Comparison of Geological Geophysical, and Geochemical Prospecting Methods at the Malachite Mine Jefferson County, Colorado

GEOLOGICAL SURVEY BULLETIN 1098-C

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By LYMAN C. HUFF

CONTRIBUTIONS TO GEOCHEMICAL PROSPECTING FOR MINERALS

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A geological and geochemical study which supplements previous geophysical studies and compares prospecting techniques for finding copper ore concealed beneath residual soil

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By Lyman C. Huff

ABSTRACT

At the Malachite mine a noteworthy discovery of copper ore was made in 1940 as the result of a geophysical survey. Geological and geochemical investigations show that both the ore body discovered in 1940 and the original ore body discovered in 1866 are within an eastward-trending vein which is 2,600 feet long and which roughly parallels the layering and schistosity of the Precambrian gneiss and schist country rock. Both ore bodies were pod-shaped shoots composed of fragments of the wallrock cemented with and partly replaced by quartz, pyrrhotite, and chalcopyrite, as well as by sparse galena and sphalerite. The ore is probably of hydrothermal origin and probably of Precambrian age.

The ore body discovered in 1866 cropped out at the land surface and apparently was easy to find. Malachite stains the gossan capping of this ore body and fragments in the soil nearby. Magnetic and self-potential measurements yield a strong local anomaly over this ore, and anomalous copper concentrations in the residual soil can be traced several hundred feet downhill. This ore body could have been found either by the newer prospecting methods or by the time-honored system of searching the land surface for float fragments of oxidized ore.

About 800 feet east of the original discovery the vein splits into two branches. One branch of the vein is exposed at the land surface 80 feet north of and uphill from the concealed ore body. The branch containing the concealed ore body pinches out about 20 feet beneath the land surface and has no visible surface indications of its existence. A geochemical anomaly covering both branches of the vein and extending several hundred feet downhill indicates abnormal copper concentrations over the ore but is less suitable than the original geophysical data in revealing the exact location of the ore.

INTRODUCTION

The development of new prospecting techniques creates a need for comparing their usefulness in ore discovery. New geophysical and geochemical prospecting methods have received much attention lately, and there is some danger that the novelty and attractiveness of these new methods may cause neglect of the older prospecting methods. Comparisons of both new and old techniques can be provided by case studies of particular ore discoveries. The investigation described here is such a study of the Malachite mine.

The Malachite mine is in the Front Range of the Rocky Mountains about 12 miles west of Denver (fig. 21). Precambrian metamorphic rocks comprise most of the Front Range near the mine. Late Precambrian granitic intrusive masses are located to the west and north. About 3 miles east of the mine are the eastward-dipping Paleozoic and Mesozoic sedimentary rocks along the margin of the Great Plains. The famous Central City mining district is about 15 miles to the west and includes the nearest mines of importance.

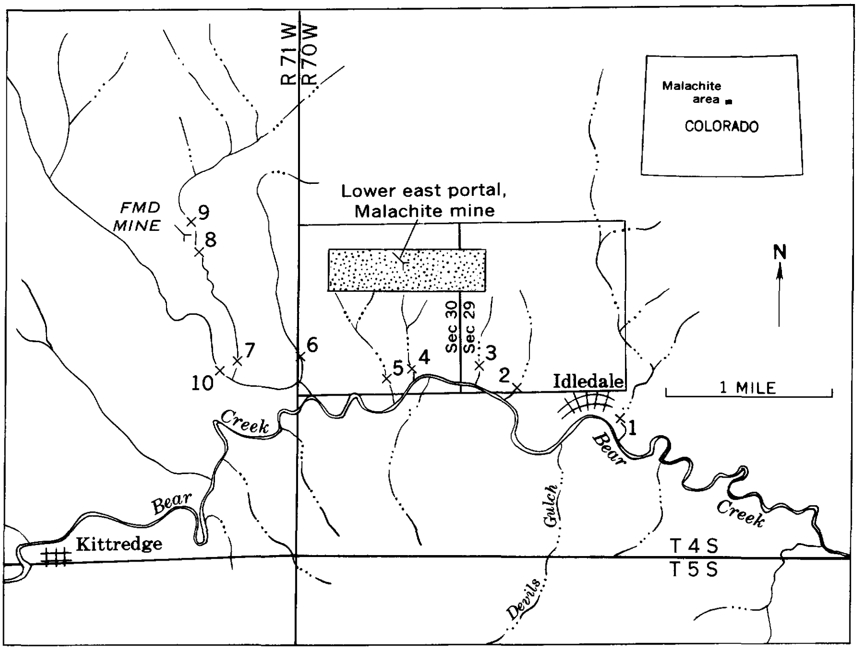

FIGURE 21.—Index map of the Malachite mine area, Jefferson County, Colo. Numbers indicate location of samples collected for preliminary geochemical study. Area of plate 8 shown by stipple pattern.

Physiographically, the Malachite mine is located on the north side of Bear Creek Canyon at an altitude of 7,400 feet. Although the terrain is steep and mountainous with numerous exposures of bedrock, most of the land surface is smooth and covered with a thin soil. The area near the mine is mostly grassland, but there are numerous brushy thickets and groves of pine trees.

In 1948 the writer collected soil samples near the Malachite mine for use in developing geochemical prospecting tests. Several years later, sampling was extended to outline the anomalous area and a topographic and geologic map was prepared using planetable and alidade.

This report concerns chiefly the geology and geochemistry of the area; a full description of geophysical results is available elsewhere (Heiland and others, 1945). In the final section of this report the results of the various prospecting techniques—geological, geophysical and geochemical—are compared by use of cross sections through the ore bodies.

The writer is indebted to the Department of Geophysics, Colorado School of Mines, for permission to use their geophysical data. Harold Bloom made the topographic base map, and other personnel of the U.S. Geological Survey assisted in collecting samples. Harold Bloom, Albert P. Marranzino, Harry E. Crowe, and J. Howard McCarthy, Jr., of the U.S. Geological Survey, made the chemical analyses.

GEOLOGIC SETTING

The Precambrian country rock of the area mapped (pl. 8) includes quartz-biotite schist and hornblende gneiss apparently correlative with the metasedimentary schist of the Idaho Springs Formation and Swandyke Hornblende Gneiss (Lovering and Goddard, 1950, p. 20). Interbedded lenses and layers of these rocks from a few to several hundred feet thick have an easterly strike, and a steep dip to the north. These older rocks are cut by a swarm of northeastward-trending pegmatite dikes and by an eastward-trending vein or mineralized fault which contains the two principal ore bodies.

ORE DEPOSITS

The Malachite mine has produced ore valued at about $80,000 from the two ore bodies. The ore bodies, which will be referred to here as the east and west ore bodies, are in the vein and are about 800 feet apart (pl. 8).

MINING HISTORY

The original discovery at the Malachite mine was made about 1866; in that year claims were filed on the western ore body by R. G. Morrison and J. L. Wilson (Morehouse,[1] p. 20). Considerable oxidized ore was removed from a shaft (pl. 8) in this ore body between 1888 and 1893 (Heiland and others, 1945, p. 2), and most of the prospect pits were probably dug shortly thereafter. The distribution of malachite and of gossan apparently guided the original prospecting.

Lindgren (1908) made the first geologic study of the Malachite deposit when he examined a 130-foot shaft in the western ore body. During his examination, an adit was being extended to connect with

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[1] Morehouse, G. E., 1950, Geology of the Malachite Mine, Jefferson County, Colorado: Colorado School Mines, unpublished M.S. thesis 675.

the base of the shaft. Lindgren reported that $35,000 worth of partly oxidized copper ore had been taken from the shaft. He described the primary ore as an aggregate of coarsely crystalline pyrrhotite, chalcopyrite, and dark-brown sphalerite, all intergrown with augite and feldspar in a manner that suggests simultaneous crystallization. Lindgren concluded from this intergrowth and from the association of the ore with hornblende gneiss that the ore is a magmatic segregation from the hornblendite.

The northeast adit and the 50-foot shaft connecting this adit to the land surface (fig. 22A) may have been excavated shortly after Lindgren's visit. These workings are clearly very old and yielded little or no ore.

Boyd[2] identified the rock at the face of the west adit as a hornblende-rich quartz-diorite dike and, like Lindgren, concluded that the ore was a magmatic concentration. His conclusion was based largely upon the presence within the ore body of high temperature minerals—such as hornblende, biotite, and pyrrhotite—indicating origin at a great depth. Because unmetamorphosed Paleozoic rocks are present within 3 miles of the mine, Boyd considered it unlikely that the host rocks could have been buried deeply or metamorphosed appreciably since the Precambrian, or that the ore could be anything but Precambrian in age.

In 1937, while using the Malachite area as a training ground for classes, geophysicists from the Colorado School of Mines discovered geophysical anomalies east of known ore. Shortly thereafter the mine operators drove the southeast adit beneath an area lacking outcrops (fig. 22) to explore a large magnetic anomaly, and discovered the eastern ore body. Ore shipped from this ore body between September 1940 and March 1941 contained $44,000 worth of copper, gold, and silver (Heiland and others, 1945).

Morehouse[3] mapped the eastern ore body and all the older workings. After a detailed study of the mineralogy and mineral paragenesis, he concluded that the ore deposits are not magmatic concentrations, but are hypothermal vein deposits and replacements along a fault or shear zone and that a Precambrian age is unlikely. During 1956 and 1957, after the geochemical studies were made by the U.S. Geological Survey, a large amount of bulldozing in the vicinity of the eastern ore body covered the eastern adit and changed the appearance of much of the land surface.

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[2] Boyd, James, 1934, Pre-Cambrian mineral deposits of Colorado: Colorado School Mines, unpublished Ph. D. thesis 552.

[3] See footnote 1, p. 163.

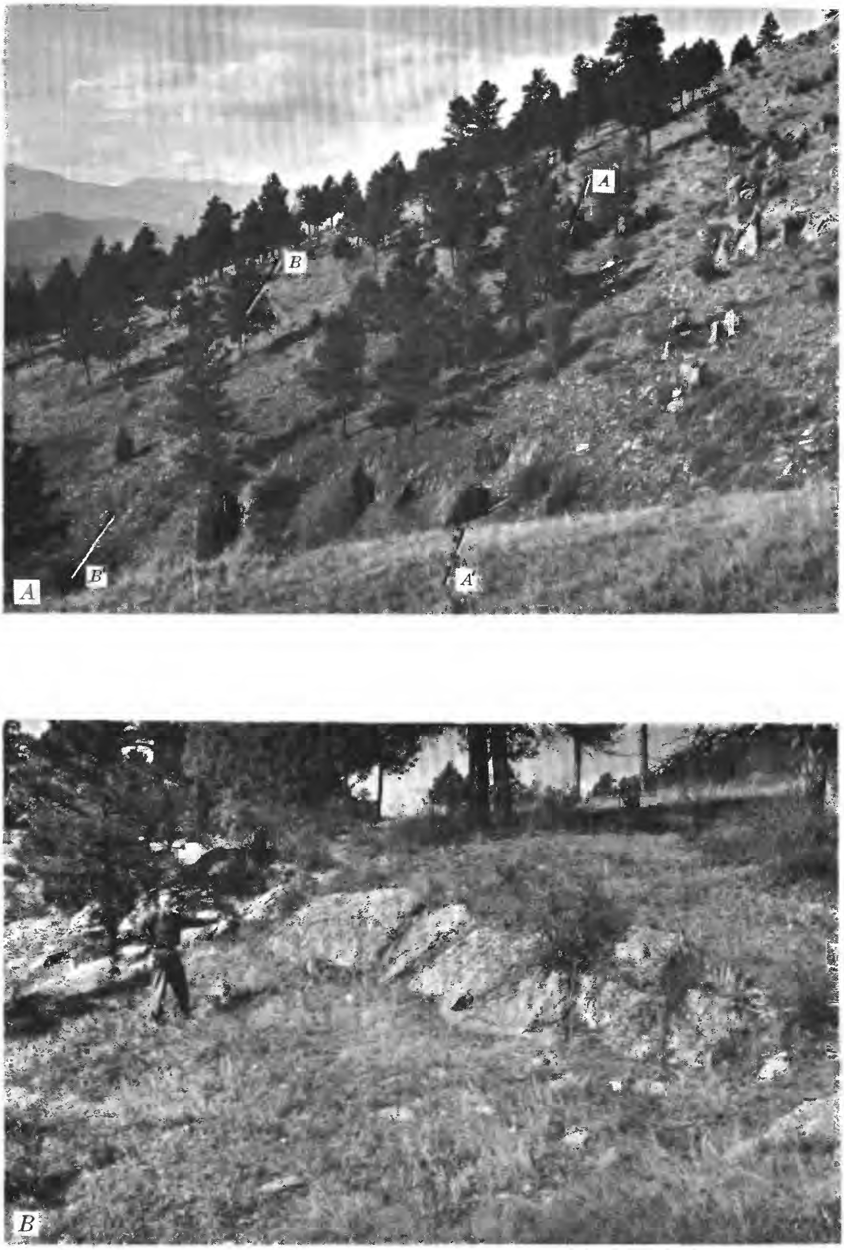

FIGURE 22.—Views of northeast adit and typical pegmatite dike. *A*, Surface overlying concealed ore body, looking west. Rocky knobs on right are outcrops of hornblende gneiss. North branch of vein is exposed as mineralized outcrops along *A–A'*; ore body is along south branch of vein concealed beneath soil cover along *B–B'*. *B*, Pegmatite dike 400 feet southeast of sample site M25. Most of the Malachite area is covered with a thin soil through which many of the pegmatite dikes, like this one, crop out as low rocky ridges.

ORE BODIES

The mineralogy of the east and west ore bodies is similar; chalcopyrite and pyrrhotite are the principal minerals in the ore, but also present are some galena, dark-brown sphalerite, vein quartz, and a little gold and silver. Locally, the ore and rock minerals are intergrown, but in most places the ore minerals fill fractures and interstices between angular fragments of the country rock. No evidence was found of any downward leaching of copper from the oxidized zone or of any supergene enrichment of the copper.

The west ore body was an irregular pipelike body averaging about 40 feet in diameter which plunged steeply northwest to a depth of 150 feet (pl. 8, section M1–A1). The east ore body was a tabular body with an east-west strike and a dip to the south; it averaged about 350 feet in length, about 40 feet in width, and extended to at least 40 feet below the adit level (pl. 8). It was highly irregular in the plane of the vein; one pipelike chimney of ore extended to a point 80 feet above the adit level and about 20 feet beneath the land surface (pl. 8, section M17–A17).

STRUCTURAL CONTROL

The fault is the primary structural control for the two ore bodies. At the land surface this mineralized fault or vein is about 20 to 30 feet wide and can be traced about 2,600 feet by means of outcrops, float, and scattered prospect pits (pl. 8). The south, or downhill, margin of the vein could be mapped only approximately because of slope wash. The only branching or splitting of the vein noted is near the east ore body (pl. 8, section M17–A17). Here surface indications of mineralized rock are all along the exposed northern branch, but the ore body is on the concealed southern branch.

During the geologic mapping, close attention was paid to intersections of the pegmatite dikes and the vein to determine their age relations. In some places the pegmatite dikes appear to be displaced by movement along the vein and in other places they do not appear to be displaced. In the adit of the east ore body a dike is impregnated with sulfide minerals. This occurrence, and similar ones found elsewhere, have been interpreted by Morehouse[4] as an indication that sulfide mineralization postdated pegmatite emplacement.

ORIGIN

Studies of the mineralogy and texture of the ore do not establish conclusively whether it is magmatic, as suggested by Lindgren and

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[4] See footnote 1, p. 163.

Boyd, or hydrothermal, as suggested by Morehouse. If the ore is magmatic it is undoubtedly Precambrian; but if it is hydrothermal the Precambrian age is less certain. A magmatic concentration presupposes settling of a heavy sulfide phase in a body of molten magma, so that the ore should be at or near the base of the parent magma body. If the ore is hydrothermal, however, the ore should be concentrated along faults or fractures, particularly at their intersections.

The ore deposits are clearly within the prominent vein-fault (pl. 8), rather than closely associated with the hornblende gneiss. The west body is within a thick layer of hornblende gneiss as noted by Lindgren (1908) and Boyd,[5] but the east ore body is separated for a considerable distance from the main belt of hornblende gneiss by biotite schist (pl. 8, section M17–A17). Thus, the association of ore with hornblende gneiss is not as close as originally supposed. Particularly noteworthy is the occurrence of the east ore body at a split in the vein (pl. 8, section M17–A17) as might be expected of hydrothermal deposits. Geologic mapping disclosed no other ore deposits although there are many other belts of hornblende gneiss.

Both structural and geochemical evidence appear to favor a hydrothermal origin. Magmatic ore deposits commonly are surrounded by an extensive primary geochemical anomaly related to the high ore-metal content of the parent igneous rock. Many magmatic deposits of nickel and chromium, for example, are surrounded by extensive areas where nickel and chromium contents of rocks and soils are abnormally high. It may be supposed that magmatic copper deposits would be associated with cobalt and nickel, and would be surrounded by an extensive geochemical anomaly related to the hornblende gneiss. The chemical anomaly, however, is not an extensive primary anomaly of this type.

It is tentatively concluded that the ore was deposited by Precambrian hydrothermal solutions in a fault breccia.

ORE WEATHERING AND SOIL FORMATION

Near the land surface, the ore has been oxidized to an iron-stained gossan which locally has a little malachite on joint surfaces. Malachite fragments are present mainly along the vein, and all the malachite-rich areas have been explored by prospect pits or surface workings. Float of iron-stained gossan can be traced locally several hundred feet downhill from the vein. Because the distribution of this float guided early prospecting it is shown on the geologic map (pl. 8) for comparison with other prospecting guides. Observation of the

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[5] See footnote 2, p. 164.

distribution of float was required in order to map the uphill margin of the vein and its lateral limits in soil-covered areas.

A study of the soil was required to facilitate geologic mapping and also to interpret the geochemical data. The transported soil, here called colluvium, is a crudely stratified and poorly sorted mixture of silt, sand, and gravel, ranging from 1 to about 20 feet in thickness where shown on the geologic map (pl. 8). The colluvium occupies several valley bottoms along the small creeks draining the area mapped, and in one place it covers the mineralized zone. In the southern part of the mapped area, the banks of several entrenched gulches form exposures of the entire thickness of colluvium. Most of the colluvium appears to have been derived by slope wash from adjacent hillsides, but it includes some alluvium deposited by local creeks.

The residual soil, which covers about nine-tenths of the land surface mapped as bedrock (pl. 8), is a thin, rocky noncarbonate soil with three poorly defined but recognizable soil horizons. The A horizon is commonly 0.5 to 1.0 foot thick; it is a dark-brown to black friable mixture of silt, sand, and rock fragments with some plant roots and partly decayed organic material. The B soil horizon is about 1.0 foot thick and grades into the A horizon above and the C horizon below. The B horizon is a light-brown friable mixture of silt, clay, sand, and weathered rock fragments. The clay content and brown color best distinguish it from the A horizon above. The C horizon, which is at a depth of 1.5 or 2.0 feet beneath the land surface, consists of light-brown weathered bedrock. The low clay content and lack of mechanical disturbance distinguish it from the B horizon above.

Study of soils along geologic contacts shows that the three soil horizons may differ considerably in pebble composition. The C horizon consists of thoroughly weathered bedrock which has not been transported; and the B horizon consists of rock which has been transported several feet and partly mixed. The A horizon is thoroughly mixed and commonly contains many hard angular rock fragments which have been transported several tens of feet. The hardest rocks, like the pegmatite and hornblende gneiss, crop out as low rocky ridges (fig. 22*B*) and contribute many cobbles and pebbles to the A horizon. Locally, these fragments can be traced 100 to 200 feet downslope.

GEOPHYSICAL PROSPECTING

The first geophysical study of the area was a preliminary magnetic survey made by J. E. Hawkins in 1937. In 1938 and 1939 a student class of the Colorado School of Mines, while making self-potential surveys, discovered a prominent self-potential anomaly that was east of any ore known at that time. Shortly thereafter the mine operators, encouraged by the geophysical results, drove the southeast adit and discovered the east ore body (Heiland and others, 1945).

Subsequent geophysical studies by personnel of the Colorado School of Mines revealed marked vertical magnetic, resistivity, and equipotential line anomalies near the new ore body. These anomalies agree well with each other and with the location of the ore body. In addition, resistivity-sounding experiments indicated a depth to the ore closely approximating the depth actually measured when the ore was mined. For comparative purposes, the geophysical results are summarized here by the self-potential and vertical-magnetic anomalies along sections shown on plate 8.

The ore bodies of the Malachite mine are particularly suitable for the use of geophysical methods. Magnetic anomalies are strong because of the high content of pyrrhotite in the ore. The self-potential anomaly is caused by oxidation of the sulfide ore body. The resistivity and equipotential line anomalies probably are related both to the electrical conductivity of the ore and to that of the electrolytes from the oxidizing ore. These geophysical methods, which measure different physical and chemical attributes, all yield strong anomalies near the ore bodies.

GEOCHEMICAL PROSPECTING

Several students of the Colorado School of Mines have made geochemical studies in the Malachite area. Pierce and Dias (1950) sampled soil along three traverses and found a marked total heavy-metal anomaly near the mineralized zone. Horino[6] demonstrated by spectrographic analysis the presence in the mineralized rock of trace amounts of nickel and cobalt which had not previously been detected.

RECONNAISSANCE GEOCHEMICAL STUDIES

The initial U.S. Geological Survey investigations were made in part to test analytical methods and in part to evaluate the usefulness of residual soil in geochemical prospecting. The first results demonstrated a marked copper anomaly in the residual soil near ore (Huff, 1952). The investigation was continued to compare soil composition with that of other materials such as water, alluvium, plants, and weathered rock.

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[6] Horino, F. G., 1951, Geochemical-spectrographic prospecting at the Malachite Mine, Jefferson County, Colorado: Colorado School Mines, unpublished M.S. thesis 711.

TABLE 1.—*Analyses of alluvium and water samples collected in the vicinity of the Malachite and FMD mines*

[Analytical methods described by Lakin and others (1952)]

Sample (fig. 21)	Water			Alluvium (minus 80-mesh)
	Total heavy metal (ppm)	Acidity (pH)	Sulfate[1]	Total heavy metal (ppm)
1	0.01	7.7	97	75
2	(2)	----------	----------	75
3	(2)	----------	----------	75
4[3]	.02	7.7	84	100
5[3]	.01	7.7	92	75
6[3]	.01	7.7	90	75
7[3]	.01	7.7	95	150
8[3]	.30	7.7	95	250
9	.01	7.7	99	75
10	.01	7.7	98	75

[1] Measured arbitrarily as optical transmittancy of water after adding barium chloride. A low value indicates a high-sulfate content.

[2] Dry, no sample.

[3] Samples collected downstream from known ore deposits.

Water and alluvium samples were collected at places shown on the index map (fig. 21). Samples of water and alluvium were collected about 0.5 mile downstream from the Malachite mine, where two small gulches that drain the mine area discharge into Bear Creek. Samples were collected upstream and downstream from the FMD copper mine, which is 1.5 miles west of the Malachite mine and whose ore is similar to that of the Malachite deposit. Samples were also collected from the mouths of neighboring gulches that drain basins containing no known copper deposits.

The water and alluvium samples were analyzed by the total heavy-metal test (Lakin and others, 1952) which is a much-simplified geochemical prospecting test designed to distinguish any samples containing copper, lead, or zinc in abnormal amounts. The analyses of these samples show detectable anomalies downstream from the Malachite and FMD copper deposits (table 1). The highest values obtained are about 30 times background for the water and about 3 times background for the alluvium. Part of the anomaly in the water and alluvium must be attributable to accelerated weathering and erosion caused by the mining of the ore deposits, but the magnitude of this portion is not known. The concentrations measured appear consistent with the small size of these ore deposits in comparison with the size of their respective drainage basins.

Biogeochemical prospecting, prospecting by plant analysis, was tried briefly by a series of 14 samples of pine trees. Needles and twigs of pine trees were sampled along a traverse extending across the mineralized zone over the ore body where the copper and zinc content of the soil showed a marked increase. These plant samples were analyzed for copper, lead, and zinc.

The plant and soil samples described later are located with reference to the School of Mines geophysical grid. Key locations such as A1, M1, A25, and M25 are shown on plate 8; some others mentioned in the text or in tables are not numbered on plate 8 but can be found by counting from those shown.

The highest copper and zinc values of plant samples, 20 and 55 ppm respectively, are from G10 (not numbered on pl. 8) collected close to ore (table 2), but these values are so little above background that the existence of an anomaly related to ore remains questionable. Much larger anomalies in plants have been obtained near some other copper deposits (Cannon, 1960, p. 595).

TABLE 2.—*Metal content of pine needles and twigs collected along traverse across the Malachite ore zone*

[Analyses by Harold Bloom]

Approximate location of sample on traverse	Metal content in parts per million [1]					
	Copper		Zinc		Lead	
	Needles	Twigs	Needles	Twigs	Needles	Twigs
C10	12	15	20	----------	8	----------
E10	8	----------	25	----------	----------	----------
F10 (near ore)	12	----------	30	----------	----------	----------
G10 (near ore)	20	21	55	----------	5	----------
H10	8	----------	30	----------	----------	----------
J10	15	----------	50	----------	----------	----------
L10	12	----------	35	----------	----------	----------
M10	12	16	35	----------	----------	----------
N10	13	----------	30	----------	----------	----------
O10	17	----------	35	----------	----------	----------
Q10	17	----------	40	----------	----------	----------

[1] Dashes indicate no measurement.

PRELIMINARY SOIL SAMPLING

Before mapping the distribution of copper-rich soil in relationship to ore, pilot studies were made of the distribution of copper by depth in the soil profile, by size fraction in the surface soil, and of various geochemical prospecting tests for copper. Studies were also made of other trace constituents of the soil to find out if any other constituent might be more suitable for geochemical prospecting than copper itself. For these studies, samples were collected along several north-south traverses crossing the vein at a right angle so that both barren and anomalous samples would be included. At most sample sites the surface soil was sieved to minus 80 mesh with a stainless steel sieve when collected.

TRACE CONSTITUENTS OF THE SOIL

Soil samples from these traverses have a range in copper content from 50 to 550 ppm, an elevenfold range which is large in comparison with that of other metals (tables 3 and 4). Zinc, cobalt, and silver also are high near the vein. Further testing showed that the iron content among these samples ranges from 12 to 6 percent, the sulfate from 0.7 to 0.2 percent, and the soil acidity from a pH of 6.2 to 6.8. Three samples were panned without finding any gold colors, but the one collected near the vein (H10) yielded an assay result of 0.02 ounce combined gold and silver per ton.

Table 3.—*Metal content of soil samples collected along traverse from C10 to P10*

[Analyses by Harold Bloom, Victor Kling, J. P. Schuch, and A. P. Marranzino]

Location of sample on traverse	Laboratory analysis (ppm) [1]			Geochemical prospecting tests (ppm) [2]						
	Zinc	Lead	Copper	Total heavy metal	Copper by chromograph	Copper by dithizone	Zinc by dithizone	Cobalt by chromograph	Nickel by chromograph	Silver by chromograph
C10	80	25	50	50	50	35	120	10	0	0
D10	120	45	50	80	10	45	80	10	0	0
E10	85	20	100	100	10	60	80	10	0	0
F10 [3]	160	10	340	200	300	280	150	10	0	.2
G10 [3]	500	60	5,300	2,000	4,000	5,500	800	20	0	12.0
H10	410	40	1,900	800	1,000	1,600	400	20	0	1.0
I10	260	55	830	400	500	800	400	10	0	.4
J10	270	40	510	300	400	360	300	10	0	.4
K10	210	30	440	200	200	340	300	10	0	.4
L10	160	35	300	100	300	300	200	10	0	.4
N10	260	35	350	300	300	300	300	10	0	.4
P10	210	70	400	500	300	---------	300	5	0	.4

[1] Methods described by Holmes (1945).
[2] Methods described by Lakin and others (1952).
[3] Vein is between F10 and G10.

Table 4.—*Metal content of soil samples collected along traverse from C25 to L25*

[Analyses by Harold Bloom, Victor Kling, and J. P. Schuch]

Location of sample on traverse	Laboratory analysis (ppm) [1] copper	Geochemical prospecting test (ppm) [2]			
		Total heavy metal	Copper by chromograph	Zinc by dithizone	Copper by dithizone
C25	50	80	10	90	30
D25	55	80	20	60	45
E25	60	50	10	60	40
F25 [3]	70	100	50	90	60
G25 [3]	400	300	500	200	400
H25	240	300	150	200	210
I25	160	200	100	200	150
J25	100	100	80	100	80
K25	80	100	10	100	70
L25	85	80	50	-----------	60

[1] Methods described by Holmes (1945).
[2] Methods described by Lakin and others (1952).
[3] Vein is between F25 and G25.

DISTRIBUTION OF COPPER IN THE SOIL PROFILE

In one series of samples collected at various depths in the soil profile, the copper content is at a maximum (15,000 ppm) in the C soil horizon or weathered bedrock close to the vein, but abnormal copper concentrations are most widely dispersed in the A horizon or surface soil (table 5). The B soil horizon is intermediate in copper content between the A and the C horizons. In the A horizon the maximum copper content is only 5,300 ppm, but abnormal values extend over a broad area apparently as a result of the dispersion and dilution of copper by soil creep and mixing processes during weathering and erosion (Huff, 1952). In the samples collected more than 50 feet downhill from the vein, the surface soil contains more copper than the soil and weathered rock underneath (table 5).

TABLE 5.—*Copper content, in parts per million, of soil samples collected at various depths along traverse from C10 to P10*

[Analyses by Harold Bloom after method given by Holmes (1945)]

Location of sample on traverse	Copper content at various depths				
	Surface	0.5 (ft)	1.0 (ft)	1.5 (ft)	2.0 (ft)
C10	50	85	60	[1] 160	----------
D10	50	65	[1] 90	----------	----------
E10	100	50	60	[1] 50	----------
F10 [2]	340	1,600	1,000	1,800	1,400
G10 [2]	5,300	2,900	6,500	[1] 15,000	----------
H10	1,900	1,200	[1] 950	----------	----------
I10	830	500	[1] 180	----------	----------
J10	510	410	[1] 260	----------	----------
K10	440	300	310	[1] 250	----------
L10	300	280	280	[1] 150	----------
N10	350	300	290	[1] 300	----------
P10	400	280	350	[1] 180	----------

[1] C soil horizon (weathered bedrock); surface soil is A soil horizon and soil at 0.5 and 1.0 ft is B horizon except where noted otherwise.

[2] Vein is between F10 and G10.

DISTRIBUTION OF COPPER BY PARTICLE SIZE

The copper derived from the ore is present in all size fractions of surface soil (table 6). Uphill from the vein (D10), where presumably the copper content of the soil is mostly in hornblende derived from the underlying rock, all size grades in the soil have almost the same copper content. The same is true just downhill from the ore (H10), where the copper content is high and where most of the copper must be derived from the ore. In the soil 150 feet downhill from the ore zone (L10), however, the copper content is highest in the fine-size fractions. This relationship suggests that copper derived from the ore may become concentrated in the smaller particles as the soil creeps downhill. The use of a fine fraction of the soil not only eliminates the need to grind the samples but also probably facilitates detection of faint geochemical anomalies.

COMPARISON OF GEOCHEMICAL PROSPECTING TESTS

A comparison of several geochemical prospecting tests for representative samples (tables 3 and 4) shows that several can detect significant differences in copper content but does not establish which is best. In a separate study, 52 samples collected in duplicate in the Malachite area were compared in terms of cost, discrimination, precision, and accuracy. Of the methods compared, dithizone and biquinoline prospecting tests give the most reproducible results and permit the best distinction to be made of background and anomalous samples (Huff, and others, 1961). One of these methods, the dithizone, was therefore selected for mapping the distribution of copper throughout the area.

TABLE 6.—*Copper content of different size fractions in three surface soil samples*

[Analyses for copper by J. H. McCarthy, Jr., after method given by Holmes (1945)]

Location of sample	Size fraction (by U.S. mesh number)	Percent of sample by weight	Copper content (ppm)
At D10, about 100 feet uphill from vein	5–10	7	52
	10–18	10	43
	18–35	14	57
	35–60	29	42
	60–120	22	50
	120–250	12	60
	<250	6	80
At H10, about 100 feet downhill from vein	5–10	8	2,000
	10–18	9	2,600
	18–35	11	2,100
	35–60	24	2,000
	60–120	28	2,050
	120–250	14	2,100
	<250	6	2,300
At L10, about 300 feet downhill from vein	5–10	7	160
	10–18	7	170
	18–35	12	175
	35–60	26	245
	60–120	24	365
	120–250	16	400
	<250	8	430

AREAL DISTRIBUTION OF COPPER-RICH SOIL

To map the copper-rich soil, about 600 samples were collected along traverses following the Colorado School of Mines grid and along extensions of it made with tape and Brunton compass. Soil samples were taken at sample sites marked with wooden stakes and spaced at 50- or 100-foot intervals along these survey traverses. After the copper content of these samples was determined by the dithizone method, the analyses were plotted on the topographic map and areas of high copper content were outlined (pl. 8).

The soil with the highest copper content occurs close to or downhill from the mineralized zone. The copper content of the soil ranges from a low between 20 and 50 ppm, which may be taken as background, to a high of more than 5,000 ppm. The copper content of the soil is particularly high near occurrences of malachite and, to a lesser extent, within the area characterized by iron-stained float (pl. 8). There are four different areas along the ore zone having copper concentrations in the soil in excess of 1,000 ppm.

Most of the dispersion of the copper during weathering and erosion appears to be by soil creep. Abnormal copper concentrations uphill from the mineralized zone might result from hydrothermal dispersion of copper in the wallrock or from diffusion uphill during weathering and erosion. Apparently neither of these processes was significant; the copper content of the soil decreases abruptly uphill from the mineralized zone. Downhill from the mineralized zone the distribution of copper-rich soil is much more extensive, and the copper isograds outline lobate areas extending as much as 900 feet downhill. Some copper may be transported in ground water; however, it seems evident that the copper must be relatively insoluble in meteoric waters or it would not be transported for long distances within the soil mantle.

The geochemical map shows a fairly close spatial relationship between copper-rich soil and the ore bodies. Both of the ore bodies are in areas where the copper content is highest; they are both within areas where the copper content of the soil exceeds 1,000 ppm. The relationship shows that the copper content of soil can be used for prospecting in much the same manner as the distribution of iron-stained float.

COST OF GEOCHEMICAL PROSPECTING

An evaluation of geochemical prospecting should include some consideration of its cost. If we do not consider the capital cost of equipping a chemical laboratory, then the principal cost is in salaries and can be expressed in man-days. The chemicals for making the analyses actually cost less than the sample containers and wooden stakes needed to mark the sample sites and are negligible in comparsion to salary. Mapping the copper content of soil in the Malachite area required collection and analysis of about 600 samples which were collected by a field team of two at a rate of about 100 samples per day. Collection of the samples thus took approximately 12 man-days. The analysis of the samples also required approximately 12 man-days, which makes a total of 24 man-days to prepare the geochemical map. The geological mapping also required about 24 man-days, exclusive of the time needed to prepare the topographic base. Consequently, the cost of the geochemical mapping was roughly the same as that of the geological mapping.

COMPARISON OF PROSPECTING TECHNIQUES

To compare geologic, geophysical, and geochemical prospecting techniques, critical data have been compiled on three cross sections (pl. 8). Cross sections are shown for the west ore body discovered in 1866 (M1–A1), for a traverse crossing the vein several hundred feet east of known ore (M25–A25), and for the concealed east ore body discovered in 1940 (M17–A17).

Near the west ore body (section M1–A1) all prospecting guides should encourage exploration. Malachite-stained fragments of gossan are abundant and provide an obvious geologic guide on the vein outcrop. The copper content of the surface soil exceeds 100 ppm for more than 300 feet downhill. The magnetic anomaly is intense and about 50 feet wide. These relations suggest a shallow ore body, which is what was found and exploited years ago. For this ore body the geochemical methods yield the most extensive indications of copper mineralization and the other prospecting methods give the most accurate location of the ore.

Along the section several hundred feet east of known ore, a thin layer of colluvium and soil covers the vein (section M25–A25). Here there is no gossan or other visible evidence of mineralized rock, but both geophysical and geochemical data yield anomalies over the vein. The magnetic anomaly between C25 and E25 bears no relation to known copper mineralization and probably is caused by a local accumulation of magnetite in the gneiss. Thus, along this section the geochemical data give the most definite indication of the copper mineralization.

Near the concealed or east ore body (section M17–A17), all surface indications of ore are on the uphill branch of the vein. The exposed uphill branch of the vein is easily identified on the land surface from outcrops and the distribution of gossan and malachite-stained float; there are no outcrops (fig. 22) or other surface evidence of the downhill branch. If this branch contributes any gossan to the soil cover, it is completely obscured by gossan float from the uphill branch.

The copper content of soil is anomalous in an area extending over the concealed ore body. The critical question concerning the soil data is whether the anomaly can be attributed solely to the mineralized outcrop. In other words, if this geochemical data had been available before 1940, would the geochemist have suspected the existence of ore on a concealed branch of the vein? The geochemical data would certainly favor exploration in this area; however, the area underlain by the east ore body forms only a relatively small part of the total area covered by copper-rich soil, which presumably might be considered favorable for exploration on the basis of the geochemical data. This relationship clearly illustrates one limitation of geochemical prospecting by analysis of surface soil. A geochemical anomaly for one ore body may be obscured by the occurrence of mineralized areas higher on the hillside.

The magnetic data indicated a strong anomaly about 100 feet in width over the concealed ore body (pl. 8, section M17–A17). The width of the anomaly indicates the presence of a large magnetic body at depth, and undoubtedly provides the best guide for the concealed ore body.

The investigations at the Malachite mine illustrate some characteristic differences of geologic, geophysical, and geochemical prospecting techniques. Geochemical methods are direct; a copper anomaly in residual soil unquestionably indicates the presence of copper. Certain analytical techniques, such as spectrographic analysis, give some opportunity of discovering valuable concentrations of rare elements which otherwise might be unnoticed. Geochemical methods require a minimum amount of equipment and no especial preparation before sampling. Because geochemical anomalies are broad, sampling can be done at widely spaced intervals and large areas can be investigated in a comparatively short time.

In contrast to the geochemical methods, the geophysical are indirect; geophysical anomalies may indicate either a concentration of the ore sought or some other rock with similar physical properties. For best results, the physical properties of the ore must differ measurably from those of the wallrock. The ore at the Malachite mine is ideal for geophysical methods because of its high pyrrhotite content. The vertical magnetic anomaly along profile A1 to M1 (pl. 8) is only 50 feet wide. Sharp anomalies necessitate closely spaced measurements but permit accurate outlining of ore bodies. Under favorable conditions, as at the Malachite mine, geophysical methods can detect ore bodies at a considerable depth.

Geologic data are particularly difficult to evaluate. With the origin of the ore in doubt, geologic prospecting guides at the Malachite mine are far from perfect. Geologic observations, however, favor a hydrothermal origin with local branching and pinching of the vein. Both ore bodies are near pinchouts of the vein and one is in the only known branch. The branching explains in a large part why the concealed body was not found before 1940 and provides some justification for exploring for similar concealed bodies elsewhere.

Because geological, geophysical, and geochemical prospecting techniques each have characteristic advantages, it is almost self-evident that the best results for deposits like that at the Malachite mine can be obtained not by the use of one particular technique, but by the use of all three in combination. The main question is not which to use but how they should be combined.

Coordinating different prospecting techniques may be of considerable importance for large prospecting programs. Commonly, a reconnaissance technique is used to cover the entire area being prospected and to eliminate large parts of it from further consideration. Then detailed techniques are used in the remainder to select targets for physical exploration. Geologic reconnaissance and airborne geophysical methods are both used commonly as a reconnaissance prospecting method. Geochemical techniques using alluvium (Bloom and others, 1956) and soil (Gilbert, 1953, p. 52) are being used more and more for reconnaissance.

In several successful exploration projects, geochemical studies using alluvium and widely spaced soil sampling preceded ground geophysical surveys. At the Charlotte property in New Brunswick, for example, a geochemical anomaly was discovered by stream-sediment and soil sampling in 1954 and 1955. In 1958, self-potential surveys and subsequent diamond drilling successfully outlined an ore body containing pyrite, sphalerite, and galena beneath 10 to 15 feet of surficial material (Hawkes and Webb, 1962, p. 333–337). In areas of residual soil like that at Malachite, where the geochemical anomaly is very broad in comparison with geophysical anomalies, a combined investigation with geochemical study preceding the geophysical study seems to be the logical sequence in exploration.

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