Mineral reconnaissance in the Chagai District, Pakistan, using a four-dimensional vector method of digital classification of Landsat data

by

Robert G. Schmidt

Contents

Illustrations

Tables

Mineral reconnaissance in the Chagai District, Pakistan, using a four-dimensional vector method of digital classification of Landsat data

by

Robert G. Schmidt

Abstract

Mineral reconnaissance in Pakistan using satellite remote sensing has sought to identify large areas of hydrothermal alteration and sulfide mineralization, such as the previously known Saindak porphyry copper deposit in the Chagai District, which was used as a control site. Additional experimentation on the use of digital-computer classification of Landsat multispectral scanner data for mineral exploration, using the same control area and test region in Pakistan, has produced a better understanding of method and better results.

A four-dimensional vector algorithm was used in this third remote-sensing experiment. The first experiment involved visual examination of false-color composite images, using standard photogeologic techniques; in the second experiment, a "parallelepiped" algorithm for digital classification was used. Whether the vector method is itself significantly superior is not clear, but we have certainly seen that the earth scientist must interact directly with the computer while classification tables are being prepared. The preparation of classification tables suitable for sulfide mineral exploration was found to be a longer procedure than had been possible under the conditions of the parallelepiped experiment.

U. S. Geological Survey
OPEN FILE REPORT 80-721
This report is preliminary and has not been edited or reviewed for conformity with Geological Survey standards or nomenclature.

The first remote-sensing experiment conducted in the area used false-color composite images, including a digitally enhanced composite. These were examined for evidence of hydrothermal alteration. No significant mineralization was identified by this process.

The parallelepiped digital-computer classification used unprocessed reflectance values and sought to delineate areas that had reflectance characteristics similar to the known porphyry copper deposit. The experiment resulted in the discovery in October, 1974, of several large mineralized areas of the porphyry-copper type. The third experiment was conducted in 1975 with the same control and test areas and used a classification algorithm that considers a hypothetical four-dimensional color space--the four axes of this hyperspace are the four Landsat bands. The reflected radiation from each unit area or pixel can be represented as a four-dimensional vector in this color space; the single vector thus defined is a unique representation of the measured reflected radiation from that pixel. The direction of a pixel vector in the color space represents the color balance between the four bands (or axes), and the magnitude of the vector is related to the pixel's total radiation brightness. A factor that controls the tolerance for pixels having vectors close to, but not the same as, the unique vector of a class can be varied by the user. In classifying pixels, it is sometimes important that color balance be considered independently of the brightness; that is to say, two pixels of similar color but of different brightness should be classified together as the same type of surface. The vector algorithm enables classification solely on the basis of color balance with as little or as much dependence on brightness as is desired by the user.

In the vector algorithm experiment, classification tables were revised 70 times using five small test areas of known geology, including areas of porphyry copper mineralization and other important rock types for control areas. The resulting classification tables were used to classify digitally 3300 km^2, and 25 sites were selected for field checking, of which 17 have now been examined in the field. Three of these are strongly mineralized, and four are weakly mineralized; these seven have the general characteristics of porphyry copper systems. One site known to be mineralized was not detected in this experiment. The total area evaluated in the vector experiment was larger than that of the earlier experiment, and it included seven new areas designated for field checking outside the original area. Only three have been checked and these were found to be barren.

The mineral-discovery success of this experiment is the result of applying a viable remote-sensing system in an unexplored ideal desert terrain having a remarkably high potential for porphyry copper mineralization. The remote-sensing system is believed to owe its success to the combination of persistent repetitive use of a flexible interactive digital classification program with sound geologic information in selected control areas.

Introduction

In many of the experiments made so far in remote sensing for sulfide ores geologic structural data extracted from Landsat images have been analyzed. Generally the structural features selected have been linear and circular. In other experiments, various digital-processing techniques have tested to identify areas of unusual redness, such as are commonly associated with oxidized sulfide-rich zones. The experiment described here sought to identify the four-band spectral reflectance of the hydrothermally altered zones normally associated with porphyry copper deposits. These characteristic reflectances are believed to be related to minerals formed by the pervasive alteration process, perhaps clay minerals and others as well as the generally assumed iron-oxide minerals, but the specific minerals involved have not been identified.

The Saindak porphyry copper deposit and the nearby Mashki Chah region in the Chagai District of Baluchistan, Pakistan, have been the sites of three U.S. Geological Survey remote-sensing experiments, including this study (Fig. 1). The Saindak deposit, in a very arid

---

Figure 1 near here.

---

location, is well exposed and well mapped (Khan, 1972) but undisturbed by mining, making it an excellent control site. At the outset of the experiment, the area to the east of Saindak, the Mashki Chah region, was considered to be an area where the occurrence of other porphyry-type deposits was possible, but few copper showings had been reported and no porphyries were known to be present. Subsequent field checks of sites indicated by the remote-sensing experiments have so far resulted in finding several porphyry-copper type prospect areas. Undoubtedly these might have been found in another way, but they had not been, and most are in locations that were not considered outstanding prospecting targets when

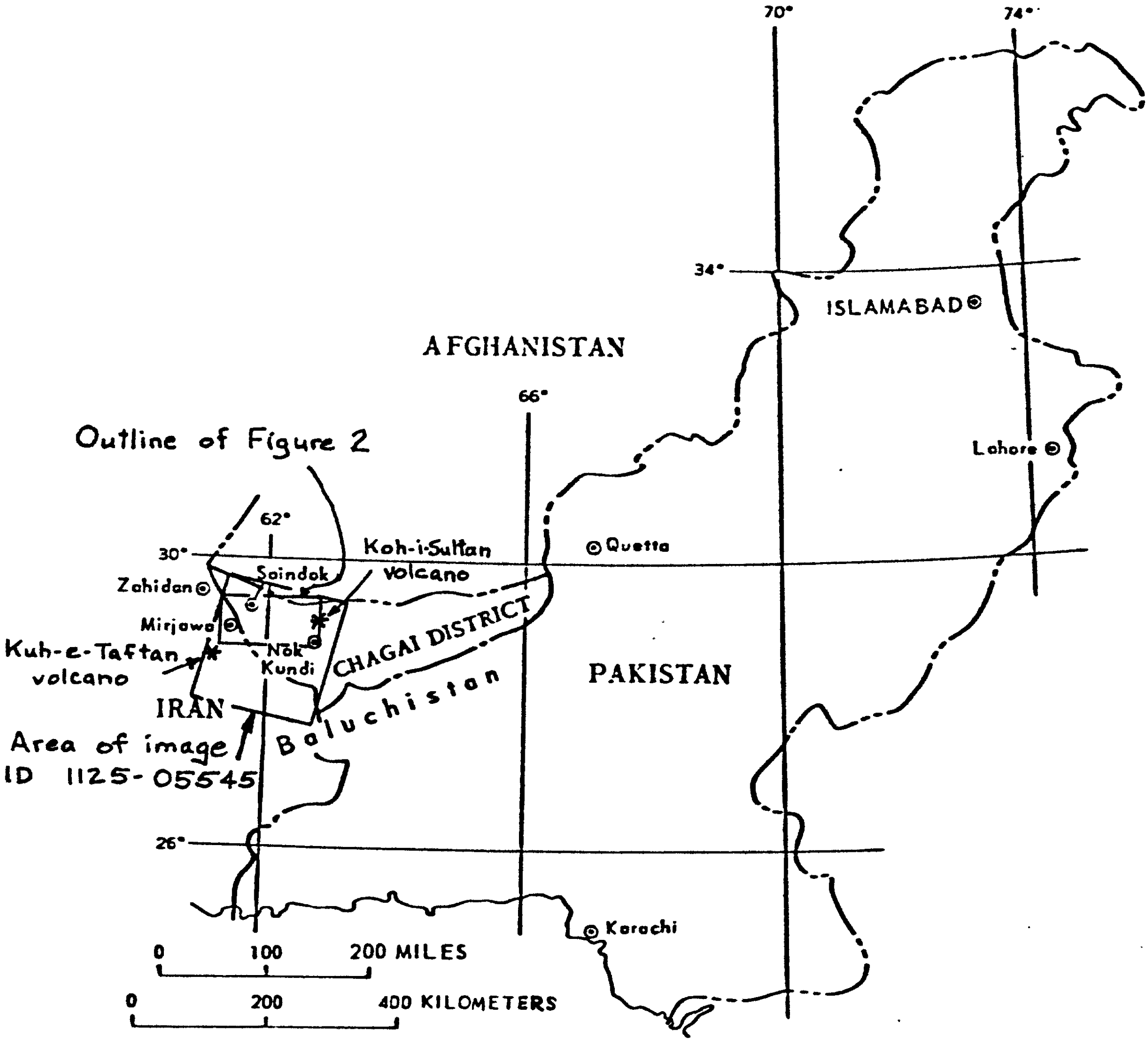

Figure 1. Index map showing the Chagai District and Saindak, Pakistan

they were studied on aerial photographs before the field checks were made.

In the first remote-sensing experiment, conducted by the U.S. Geological Survey in cooperation with the National Aeronautics and Space Administration, false-color composite transparencies and a digitally enhanced composite provided by the IBM Corporation were studied for evidence of sulfide mineralization (Schmidt, 1974). Seven areas were chosen for prospecting, using a combination of high-albedo patches, geologic inferences made from study of the images, and existing geologic data. Six of the seven areas have been field checked, and only one of these is mineralized, and that mineralization is very weak.

Later analyses of the composites by three photogeologists who had no previous knowledge of the area indicated that if 50-100 bright areas had been selected by visual examination, 4-6 previously unknown porphyry-type systems would have been included, but without priority over the other chosen sites. No further work has been done to compare the results of photogeological analysis with those from our digital classification, but the photogeologic analyses proved that selection of light-toned patches alone was an insufficient basis for reliably distinguishing mineralized areas.

In the second experiment, digital multispectral classification was performed in the IBM Digital Processing Facility at Gaithersburg, Maryland (Schmidt, 1976; Schmidt, Clark, and Bernstein, 1975). Data were extracted for a 55 km^2 area, including the known Saindak porphyry copper deposit, and for a gray scale image displayed in photographic form, using an imagery printer (outline shown on Fig. 2). Small test areas were selected which were believed to include relatively uniform outcrops of common rock units, and reflectance values for MSS bands 4, 5, 6, and 7 were extracted for individual pixels. Provisional classification tables in the parallelopiped style, using a minimum and a maximum count value for each band to define a class, were prepared for a few selected surface types; each table was used to classify the test area, and the tables were modified upon comparison of these results with the known geology. The whole cycle was repeated five times until a classification table was developed that seemed likely to provide information useful in mineral evaluation. A better table could have been prepared if aerial photographs of the area could have been used, and if a visit to the field had been possible during this stage.

In using the parallelepiped algorithm, an attempt was made to minimize false classifications for rock types where the reflectance values are close to each other by using a high and low confidence class for each of these rock types (Schmidt, Clark, and Bernstein, 1975, p. 1017). The data were not properly handled in preparing the reflectance values for the eolian sand classes, which caused many false classifications in the final results of the experiment. Although the Saindak region has less than 10 percent of any rock or soil surface obscured by vegetation, wind-blown sand is ubiquitous. Surfaces that a geologist would consider bare outcrop may be mantled by thin sand screening as much as 70-80 percent of the surface. Thus, surfaces of wind-blown sand form a continuous series with all other surface types.

After five revisions of the parallelepiped classification table, a line-printer map was made and used for an experimental mineral evaluation of 2100 km^2 in the Mashki Chah region, and a partial field check of the results was conducted in 1974 (Fig. 2). Fifty clusters of pixels classified as hydrothermally altered rock were selected for evaluation; study of them on aerial photographs made it possible to reduce the number to 23 prospecting targets. In the 1974 field examination, five major localities that contain hydrothermally altered and mineralized rock, mostly quartz feldspar porphyry, were identified (Table 1). In 1976, some areas were rechecked and additional sites visited, and another area of mineralization was found. Evaluation of these prospects is now in the hands of the Government of Pakistan.

Table 1.--Sites chosen for field examination in 1974 and 1976 digital classification experiments [for location of sites, refer to figure 2].

[For location of sites, refer to figure 2]

Identifying number	Chosen 1974	Chosen 1976	Results of field examination
AREA COVERED IN BOTH 1974 AND 1976 EXPERIMENTS			
1a(24233)	x		Barren
2b(25214)	x	x	Hydrothermal alteration, weak mineralization
25241/25332		x	Unchecked
2c-3a(25323/4)	x	x	"Barren," but it is not certain we checked correct place. Counted as two sites in 1974 experiment.
2d(25331/2)	x	x	Hydrothermal alteration, weak mineralization
3b(25313)	x		Unchecked
3d(25334)	x		Barren
3e(25343/4)	x	x	Barren
4c(26411/2)		x	Barren
5b(25523/25532)		x	Hydrothermal alteration, mineralization
5c(25533)	x	x	Hydrothermal alteration, weak mineralization
5d(26512/26521)	x	x	Hydrothermal alteration, weak mineralization
6b	x		Unchecked
6c	x		Unchecked
6d(25543/26512/1)	x		Hydrothermal alteration, mineralization
6e(25544)	x	x	Same

Table 1(cont.).--Sites chosen for field examination in 1974 and 1976 digital classification experiments

Identifying number	Chosen 1974	Chosen 1976	Results of field examination
6f(26511/36122)	x		Bedrock is sulfide bearing but exposed surface is mostly dune sand
7f(35131/4)	x	x	Barren
8a(35232)	x	x	Hydrothermal alteration, mineralization
8d	x		Unchecked
9b(34331/4)		x	Unchecked
9c(36323/4/36331/2)	x	x	Barren
11a(35411)	x		Unchecked; probably solfataric alteration
11b(35443)		x	No regular field check but no mineralization noted when crossed in jeep
11c(36444)		x	Not adequately checked
11d(37421)	x	x	Unchecked
12b	x		Barren
12c(34533/4)	x	x	Barren fan; detritus may include solfatarically-altered fragments
	AREA COVERED IN 1976 EXPERIMENT ONLY		
14431		x	Barren
14442/3		x	Barren
14443/4		x	Barren
15334/16312		x	Unchecked

Table 1(cont.).--Sites chosen for field examination in 1974 and 1976 digital classification experiments

Identifying number	Chosen 1974	Chosen 1976	Results of Field Examination
17542/3		x	Unchecked
24421/2		x	Unchecked
34121/2		x	Unchecked

The successes of the 1974 experiment notwithstanding (Schmidt, 1976), interpretation of the line printer maps resulted in many false identifications of rock types. Though the number of sites falsely classified as mineralized was not unreasonable when compared with other standard field methods of mineral prospecting, there was reason to believe that better results could be achieved with Landsat data, and certainly better results would be necessary in areas where the identification of hydrothermal alteration is more difficult than in this ideal test area. Such improvements, plus the development of standardized methods for preparing satisfactory classification tables, have been the goal of the third experiment described here. Much of the improvement of results in this third experiment is due to the flexibility of the programs for handling Landsat data, and to the greater ease with which a geologist can interact with the computer. However, with more revisions of the tables and more experience, the method used in the parallelepiped experiment might have resulted in the selection of fewer than 50 sites.

The third experiment has used a four-dimensional vector algorithm and the computer facilities of the Institute for Space Studies of the NASA Goddard Space Flight Center. Dr. Stephen Ungar of the Institute generously aided in establishing access to the computer facilities, and provided helpful and needed advice throughout the project. The Department of Earth Sciences, Dartmouth College, Hanover, New Hampshire, also cooperated in the third experiment. Jon Dykstra, of that department, prepared final line printer maps and also participated in the field checking done in 1976.

Field checking for all three remote-sensing experiments was made possible by the generous support of the Resources Development Corporation, Ltd., an agency of the Government of Pakistan. Their personnel helped in planning field work and also provided much geological information. Resource Development Corporation furnished complete logistical support for the work, including geologists familiar with the region, cooks, and drivers, and vehicles and camping gear, for both 1974 and 1976 field programs.

Information collected during both trips has been used in this report to evaluate the results of all three experiments.

To prepare and test new classification tables in a standard fashion, test areas 30 x 41 pixels in dimension (quads), each containing 2.4 km^2, were selected. Five major quads were regularly used in most tests: 1) the Saindak porphyry copper deposit; 2) one of the new porphyry prospect areas adjacent to a dune tract; 3) a highly altered and mineralized new prospect that has been very difficult to resolve by any digital classification method tested; 4) an unmineralized felsic stock and adjacent fan of gravel derived from the stock; and 5) a large sand dune. Ten supplementary quads selected for a variety of geologic features were also available for testing new tables.

The classification tables underwent nine major modifications involving 70 separate changes, each change tested for its degree of discrimination in two or more, usually all five, of the major test quads. These tests were carried out using a small portable paper-copy terminal in Reston, Va., accessing the Goddard Institute for Space Studies computer in New York over telephone circuits.

When the ninth classification table had been revised several times, and was considered adequate to yield an improved mineral evaluation (Table 2), the digital classification map of 3300 km^2 in the Mashki Chah region was made by Jon Dykstra at the Department of Earth Sciences, Dartmouth College (outline shown on Fig. 2). This map included about 95 percent of the area of the 1974 (second) experiment, plus about 1300 additional km^2, mostly west and southwest of the area evaluated earlier. In the area common to this study and to the second experiment, this study indicated 18 sites, all of which, on the basis of office evaluation, warranted field checking (Table 1). The sites and the results of completed field checks are listed in Table 1.

Table 2.--Final digital classification table used in 1976 experiment.

	Rock type	Symbol	CMIN*	Band 4	Band 5	Band 6	Band 7	Brightness	W2+
1	Hydrothermally altered rock, Low confidence	x	0.012	0.79	0.69	0.54	1.18	3.20	0.12
2		x	0.012	0.81	0.73	0.57	1.25	3.36	0.12
3	Hydrothermally altered rock, High confidence	0	0.012	0.84	0.76	0.60	1.31	3.51	0.12
4		0	0.012	0.87	0.79	0.63	1.37	3.66	0.12
5		0	0.012	0.89	0.83	0.66	1.43	3.81	0.12
6		0	0.012	0.92	0.86	0.69	1.49	3.96	0.12
7		0	0.012	0.95	0.90	0.72	1.54	4.11	0.12
8	Barren felsic intrusive rock	+	0.025	0.87	0.72	0.57	1.24	3.40	0.18
9		+	0.025	0.90	0.77	0.61	1.33	3.61	0.18
10		+	0.025	0.93	0.82	0.65	1.41	3.81	0.18
11		+	0.025	0.95	0.86	0.69	1.49	3.99	0.18
12	Dry wash alluvium	=	0.025	0.72	0.61	0.44	1.00	2.77	0.18
13		=	0.025	0.77	0.65	0.49	1.08	2.99	0.18
14		=	0.025	0.81	0.69	0.53	1.17	3.20	0.18
15		=	0.025	0.85	0.73	0.58	1.25	3.41	0.18
16		=	0.025	0.89	0.77	0.61	1.33	3.60	0.18
17	Dune sand	•	0.025	0.73	0.66	0.53	1.11	3.03	0.18
18		•	0.025	0.77	0.70	0.56	1.20	3.23	0.18
19		•	0.025	0.80	0.73	0.59	1.28	3.40	0.18
20		•	0.025	0.83	0.78	0.62	1.37	3.60	0.18
21		•	0.025	0.87	0.82	0.66	1.45	3.80	0.18
22		•	0.025	0.90	0.87	0.70	1.54	4.01	0.18
23	Dark rocks (desert varnish coated)	%	0.025	0.64	0.48	0.37	0.74	2.23	0.18
24		%	0.025	0.66	0.51	0.38	0.83	2.38	0.18
25		%	0.025	0.70	0.55	0.42	0.92	2.59	0.18
26		%	0.025	0.74	0.59	0.46	0.99	2.78	0.18
27	Dark heavy-mineral sand	B	0.025	0.55	0.43	0.35	0.67	1.99	0.18
28		B	0.025	0.60	0.48	0.37	0.76	2.21	0.18

*A variable that controls the acceptable tolerance for pixels of near but not identical spectra.
+A weighting factor that controls the importance given to the brightness relative to the spectral vector direction.

This selection was made on the basis of the proportion of pixels classified as hydrothermally altered rock (7 classes), compared with the following classes: barren felsic intrusive rock (4 classes), dry-wash alluvium (5 classes), dune sand (6 classes), dark, mostly desert varnish-coated rocks (4 classes) and dark heavy-mineral sand (2 classes) (Table 2). A line-printer map of the stratovolcano area with areas selected as potentially hydrothermally altered is shown in Figure 5. (In 1976, the group of pixel symbols at site 6d was considered to include too few pixels classified as hydrothermally altered rock, and the site was not selected for field checking). Neither geology nor aerial photo information was used as criteria in this selection, but a geological bias may have affected some selections because the geology of the region was much better known to me after the 1974 field examination. In the earlier experiment, geologic and aerial photograph data were used in reducing the number of sites for field examination from 50 to 23. This was mostly because of problems in discriminating between areas of mineralized rock and dune sand.

Geology of the region

The rocks of the western Chagai District consist of marine and terrestrial sedimentary and volcanic rocks of Cretaceous to Holocene age, and many intrusive bodies emplaced at shallow depths. The influence of widespread volcanism of intermediate composition was continuous in the geologic record from Cretaceous time until now. The dormant solfataric volcanoes Koh-i-Sultan near Nok Kundi, and Kuh-e-Taftan in nearby Iran, are prominent peaks in the area (Fig. 1).

The Mirjawa Range area, along the border with Iran near Saindak, Amalaf, and Juzzak (Fig. 2), consists of mostly folded (along northwest trends) and much faulted sedimentary and volcanic-sedimentary strata. Except for a group of large and extensive Late Cretaceous sills, intrusive and extrusive volcanic rocks make up little of the total outcrop area; however, some of the sedimentary formations contain abundant volcanic material. Cretaceous strata, assigned to the Sinjrani Volcanic Group by Hunting Survey Corporation, Ltd. (1960, p. 292-4), include three major rock suites, so far undifferentiated as to relative age (Ahmed, Khan, and Schmidt, 1972, p. A6-A8): 1) thick flysch-type deposits; 2) shallow-water shale, sandstone, and fossiliferous reef limestone, intercalated with abundant volcanic debris and thick massive volcanic rocks that are perhaps flows or crystal tuffs of intermediate composition; and 3) a red-bed sequence of shale, sandstone, and conglomerate. These strata of Cretaceous age underlie more than three quarters of the Mirjawa Range area, rather than less than half the area as indicated on the geologic maps made by Hunting Survey Corp., Ltd.

(1960, maps 17 and 21, Schmidt, 1968, p. 53). Tertiary rocks of the Mirjawa Range area include marine shale and fluvial or deltaic sandstone and siltstone intercalated with coarse volcanic conglomerate, layers and lenses of fossiliferous limestone and limy shale, and a few submarine mafic lava flows. The lower Tertiary rocks are mostly shallow marine deposits, and upper Tertiary and Quaternary strata are largely of continental origin; the Tertiary rock types and depositional modes suggest formation in an island-arc environment. The bedded sequence is interrupted by post-Cretaceous and post-Oligocene unconformities, and all strata of Tertiary and older age have been folded about northwest-trending axes and have been cut by many steep-dipping faults. Porphyritic diorite stocks were intruded after most of the folding was completed. Later quartz diorite porphyry stocks intruded and extensively altered and mineralized the older volcanic and sedimentary rocks, including the base of a stratovolcano, part of which remains as the crest of Saindak Koh. This intrusive and the surrounding altered and mineralized rock make up the porphyry copper deposit at Saindak, described by Schmidt (1968), Ahmed and others (1972), Khan (1972), and Sillitoe and Khan (1977).

Geology is known in less detail in the Mashki Chah region (Fig. 2), an area interpreted to be a westward extension of the Chagai Hills. Rocks of Cretaceous age include a variety of volcanic rocks, ranging from agglomerate to tuffaceous shale, and also many outcrops of Humai Limestone, as described by Hunting Survey Corporation, Ltd. (1960, p. 143-147). The Tertiary rocks of this region are volcanic rocks, including intermediate and mafic flows, agglomerates, tuffs, and tuffaceous sands and shales, and numerous small subvolcanic intrusive bodies, generally porphyritic. Intense hydrothermal alteration, solfataric action, and sulfide mineralization are associated with many of these porphyritic bodies. Volcanic necks (Koh-i-Dalil) and remnants of volcanic cones (Dam-o-Dim), plug domes, and prominent thermal spring deposits attest to the widespread volcanic activity in Late Tertiary and Quaternary times. The summit of the dormant volcano, Koh-i-Sultan, is the site of widespread intense solfataric alteration and local pyritic mineralization (Fig. 1). Rocks of Cretaceous age have been deformed in open folds, mostly trending northwest. Deformation of Tertiary volcanic strata, other than possible local doming by intrusive forces, has not been observed in the area; thus, the style and degree of deformation here contrast sharply with the Mirjawa Range only a few miles to the southwest.

Five sites of major hydrothermal activity, the Chehel Koureh porphyry copper deposit at Zahedan, Iran; the Saindak porphyry copper deposit; the group of prospects near Koh-i-Dalil (sites 5b, 5c, 5d, 6d, and 6e, Fig. 2) in the basal part of a large stratovolcano; the solfatarically altered cone Dam-o-Dim; and the large dormant volcano Koh-i-Sultan are all aligned on an eastward trend. Many Quaternary calcareous sinter deposits, probably formed by large thermal springs, are located close to this trend. No age for the Zahedan porphyry is known to me, and association of the hydrothermal activity with volcanism is only assumed. Mineralization at Saindak, closely related in time and space to a volcanic edifice, has been dated at 20-21 m.y. (Sillitoe and Khan, 1977, p. B32-3). The stratovolcano near Koh-i-Dalil, by its degree of erosion, is assumed to be younger than the volcano at Saindak, but older than Dam-o-Dim. Similarly, Dam-o-Dim is more eroded and is regarded as older than the youngest, perhaps Holocene, volcanic events on the mountain Koh-i-Sultan. Thus, the intrusive/extrusive/hydrothermal alteration events along this trend are here interpreted to have taken place at progressively later times in an eastward direction from Saindak to Koh-i-Sultan.

The linear trend cuts across the boundary of the Mirjawa Range and the Mashki Chah region, and thus seems to be younger than most of the Tertiary deformation in the Mirjawa Range. It seems to align with the linear major structural boundary farther east, separating the folded Tertiary sediments of the Dalbandin trough from the little-deformed Cretaceous rocks of the Chagai Hills (Hunting Survey Corporation, Ltd., 1960, map sheets 22 and 23). A possible explanation for the late Tertiary-Quaternary volcanism along this line is that new motion along the trend of this boundary surface has extended westward across the Mirjawa Range, and that volcanism has propagated eastward along the whole line, from Zahedan, Iran, as far as Koh-i-Sultan.

Economic geology

Mineral exploration in the Chagai District has been generally reconnaissance in nature, and until the last few years the search has been mainly for high-grade deposits. Such high-tonnage low-grade deposits as those of the porphyry-copper type have only recently been considered realistic exploration targets here. The many areas in the Chagai District containing abundant intermediate and felsic volcanic rocks and small hypabyssal intrusive bodies of Cretaceous through Pleistocene age may be considered to have a good potential for large sulfide deposits of the porphyry-copper type.

At Saindak, several quartz diorite stocks along a northward trend, cut the folded Tertiary stratigraphic section. The stocks and the rocks surrounding them are hydrothermally altered and mineralized with pyrite and copper sulfides. Well-developed patterns of hydrothermal alteration zones and copper sulfide mineralization (Ahmed and others, 1972; Khan, 1972; Sillitoe and Khan, 1977) are similar to the model described by Lowell and Guilbert (1970). Detailed grade and tonnage figures for three ore bodies have been released by the Resource Development Corporation, Government of Pakistan.

The sulfide-rich zone, including both the central quartz-sericite and biotite-rich zones, and the peripheral pyrite-rich rocks, has been eroded to form a light-toned valley. In this central valley the soils and rock detritus formed on outcrop surfaces are light reddish brown to light tan. Some distinct red and orange patches are present, but they are not widespread in the valley. Windblown sand is ubiquitous in the mineralized areas, and there it seems to make up 40-80 percent of most reflecting surfaces; hence it is a major factor in determining the reflectance characteristics of any surface. In plan view, this valley is encircled by a symmetrical rim of hills more rugged and darker in tone than both the valley and the surrounding region (Ahmed and others, 1972, Fig. 2). These hills correspond to the zone of propylitic alteration, which is here more erosion resistant than the poorly consolidated Tertiary sedimentary and volcanic rocks, as well as the sulfide-rich rocks of the ore deposit.

I know little regarding the Chehel Koureh porphyry copper deposit close to the international airport at Zahedan, Iran. The east half of the deposit has been displaced by a north-trending fault; the relative direction of displacement and present location of the eastern part may be as yet undetermined.

As a result of field checking the sites selected for examination by digital classification of Landsat data during both experiments, strong hydrothermal alteration and significant sulfide mineralization of the porphyry-copper type have been located at three places (one of which includes the two close-spaced sites 6d and 6e); in addition, large hydrothermal alteration systems with considerable sulfide mineralization, interpreted to be weaker systems or peripheral parts of porphyry copper systems, were found at four places (Fig. 2). All of these are within the Mashki Chah region; of five areas indicated for field checks in the Mirjawa Range, three have been examined and found barren, and two are still unchecked. Four of the mineralized areas are within the basal part of a large eroded stratovolcano 48 km (30 mi) southeast of

Saindak near Borghar Koh and Ispeghar Koh (now designated as the Koh-i-Dalil prospects by the Geological Survey of Pakistan); two are west of the stratovolcano near Borghar, and one is located east of it, near Humai (Fig. 2). The temporal and genetic relationship of the prospects in the stratovolcano to each other is not clear. Three of the sites (5d, 6d, and 6e, Fig. 4) are almost certainly part of one large hydrothermal system; 5c may be related to the same system or be quite independent; 5b, the Max G. White prospect, does not seem to be closely related to the rest. The strongly altered site 6d, which has considerable sulfide mineralization, was not delineated in this study, although it had been identified in the earlier parallelepiped experiment. It is described below because of its relationship to sites 5d and 6e.

Site 2b.--This is a clearly defined area of hydrothermal alteration and sulfide enrichment of the porphyry type forming a broad valley trending northward 1.7 km, and 1.0 km wide at its widest point (Fig. 3). Country rocks along the east side of the prospect are crystal tuffs or volcanic sandstone of intermediate composition. These are strongly propylitized, and the propylitic zone forms a distinct erosion-resistant rampart along this eastern margin. Rocks along the western side were not examined in the brief field visit, but are probably also tuffs or volcanic sandstones. Some propylitized rocks stand as small hills on the west side, but no distinct rampart has formed there. The original character of the rocks in the few outcrops in the center of the valley could not be determined in the field. Oxidized remnants of sulfide continue northward perhaps 1 km along a narrow shear zone from the north end of the valley, possibly indicating a structural control of the alteration system.

The innermost alteration zone exposed is quartz-sericite. The central valley is interpreted to correspond closely to the extent of the pyrite-rich zone, but the total sulfide content does not seem to be very high, perhaps not greater than 5 percent. Little appraisal of the leached capping in the central part of the valley was possible because there are few rock outcrops there. Sparse dark red-brown ("live") limonite, similar to that which forms when chalocite and minor pyrite are oxidized, was identified at localities on opposite sides of the valley, suggesting that at least traces of copper sulfide were formerly present.

Provisional evaluation based on a very brief reconnaissance of this prospect is that it is either a low-sulfide low-copper porphyry system or only the uppermost lean part of a porphyry that may contain more copper and sulfide at depth. It is considered a relatively low priority exploration target at the present time.

Site 2d.--This site near Borghar is an area of high reflectance in which a variety of tuffs and flows has been hydrothermally altered to quartz-sericite rock and propylite (Fig. 3). Pyrite has been widely introduced; locally unleached pyrite makes up as much as 5 percent of the rock. No evidence of copper mineralization was seen. Although this prospect is probably part of a large hydrothermal system, the low total sulfide content and the lack of any sign of copper mineralization give it a very low priority as an exploration target.

Site 5b (The Max G. White prospect).--This important porphyry copper prospect lies on the north flank of the stratovolcano, 11 km northwest of Ispeghar Koh, and about 25 km by rough track from Humai village. Most of the 2 km^2 mineralized area underlies the bed of a broad dry wash (Fig. 4). Bedrock outcrops are low and small but are sufficient for generally outlining altered zones.

The country rock that we saw is mostly crystal tuff, tuffaceous sandstone and siltstone, and a few intercalated beds of quartz-pebble conglomerate no more than a few meters thick. Along part of the southwest side of the mineralized area, the country rock is a dull gray-green andesite prophyry containing hornblende phenocrysts a few millimeters to several centimeters long. This porphyry and the nearby sedimentary rocks are propylitically altered.

The central part of the mineralized area is underlain by a felsic porphyry containing abundant quartz phenocrysts as large as 3 mm; this is interpreted to be the porphyry to which mineralization is related. Despite profound mineral changes due to alteration, the quartz phenocrysts show that this is not the same porphyry as that in the propylitic zone along the southwest side.

The propylitic zone is well expressed in the andesite porphyry by the strong development of epidote and chlorite. Epidote is locally well developed in some of the tuffaceous sedimentary rocks, but in most of them the propylitic alteration seems expressed only in pervasive leaching and local iron-oxide staining resulting from oxidation of pyrite. Linear traces of siliceous and ferruginous rock fragments mark narrow zones of more intense alteration in the propylitic zone and also in the outer part of the quartz-sericite zone.

The quartz-sericite zone, about 2 km^2 in area, occupies most or all of the central part of the prospect, mostly underneath the broad dry-wash bed. At point 119 (Fig. 4) secondary biotite was provisionally identified, perhaps indicating some development of a potassic alteration zone. In a small area along the northeast side of the dry wash (point 117, Fig. 4), mineralization in the quartz-sericite zone consists of abundant pyrite, perhaps as much as 10 percent. Elsewhere, no fresh sulfide was seen, but evidence that sulfides have been leached is abundant in all outcrops. Stockworks of thin quartz veins are particularly abundant at points 119 and 120 (Fig. 4). Dark red-brown iron oxides ("live limonite") like those that form after the dissolution of chalcocite and minor pyrite are common at points 118-121. Veins of specular hematite, some as much as 5 cm wide, were found at several places in the prospect.

The association of widespread porphyry-type sulfide mineralization with extensive exposures of intrusive porphyry, and the presence of "live limonite" in an environment of thorough surficial oxidation and leaching, suggest that a secondary enriched zone is a reasonable possibility at the Max G. White prospect.

Site 5c.--The area of mineralization at Site 5c is in a broad low area of low relief, estimated to be about 1 km^2, on the northwest flank of the stratovolcano (Fig. 4). The relationship of it to other porphyry copper alteration systems in the stratovolcano is not known.

Quartz-sericite rock alteration is intense and it is difficult to identify the pre-alteration rock types, but they probably included some quartz latite porphyry or crystal tuff and arkosic or tuffaceous sandstone, all of which are interpreted to be volcanic rocks on the lower flank of the old stratovolcanic edifice. Thorough oxidation and leaching of sulfides have taken place over the entire surface. Most sulfide seems to have been present as veinlets forming stockworks, and disseminated sulfide was probably minor. No copper minerals were seen, but dark red-brown or maroon limonite of the type interpreted to form from dissolution of chalocite in a low-pyrite environment ("live limonite") is fairly common as encrustations of small cavity walls. The rocks of the propylitic zone were not examined.

Two brief field visits were made to this prospect. Further reconnaissance examination of this prospect, especially in view of the occurrence of "live limonite" and abundant sulfide boxworks, is considered very desirable.

Site 5d.--The highly altered rock of this prospect is roughly central in the old stratovolcano. Only areas covered by alluvium separate it from prospects 6d and 6e, and it seems reasonable to consider the three to be part of the same hydrothermal alteration system (Fig. 4). The rocks of this prospect have not weathered to low relief and, lacking the distinct topographic contrast seen in most of the other prospects, a good outline of the altered rock could not be drawn in the short time available at the site. The rocks include a porphyry stock, tuffaceous rocks, and a few porphyry dikes. Tourmaline is widespread; locally it forms abundant flow-banding streaks, the cement of a body of breccia, and veins. Sulfide and evidence of pre-existing sulfide are sparse.

This prospect is of interest only because of its probably peripheral relationship to a much larger porphyry copper-type system. The low sulfide content in 5d precludes any interest in it for its copper content.

<u>Site 6d and 6e.</u>-- Although separated by an area of alluvium 0.6 km across, these two prospect areas are almost surely part of the same hydrothermal alteration system and are described together. The area of alteration and sulfide mineralization forms a broad valley of low outcrops and wide alluvial fans trending about 5 km in a direction N. 70° E. and 1.5 km wide (Fig. 4). Low hills rim the zone of argillic and quartz-sericite alteration at the east end of the prospect. These are made up of a variety of volcanic rocks ranging from tuffaceous sandstone to volcanic conglomerate and are altered propylitically. The inner edge of the propylitic zone is probably close to the base of the low hills along the northwest side at the west end of the prospect, but the southeast limit at the west end has been only approximated. Outcrops are mostly low and generally oxidized and leached of sulfide within the argillic and quartz-sericite zones, but a low northwest-trending transverse ridge dividing the valley into two parts (marked by sample points 149, 150, 151, 152, Fig. 4) contains abundant fresh pyrite. The northwest end of the transverse ridge is made up of tuffaceous sandstone and conglomeratic tuffaceous sandstone. At point 150 in the transverse ridge, the rock consists of many small angular to rounded fragments (less than 2 cm in greatest dimension) in what looks like a tuffaceous matrix. Whether this is a conglomeratic tuff or a fine-grained explosion breccia is not clear. Aggregates of fine black tourmaline make up some of the breccia fragments, and elsewhere nearby form the matrix material of breccia. In the southeastern part of the transverse ridge, quartz feldspar porphyry was identified at several points, but generally the original rock is hard to identify. Felsic porphyry is the predominant rock in the area of prospect 6d.

Field observations in the vicinity of the transverse ridge suggest that a zone of argillic alteration is present between the peripheral propylitic zone and the central quartz-sericite zone, but this has not been confirmed by identification of clay minerals. Alunite is a major constituent of very white altered porphyry west of 6d at point 43 (Fig. 4), and in bleached porphyry at point 152 at the southeast end of the transverse ridge.

The pre-leaching sulfide content of the probably argillically altered zone of the transverse ridge was low, perhaps less than 2 percent, but in the quartz-sericite zone in the ridge and westward throughout prospect 6d the sulfide content was estimated as 5-15 percent. Secondary copper minerals are sparse, but copper carbonates are locally common in jarositic soils at 6d. No "live limonite" was observed at these two prospects. Small chip samples were collected at several localities, and the results of analyses of these are given in Table 3. A sample of unoxidized rock analyzing 0.3 percent copper was collected at point 66 in 1974. Sample 150 was taken in 1976 to check the 1974 result (sample 66), but the copper contained in it was much less.

The size of these prospects, the intensity of alteration, and the abundance of sulfide indicate that this is an important porphyry copper type system. The results of four chemical analyses of unleached sulfide-bearing rock, and the absence of "live limonite," suggest that copper, though present locally, may be generally lacking in the primary sulfide. Though further exploration of these two prospects was formerly given a high priority (Schmidt, 1976, p. 33), the priority is now revised to a secondary level.

Table 3.--Chemical analyses of composite chip samples from prospect sites. Analyses of samples 41, 46, 61, and 66 by P.J. Aruscavage and E. Campbell, U.S. Geological Survey; all others by chemical laboratories of Resource Development Corporation. Letter after sample number indicates rock containing primary sulfide (P) or oxidized rock (O)

[For location of sites, refer to figure 2; for sample locations, refer to figures 3, 4, and 6]

Prospect area	Sample number	Copper (percent)	Molybdenum (ppm)
Site 2b	132 P	0.005	
Site 5b	117 P	.034	
	118 O	.014	
Site 5c	61 O	.0027	1.6
	113 O	.001	
	114 O	.006	
Site 6d	46 P	.1	
Site 6e	66 P	.3	21
	149 P	.024	<10
	150 P	.029	<10
	151 P	.154	144
Site 8a	41 O	1.34	<0.5
	134 P	.016	<10
	135 O	.013	<10
	136 O	.013	<10
	139 P	.002	<10

Site 8a.--This area of extensive sulfide mineralization, associated with probably intrusive feldspar porphyry and well-developed propylitic and quartz-sericite alteration zones, has many features characteristic of porphyry copper deposits. The area of mineralization, more than 0.5 km^2 and probably less than 1.0 km^2, forms a low basin or saddle between hills of unaltered rocks on a ridge between two large drywashes (Fig. 6). Country rocks on the east side are feldspar-quartz (perhaps dacite) porphyry, shale, and minor interbedded limestone. North of the mineralized area is a high steep-sided butte of fine sandstone and siltstone and perhaps other sedimentary strata. The butte is capped by mafic flows, probably extrusives from the volcanic neck Koh-i-Dalil about 2 km to the northwest, and probably younger than the mineralization. Small less intensely altered hills within the western part of the mineralized area are diorite porphyry, and the low hills bounding the mineralized area to the south include tuffaceous sandstones, crystal tuffs, or flows, and some layers of limestone. It was not noted if these rocks to the south had been affected by the hydrothermal alteration and mineralization. The original rock type of much of the mineralized area cannot be determined easily, but at several places a white quartz porphyry was identified, and this is believed to have been the active source of the alteration and mineralization. At the north edge of the mineralized area, intense alteration extends beyond the edge of the porphyry into sandstone country rock. Over much of the mineralized area, where the intruded rock was probably premineral dacite or tonalite porphyry, leaching makes it very hard to recognize which porphyritic rock is present.

Hydrothermal alteration has resulted in well-developed propylitic and quartz-sericite alteration zones. Thoroughly bleached rocks on both sides of the boundary of the propylite and quartz-sericite zones resemble those in argillic alteration zones, but X-ray diffraction studies of three samples failed to detect any clay minerals.

All of the quartz-sericite zone and, at least locally, a little of the inner edge of the propylitic zone have been mineralized with 5-10 percent pyrite. Most of the sulfides have been leached out, leaving clean voids or jarosite-filled cavities; only rare residual cores of unleached rock remain. Jarositic soils and gypsum are common throughout the mineralized area. Oxidized copper minerals are sparse and no "live limonite" was seen. Narrow zones not more than 2 or 3 m wide, probably formed along fractures, were strongly silicified during hydrothermal alteration. Being somewhat more resistant to weathering, the silicified rock forms the crests and mantles the slopes of most of the small rounded mounds in the mineralized area.

The mineralized area of porphyry type has the potential of significant secondary enrichment at depth. Primary sulfide has been analyzed at one locality, and it contained only minor traces of copper, but grades for primary copper ore are unassessed for most of the area. Complete leaching by oxidation of abundant pyrite may yield an unfavorable environment for preservation of either secondary copper minerals or "live limonite." If copper were widespread in the now leached sulfide, the chance for supergene enrichment would be good. Some secondary enrichment took place at point 41 (Fig. 6) to give the high copper analysis there (Table 3). If, however, the sulfides near the surface contained copper only locally, it is possible that we have seen only the upper part of a porphyry system and that the copper-bearing part lies considerably deeper.

Conclusions

This experiment tested a four-dimensional vector algorithm for digital classification of Landsat data in the same area that had been used earlier to test a "parallelepiped" algorithm. The experiment, conducted on data from the Chagai District of Pakistan, showed that preparation of classification tables to reliably discriminate areas of hydrothermal alteration is a long procedure, that better results could be obtained than those obtained in the earlier parallelepiped experiment, but that more work must be done on development of the tables used with the parallelepiped algorithm before the two algorithms can be reliably compared.

Classification in the earlier experiment was based on the unmodified reflectance values in the four multispectral scanner bands. The classification table was tested and revised five times. From line-printer maps of 2100 km^2 made using the fifth table, 50 clusters of pixels classified as hydrothermally altered and mineralized were selected for evaluation. By study of these 50 sites on aerial photographs, the sites were reduced to 23. Most of these decisions were probably well founded, but one or two sites may have been rejected incorrectly. Of the 23 sites chosen, 17 were examined in the field and 6 were found to be areas of hydrothermal alteration and mineralization.

It was possible to make a much more thorough test of the four-dimensional vector algorithm, by means of a system that provided for direct interaction by the geologist with the digital computer. The final classification table was developed through a series of 70 modifications and tests of the resulting changes. From line-printer maps of the same area as that covered in the earlier experiment, 17 sites were selected for field checking without further office evaluations. Of these, 14 were field checked and 6 were found to be areas of hydrothermal alteration and mineralization. The number of sites selected for field checking in the second method used was somewhat fewer--18 rather than 23; the difference was even greater if we consider the 50 sites chosen before being reduced by comparison with geologic maps, Landsat images, and aerial photographs. We assume that a major factor in making the second experiment more successful was having enough time to fully develop the classification tables. More experience should make it possible to make a good table in less than 70 modification steps, although 5 is probably not enough. In each method we were able to identify one important area of alteration and mineralization that went undetected in the other experiment.

We recommend that the 7 areas delimited in the two experiments be evaluated by standard field methods. This is especially desirable for site 5b (the Max G. White prospect), site 8a near Humai, and sites 6d and 6e, which together make up a large mineralized area in the core of the stratovolcano. The 3 areas are here ranked with the most deserving site first.

The presence of small outcrops of Humai Limestone (Cretaceous age) at many locations west of the stratovolcano, between the stratovolcano and site 8a, and east of site 8a, raises the possibility that one of the large hydrothermal systems may have interacted with a mass of limestone country rock to produce skarn-type ores. Appropriate geophysical studies, such as magnetic and induced potential surveys, should be undertaken near the areas of strong hydrothermal alteration to provide guides for drilling for buried high-grade base-metal ores.

References cited

Ahmed, Waheeduddin, Khan, S.N. and Schmidt, R.G., 1972, Geology and copper mineralization of the Saindak quadrangle, Chagai District, West Pakistan: U.S. Geological Survey Professional Paper 716-A, 21 p.

Hunting Survey Corporation, Ltd., 1960, Reconnaissance geology of part of West Pakistan; a Colombo Plan Cooperative Project: Toronto, 550 p. (Report published by Government of Canada for the Government of Pakistan).

Khan, S. N., 1972, Interim report on copper deposit of Saindak. Chagai District (Baluchistan), Pakistan: Pakistan Geological Survey, Saindak copper report no. 1, 17 p.

Lowell, J. D., and Guilbert, J. M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry ore deposits: Economic Geology, v. 65, no. 4, p. 373-408.

Schmidt, R. G., 1968, Exploration possibilities in the western Chagai District, West Pakistan: Economic Geology, v. 63, n.1, p. 51-60.

_______________ 1974, The use of ERTS-1 images in the search for large sulfide deposits in the Chagai District, Pakistan: U.S. Department of Commerce National Technical Information Service, E74-10726, 38 p.

_______________ 1976, Exploration for porphyry copper deposits in Pakistan using digital processing of Landsat data: U.S. Geological Survey Jour. Research, v. 4, n. 1, p. 27-34.

Schmidt, R.G., Clark, B. B., and Bernstein, R., 1975, A search for sulfide-bearing areas using Landsat-1 data and digital image-processing techniques: NASA Earth Resources Survey Symposium, Houston, Texas, June 1975, National Aeronautics and Space Administration TM X-58168, p. 1013-1027.

Sillitoe, R. H., and Khan, S.N., 1977, Geology of Saindak porphyry copper deposit, Pakistan: London, Institute of Mining Metallurgy Transactions, v. 86, p. B27-B42.