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APPLICATION OF REMOTE SENSOR DATA TO GEOLOGIC ANALYSIS OF THE BONANZA TEST SITE, COLORADO

FINAL REPORT

by

Keenan Lee

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December 1976

REMOTE SENSING PROJECTS

DEPARTMENT OF GEOLOGY

COLORADO SCHOOL OF MINES • GOLDEN, COLORADO

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Bonanza Remote Sensing Project
Department of Geology
Colorado School of Mines
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INTRODUCTION

The Bonanza Project initially was a joint effort of the Colorado School of Mines (CSM) and the Martin Marietta Corporation (MMC). CSM brought to this effort faculty and graduate students with recognized ability in the geological sciences, while MMC demonstrated competence in aerospace technology. This combined capability then, working together with the same data from different approaches, attempted to maximize the extraction of geologic information from remote sensor data.

The Bonanza Project began in 1969 with a grant from the Office of University Affairs (OUA). Since that time, support has come jointly from both OUA and the Earth Resources Survey Program Office, under NASA Grant NGL 06-001-015.

The objectives of the Bonanza Project were twofold: (1) to develop an educational program of graduate study in geologic remote sensing, and (2) to conduct research on the applications of remote sensing to the mineral industry.

Educational Program

Faculty working under this grant have developed three graduate courses in geologic remote sensing:

Introduction to Remote Sensing

Geologic Applications of Remote Sensing

Seminar in Geologic Remote Sensing

The first course in this series, Introduction to Remote Sensing, deals with the theory of active and passive remote sensing systems, using the energy path concept in the ultraviolet through radar portions of the electromagnetic spectrum. Students are introduced to remote sensing instruments and the interpretation of representative data. Geologic applications are briefly surveyed.

This course has been offered continuously since 1969, often as part of the CSM Continuing Education Program, which made the class available to practicing scientists and engineers in the Denver metropolitan area. Enrollment has included undergraduates, graduate students and professional scientists and engineers.

The second course, Geologic Applications of Remote Sensing, stresses the application of remote sensing to geologic and mineral resource investigations. The course includes detailed study of remote sensing techniques, with field and laboratory experiments and experience in data reduction, analysis and interpretation. Case studies of demonstrated applications are presented, and potential uses are examined. Students conduct excercises in mission planning and selection of optimum sensor systems for specific geologic targets.

The third course of the series, Seminar in Geologic Remote Sensing, consists of group discussions and individual student presentations on current literature and research.

The Bonanza Project has supported the research of 14 students working toward advanced degrees. Five M.S. programs have been completed, one is in progress, and six Ph.D. programs have led to the Doctorate.

A great deal of effort, especially toward the end of the grant period, was directed toward the publication of a laboratory manual. This goal was achieved with the publication of the Laboratory Manual for Study of Remote Sensing, enclosed with this final report as Remote Sensing Report 76-1. The Manual is designed for a 10-lab, 3-hour-per-lab course in remote sensing, such as the introductory course described above.

Remote Sensing Applications

Research conducted under the Bonanza grant has always been directed toward geologic applications of remote sensing. Most of the research has dealt with remote sensing from aircraft, especially the NASA aircraft, although toward the end of the grant period research extended to space systems. Some of the latter research projects were in part supported by the Bonanza grant and in large part by NASA contracts.

The significant results of the research on geologic applications of remote sensing are presented in the next two sections, Publication of Results and Abstracts of Significant Results.

PUBLICATION OF RESULTS

The policy of the Bonanza Project, since its beginning, has been to publish the results of research as soon as significant interim results became available, rather than to accumulate them for a comprehensive final report. This procedure has resulted in numerous technical reports and publications. The rather lengthy lists are given on the following pages.

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74-4 Raines, G.L., and Lee, Keenan, 1974, An evaluation of multiband photography for rock discrimination: Paper presented at the 3rd Ann. Remote Sensing of Earth Resources Conf., Univ. of Tenn. Space Inst., 36 p.

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GEOLOGIC REMOTE SENSING STUDY

OF THE

HAYDEN PASS - ORIENT MINE AREA,

NORTHERN SANGRE DO CRISTO MOUNTAINS, COLORADO

by

Daniel C. Wychgram

The Hayden Pass--Orient Mine area includes 60 square miles of the northern Sangre de Cristo Mountains and San Luis Valley in south-central Colorado. The rocks of this area include Precambrian igneous and metamorphic rocks, Paleozoic sedimentary rocks, Tertiary intrusive rocks, and Quaternary deposits.

Remote sensor data from a NASA Convair 990 radar flight and Mission 101 and 105 have been interpreted and evaluated. Based on interpretation of the remote sensor data, a geologic map (Plate II) has been prepared and compared with a second geologic map (Plate I), prepared from interpretation of both remote sensor data and field data. Comparison of the two maps gives one indication of the usefulness and reliability of the remote sensor data.

The usefulness and reliability of the remote sensor data are a function of the type of terrain as well as the type of remote sensor used. The San Luis Valley, with low relief and sparse vegetation, proved to be the best area to apply remote sensing. The western slope of the mountains is less suitable to the use of remote sensing techniques because of the dense coniferous cover and high relief. The eastern slope of the mountains, which is very densely covered with conifers and has high relief, is least suited to the use of remote sensing.

By using remote sensing as an aid in mapping the geologic features of the area, advantages were realized over purely field methods. These advantages include time savings, a greater understanding of certain geological phenomena, and the compilation of a more accurate and complete geologic map.

Colora and color infrared photography provided the largest amount of valuable information. Multiband photography was of lesser value and side-looking radar imagery provided no new information that was not available on small-scale photography. Thermal scanner imagery proved to be a very specialized remote sensing tool that should be applied to areas of low relief and sparse vegetation where geologic features produce known or suspected thermal contrast. Low sun-angle photography may be a good alternative to side-looking radar imagery but must be flown with critical timing.

REMOTE SENSING AIDS GEOLOGIC MAPPING

by

Daniel H. Knepper, Jr.
and
Ronald W. Marrs

Remote sensing techniques have been applied to general geologic mapping along the Rio Grande rift zone in central Colorado. A geologic map of about 1,100 square miles was prepared utilizing 1) prior published and unpublished maps, 2) detailed and reconnaissance field maps made for this study, and 3) remote sensor data interpretations. The map is to be used for interpretation of the complex Cenozoic tectonic and geomorphic histories of the area.

Regional and local geologic mapping can be aided by the proper application of remote sensing techniques. Conventional color and color infrared photos contain a large amount of easily-extractable general geologic information and are easily used by geologists untrained in the field of remote sensing. Other kinds of sensor data used in this study, with the exception of SLAR imagery, were generally found to be impractical or unappropriate for broad-scale general geologic mapping; these data can, however, be effectively applied to specific problems in relatively small areas, but some knowledge of the principles of remote sensing is necessary for the acquisition of the proper data and for subsequent interpretation.

APPLICATION OF REMOTE-SENSING TECHNIQUES
TO THE GEOLOGY OF
THE BONANZA VOLCANIC CENTER

by

Ronald W. Marrs

A program for evaluating remote sensing as an aid to geologic mapping has been under way at the Colorado School of Mines for the past four years. Data tested in this evaluation include color and color infrared photography, multiband photography, low sun-angle photography, thermal infrared scanner imagery, and side-looking airborne radar.

The relative utility of color and color infrared photography was tested as it was used to refine geologic maps in previously mapped areas, as field photos while mapping in the field, and in making photogeologic maps prior to field mapping. The latter technique served as a test of the maximum utility of the photography. In this application the photography was used successfully to locate 75% of all faults in a portion of the geologically complex Bonanza volcanic center and to map and correctly identify 93% of all Quaternary deposits and 62% of all areas of Tertiary volcanic outcrop in the area.

Attempts were made to enhance geologically significant contrasts and to detect and delineate lithologically and structurally important features using multiband photography. The multiband techniques were generally unsuccessful in the heavily forested volcanic terrain of the Bonanza area. Color-additive viewing of the multiband photography also failed to produce any obvious contrast improvement.

Daytime thermal infrared imagery was useful for locating faults despite strong interference from topography. Pre-dawn thermal imagery was also affected by topography in areas of high relief, but revealed moisture and vegetation patterns in areas of low relief. Some of these patterns proved to be geologically significant.

Low sun-angle photography was more useful than available side-looking radar for geologic mapping in the Bonanza volcanic center where the main object of low-angle illumination was enhancement of topographically expressed structures. The low sun-angle photography has its major advantage in superior resolution, but lacks the flexibility of side-looking radar with regard to "look-direction". For both sensors, the best illumination direction is one which is very nearly perpendicular to the structural trends and "looks down" the dominant topographic slope.

Geologic mapping done in conjunction with the remote-sensing evaluations of the previously unmapped area to the south and west of the central Bonanza mining district confirms the existence of the Bonanza caldera and demonstrates that structures related to the formation of the caldera dominate the geology of the area.

The Oligocene volcanic sequence of the Bonanza volcanic center is typical of volcanism in and around the San Juan volcanic field. It begins with intermediate andesitic flows and breccias, followed by more silicic pre- and intra-caldera lavas and ash flows, and terminates with small, latitic and rhyolitic flows. Caldera collapse is associated with the eruption of the middle ash-flow sequence which serves as a geologic marker for the structural interpretation and as an indicator of the geologic evolution of the magma which produced the Bonanza volcanic pile.

Interpretation of the structural pattern of the Bonanza area as the result of large-scale subsidence is supported by all the observed structural and stratigraphic relationships, and is further confirmed by gravity data (Karig, 1965).

The radial and concentric pattern of faulting which resulted from collapse of the Bonanza caldera has controlled post-volcanic ore deposition in the area. Mineralogical similarities among deposits demonstrate that mineralizing fluids moved out along radial fractures. The largest areas of alteration and mineralization are located at the intersections of the major radial and concentric faults.

Evidence of post-caldera movements on the Western Boundary Fault of the Bonanza caldera and the coincidence of the Western Boundary Fault of the caldera with the west boundary fault of the Arkansas Valley graben indicates that the caldera fault system has been undergoing additional displacement as a part of the presently active Rio Grande rift system. This late movement helps to explain why the west boundary of the Bonanza caldera shows more structural displacement than the east boundary.

EVALUATION OF MULTIBAND PHOTOGRAPHY

FOR ROCK DISCRIMINATION

by

Gary L. Raines

With the advent of the ERTS and Skylab satellites, multiband imagery and photography have become readily available to geologists. However, the direct application to geology of this multiband space imagery and photography and similar aircraft data has been somewhat hit-or-miss. In large part, this has been due to a lack of orderly, programmed multiband research and premature attempts to apply multiband remote sensing techniques directly to specific, complex, economic situations before their basic capabilities had been demonstrated on simple geologic problems. The fundamental research reported here examines one basic aspect of geologic remote sensing -- namely, the ability of multiband photography to discriminate rock variation. The concept evaluated is that narrow portions of the visible and photographic infrared spectrum, where reflectance differences occur, can be utilized to discriminate rocks by the use of multiband photography.

In order to take advantage of subtle reflectance differences, these differences must be recognized. Therefore, a simple filter wheel photometer (FWP) was designed for *in situ* measurement of band reflectances of the rock types to be discriminated. "Band reflectance" refers to the average spectral reflectance within a wavelength band, the width of which is defined by the transmission characteristics of the filter under consideration. Thirteen bands were selected on the basis of filters suitable for multiband photography. The FWP is small, light, and costs less than $200. Data acquisition is rapid, data reduction is simple, and all the spectral reflectance information needed for designing multiband photography can be acquired. The accuracy of the instrument when compared with standard techniques is good; the average error in band reflectance for most geologic targets is 20 percent and the precision is 3 to 5 percent.

Using the FWP, more than 8,600 in situ measurements of band reflectance of several sedimentary rocks were performed. The formations measured consist of carbonates, sandstones, and shales that are exposed in the Front Range of Colorado, mostly around Canon City, Colorado. From these 8,600 measurements, the following conclusions are drawn. The typical spectral reflectance curve for a geologic formation shows a gradual increase of spectral reflectance with increasing wavelength. The average band reflectance is about 0.20. Within a formation, the minimum natural variation is about 0.04, or about 20 percent of the mean band reflectance, and is commonly as high as 0.07, or 35 percent of mean band reflectance. The contrast ratio between formations (ratio of the bank reflectances for two formations, calculated to give a number greater than 1.00) is generally less than 1.80, and between any two formations the typical arithmetic difference between contrast ratios of different bands is 0.20. Statistical analysis shows it is necessary to have a minimum sample of 150 measurements per formation in order to select "best" film/filter combinations with differences of this magnitude, and in some cases, 300 measurements would be required. Therefore, "best" film/filter combinations cannot be selected, with acceptable statistical confidence, unless an impractical number of measurements is made.

At three test sites in the Colorado Front Range, the similarities of all band reflectances for a formation were tested. First, it is concluded that, for 13 bands, the mean band reflectance of a formation is statistically the same over a distance of 100 miles, although there are significant changes in the variance. Second, the conclusion concerning sample size is correct at all three sites.

Aerial multiband photography using various filter combinations was acquired using an International Imaging System (I^2S) camera. All the photographs were processed to I^2S specifications. These photographs were acquired in a manner that would allow for testing of the numerical conclusions and an evaluation of the numerous enhancement procedures that have been proposed.

Using this aerial photography, the numerical conclusions have been tested and evaluated. It is concluded from analysis of this aerial multiband photography that (1) the differences in contrast ratios observed between all the filters considered are not statistically significant and (2) the spectral information in different bands is not advantageous. Therefore, because of the problem of getting multiple and simultaneously and correctly exposed photographs, the time involved in photographic manipulation, and the lack of statistically significant rock reflectance differences, the designed multi-band photography concept for rock discrimination is not a practical method of improving sedimentary-rock discrimination capabilities. Concerning the general applicability of these conclusions, the formations considered have not been selected in a manner that would allow statistical inferences to be made about all rocks or even all sedimentary rocks. However, there is no geologic reason to suspect that the rocks and formations considered have unique reflectance properties. Therefore, the conclusions drawn apply in detail only to the formations considered; however, generalizations of conclusions are probably valid for most sedimentary rocks.

NEW USES OF SHADOW ENHANCEMENT

by

Don L. Sawatzky
and
Keenan Lee

Shadow enhancement of topographic linears in photographic or scanner images is a valuable tool for interpretation of geologic structures. Whether linears will be enhanced or subdued depends on sun angle and azimuth. The relationship of the sun's attitude to topographic slopes determines which trends are available for interpretation in existing imagery, and it can be used to select the time of day, surface properties, and film and filter characteristics in planning aircraft flights or satellite orbital passes. The technique of selective shadow enhancement can be applied to all photographic or imaging experiments, but is best for snow-covered scenes, side-looking radar images, and painted relief models.

GROUND INVESTIGATIONS IN SUPPORT OF REMOTE SENSING

by

Keenan Lee

One nationally-known remote sensing research organization used to have a large, hand-lettered sign on a blackboard within its facility that read: HELP STAMP OUT GROUND TRUTH. That statement stimulated considerable conversation, argument, and amusement. Its message is important, however, for it is the key to successful operational use of remote sensors.

The early thrust of ground investigations (ground truth) was to verify results of research projects, where it was often necessary to have complete ground information for the study area. It should be clear that when complete ground information is available, remote sensing is no longer needed. Yet when no information is available, remote sensing may not achieve the degree of accuracy required operationally. Thus, there is a need to differentiate between ground data requirements in research and in operational situations. In either case, it is essential that the project manager carefully analyze the job at hand to determine what information is required to meet the needs of that particular job.

Proper selection of ground truth equipment is dependent upon proper selection of the variables to be measured. The selection process is complicated because we do not adequately understand all of the interrelationships in the environment that affect remote sensing. The tendency to measure some environmental parameter, simply because some other investigator has measured that parameter and found it useful, should be resisted. This is particularly true in those cases where available funding and manpower constraints prevent measurement of all parameters that could affect the objectives of the mission (this includes virtually every project, in either the research or operational mode).

Field-checking to verify remote sensing data interpretations results in a post facto form of ground investigations, generally the most common form. When correctly used, combined remote sensing and ground investigations can reduce the time required by one-third to one-half, as compared with ground procedures alone. This is the least expensive form of ground investigations, a factor that accounts for its popularity.

Some surface conditions are so dynamic that they change within the hour. Under such conditions, ground data collection at the time of overflight is the only way to verify what was present, and what the imagery may subsequently reveal. It is this kind of data collection that is most expensive and that may require the greatest instrumentation.

One aspect of ground investigations often neglected is the collection of surface data prior to remote sensing missions. Almost without exception, the probability of success of such a mission will be increased by using ground information in a predictive manner, to more rationally design sensor configurations and to specify conditions of data acquisition.

This chapter on ground investigations in support of remote sensing begins with a discussion of the philosophy and use of test sites. Subsequent sections treat ground investigations that are oriented to specific disciplines; these sections provide an introduction to Volume II of the Manual, which is discipline-oriented.

GEOLOGIC AND MINERAL AND WATER RESOURCES INVESTIGATIONS IN WESTERN COLORADO USING ERTS-1 DATA: FINAL REPORT

by

Daniel H. Knepper

The major goals of this investigations were to evaluate the geologic information content of ERTS-1 imagery and to study some possible geologic applications of the extracted information. Results of several independent studies conducted within the Colorado School of Mines ERTS-1 investigation provide the basis for the following conclusions:

1) The amount of geologically-relevant information that can be interpreted from ERTS-1 imagery far exceeds initial expectations.

2) Most of the geologic information in ERTS-1 imagery can be extracted from bulk processed black and white transparencies by a skilled interpreter using standard photogeologic techniques. Stereoscopic analysis is invaluable.

3) Various image enhancement techniques, including color additive viewing, color separation and density slicing, can be effectively used to selectively enhance certain geologic phenomena on the original imagery. The enhancement processes, however, produce an overall degraded image; enhanced images are unsatisfactory for general geologic interpretation.

4) In central and western Colorado, the detectability of lithologic contacts on ERTS-1 imagery is closely related

to time of year the imagery was acquired. Furthermore, some contacts are most easily detected on wintertime imagery; others are best expressed on summertime imagery.

5) The lithologic information content of ERTS-1 imagery is also strongly sensitive to the time of imagery acquisition; the band of imagery used in unimportant. Most of the information capable of being extracted can be found by interpreting imagery from only the winter and summer seasons together, thereby eliminating the need to examine great volumes of imagery.

6) Geologic structures are the most readily extractable type of geologic information contained in ERTS-1 images. The usefulness of this information appears to be limited only by the skill and imagination of the investigator.

7) Major tectonic features and many associated minor structures can be rapidly mapped from ERTS-1 images, allowing the geologic setting of a large region to be quickly accessed.

8) The detability of linears and trends in ERTS-1 images varies greatly between image generations and depends on sun attitude and surficial tonal contrasts due to seasonal effects.

9) The high resolution of ERTS imagery allows detection and connection of longer linear features than is possible with relief maps and topographic maps.

10) The trends of geologic structures in younger sedimentary appear to strongly parallel linear trends in older metamorphic and igneous basement terrain.

11) Landforms can be recognized on ERTS-1 images by the shape of tonal and textural patterns. These patterns are mostly the result of topographic and vegetative phenomena. Low sun-angle, wintertime ERTS-1 imagery is best for studying landforms in central and western Colorado.

12) Linears and color anomalies mapped from ERTS-1 imagery are closely related to loci of known mineralization in the Colorado Mineral Belt. Plotting frequency of linear intersections, combined with the location of "reddish-brown" color anomolies, appears to be a relatively quick and effective way of isolating primary target areas for metallic mineral exploration.

EVALUATION OF SKYLAB PHOTOGRAPHS OVER CENTRAL COLORADO FOR LOCATING INDICATORS OF MINERALIZATION

by

Gary L. Prost

Skylab S190A and S190B photographs over central Colorado, covering approximately 47000 square kilometers of the Rocky Mountains, were analyzed to determine which features associated with known mining districts are recognizable on space images. Results of this analysis indicate that visible features associated with mineralization include high densities of linears, complex linear intersections, red-ocher and ligh color (alteration) anomalies, and perhaps vegetation patterns unique to mineralized areas. It was assumed that linears designate prospective ore-controlling faults and fissures, and that color anomalies are related to gossans or hydrothermally-bleached intrusives.

The Skylab photographs (taken 11 June and 4 August 1973) were then studied in an attempt to locate the features indicative of mineralization. Two target areas were chosen where several favorable features coincided; a primary study area (32.5 km^2) was established at Weston Pass, and a secondary area (130 km^2) was located at Dome Rock. Ground truth, obtained at the primary target area by geologic mapping at a scale of 1:12000, was used to identify the features seen on the photography and to evaluate orbital imagery as a tool in mineral exploration. The secondary target was briefly field checked by identifying the sources of color anomalies and linear features in a reconnaissance fashion. The purpose of evaluating a secondary site was to determine if indicators of mineralization are consistent throughout the region.

Results of field work indicate the original assumptions were incomplete. Linear features may be attributed to aligned or straight streams, ridges, vegetation, and cultural features such as roads, fences, powerlines, and contrails, as well as geologic features including faults, joints, shear zones, dikes, contacts, and paleovalleys. Local linear patterns may not be unique to a given area, nor are high densities and intersections of regional linears the only structural controls on mineralization.

Red-ocher colors in central Colorado may result from sedimentary red-beds, microcline-rich crystalline rock or grus, iron-oxide alteration, or combinations of these. Light color anomalies were attributed to quartz-rich pegmatites, light-colored sedimantary units or talus, as well as to altered intrusives.

Vegetation was found to be influenced more by moisture, slope steepness and direction, season, and altitude, than by composition of the substrate.

Orbital photography in itself is considered inadequate to fulfill exploration needs; like other remote sensing techniques, it may be a powerful tool when used in conjunction with detailed field work.

GEOLOGIC INTERPRETATION OF SKYLAB PHOTOGRAPHS

by

Keenan Lee
and
Robert J. Weimer

Satellite images contain the same geologic information as do conventional aerial photographs, but at a smaller scale and with correspondingly poorer resolution. As with aerial photographs, maximum geologic information currently is derived from photointerpretation, a deductive process best carried out by a geologist-interpreter.

Skylab photographs are superior to ERTS images for photogeologic interpretation, primarily because of improved resolution. Similarly, S190B photos provide more geologic information than do S190A photos. Multiband photography shows no apparent advantage over good color photography; S190B stero color photos, where available, provide maximum geologic information.

Topography is the single most important surface phenomenon in photogeologic interpretation. Vegetation, especially coniferous forests, severely limits interpretation. Maximum information is extracted through the iterative process of photointerpretation and field checking.

More geologic information is contained in space images than can be interpreted or mapped at original scales. Interpretation is best with optical magnification of low-generation contact transparencies, with annotations put on enlarged transparencies. Optimum scale for geologic mapping in this study area is about 1:62,500.

All stratigraphic units at or above formation-rank can be mapped in this area, and many formations can be effectively subdivided into members. Conjunctive use of topo maps permits estimation of section thicknesses and lateral thickness changes. Stratigraphic pinch-outs, intertonguing sedimentation, and lateral facies changes have been accurately mapped with S190B photos.

All major structures in the study area can be recognized on the space photographs. Major folds were mapped accurately, even those with very gentle flexures, as well as several secondary drag folds. Faulting is recognized in considerable detail, both large, fold-bounding faults and subsidiary collapse systems. The ability to interpret detailed stratigraphy and structure allows recognition of recurrent structural movement on some uplifts.

LABORATORY MANUAL

FOR STUDY OF

REMOTE SENSING

by

Keenan Lee

This manual is designed to be used for laboratory exercises that are part of an introductory course in remote sensing. Although the exercises are directed toward geology students, most illustrations are of a general nature, and they have been used satisfactorily by students in other disciplines.

The manual is further designed to be used with supplemental materials. The illustrations are, of necessity, half-tones in order to keep the manual costs low. Many of the illustrative examples, therefore, lose significant information content, and the student should work with photographic prints provided in the lab and annotate the copies in this manual.

The sources of the illustrations are noted, where known. In some cases I have had the materials so long their source is obscure; certainly some of them are from the course in remote sensing I took from Ron Lyon. Financial support for part of the work on the manual was provided by NASA under grant NGL-06-001-015.

REMOTE SENSING APPLIED TO EXPLORATION FOR VEIN-TYPE URANIUM DEPOSITS, FRONT RANGE, COLORADO

by

James C. Fisher

Uranium ore of the Front Range, Colorado, is found in north-northwest-trending fault breccia systems that cut Precambrian metamorphic rock. The uranium probably had its source in these Precambrian metasediments and was mobilized during Laramide tectonism (~65 m.y.) into the breccia veins. Lithology controls the occurrence of uramium only inasmuch as providing brittle rocks to form excellent breccias. Amphibolite gneisses and quartzites are, therefore, potentially excellent host rocks for the uranium in the veins, but mica schists are not. Areas where Laramide faulting is at a high angle to metamorphic foliation provide excellent prospecting targets, because fault dilation and brecciation are maximized. In contrast, faulting subparallel to metamorphic foliation generates bedding plane slippage and little dilation and brecciation.

A remote-sensing program consisting of two main sensors, medium-altitude black and white photography and low-altitude color photography, could adequately map most of the important geologic features and ore controls. Medium-altitude (~1:40,000 scale) black and white photography is useful to map major throughgoing fracture trends, major metamorphic foliation trends, major rock types, and areas of intense fault branching.

Low-altitude (~1:12,000) color photography is useful to map and differentiate limonitic and hematitic color anomalies, details of fault and foliation intersections, lithologies, and breccia-zone indications. Together, these two sensors can be used effectively to outline target areas which would lead to a more successful ground-based uranium exploration program.

The most useful follow-up ground exploration techniques tested in the prime remote-sensing target areas include alpha track-etch radon prospecting and horizontal resistivity surveys; copper-in-soil sampling is of some, but lesser, value. Alpha track-etch radon prospecting is highly useful in exploring for very narrow vein-breccia uraninite deposits. Surficial leaching in the Front Range has removed the uranium from the upper soil layers, rendering the traditional radioactivity exploration techniques useless. Once an area of anomalous radon has been located beneath the soil and colluvium, a horizontal resistivity survey is the most useful technique in locating, in detail, the vein-fracture breccia systems. Drilling is then used to locate the mineralization, the source of the radon. The use of the recommended program would have successfully discovered the Schwartzwalder Mine, the largest vein-type uranium deposit in the United States.

HYDROGEOLOGY OF THE UPPER DRAINAGE, MIDDLE FORK, SOUTH PLATTE RIVER, PARK COUNTY, COLORADO

by

Robert Butler

Color aerial photography was found to be of limited usefulness in studying the hydrogeology of mountainous terrain. Geologic mapping was severely hampered because of heavy vegetation and surficial deposits. Mapping of the surficial deposits was greatly enhanced using the air photos, but unfortunately the surficial deposits were of limited usefulness in interpreting the hydrogeology of the region.

The air photos were of no value in directly interpreting the permeability of the different lithologies. Permeability grouping is possible by assigning a value to the interpreted rock type and does not come directly from the air photos. An exception is where pervasive fracturing is present in the crystalline rocks.

The air photos were of little value in interpreting the most favorable areas of a given rock type for the best well yields. Two favorable features in crystalline rocks, pegmatite dikes and fractures, were easily recognized on the air photos and have been cited as more productive areas for domestic wells.

The air photos were of no help in studying the water chemistry of the area except for locating potential pollution sources, such as mine dumps and tailings ponds.

Major vegetation associations were easily interpreted from the photos. The most dependable hydrologic indicator is willow. A very shallow water-table and often saturated ground exist where the willow grows.

Ground-water movement was interpreted from the air photos by integrating topography, lithology, and structure with the theory of regional ground-water flow. Shallow ground-water movement follows topography and is the easiest to interpret. Only cursory information was obtained about ground-water movement in the bedrock units by noting fractures and attitudes of dipping beds.

It should be emphasized that these results may apply only to the thesis area. Other areas may be more favorable for interpreting hydrogeologic information from air photos. Subsequent work by the author indicates that the ability to do photogeology and interpret litholigies is paramount to understanding the hydrology of an area. Adequate field checks must be used in the photo interpretation process.

GROUND WATER RECHARGE TO THE AQUIFERS OF NORTHERN SAN LUIS VALLEY, COLORADO: A REMOTE SENSING INVESTIGATION

by

David Huntley

The northern San Luis Basin can be divided into three distinct, but hydrologically connected provinces: the Sangre do Cristo Mountains, a region of relatively low, depth-dependent permeability, low ground water flow rates, and high surface water flow rates; the San Juan Mountains, a region of relatively high, strongly anisotropic permeability, high ground water flow rates, and low surface water flow rates; and San Luis Valley, a region of high permeability and high rates of evapotranspirative discharge. Faults are important in all regions, providing areas of increased permeability in the Sangre de Cristo and San Juan mountains, while acting as ground water barriers in San Luis Valley. Faults have controlled sedimentation patterns in the basin from Paleozoic through Quaternary time.

Ground water is calcium bicarbonate type in the recharge areas of the basin, changing to sodium bicarbonate toward the center of discharge of the basin. A sharp increase in the proportion of sodium relative to calcium in the water of the confined aquifer along the eastern margin of San Luis Valley probably is caused by hyperfiltration of ground water as it flows through confining clays. The distribution of sodium/calcium ratios in water of the confined aquifer can be used to estimate the lateral extent of the confining clays.

Recharge to the aquifers of western San Luis Valley is largely from ground water inflow from the permeable volcanic rocks of the San Juan Mountains. Recharge to the aquifers of eastern San Luis Valley is dominantly from stream seepage into alluvial fans along a narrow strip bordering the Sangre de Cristo Mountains. The limit of flowing wells in San Luis Valley corresponds neither to the limit of confining clays nor the limit of the ground water recharge zone.

Use of aerial photography and thermal-infrared imagery resulted in a significant savings in time and increase in accuracy in this regional ground water study. The most important feature governing the usefulness of aerial photography is the ground resolution. Reflectance measurements of moist and dry soils, saline soils, and volcanic rocks show that, like sedimentary rocks, there is no unique spectral "signature" that can be assigned to a rock or soil type, and that absolute reflectance differences in one part of the spectrum can be extrapolated to the rest of the photographic spectrum. Spectral variations related to vegetation variation, in turn related primarily to water availability, are extremely important in hydrogeologic studies, however. Color-infrared film is the most useful film for such a study.

Both vegetation and saline soils can be used to distinguish between shallow (~4 m) and deep ground water, but saline soil distribution is a more dependable and widespread indicator in San Luis Valley.

Temperature differences seen on thermal-infrared imagery can be related to differences in thermal inertia, solar reflectance, evaporation rates, or subsurface temperature distribution. Increases in soil moisture cause an increase in thermal inertia and a decrease in reflectance, theoretically cuasing decreased daytime temperatures and increased nighttime temperatures. An increase in evaporative cooling rates with increasing soil moisture partly counteract this effect, however, causing decreased daytime and nighttime temperatures. Temperature effects due to varying ground water depth, while transferred in a damped state to the surface, are complotely overshadowed by effects due to varying evaporative cooling rates. Both evaporative cooling and temperature effects due to varying ground water depth affect the diurnal temperature curve in the same manner and are indistinguishable.