsequently to undergo a period of erosion and fluvial deposition in the early Tertiary and gentle arching and profound erosion in the middle Tertiary. Volcanic activity (late Pliocene-Pleistocene) occurred at the site of Mount Taylor and along a north-northeast trend which it straddles. Later basalt eruptions occurred in the areas of the Zuni Mountains and Bluewater.

Uranium is the only metal recovered from some deposits, but vanadium or copper is a co-product from others. Primary ore minerals are oxides and silicates of uranium and vanadium and common copper sulfides. The ore primarily fills pores in the sandstones and has also partially replaced carbonized fossil wood and sand grains (Fischer, 1970).

The peneconcordant deposits are tabular bodies that are approximately parallel to the bedding but do not follow beds in detail. These layers vary in thickness but average only a few meters. They range up to hundreds of meters across and are irregular in plan. The ore bodies tend to be elongate in the same direction as the long axis of the host sandstone lenses and are generally controlled by sedimentary structures (Fischer, 1970).

The peneconcordant deposits are enveloped in altered rock, which extends laterally a few hundred meters to a few kilometers and consists mainly of the addition of finely disseminated pyrite and a bleaching of the rock. The pale reddish sandstones are altered to pale gray or white and the red mudstones are altered to gray or green (Fischer, 1970).

The ore-bearing solutions are thought to have been groundwaters moving through altered sandstone generally parallel to the tabular ore bodies. Ore was probably deposited in a static (stationary) reducing environment, associated with organic material (Fischer, 1970).

Although this description of the geology of the Grants area is important for the development of any exploration technique, it is primarily an analysis of the surface expression of the geology which can be accomplished with Landsat data. As this study was modeled after a technique which was applied successfully to similar uranium deposits near Cameron, Arizona (Spirakis and Condit, 1975) a comparison of the surface features of both areas is appropriate.

In the Cameron area the topography is of low relief, and this, combined with low regional dip, gives broad exposures of individual formations. Vegetation is sparse, and the badland terrain clearly shows the bedrock color. The uranium occurrences are on a broad pediment southwest of a scarp of the Glen Canyon Group (Jurassic) which has been preserved by the Shinarump scarp.

The uranium production is largely from the lower part of the Petrified Forest member, a sandstone lens (non-scarp forming) within the Chinle formation (Triassic). The latter is mostly composed of bentonitic muds and clays attributed to volcanic debris.

The dominant color is blue-purple-gray throughout the Chinle. The leached zones containing ore deposits are up to 0.4 km in length and are surrounded by alteration haloes in which the color is yellow or light brown.

In contrast the topography of the Grants region is complex. The Chinle formation (non-producing in this area) forms a sloping pediment north of the Zuni uplift. The main production is from the Jurassic which crops out in a complex scarp topography. The main scarps are formed by sandstones of Cretaceous age. The most important commercial horizons are the sandstones of the upper Jurassic Morrison formation which crop out in the steep slopes of the Dakota scarps. The Morrison sandstones may or may not form benches in the Dakota scarp.

Below the Morrison the Entrada sandstone (middle Jurassic) forms a minor scarp and northward dipping bench. The Todilto limestone is preserved on the Entrada bench and is exposed locally.

The outcrop colors in the Grants area are complex. The Entrada sandstone is strikingly red as is the Bluff sandstone (less indurated and poor scarp former) which occurs between the Todilto limestone and Morrison formation.

The shales in the Morrison are dominantly gray with chocolate colored layers, and the Morrison sandstones are light brown to red-brown in color.

The color range in the producing zone varies from red through red-brown to blue-gray. However, the color of the outcrops is complicated by the structures; for instance the San Mateo Fault zone forms a north-south valley cutting the Dakota-Morrison scarp; producing variations in height of the Morrison outcrops. Thus in higher scarps all the producing sandstones crop out but in the lower scarps only the upper producers are exposed.

The base of the scarps is frequently covered by badland-type landslide zones formed by the slumping of shale horizons; while the rock face itself is in part masked by Dakota sandstone scree and by shale debris moving down slope.

The geological differences between the Cameron area and the Grants area are basically that the Cameron deposits sit on a sloping pediment with little cover of soil or debris, they have a large surface area and a simple color change. However, the deposits in the Grants area occur in two main stratigraphic positions: the smaller in the Todilto limestone which crops out on a bench, the larger in the Morrison formation which crops out on a steep slope and extends down dip under a deep cover of Cretaceous rocks.

The surface outcrop of the Morrison producing horizon is very narrow when viewed from above (except in a few localities where the sandstones form benches at or near the base of the Dakota scarp, e.g. Poison Canyon Mine). In addition, the Grants area has a complex stratigraphy with a series of producing sandstones within shale and sandstone interbeds. The color changes across the Jurassic are multiple and variable.

Color changes due to the passage of solutions (bleaching) were observed in the field. Most of these were distinct but very localized, some occurring within individual producing beds; however, mass scarp color changes do occur along "trends" of main mineralization. The bleaching spreads down the scarp and across most, if not all the sandstone. Thus, zones of alteration apparently due to preferred fluid paths are more extensive than zones of mineralization in individual mines. Large concentrations of ore bodies have been found in the zones of alteration.

In general, the surficial expressions of color changes due to alteration in the Grants area are less dramatic than at Cameron, but both areas are characterized by bleached zones resulting from reducing alteration. At Cameron the unmineralized rocks are typically purple or gray and are in striking contrast with the light brown and yellow alteration zones. However, in the Grants area the unmineralized sandstones are light brown, red-brown, or blue-gray and alteration zones may be pale gray, pale green or white.

RESULTS

Using the procedures described above two sets of processed ratio images were produced from the basic digital MSS tapes of the study area. These are: 1) linear-ratio images and 2) arc tangent or angle images. Although the promise of this investigation lies in the more recently developed angle image enhancement, the primary interpretation work was performed on the original linear-ratioed images of the Ambrosia Lake area.

Linear-Ratio Images - Rowan and others (1974) have shown that these ratioed images are a powerful tool for detecting some alteration zones. The work of Spirakis and Condit (1975) supported these findings. This technique provides a means for enhancing subtle spectral differences. Rowan and others (1974) describe the resultant image as "a visual display of the differences between the bands in slope of the spectral-reflectance curve of each geologic unit".

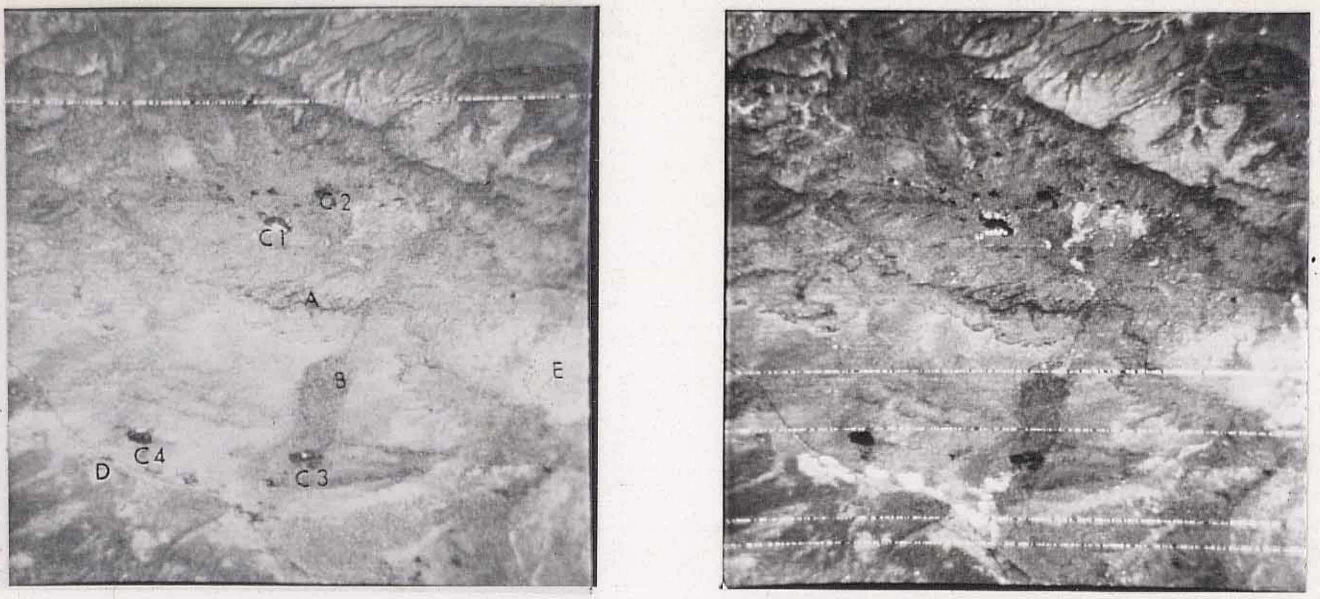
The linear-ratioed images were displayed as ratios of two bands (e.g. band 4/band 5) and also as color composites (e.g. band 4/band 7 assigned to blue, band 6/band 4 to green and band 7/band 4 to red). Images were generated for five different areas within the scene covered by the data tape. Each area is 384 lines by 512 pixles and was chosen for its relevance to geologic analysis. The principle study area centers around the Kerr McGee uranium mill (Figure A-5).

Of all the ratios attempted, the ratios of bands 5 and 4 offer the most possibilities for geologic interpretation. Spectral response from vegetation is minimal, while response from rock and/or soil is emphasized. The scene contrast is increased, allowing improved discrimination of rock and soil type (Table 1).

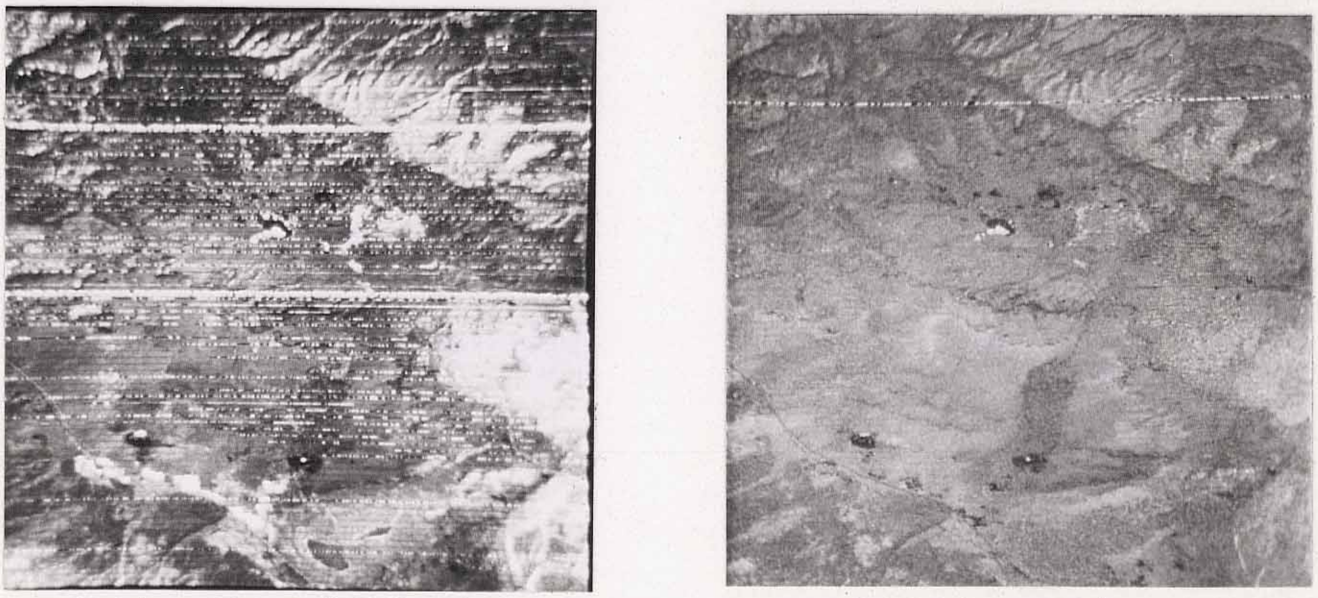
While the individual mineralized sandstone outcrops along the scarps are small, some of the scarps with extensive scree deposits are within Landsat resolution. Several stretched-ratio and color composite images were examined and no obvious variation in the reflectance along the Jurassic scarp was seen. This may be due to one or more of the following: 1) the limited width of the sandstone outcrops along the scarp; 2) the color changes due to alteration were too subtle for this technique; 3) imperfections in the data tapes. The data tape for northwest New Mexico contained numerous data omissions in several bands and band 7 in particular. These omissions produced a color variation not representative of the feature's response and rendered those areas uninterpretable.

Other uses of this imagery included the elucidation of geologic structures and lithologic contacts. The lithologic contacts as interpreted on these images are in good agreement with published geologic maps of the area (Chapman, Wood and Griswold, Inc., 1974; Thaden and others, 1967a). In trying to establish the extension of mineralization down dip from the outcrop, studies in the location and distribution of geologic structures were undertaken. In addition to the stretched ration images, Skylab S190B black-and-white photographs, side-looking radar imagery, and conventional color aerial photographs were analyzed. No features uniquely attributed to uranium mineralization were observed on any of these images.

In all cases of rationing for feature delineation the geologic, vegetational and cultural properties were shown differentially depending on the ratios applied. The selection of specific features requires the selection of specific ratios.



Ratio of band 5/band 4 Ratio of band 6/band 4



Ratio of band 7/band 4 Ratio of band 4/band 5

Figure A-5. Linear-ratio Landsat MSS images of the study area showing variation in (A) outcrop of the Morrison formation, (B) alluvial fill, (C) mine and mill wastes and settling ponds: 1) Kerr McGee, 2) Phillips, 3) United Nuclear-Homestake, 4) Anaconda; (D) irrigated fields, and (E) natural vegetation. Scale is approximately 1:500,000.

The matrix in Table 1 relates the specific ratios used and the resulting delineation of the surface features in the Ambrosia Lake area training site.

<u>Angle Images</u> - The technique of angle image enhancement previously described was applied to the Ambrosia Lake test site and the Laguna uranium district east of Mount Taylor. The application of the enhancements is similar to the ratioed images in that selected features require selected angle ratio images. Using this technique allows the introduction of a response consistant from scene subsection to subsection and from scene to scene, a consistancy which is not possible using the linear-ratio approach. An example of this improved reliability can be seen in the Morrison formation (Figure A-6) of a color composite of 4/5 green, 4/6 red and 4/7 blue. The Morrison formation appears to change color as it extends along the Jurassic scarp. The green band is the Morrison formation exposure, but at points A, B and C a blue tone has replaced green and its at these points that the Morrison has been buried by talus. The aspect and outcrop width are not limiting factors. This is an improved display for lithologic interpretation over those using a linear ratio.

A matrix, Table 2, for angle image interpretation generally indicates a more successful delineation of surface features than that of the linear-ratio set.

The color composite of 5/6 green, 5/7 red and 6/7 blue (Figure A-6) shows a spectral response previously not delineated. Although standing water will be seen in several mill ponds, only one of the ponds shows a bright yellow signature. The pond is part of an inactive mill and probably is of a different water quality than other water bodies. Since the scene was from 1973, field checking was of no value; but, by examining other ponds in the Laguna site which produced a similar spectral response, it is felt that water depth, sediment load or turbidity are all or partly responsible.

As in the linear-ratio images no response could be attributed to uranium mineralization although a number of possible applications do exist in inventorying of soils, vegetation, cultural features and water quality.

Table 1. Comparison of features on linear-stretched images.

Color Composites

B	G	R	Mine & Mill Wastes	Water-bodies	Natural Vegetation	Irrigated Vegetation	Morrison Formation	Other sandstone	Alluvium/ Colluvium
4	5	7	White	Black	Red	Red	*	*	-
5/4	6/4	4/7	Black	White	White	White	*	*	*
4/7	6/4	7/4	Black	White	Yellow/ White	White	*	*	*

Black and White

	Mine & Mill Wastes	Water-bodies	Natural Vegetation	Irrigated Vegetation	Morrison Formation	Other sandstone	Alluvium/ Colluvium
4/5	Black	White	White	-	*	*	*
5/4	Black	White	White	-	*	*	*
6/4	Black	White	White	White	*	*	*
4/7	-	-	-	-	-	-	-
7/4	Black	White	White	White	-	-	-

● denotes feature can be delineated
- denotes feature cannot be delineated

Table 2. Comparison of features on angle images.

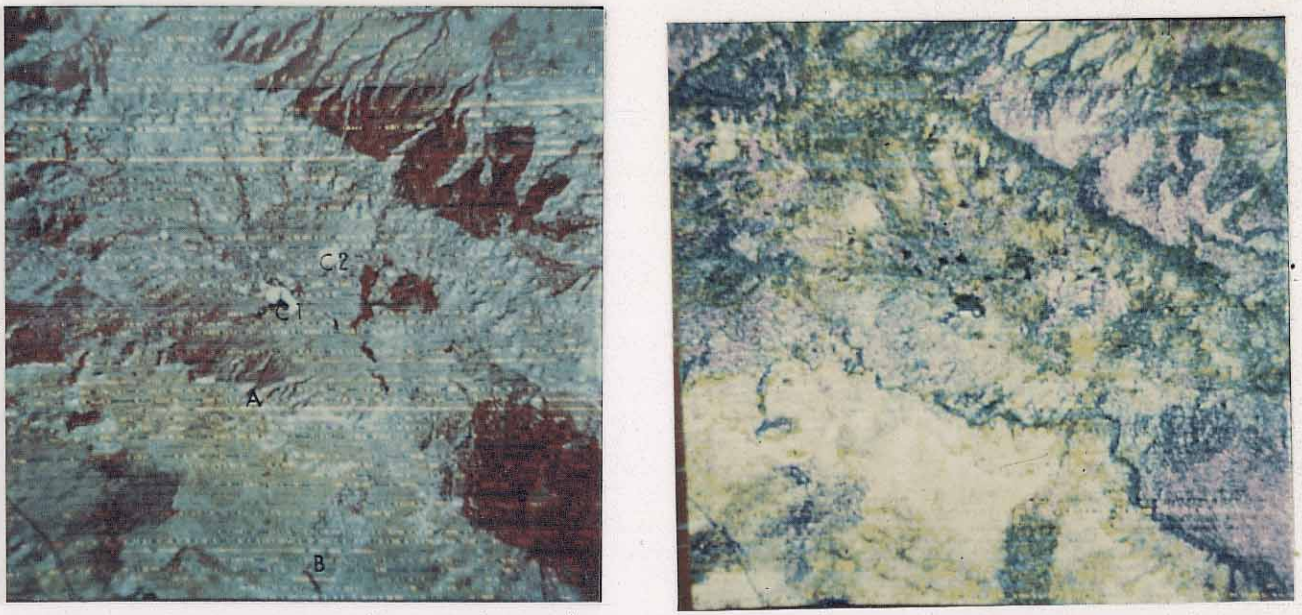
Color Composites

B	G	R	Mine & Mill Wastes	Water-bodies	Natural Vegetation	Morrison Formation	Other Sandstone	Alluvium/ Colluvium
4	5	7	White	Black	Red	*	-	-
4/7	4/5	4/6	Blue/ Green	White/ Blue	Pink	Green	*	*
6/7	5/6	5/7	Black	Pink/ Yellow	White	*	*	-

Black and White

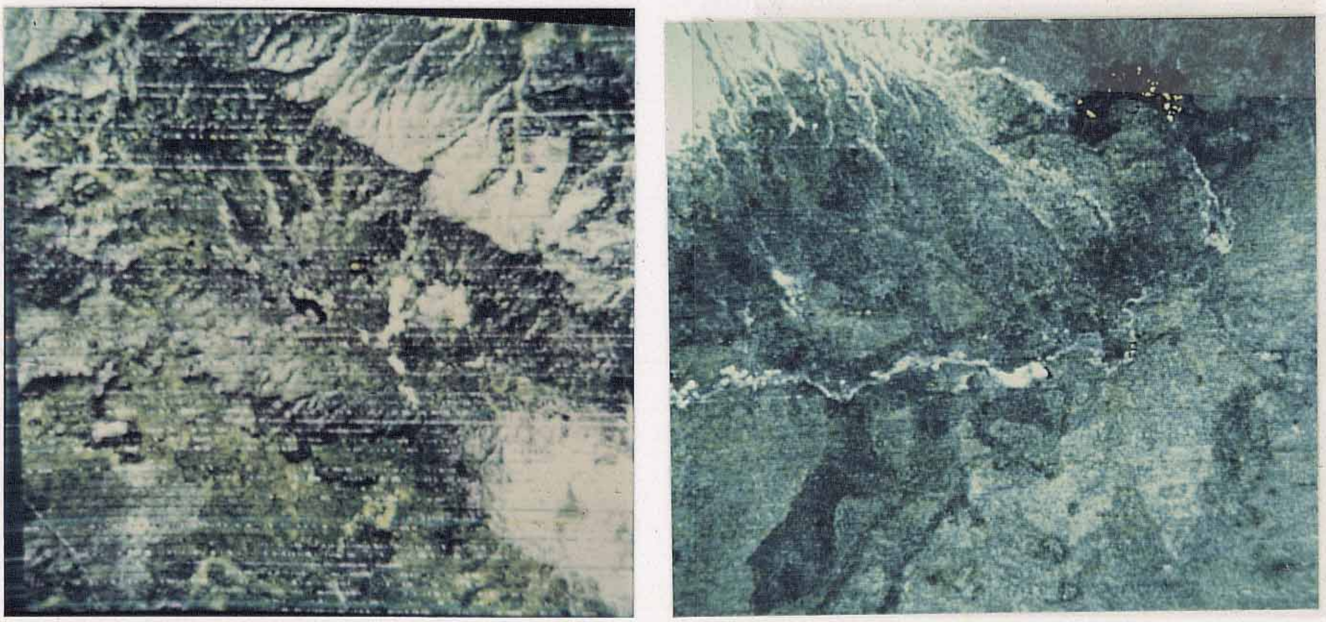
	Mine & Mill Wastes	Water-bodies	Natural Vegetation	Morrison Formation	Other Sandstone	Alluvium/ Colluvium
4/5	Gray	White	White	-	-	*
5/4	Gray	Black	Black	-	-	*
6/4	Black	White	White	*	*	*
4/7	White	Black	Black	-	-	-
7/4	Black	White	White	-	-	-
5/7	White	Black	Black	*	*	-
5/6	White	White	Black	●	●	-
7/6	Black	White	White	-	-	-

● denotes feature can be delineated
- denotes feature cannot be delineated



False color composite Ambrosia Lake area. Band 4 in blue, band 5 in green, band 7 in red.

Angle image color composite Ambrosia Lake area. Ratio 4/5 in green, ratio 4/6 in red, ratio 4/7 in blue.



Angle image color composite Amrosia Lake area. Ratio 5/6 in green, ratio 5/7 in red, ratio 6/7 in blue.

Angle image Laguna district. Ratio 5/6 in green, ratio 5/7 in red, ratio 6/7 in blue.

Figure A-6. Color composites of study areas. Letters A through E denote same features as in Figure 5, (F) Rio San Jose, and (G) Jackpile, Woodrow and Paguate mines, Laguna District. Scale is approximately 1:500,000.

The use of selenium plant communities in uranium exploration has been shown to be effective (Cannon, 1953 and 1957) at low altitude or ground level. However, mapping of any plant community from Landsat is limited by the density of the vegetation itself. Grasses, forbs and shrubs vary relative to the area's cultural practices, increasing the variation in plant distribution and allowing only generalized or dominant species mapping from satellite. Northwest New Mexico has a sparse vegetation cover in the non-mountain areas, mapping of vegetation is hindered by the soil background. The seleniferous plants of northwest New Mexico are not dominant and therefore, were not interpreted from any of the composites or ratios made.

CONCLUSIONS

Neither of the computer-enhancement techniques described here yielded significant results. No signatures associated with alteration zones or selenium plant communities were observed. The enhanced images however, may prove to be more useful for standard photo interpretation techniques of mineral exploration. Such investigations could include identification of linear features, variation in local lithology and structure, geomorphology, and surficial geology.

The computer-enhancement techniques may yield more favorable results in target areas where the Morrison formation forms wide benches. However, there is little reported on uranium in such areas, which may indicate the absence of near-surface ore indicators.

The technique of displaying a value determined by the arc tangent of the angle of the slope offers new prospects for further study. Although this technique did not provide solutions for this study, it is hoped that it will prove to be beneficial for inventorying and monitoring of surface resources.

The technique also offers promise in the improvement of automated classification systems.

RECOMMENDATIONS

The images and techniques generated in this study and similar ones will be useful for environmental planning in the Grants area. This type of planning is necessary as Grants is currently experiencing its third "boom" in the last 25 years. These images could supply important information of the regional geologic setting; information which is needed to define areas suitable for residential expansion, areas suitable for disposal of mine and mill wastes (liquid and solid), and areas of potential ground water pollution.

The application of the angle enhancement technique was not thoroughly evaluated since its development came late in the study. The water quality and depth determination aspect of this technique could have use in the shallow water impoundments of the southwestern United States. Automated classification systems would also be a logical next step in the application of the technique.

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APPENDIX B

Structural Study of the Datil-Mogollon Volcanic Area Southwestern New Mexico from Landsat Imagery

INTRODUCTION

The Datil-Mogollon volcanic area comprises roughly 18,000 square kilometers of southwestern New Mexico (Elston, and others, 1970). This area is part of a blanket of mid-Tertiary continental volcanic rocks that extends from New Mexico over southeastern Arizona, western Texas, and part of northern Mexico. Since the Datil-Mogollon volcanic area is quite remote, encompassing all or part of two wilderness areas, the geology has not been worked out in great detail. In the area, large volumes of volcanic rock were errupted from various centers beginning about 40 million years ago (Elston, and others, 1973) leading to the development of calderas or large collapse features. The calderas were subsequently filled with more volcanic material and in some cases have undergone resurgent doming of the central portion. Further complicating the geology of the area is the tectonic overprinting on the cauldron collapse features of high angle normal faults associated with the later Basin and Range period of crustal extension which began almost concurrently with Rio Grande Rift formation approximately 20 million years ago (Chapin, 1971).

Elston and others (1976) postulate the volcanics of the Datil-Mogollon area are the result of surficial blistering above a large pluton about 125 kilometers in diameter. An analysis of Landsat-B imagery was undertaken following Rhodes' (1974) suggestion in our Landsat-A investigation to use its broad synoptic view to provide new insights into the regional structure that would help in understanding the complex tectonic and volcanic history of the Datil-Mogollon area and provide a useful framework for mineral exploration. The analysis was made using normal photointerpretative techniques. Good stereoscopic coverage exists in the areas of sidelap on two consecutive orbits. Reasonably good stereoscopic viewing can be achieved by using coverage from different dates for the same scene. Curvilinear and linear features were drawn on the basis of the following criteria: visible scarps, long straight stream segments, abrupt changes or displacements in lithology (tonal differences), and abrupt changes or displacements of the structural grain.

DISCUSSION OF RESULTS

The resulting map of linear and curvilinear features produced from the analysis of the three images (E 2258-17023-7, E 2259-17084-7, and E 2276-17022-7) covering the Datil-Mogollon area is shown in Figure B-1. This map shows good agreement with published maps of the structure of the area (Figure B-2). Many linear features coincide with previously mapped faults and others are close to the position of known faults. Landsat linear features tend to smooth or generalize detailed fracture patterns mapped by field studies, but for the most part accurately depict the trend of structures observed on the ground. Some Landsat linears have no counterpart on existing maps and many probably represent unmapped faults; conversely, a number of mapped faults are too subtle

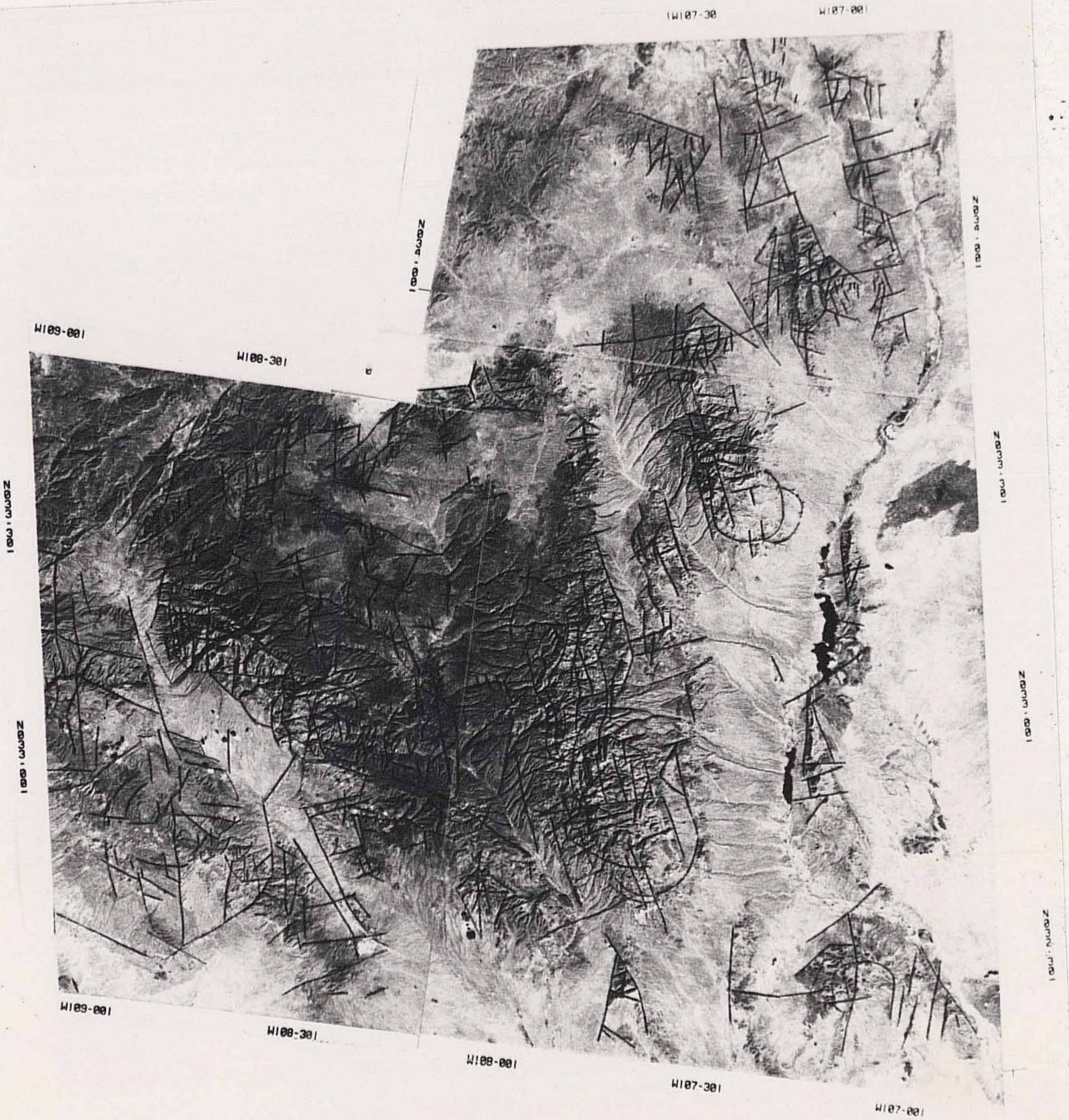
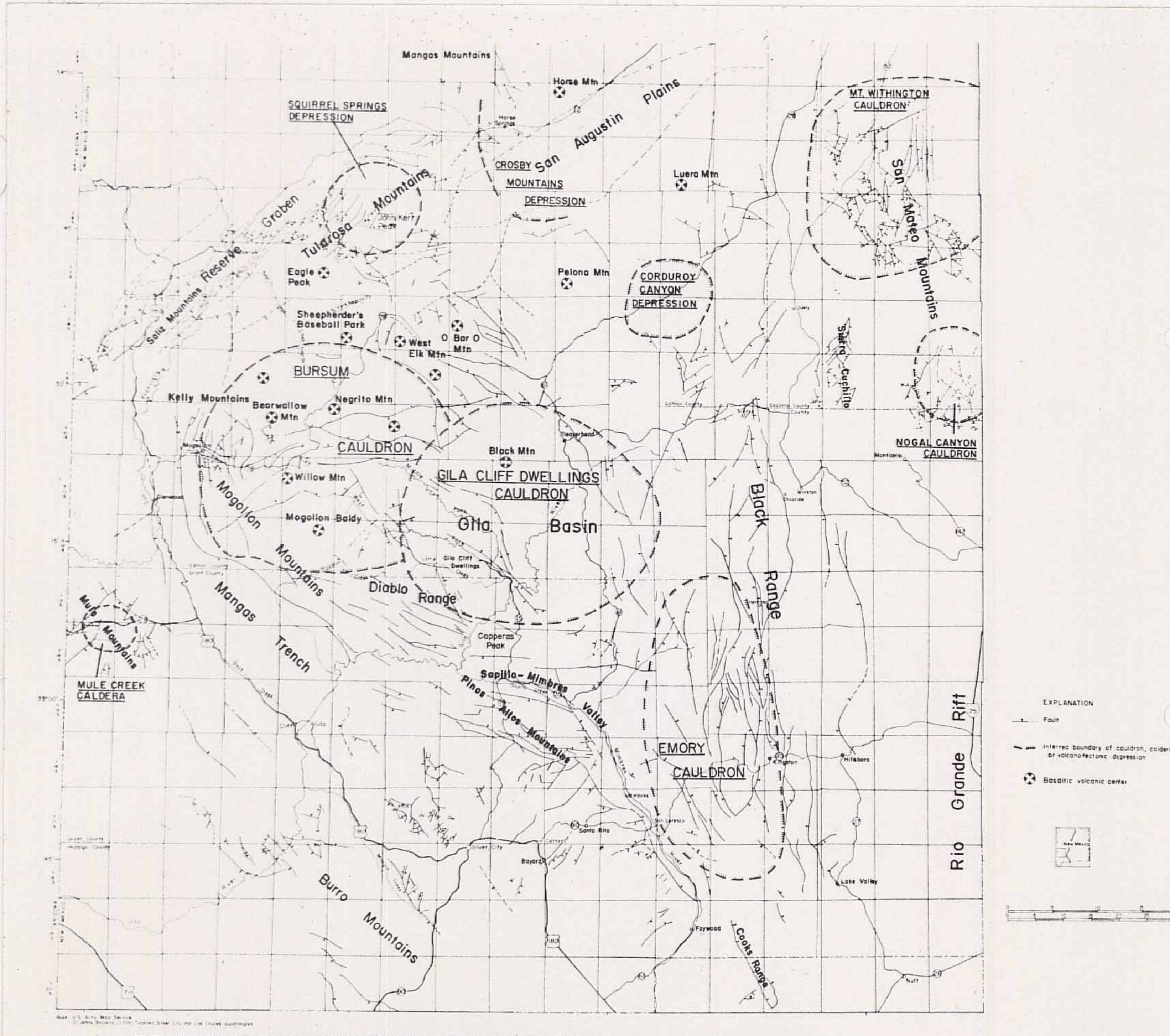


Figure B-1. Map of linear and curvilinear features.
Scale is approximately 1:1,520,000.

Figure B-2. Tectonic map (from Elston and others, 1976)



PRELIMINARY TECTONIC MAP OF PART OF THE MOGOLLON-DATIL VOLCANIC PROVINCE, NEW MEXICO
1976

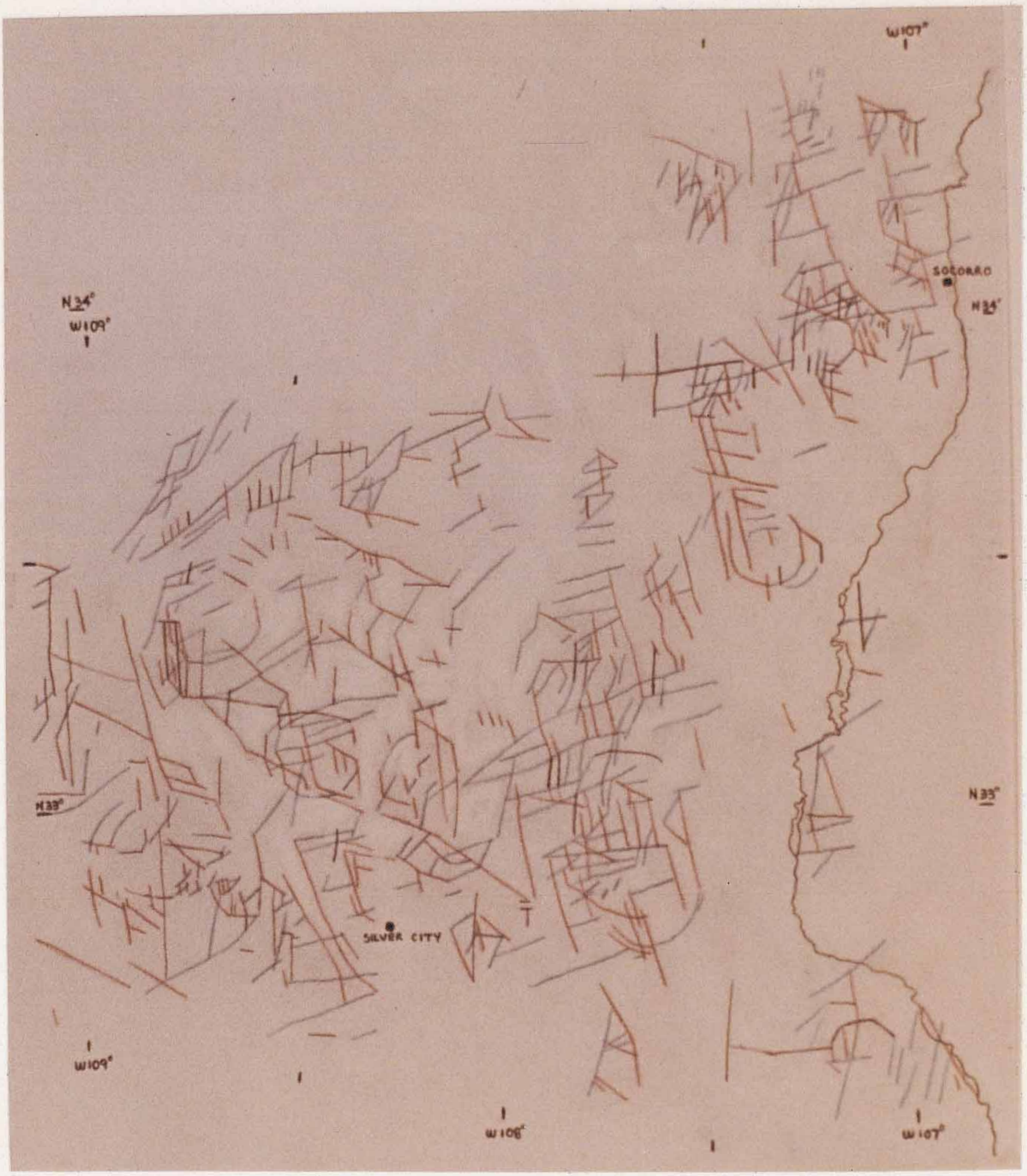


Figure B-3. Landsat linear directions by color; E-W and N-S in black, NW in red, and NE in blue. Scale is approximately 1:1,385,000.

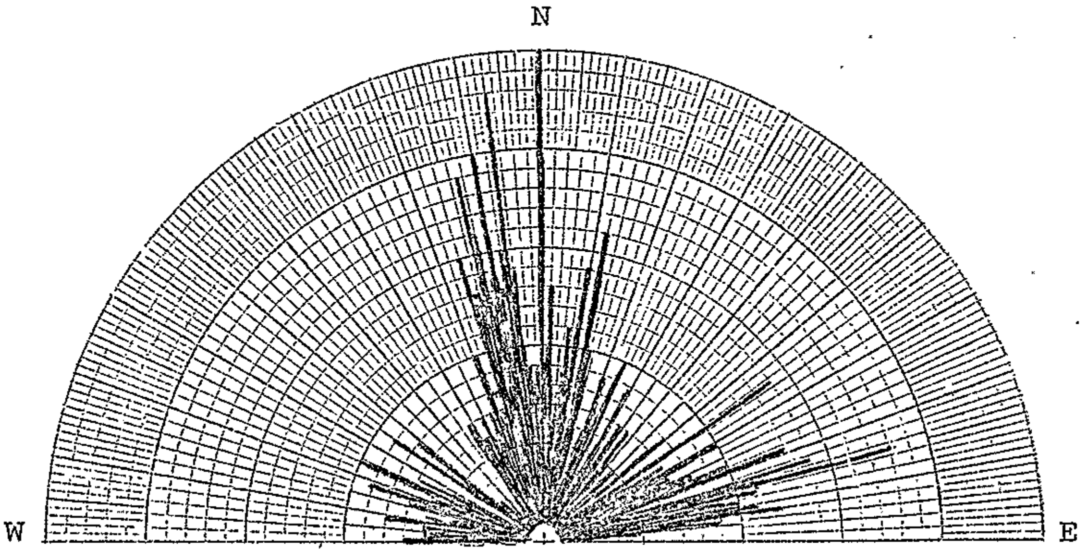


Figure B-4. Rose diagram of Landsat linear directions.

to be detected on the Landsat imagery. Therefore, the most comprehensive approach to mapping structural features would be a combination of remote sensing and field studies.

Figure B-3 shows the Landsat linear features broken down by colors into directional categories: E-W and N-S trending features in black, NW trending features in red, and NE trending features in blue. When azimuths of the linear features are plotted on a rose diagram (Figure B-4) the strong directional trends become apparent. By far the most prominent trend is the NW trend which reflects the most recent period of tectonism, a period of crustal extension in late Cenozoic time. This trend is particularly evident in the eastern part of the study area along the edge of the Rio Grande Valley. The general orientation of this trend is N 7° W. The other strong trend, at N 75°E, is also probably related to the late Cenozoic extensional period. Taken with the previous trend they form a nearly orthogonal set of lineaments. The other, but less prominent, conjugate set of linear features, with trends at N 66°W and N 12°E, may be related to the older Laramide orogeny.

Circular as well as linear features are evident on the Landsat imagery of the Datil-Mogollon area (Figure B-5). Many of these features correspond to known or proposed cauldrons or volcanic depressions (Figure B-6). The Emory cauldron (1) (Elston and others, 1975), Nogal Canyon cauldron (2) (Deal and Rhodes, 1974), Blue Creek depression (3) (Seager and Clemons, in press), Mount Withington cauldron (4) (Deal and Rhodes, 1974), Bursum cauldron (6) (Elston and others, 1968), Gila Cliff

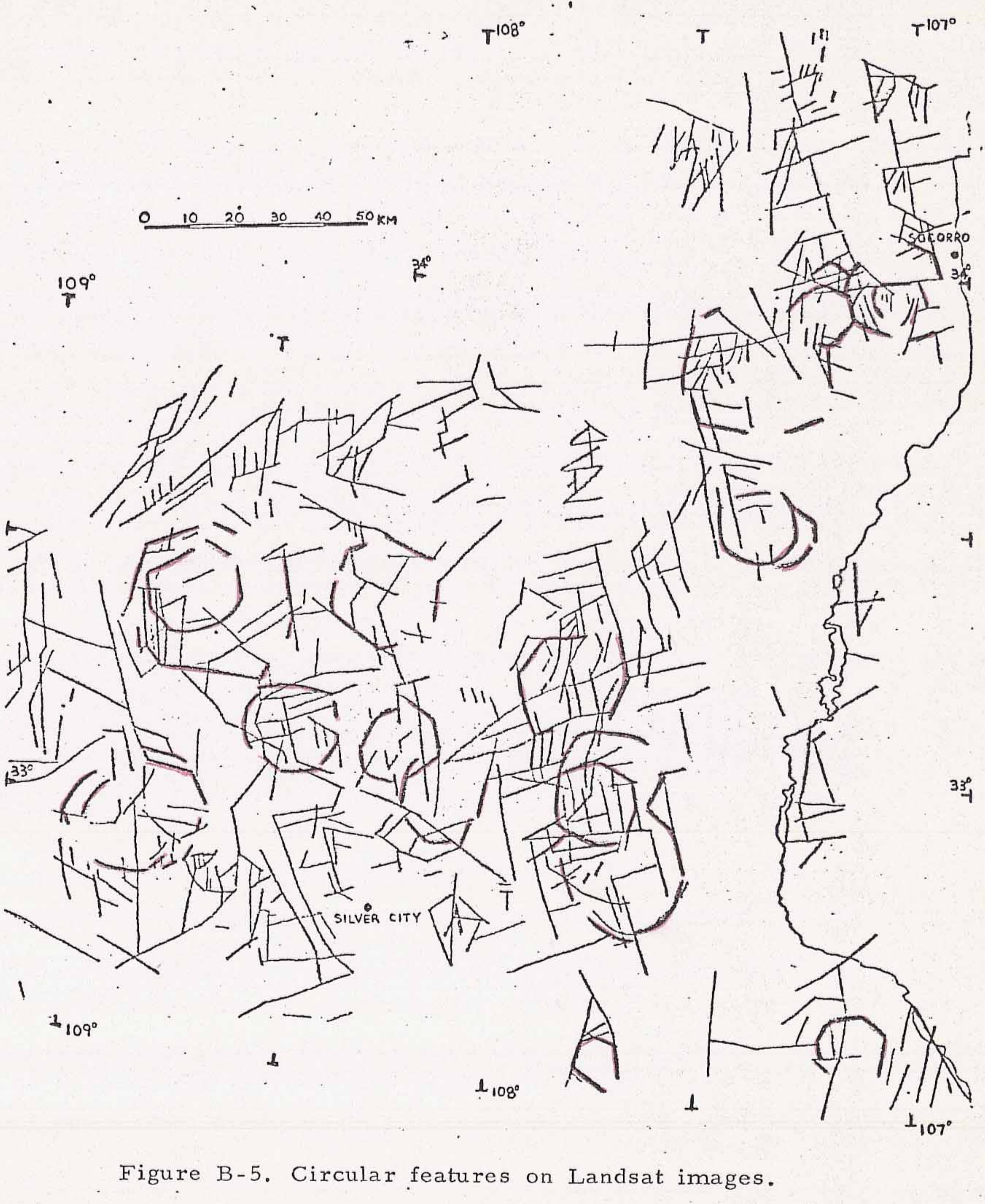


Figure B-5. Circular features on Landsat images.

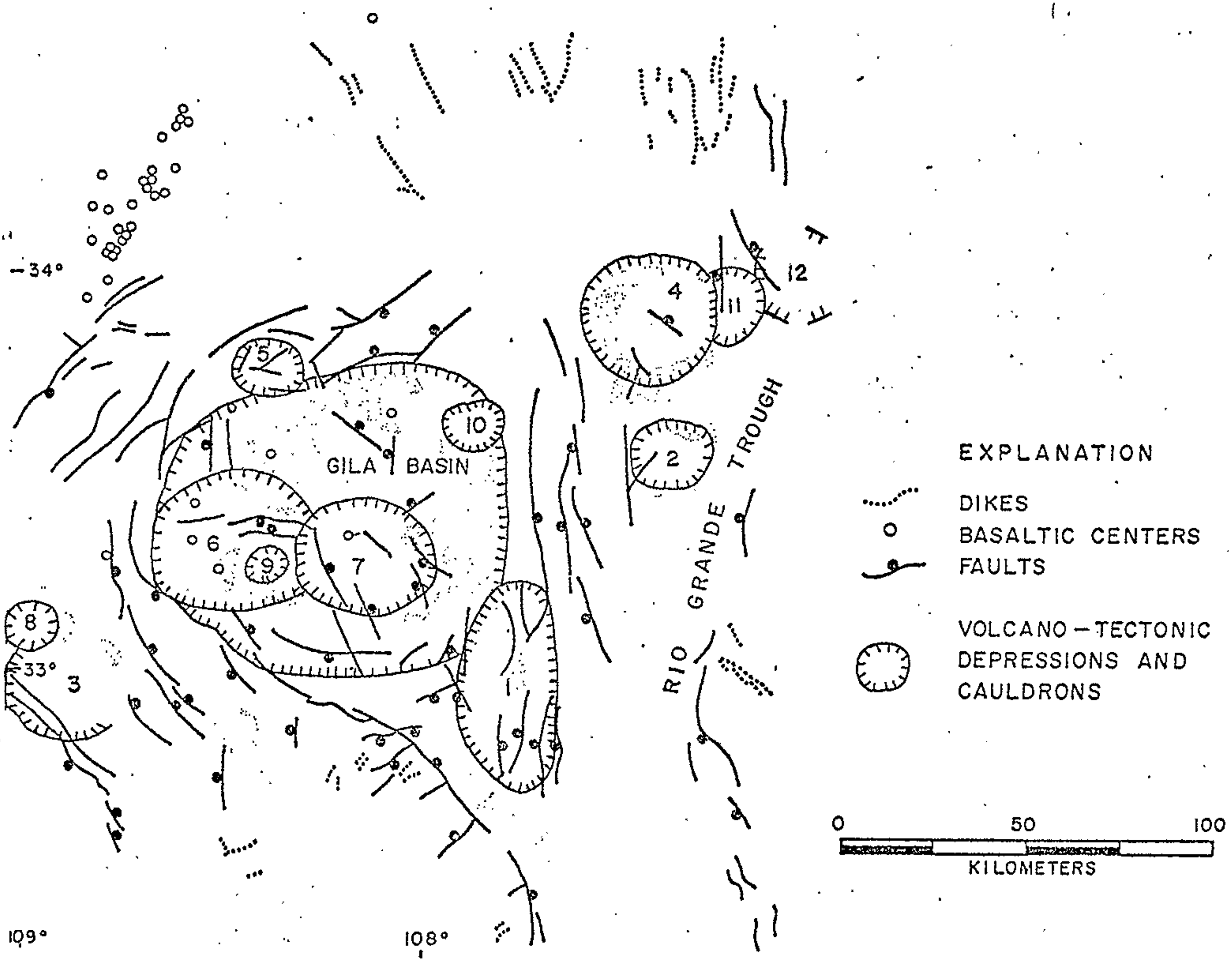


Figure B-6. Known or proposed cauldrons and volcanic depressions.

Dwellings cauldron (7) (Elston and others, 1968), "Magdalena" cauldron (11) (Chapin, 1974), "Socorro" cauldron (12) (Chapin and Chamberlin, 1976), and the Goodsight-Cedar Hills depression (13) (Seager, 1973) all have recognizable counterparts on the Landsat map.

The circular features corresponding to the "Magdalena" and "Socorro" cauldrons were identified on the Landsat imagery prior to their mention in recent papers and maps (Woodward and others, 1975 Chapin and Chamberlin, 1976). The cauldrons' existence was learned of from consultation with Dr. Chapin about the on-going work in the area by himself and his students. This indicates that Landsat imagery can be useful in identifying regional structures in complex volcanic terranes. New insights into the structure of the previously recognized cauldrons can be found on the Landsat map, too. The Emory cauldron, rather than a single elongate structure, appears to be made up of several overlapping circular features. The same can be said for the Nogal Canyon cauldron. Nearly concentric circular features overlie the Bursum cauldron and the Blue Creek volcanic depression suggesting their structure is more complex than a single collapse feature. Christiansen (1976) has suggested that with increasing time between ash flow eruptions, the collapse or cauldron features diverge in space as well. Nested or closely concentric calderas are usually formed within a span of several tens of thousands of years while clustered or slightly more divergent features indicate formation over a span of as much as one million years.

Three of the cauldrons shown in Figure B-6 have no equivalent on the Landsat map; the Mule Creek cauldron, Corduroy Canyon cauldron, and Squirrel Springs cauldron. None of these structures are well documented by field studies. One reason for their poor documentation and a possible explanation for their not being recognized on Landsat imagery is the fact that each has been buried under a considerable thickness of younger volcanic and sedimentary deposits. None of these three structures has been exhumed enough to allow good definition on the ground or from satellite imagery.

Four circular features are apparent on the Landsat imagery which have no similar structure known or proposed in the literature as a result of field studies. Three of these occur to the north of Silver City, and the fourth is located to the south of the Emory cauldron in the Cooks Range. The two intersecting circular features of the northeast of Silver City are associated with two of the oldest centers of volcanic activity recognized in the Datil-Mogollon province, the Alum Mountain and Copperas Peak center (Ratte and others, 1972; Elston and others, 1970). The Landsat interpretation offers a new definition of the size and shape of these centers which are evident in the field only in erosional windows through a thick pile of overlying volcanic rocks. The circular feature northwest of Silver City is also associated with a poorly defined, old volcanic center. The southern half of this feature encloses the Brock Canyon volcanic center (Ratte and others, 1972). The fourth unidentified feature on the Landsat map is in an area in the southern Cooks Range rimmed by uplifted Paleozoic and Mesozoic rocks which have been intruded by

Tertiary granite stocks. These stocks may represent the exposed roots of an old eruptive center. The early volcanic rocks of the Rubio Peak and Sugarlamp Formations which Elston (1957) found around this area may possibly have come from this center.

CONCLUSIONS

Landsat imagery can be used with good results to study regional geologic structures, even in complex volcanic terranes. Two pair of lineament trends are apparent on the imagery: a less prominent (older, probably Laramide in age) pair trending N-NE and W-NW, and a strongly developed (younger, probably Basin and Range in age) pair trending N-NW and E-NE. Comparison of the Landsat interpretation with detailed field study maps (Elston and others, 1976) shows Landsat linears tend to smooth small complex faulting patterns while preserving the general grain and trend of the faults. Most major, regional fractures are prominent and easily mapped on Landsat imagery.

Circular features related to cauldrons or volcanic centers are also apparent on Landsat imagery. Many of the known cauldron complexes, most of intermediate age in comparison with the time span of Datil-Mogollon volcanic activity, are easily defined on the imagery as well as on the ground. New insights into the complexity of their structure are offered by Landsat. Young cauldrons complexes, particularly those buried by thick accumulations of volcanic and sedimentary rocks, are not apparent on Landsat imagery, and cannot be well defined on the ground either. Other volcanic centers, generally the oldest ones in the area, are more easily defined on the imagery than on the ground.

The study of Landsat imagery complements field investigations. Small areal studies may be initiated by examining Landsat images to see how the local area of interest fits into the larger regional picture, and Landsat imagery can be used to help construct a regional structural picture using several small field studies as ground truth, as in this study.

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APPENDIX C

The Use of Landsat Imagery as a Mineral Exploration Tool
in the Datil-Mogollon Volcanic Area
Southwestern New Mexico

INTRODUCTION

A major part of the state's metallic mineral wealth is found in southwestern New Mexico in the Datil-Mogollon volcanic area. The location and production in dollars for mining districts of mid-Tertiary age in the Datil-Mogollon area is given in Figure C-1. Although most of these districts have been dormant in recent years, past production has totalled over 81 million dollars. A major part of the production dates from 1890 to 1930 which means that in terms of today's dollars and metal prices the value produced would be several times higher.

DISCUSSION OF RESULTS

In order to study how structures recognized on the Landsat imagery relate to the known mineral occurrences in the area, transparent overlays of copper, lead and zinc, manganese, silver, gold, iron, and fluorite deposits were prepared for analysis with the Landsat structure map. The results of this analysis are present in Table C-1. The relationship between Landsat identified structures and the known mineral deposits are as follows: gold, iron, and fluorite deposits are found predominantly along northwest trending fractures while deposits of copper, lead and zinc, manganese, and silver are most commonly found along northeast trending fractures.

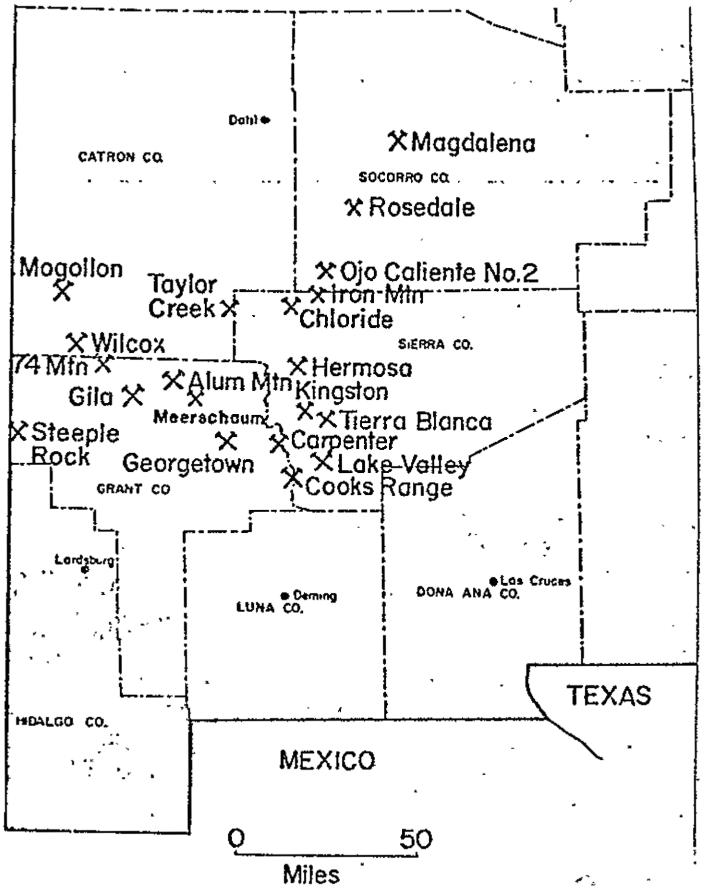

Figure C-1. Important mid-Tertiary mining districts of the Datil-Mogollon volcanic area. (modified from Elston and others, 1976)

DISTRICT	PRODUCTION(millions of dollars)
Magdalena	28.4
Rosedale	0.3
Ojo Caliente	small
Taylor Creek	small
Chloride	1.0
Hermosa	1.5
Kingston	6.4
Tierra Blanca	0.2
Carpenter	small
Iron Mountain	small
Lake Valley	5.5
Cooks Range	3.7
Steeple Rock	6.0
Gila	small
Wilcox	small
Georgetown	3.5
Alum Mountain	small
Mogollon	25.0

Table C-1. Relationships between Landsat identified structures and known mineral deposits.

Type of deposit (number) Associated Landsat feature	Cu (27)	Pb+Zn (6)	Mn (74)	Ag (15)	Au (19)	Fe (11)	F (59)	Total (211)
Not associated with Landsat features	2 (7%)	0 (0%)	11 (15%)	3 (20%)	1 (5%)	1 (9%)	7 (12%)	25 (12%)
Associated with: NW-SE linear features	8 (30%)	2 (33%)	14 (19%)	2 (13%)	12 (63%)	5 (45%)	23 (39%)	66 (31%)
Associated with: NE-SW linear features	12 (44%)	3 (50%)	28 (38%)	6 (40%)	3 (16%)	3 (27%)	13 (22%)	68 (32%)
Associated with: N-S Linear features	3 (11%)	1 (17%)	12 (16%)	3 (20%)	2 (11%)	1 (9%)	13 (22%)	35 (17%)
Associated with: E-W linear features	2 (7%)	0 (0%)	9 (12%)	1 (7%)	1 (5%)	1 (9%)	3 (5%)	17 (8%)
Associated with: Circular features	8 (30%)	4 (67%)	25 (34%)	7 (47%)	8 (42%)	1 (9%)	9 (15%)	62 (29%)
Junction of two or more linear features	17 (63%)	5 (83%)	29 (39%)	11 (73%)	15 (79%)	7 (64%)	18 (31%)	103 (49%)

Two other interesting relationships are apparent in the results given in Table C-1. Each mineral category has a strong association with intersections of two or more linear features and the deposits of lead and zinc, manganese, silver, and gold show affinities with circular features also. A number of recent papers put forth explanations for the relationship between mid-Tertiary tectonism and the origin and location of mineral deposits of this region (Elston, 1970; Elston and others, 1973, 1976; Ratte, 1975; Ratte and others, 1972, 1974; Chapin and others, 1974a, 1974b). These writers all suggest important mineral deposits are associated with the intersections of major faults and of faults with cauldrons, the ring fracture zones and the central parts of resurgent cauldrons, and with subvolcanic intrusive centers. The Landsat map of linear and circular features was restudied using these guides to mineral deposits as the criteria for selecting targets for mineral exploration.

A map showing the 149 target areas selected is presented in Figure C-2. After the target areas were chosen, they were compared with maps giving the location of known mining and mineral districts (Rothrock and others, 1946; Anderson, 1957; Farnham, 1961; Mardirosian, 1971). The 70 target areas which coincide with known mining and mineral districts of gold, silver, copper, lead, zinc, iron, manganese or fluorite deposits are shown in red in Figure C-2. Almost half the target areas (47%) picked from the Landsat map coincide with known areas of mineralization. Twenty-five percent of the targets not associated with any mineralization fall in the poorly known, little

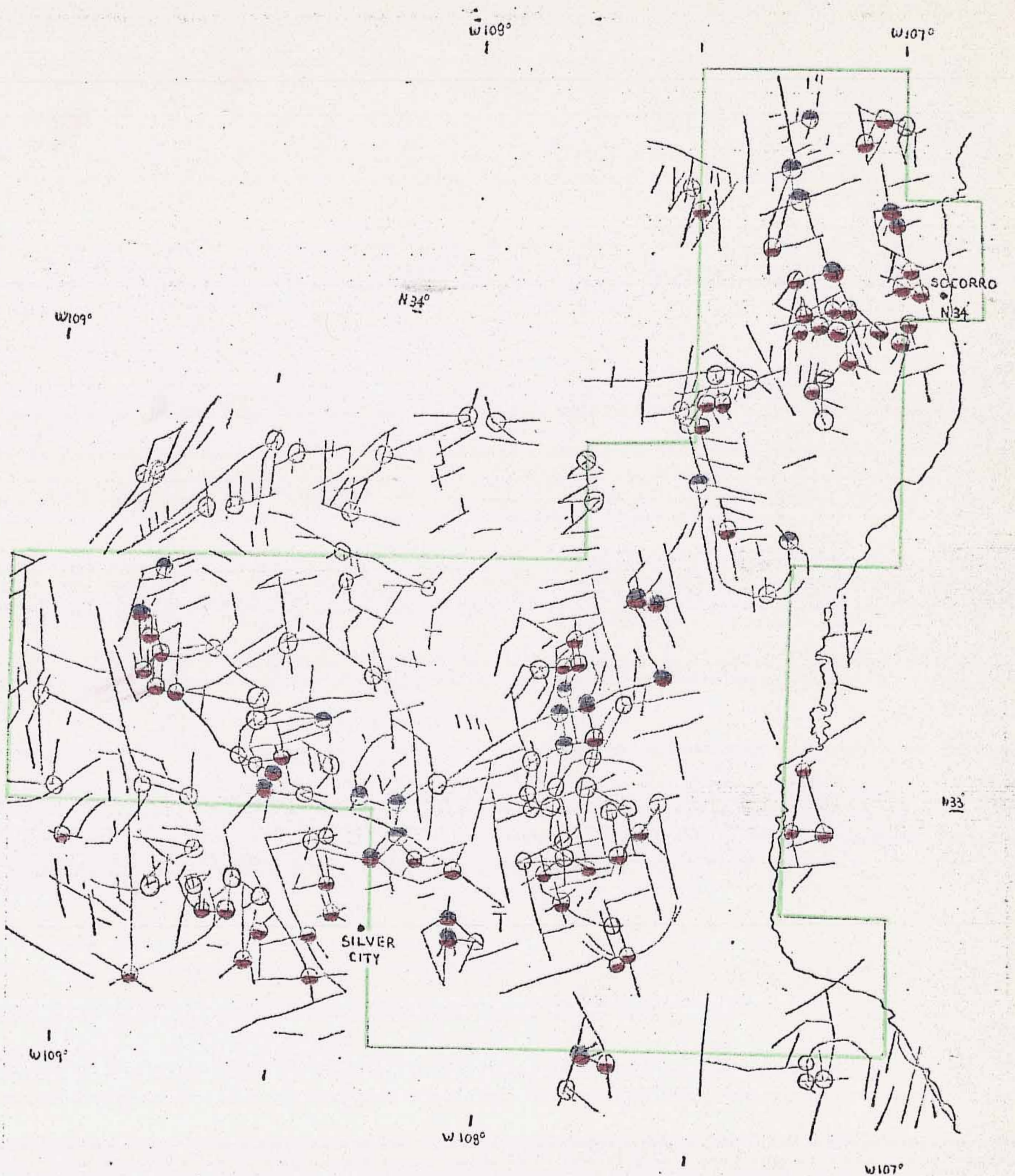

Figure C-2. Landsat identified exploration targets; ones colored red have mineralization, ones in blue have magnetic anomalies, green line indicates aeromagnetic coverage area. Scale approximately 1:1,340,000.

prospected northwestern part of the Datil-Mogollon area.

Since metallic mineral deposits are often associated with anomalies having high magnetism, the aeromagnetic maps available for the Datil-Mogollon region (coverage area outlined in green in Figure C-2) were examined to see what relationship exists between the target areas and the magnetic map patterns. Some magnetically high anomalies were discounted where it appeared they may simply reflect topographic differences. The 27 targets found to lie on or along the flanks of areas of significantly high magnetism are colored blue. Half of the targets over magnetically high areas also have known mineral occurrences. These magnetically high, mineralized target areas are mostly associated with Cretaceous to mid-Tertiary aged granitic stocks. These stocks are exposed at Santa Rita, Pinos Altos, Cooks Peak, the Cuchillo Mountains, and the northern Magdalena Mountains. Ratte (1975) has suggested that the Mogollon mining district on the west edge of the Bursum cauldron, another target area with mineralization and magnetic anomalies, may be located over a shallow pluton which was intruded along the ring fracture zone of the cauldron. Similar shallow plutons may also be associated with several other such targets with anomalous mineralization and high magnetism.

CONCLUSIONS

Multiple intersections of Landsat identified linear and circular features can be used as guides to possibly mineralized targets and thereby reduce exploration efforts in large areas such as the Datil-

Mogollon volcanic area covering as much as 18,000 square kilometers. Priority for field checking the targets can be assigned using any collateral information about known mineralization and geophysical features of the region. Using this approach, the following exploration program could be set up for the Datil-Mogollon area. First priority should be directed at presently inactive target areas having mineralization and magnetic anomalies. These areas, from west to east, correspond to the Mogollon mining district, the Brock Canyon-Gila Fluorspar area, the Pinos Altos district, the Hermosa district, the Sierra Cuchillo-Chloride district and the southern Cuchillo Mountains, the Magdalena district and the San Lorenzo-Lemitar Mountains area. Two anomalous target areas directly east of Silver City cover the presently productive Santa Rita district which includes the Chino open pit copper mine.

Areas with known mineralization but without a corresponding high magnetic anomaly should be considered second priority exploration targets, especially where closely clustered or concentrated along a particular structure. These areas include the southwest edge of the Bursum cauldron, the north end of the Black Range, the southwestern part of the Emory cauldron, the northwest part of the Mount Withington cauldron, the northern part of the "Magdalena" cauldron, and the northern edge of the "Socorro" cauldron. Third priority should be assigned to areas with high magnetic anomalies but no known mineralization.

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APPENDIX D

Vegetation and Land Use Map
of New Mexico

INTRODUCTION

The purpose of this study was to map the vegetational and land use patterns of New Mexico in so far as they may be observed or inferred from small scale satellite images. Secondarily we have incorporated information pertaining to landforms and geology.

This map was produced using Landsat imagery as a mapping base. Boundaries between categories at the 1:1,000,000 scale meet U.S.G.S. Topographic Division mapping standards for accuracy. Transition zones between vegetation categories are less accurately mapped because of the overlapping nature of dominant species, but the boundary delineations are still more exact than would be the case without a photographic mapping base. The use of satellite imagery also insures a nearly common date of data acquisition. By applying a comprehensive interpretation to uniform statewide base, a consistent map of the vegetation types and land uses in New Mexico has been produced (Plate in pocket).

Work began on the Vegetation Type and Land Use Map with a careful review of all such existing maps of New Mexico. Several maps by various federal and state agencies were found which, although useful for their intended purposes, were prepared to meet the specific needs of the originating agencies and were not necessarily intended for broader use. In some cases, data sources were not indicated, in others the map categories were ill-defined, and in all cases the accuracy of category boundary lines was unknown because a photographic base was not mentioned as used in the mapping.

MAP COMPILATION

The New Mexico Vegetation Type and Land Use Map was prepared directly from 24 separate Landsat color composite transparencies at the scale of 1 : 1,000,000. The color composites were made by the EROS Data Center in Sioux Falls, South Dakota from bands 4, 5 and 7 (visible green, visible red and infrared bands respectively).

The initial interpretation consisted of drawing boundary lines onto a mylar overlay of New Mexico using topography and color changes as the basis for delineation. No attempts at typing the vegetation or classifying land use were made at that time. When each image had been studied and compiled on the overlay, the map was re-examined for possible corrections of the boundaries and to make sure boundaries crossing from one image to another were consistent.

The next step involved categorizing the areas delineated as to their vegetative cover, land use and landform. The vegetation categories follow the style employed by Kuchler (1964) on his map of Potential Natural Vegetation of the Conterminous United States with modifications due to local conditions. The New Mexico map, however, shows actual vegetation and not potential natural vegetation. Decisions on vegetation type were made on the basis of personal knowledge of the state together with knowledge of the general vegetation relationships in the southwest. Maps from existing sources were also consulted for appropriate areas. Land use and topographic data, derived from the Landsat images, knowledge of existing ground cover, and information obtained from published sources (see references), are superimposed on the vegetation type data.

The map compiled from Landsat imagery was field checked for accuracy. Two-man teams traveled over 4,200 miles of major and secondary highways taking note of the types and boundaries for the areas of differing vegetation, land use and landforms as they were encountered. The vegetation category boundaries were found to be accurate, particularly in forested regions where cover type changes proved to be within several hundred meters of their plotted positions. Boundaries plotted between transitional vegetation types were less accurate.

The accuracy of categorization was not as great as that for delineation of boundaries. Although correctly delineated, several areas were found to be incorrectly classified, and in some cases, after field checking, entire categories were added or deleted from the original compilation. In other areas, no single dominant vegetation type was found and for these areas the two or more dominant types are shown on the map as striped patterns. An attempt was made to vary the width of the striped lines in proportion to the relative dominance of one species over another. It was found that this could not be done with consistent accuracy in all areas of the map. Therefore, the stripes have been made the same width to simply identify the vegetation types and not make any inference of dominance. To do otherwise would be to imply an accuracy in categorization which the authors could not feel confident making.

All areas delineated on the map are defined by three factors: vegetation type, land use and landform. Vegetation categories are portrayed by colors while land use and landform are keyed to letters and numbers respectively. Selected examples of the alpha-numeric symbols used for land use and landform are: G4 (grazing on gently rolling to flat terrain), A5 (agriculture on river bottoms), R1 (recreation in mountains or hills).

VEGETATION DIVISIONS

In organizing the map categories into a logical sequence, we have divided the types into physiognomic groupings. They are: 1) forests and woodlands, 2) shrubland and shrub savanna, 3) grasslands and steppes, 4) barren and 5) cultivated.

The forest and woodlands division has five types and includes evergreen, deciduous and mixed genera. The deciduous types are found almost exclusively along stream and river channels while the evergreen and mixed types occur predominantly in mountainous environments.

The shrubland and shrub savanna division is separated from the forest and woodland division for several reasons. Aside from their distinctive physiognomy there is a vast economic difference in the use of these lands. Shrubs are normally in a height class of under 2-3 meters and much branched at the base. Furthermore, the shrub savanna areas usually contain large areas of grass. These areas are concentrated in the drier southern half of the state in the lowlands and foothills.

The grasslands and steppes division covers a large proportion of the state. The grassland categories include several typical high plains grasses but also include two higher elevation meadow categories. The meadows are divided into alpine, or exposed mountain tops, and intermontane, meaning valleys protected by surrounding mountains. Of the steppe categories one is a shrub steppe containing grasses and semi-arid shrubs and the other is a semi-arid steppe containing xerophytic species dominated by yucca and cholla.

The areas in the barren division contain a few widely scattered plants but, for the most part, were devoid of vegetation. Included in this division are playa lakes, sand dunes, and major lakes and reservoirs.

In the cultivated division, the three categories are irrigated, dryland, and orchard. The irrigated and dryland categories, although often highly intermixed, are easily delineated on Landsat imagery on the basis of color. Irrigated fields appear bright red during the growing season and the dryland fields are tan to light brown. The orchard crops also appear bright red but are easy to differentiate from irrigated agriculture because they are confined mainly to a few narrow mountain valleys.

The "slash" or diagonal symbol is used repeatedly throughout the vegetation legend and is intended to mean "and/or". In areas which have a category containing more than one vegetation type the symbol signifies that the area may be occupied by all the types of that category, combinations of those types, or in places single types only. Following the common names of the vegetation types are the Latin names in parentheses. The Latin names appear in the same order as the common names and are similarly separated by slash symbols.

LAND USE DIVISION

There are eight categories of land use on this map. They are: A) agriculture, F) forestry (multiple-use), G) grazing, M) military, R) recreational, U) no dominant use, ⚒) and △) extraction, and ●) urban.

Agriculture land is broadly defined as land used for the production of food fiber. Agricultural areas are easily identified on satellite imagery by the geometric or regular shapes of the fields. Further breakdowns of agricultural land use to irrigated and dryland are made on the basis of color. Orchard crops appeared in narrow valleys and are the same color as irrigated crops.

The forestry category is, in fact, a multiple-use category. When one sees the F symbol on the map it is safe to assume that besides the normal forestry activities which take place, there are also relatively significant amounts of recreational as well as grazing activities.

Grazing is by far the dominant land use in the state. Grazing activities are found in nearly all grassland and lowland areas as well as in many of the mountainous areas under the multiple-use F label.

Boundaries for the military and recreational land use categories were taken off of existing maps because the impact of these land uses are very seldom visible on the imagery. However, the changes in land use across these boundaries is often striking, especially in the case of military reservations. Recreational boundaries are placed around wildlife refuges, wilderness areas, and national parks and monuments. Some areas are labeled recreational even though they do not fit any of the above criteria. These areas are known to support a large amount of recreational activities but are not designated as wilderness or park areas.

The symbol U stands for areas in which there is no dominant or apparent use. These areas are restricted mainly to high mountaintops, playa lakes, and lava flows. These are usually areas which are barren or nearly barren of vegetation or are of rough terrain which would preclude use of the land for grazing or farming.

The two map symbols for extractive land use are shown only for those locations which are visible on the Landsat imagery. Known areas of extractive land use not detectable on the imagery are not included on the map. In the case of oil and gas fields, the symbols indicate extractive regions rather than specific sites. Included in the extractive category are areas of mineral, mineral fuel, and petroleum product removal.

Urban areas are displayed mainly as a geographic reference rather than on the basis population size. The boundaries of the urban areas are extended out as far as their respective city limits and these areas are colored black.

LANDFORM DIVISIONS

Nine categories of landforms are identified on the Landsat imagery. They are: 1) mountains and hills, 2) dissected surfaces, 3) bajada surfaces, 4) gently rolling to flat terrain (including mesa tops), 5) river bottoms, 6) scarps, 7) lava flows, 8) enclosed basins, and 9) volcanic cones.

The mountains and hills category is easy to delineate by structure as well as by the vegetation types which occupy these landforms. The spruce, fir, and pine types are found almost exclusively on these landforms while the pinon/juniper occupied the lower mountain slopes, foothills and the flatlands.

Highly dissected areas are defined as having dense drainage networks and a relatively large amount of gully erosion. These gully and stream networks are easily identifiable on the satellite images and may have a s strong effect on the use of the land.

Bajadas, or alluvial fans, are gently sloping surfaces of sediments eroded down around mountains and rocky outcrops. They are generally bouldery near the tops and grade into sand and silt downslope. The fans often converge with other fans to form pediments.

The gently rolling to flat category needs little further definition. The term "gently rolling" refers to the undulating terrain characteristic of the Great Plains but does not include forms such as the foothills of mountains.

The river bottom category includes all river and stream channels and flood plains which are wide enough to be visible on the imagery. The vegetation of these features is characteristically irrigated agriculture or cottonwood/willow/tamarisk.

Scarps have been indicated in two ways. The number 6 refers to those scarpfaces which are wide, are gently inclined so they can support vegetation, and can be mapped on the satellite imagery. In other areas, where it is obvious that a scarp is present but is too steep to show, the scarpface symbol is used. The teeth are oriented to point down the scarpface. By no means have all the scarps in New Mexico been shown here, but the great majority of those visible on the Landsat imagery are located on the map.

Lava flows are solidified, stationary masses of rock formed when lava streams cooled. They are generally very thin when compared to their horizontal extent. The lava flows of New Mexico are much more extensive than are shown on the map, but due to their differing ages, composition, stages of erosion, and overlying vegetation they are difficult to identify and map.

Enclosed basins are extensive, low-lying areas into which the adjacent land drains, having no surface outlet. The enclosed basins of New Mexico are usually occupied by playa lakes.

Volcanic cones, category 9, are easily separated from lava flows because they have the shape of roughly circular hills or mountains. Volcanic cones are cone-shaped structures formed by localized volcanic discharges.

CORRELATION OF NEW MEXICO CATEGORIES WITH THE U. S. G. S. CLASSIFICATION SCHEME

A land use classification system was developed by Anderson, Hardy, Roach and Witmer (1976) for use with remotely sensed data (see Table 1). The idea behind this classification scheme was to provide a system which would be comprehensive but at the same time general enough to be accepted as the standard for land use mapping. The classification system was designed for level I and II mapping and was deliberately left open-ended so that third and fourth levels may be employed by local authorities to fit their particular needs.

We are able to map vegetation by inference, experience and field examination to the third level. Care was taken to structure our classification so that each category on the New Mexico map has a level I and II equivalent in the U. S. G. S. system. The New Mexico categories and the U. S. G. S. scheme are correlated in Table II. This correlation table does not show a level by level comparison between the two classification systems but rather shows rough equivalents in order to allow cross-referencing our map with other maps using the U. S. G. S. scheme. It should be noted that the column of New Mexico categories included a mixture of several levels while the U. S. G. S. scheme is organized into two distinct levels.

Table 1 - Land use and land cover classification system for use with remote sensor data

	Level I		Level II
1	Urban or Built-up Land	11	Residential.
		12	Commercial and Services.
		13	Industrial.
		14	Transportation, Communications, and Utilities.
		15	Industrial and Commercial Complexes.
		16	Mixed Urban or Built-up Land.
		17	Other Urban or Built-up Land.
2	Agricultural Land	21	Cropland and Pasture.
		22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas.
		23	Confined Feeding Operations.
		24	Other Agricultural Land.
3	Rangeland	31	Herbaceous Rangeland.
		32	Shrub and Brush Rangeland.
		33	Mixed Rangeland.
4	Forest Land	41	Deciduous Forest Land.
		42	Evergreen Forest Land.
		43	Mixed Forest Land.
5	Water	51	Streams and Canals.
		52	Lakes.
		53	Reservoirs.
		54	Bays and Estuaries.
6	Wetland	61	Forested Wetland.
		62	Nonforested Wetland.
7	Barren Land	71	Dry Salt Flats.
		72	Beaches.
		73	Sandy Areas other than Beaches.
		74	Bare Exposed Rock.
		75	Strip Mines Quarries, and Gravel Pits.
		76	Transitional Areas.
		77	Mixed Barren Land.
8	Tundra	81	Shrub and Brush Tundra.
		82	Herbaceous Tundra.
		83	Bare Ground Tundra.
		84	Wet Tundra.
		85	Mixed Tundra.
9	Perennial Snow or Ice	91	Perennial Snowfields.
		92	Glaciers.

Table II. Correlation of New Mexico Categories with U.S.G.S. Professional Paper 964

USGS Professional Paper 964 Classification Scheme		New Mexico Categories
Level I	Level II	
1 Urban or Built-up Land	16 Mixed	Urban Areas
2 Agricultural Land	21 Cropland and Pasture	Irrigated Agriculture Dryland Agriculture
	22 Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas	Orchard Crops
3 Rangeland	31 Herbacaeous	Grama/Calleta Steppe Grama/Buffalo Grass "Shortgrass Prar Intermontane Meadows
	33 Mixed	Great Basin Sagebrush Saltbush/Greasewood Creosote Bush/Tarbush Scrub Oak Grama/Tobosa/Mesquite Schrub Steppe Yucca/Cholla
4 Forest Land	41 Deciduous	Cottonwood/Willow/Tamarisk
	42 Evergreen	Spruce/Fir Pine/Fir Pinon/Juniper
	43 Mixed	Juniper/Oak
5 Water	52 Lakes 53 Reservoirs	Major Lakes and Reservoirs
7 Barren Land	71 Dry Salt Flats 73 Sandy Areas other than Beaches	Playa Sand Dunes
8 Tundra	85 Mixed	Alpine Meadows

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APPENDIX E

Rural Land Cover Mapping in Socorro County, New Mexico

INTRODUCTION

The purpose of this mapping effort was to weigh the value of using high altitude photography in rural land cover mapping in New Mexico versus a satellite data base. Socorro County is representative of most New Mexico counties: rural character, large land area, small population and a mixture of grazing and valley agriculture. Topographic relief is great within the county and the semi-arid conditions result in a fragile environment.

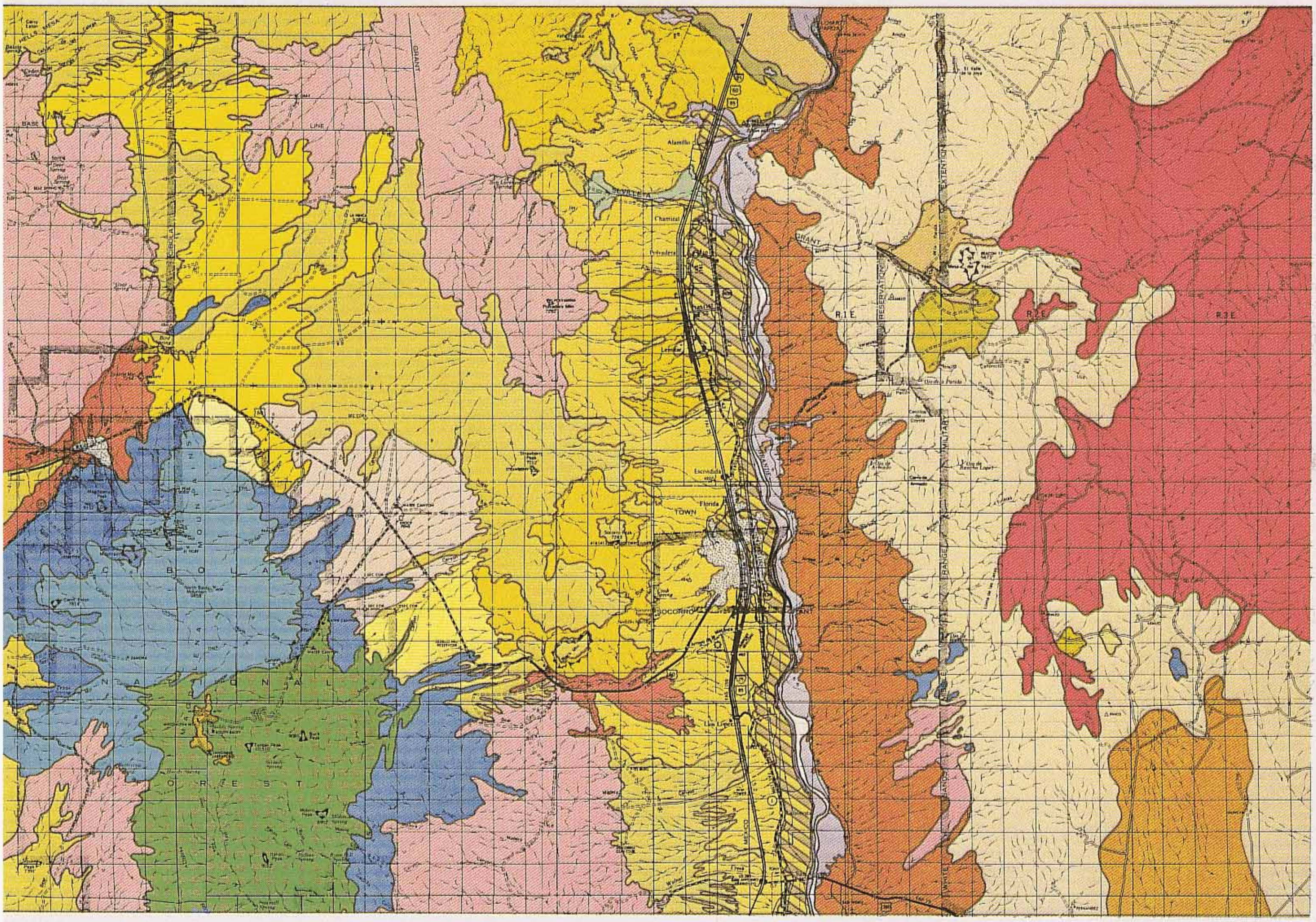
Interpretation of nine (9) high altitude color photographs flown by NASA in May of 1975 served as the base for the vegetation and land use map of the Socorro area (Figure E-1). Boundary delineations and classifications were made based on photo tone and texture. As interpretation progressed field trips were made to verify and correct the vegetation type and land use. The 1:112,000 scale photos were slightly underexposed and distortions were present which affected the efficiency of mapping; therefore, more field time was required for classification. Following the mapping and verification phases, the delineations were reduced in scale to 1:126,720 in order to conform to the State Highway Department base map. Corrections for distortions were made at this time.

INTERPRETATION

The prints and transparencies used in the study were underexposed. This led to some problems in delineating cover types. Marginal interpret-

VEGETATION TYPES OF THE SOCORRO AREA, NEW MEXICO

TECHNOLOGY APPLICATION CENTER in cooperation with the NEW MEXICO BUREAU OF MINES



▨ URBAN OR BUILT-UP AREAS

▨ IRRIGATED AGRICULTURE

RANGELAND

- 🟨 Alpine meadows
- 🟨 Sacaton (Sporobolus)
- 🟨 Grama (Bouteloua)
- 🟨 Creosote (Larrea)
- 🟨 Cholla (Opuntia)
- 🟨 Cholla/Grama (Opuntia/Bouteloua)
- 🟨 Cholla/Grama/Yucca (Opuntia/Bouteloua/Yucca)
- 🟨 Creosote/Piñon/Juniper/Grama (Larrea/Pinus/Juniperus/Bouteloua)
- 🟨 Creosote/Grama (Larrea/Bouteloua)
- 🟧 Mesquite/Yucca/Snakeweed/Sacaton (Prosopis/Yucca/Gutierrezia/Sporobolus)
- 🟨 Creosote/Snakeweed/Sacaton/Grama (Larrea/Gutierrezia/Sporobolus/Bouteloua)
- 🟧 Indigobush/Grama/Creosote/Snakeweed (Dalea/Bouteloua/Larrea/Gutierrezia)
- 🟨 Indigobush/Sand (Dalea)
- 🟥 Piñon/Juniper/Grama/Sacaton (Pinus/Juniperus/Bouteloua/Sporobolus)
- 🟪 Piñon/Juniper/Grama (Pinus/Juniperus/Bouteloua)
- 🟥 Grama/Four-wing saltbush (Bouteloua/Atriplex)
- ⬜ Grama/Yucca (Bouteloua/Yucca)

FOREST LAND

- ⬜ Willow/Tamarisk/Cottonwood (Salix/Tamarix/Populus)
- 🟦 Piñon/Juniper (Pinus/Juniperus)
- 🟦 Piñon/Juniper/Pine/Oak (Pinus/Juniperus/Quercus)
- 🟩 Fir/Oak/Pine (Abies/Quercus/Pinus)
- 🟩 Piñon/Juniper/Tamarisk/Grama (Pinus/Juniperus/Tamarix/Bouteloua)

▨ SAND

☐ WATER

1 0 1 2 3 4 5
MILES

Compiled 1976 by Amelia Komarek and Mike White.

Data base: NASA U-2 photography flown 1975.

Map base: New Mexico State Highway Dept., General Highway Map for Socorro County, 1968.

ability of certain cover types on high altitude photography also created mapping problems. In some cases soil exposure due to sparse vegetation led to an initial misclassification on the photos.

The problem of relating data on the photos to that on the ground was not present due to the close proximity of flight season to the season of the field work. The interpretation and field work were done approximately twelve (12) months after the photos were taken, and, therefore, vegetation was approximately at the same stage of growth.

Some photo distortion was compensated for by using the 60% endlap. Side-lap was minimal however, and correction for distortion required the use of many ground control points. The most distortion was found in areas of high relative relief. During the second drafting of the map, scale adjustments were made to the base map. The scale was changed from 1:112,000 to 1:126,720.

Stereo was found to be useful when separating the geology and the vegetation patterns and generally contributed to the ease of interpretation. A useful, and probably the most needed aide, was the 7 power, hand magnifier which helped in identifying many of the vegetation types and for locating rural buildings. The pinon/juniper association was the easiest vegetation to identify using the magnifier. Grassland identification was greatly improved but not finalized using the magnifier.

High altitude color photography proved to be very acceptable for vegetation and land use delineations in rural areas. The natural color photography was felt to be of more value than color infrared for the semi-arid environment. Based on tonal and textural elements, lines were found to correspond to ground data.

Vegetation was delineated on the basis of type rather than by density. Pinon/juniper trees were most easily classified and this association appeared characteristically as small dots. Areas of grassland were also easy to delineate. These, however, could only be classified taxonomically by field visitation. In some cases it was difficult to separate shrubs from grasses on the photos. Vegetation could easily be confused among the geology and soils and could only be identified through field work. This was particularly true in the sparsly vegetated area east of the Rio Grande. Reparian forests consisting of cottonwood, tamarisk and willow were all identified without difficulty. Lines depicting soil or geological conditions were eliminated.

Agricultural field patterns and irrigation systems along the Rio Grande Valley were obvious on the photos. Some pastures were identified on the basis of tonal variations usually suggesting a fence or density difference caused by intensive grazing practices. This was most visible on the photos showing the grama grass area between the Magdalena and Socorro Mountains. Some grazing patterns could be detected on the photos in the extreme southeastern corner of the study area, dominated by sacatone grass.

Drainage lines are visible on the photos but only major streams and rivers were mapped. The Highway Department base map already contained the drainage net, and was accurate enough to preclude analysis by photo interpretation. Minor corrections in the channel of the Rio Grande and the Rio Salado, and intermittent stream, were made. Soil variations and geology show well in the photography, especially east of the Rio Grande where the vegetation is sparse.

Cultural features such as highways, irrigation systems, towns, mines and buildings, were all visible on the photos. Urban areas are easy to find, but to determine further urban breakdown (commercial, industrial and residential) was difficult from high altitude photography. The development of small cities and towns does not follow the zoning effect usually seen in larger urban areas where planning controls exist. Commercial activity in small cities may be interspersed with residential, recreational or industrial use.

EXPLANATION OF CLASSIFICATION SYSTEM

The classification scheme for the Socorro Land Use Map was modelled after the U. S. Geological Survey Professional Paper 964 (Figure E-2). A total of 27 categories were identified under the following six major (Level I) classification units.

1. Urban or Built-Up Land

Individual land uses within the small cities and towns cannot be determined from the high altitude photos; therefore, all urban settlements in the study area are classified as mixed urban or built-up land. This classification combines residential, commercial

Table E-1.

Land use and land cover classification system for use with remote sensor data

	Level I		Level II
1	Urban or Built-up Land	11	Residential.
		12	Commercial and Services.
		13	Industrial.
		14	Transportation, Communications, and Utilities.
		15	Industrial and Commercial Complexes.
		16	Mixed Urban or Built-up Land.
		17	Other Urban or Built-up Land.
2	Agricultural Land	21	Cropland and Pasture.
		22	Orchards, Groves, Vineyards, Nurseries, and Ornamental Horticultural Areas.
		23	Confined Feeding Operations.
		24	Other Agricultural Land.
3	Rangeland	31	Herbaceous Rangeland.
		32	Shrub and Brush Rangeland.
		33	Mixed Rangeland.
4	Forest Land	41	Deciduous Forest Land.
		42	Evergreen Forest Land.
		43	Mixed Forest Land.
5	Water	51	Streams and Canals.
		52	Lakes.
		53	Reservoirs.
		54	Bays and Estuaries.
6	Wetland	61	Forested Wetland.
		62	Nonforested Wetland.
7	Barren Land	71	Dry Salt Flats.
		72	Beaches.
		73	Sandy Areas other than Beaches.
		74	Bare Exposed Rock.
		75	Strip Mines Quarries, and Gravel Pits.
		76	Transitional Areas.
		77	Mixed Barren Land.
8	Tundra	81	Shrub and Brush Tundra.
		82	Herbaceous Tundra.
		83	Bare Ground Tundra.
		84	Wet Tundra.
		85	Mixed Tundra.
9	Perennial Snow or Ice	91	Perennial Snowfields.
		92	Glaciers.

and industrial uses along with other miscellaneous uses.

2. Agricultural Land

Agricultural land along the Rio Grande is identified in Level II as Cropland and Pasture.

3. Rangeland

Rangelands in the study area separate into three types in the Level II classification: Herbaceous Rangeland, Shrub and Brush Rangeland and Mixed Rangeland. The Herbaceous Rangeland consists of lands dominated by naturally occurring grasses and forbs. Identified in this category for the Socorro area are Alpine Meadow, and open, grassy area found in the Magdalena-Mountains, though not above timberline; Sacatone Grass, found mainly in the rangelands east of the Rio Grande; and Grama Grass, which is located throughout the study area, mainly in rangelands at higher elevations east and west of the Rio Grande Valley.

Creosote bush and Cholla cactus found in the study area are classified as Shrub and Brush Rangeland. This category encompasses typical shrubs found in arid and semi-arid regions characterized by xerophytic vegetative types. The Creosote bush is such a plant and grows mainly on a wide strip of alluvial plain adjacent to the Rio Grande. A large Cholla patch is found at the northeastern base of the Magdalena Mountains.

The majority of the rangeland associations defined in the Socorro area are classified as Mixed Rangeland. This category combines those associations that include both herbaceous and shrub/brush rangeland species.

4. Forest Land

Three forest land categories are found in the study area: Deciduous Forest Land, Evergreen Forest Land and Mixed Forest Land. The willow, tamarisk, and cottonwood growth has been classified as Deciduous Forest Land rather than Forested Wetland, because the water table in this area is not high enough to qualify as a Wetland. The only Evergreen Forest Land category found in the study area consisted of the pinon/juniper (PJ). Other evergreen trees were found mixed with deciduous trees and therefore fall into the Mixed Forest Land unit. These include Fir-Oak-Pine and PJ-Pine-Oak associations found in the mountainous regions. A PJ-Riparian-Grama Grass association was found in an arroyo on the alluvial plain west of the Rio Grande Valley.

5. Water

The only appropriate category for water is Streams and Canals which classifies the Rio Grande River.

7. Barren Land

Barren land in the Socorro study region falls into the category "Sandy Areas Other Than Beaches". These are the sand dunes of the Rio Salado found in the northern section of the study area.

CONCLUSIONS

New Mexico planning and decision making is strongly tied geographically to the county. It is at the county level that decisions reflecting use and management of resources are made, and it is the county boundary that defines the planning districts for state government.

High altitude photography and Landsat imagery are both useful in mapping natural resource patterns, which, in turn, are valuable clues to help plan rural land use development. Areas susceptable to erosion, high runoff and flash flooding can be evaluated using rural maps such as the Socorro area map. Planning data in map form can be more readily used and can have a substantial role in the development of rural geographic areas and small communities which do not presently benefit from planned development.

High altitude photography is better suited for small areal studies such as this one where greater detail is desired. Natural color and superior resolution make the aircraft photography a preferred choice of data sources for small detailed land use mapping.

Landsat imagery cannot provide the same visual detail for small areas; however, for large areas, such as the state of New Mexico, it can provide sufficient resolution. Cost-wise Landsat data becomes more attractive as the area of interest increases. Landsat also requires fewer images to cover large areas making it less unwieldy to analyze such areas. Finally, Landsat offers easily obtainable repeated coverage.

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