

Institute on Lake Superior Geology

GEOLOGICAL EXPLORATION

A collection of twelve papers and three panel discussions
presented at the Institute on Lake Superior Geology,
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Institute on Lake Superior Geology

GEOLOGICAL EXPLORATION

Edited by A. K. Snelgrove

Houghton

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Geological Exploration

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FOREWORD

This publication is the record of the Institute on Lake Superior Geology which was held at the Michigan College of Mining and Technology, Houghton, Michigan, on May 11 and 12, 1956.

The theme of the Institute was Geological Exploration and its purpose was to review exploration developments on both sides of the international border in both practice and theory.

The Institute was made possible through the full cooperation of governmental agencies, the mineral industries, the institutions of higher education represented, and by private consultants who gave freely of their rich background of experience. All of the speakers were specially invited as leaders in their fields. The Institute is particularly indebted to the United States Geological Survey, the United States Atomic Energy Commission, the Geological Survey of Canada and the Ontario Department of Mines.

The considerable task of transcribing the tape-recordings of several of the papers and all of the discussions was efficiently performed by Mrs. Marian L. Hoyt, Secretary of the Department of Geology and Geological Engineering, Michigan College of Mining and Technology. These discussions are reported in semi-colloquial style.

The three cosponsors, The Geological Survey of Michigan, the Exploration Subsection of the Upper Peninsula of Michigan Section of the American Institute of Mining, Metallurgical and Petroleum Engineers, and the Michigan College of Mining and Technology, join in thanking most cordially the participants and are glad to share with them the satisfaction of service to the profession of Geology.

A. K. Snelgrove

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REGIONAL STRUCTURAL SETTING OF THE MICHIGAN NATIVE COPPER DISTRICT*

by

Walter S. White

Introduction

The native copper deposits of Michigan are in mafic lavas and conglomerate beds of middle Keweenawan age. These rocks crop out all around the Lake Superior basin (Fig. 1). Although

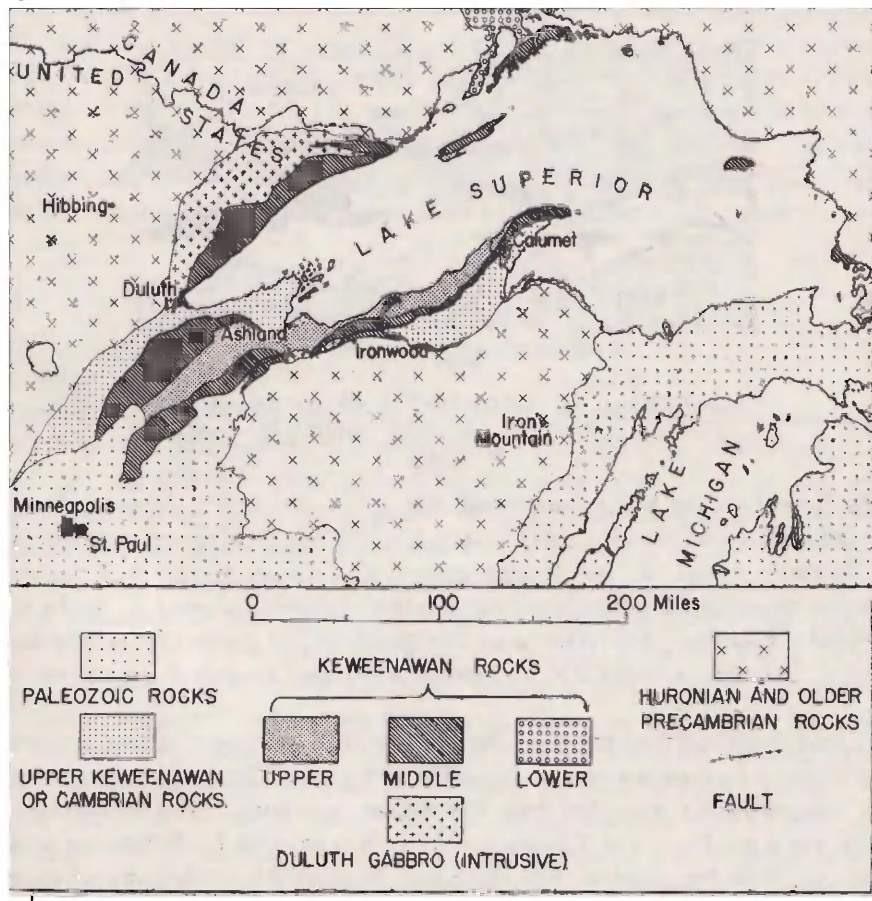
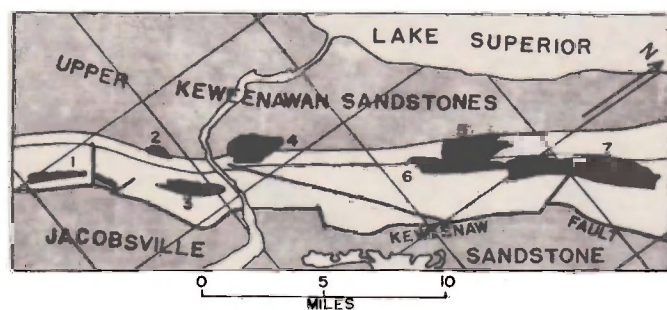


Fig. 1 - Generalized geologic map of the Lake Superior region. Modified after Leith, Lund, and Leith (1935, pl. 1)

*Publication authorized by the Director, U.S. Geological Survey.

the lavas, in particular, contain small amounts of copper almost everywhere, over 97 percent of the native copper mined from the region has come from a single area less than 30 miles long and only 2 or 3 miles wide - about 1 percent of the total area in which lavas of middle Keweenaw age form the bedrock. This paper proposes a possible explanation for this apparent concentration of economic deposits. The explanation is admittedly a very great oversimplification of a complex problem, but though we may not know all the reasons for localization of an ore deposit or district, we have useful if not infallible, tools for exploration when we know one or more of the most fundamental reasons. If the explanation proposed here is a correct one, it suggests one measure of the relative promise of various parts of the Lake Superior basin, and may even have application in other areas of the world with thick accumulations of basaltic lava.

The general characteristics of the native copper deposits of Michigan have been described many times, and need not be reviewed in detail here. The most complete description is by Butler^x and others (1929), and briefer summaries can be found in Lindgren (1933, p. 517-527), Bateman (1950, p. 496-498), and other textbooks. The copper district (Fig. 2) lies on the south flank of the



GENERALIZED GEOLOGIC MAP OF MICHIGAN
COPPER DISTRICT SHOWING PRINCIPAL MINES
IN PLAN

Fig. 2 - Middle Keweenaw lavas (unshaded) dip 25° - 70° NW. Mines, shown by dark shading, are numbered as follows: 1. Baltic amygdaloid mines (Champion mine at south-west end); 2. Atlantic mine; 3. Isle Royale mine; 4. Quincy mine; 5. Calumet & Hecla mine; 6. Osceola amygdaloid mine (workings partly beneath Calumet & Hecla mine); 7. Kearsarge amygdaloid mines. The village of Houghton is just north of the Isle Royale mine and the village of Calumet is underlain by workings of the Calumet & Hecla mine.

Keweenaw basin, and the stratified rocks of the district dip northwest toward the center of this basin. The lavas of middle Keweenaw age (unshaded in Fig. 2) have dips that range from 25° to 70° NW., with the steeper dips prevailing near the Keweenaw fault. The sandstones of late Keweenaw age dip more gently. The Keweenaw fault is a reverse fault that separates the lavas of middle Keweenaw age from the more or less flatlying Jacobsville sandstone, of upper Keweenaw or Cambrian age.

Native copper occurs as fillings in the amygdules and interstices of the fragmental tops of individual lava flows. This copper is associated with a number of other secondary filling minerals, principally chlorite, calcite, prehnite, epidote, and quartz, with subordinate red potash feldspar and zeolites. Some copper is found as interstitial fillings and replacements in rhyolite conglomerate beds lying between a few of the lava flows; nearly 40 percent of the copper from the district came from the single major conglomerate ore body discovered to date.

Individual ore deposits are large in terms of area (Fig. 2). The amygdaloidal top of the Kearsarge flow has been continuously mined for six miles along the strike, and for nearly a mile down the dip, on the average. The ore body in the Calumet and Hecla conglomerate at Calumet covers an area of more than three square miles in the plane of the conglomerate bed. The thickness of the individual flow tops and conglomerate beds in these and other ore bodies ranges, at most places, from about 5 to 25 feet. The average grade of ore that has been mined from the lavas is probably a little less than 1 percent, whereas that from the Calumet and Hecla conglomerate averaged between 2 and 3 percent.

The origin of the copper deposits has been debated for many years, as befits a district that has been prominent in the literature of mining and geology for more than a century. Some features of their origin, however, now seem well established. The copper is definitely epigenetic where it is present in sufficient abundance to make ore deposits. There is also good presumptive evidence that the copper moved up rather than down the dip of the amygdaloidal layers and conglomerate beds to reach its resting place in the present ore deposits. Detailed evidence on these important points has been presented by Butler and others (1929, p. 101-127) and Broderick and others (1946, p. 690-693, 696-697). Knowledge of the reasons for the location of individual ore deposits and of the district itself, therefore, must stem at least in part from an understanding of what lies down the dip from the present deposits, where the copper presumably came from. This area is deeply buried, and we cannot hope to inspect it, but we can make some educated guesses about it, based on what can be seen at and near the surface.

Keweenawan Paleogeography

The Keweenawan basin or syncline was formed primarily by downwarping during or since latest Keweenawan time. Even the youngest Keweenawan rocks locally have nearly vertical dips. The basin is also a basin of accumulation; that is, the downwarping began during the time the lavas and sediments themselves were filling the present basin. This is shown by the fact that the major stratigraphic units thicken down the dip toward the center of the basin.

Evidence for the direction of flow of the lavas nearly everywhere indicates that the lavas have flowed outward from the center of the basin towards the margin. Pipe amygdules at the base of lava flows commonly show southward flow in the Michigan copper district (Butler and others, 1929, p. 26-27) and westward flow on the Minnesota coast (Sandberg, 1938, p. 818-820). This evidence for flow toward the margin has generally been taken to indicate that the vents themselves were located in the center of the basin, but this need not necessarily be true. As will be shown below, the copper district probably lies closer to the center of the present basin than any part of the Lake Superior region in which lavas of middle Keweenawan age are now exposed, but so far as is known, it contains no dikes that might have served as feeders. In contrast, dikes and sills are fairly common in the Keweenawan series of Minnesota, farther from the center, and many unmetamorphosed basaltic dikes that may well be Keweenawan in age cut the Huronian rocks that surround the Keweenawan basin (Van Hise and Leith, 1911, p. 411). Lava extruded anywhere within, or even on the rim of a physiographic basin would flow to the lowest point and then spread out from there. Outward spreading of the lavas from the center of the basin, therefore, does not necessarily indicate that the feeders were in the center, and the distribution of dikes suggests that many of the vents, at least, may have been at or outside the margins of the basin.

The petrology, abundance, and distribution of so-called Keweenawan dikes throughout the Lake Superior region deserve more study.

Some conglomerate beds seem to have been deposited by streams flowing inward from the margins of the basin. This is shown by foreset beds and imbrication of pebbles in the Houghton conglomerate (White, 1952), and by foreset beds in the Baltic (No. 3) conglomerate at the Champion mine (most southwesterly mine on Baltic amygdaloid as shown on Figure 2). The conglomerates and sandstones of late Keweenaw age on the south limb of the basin contain numerous foreset beds, and these consistently indicate northward flow of streams. Finally, the middle, and particularly the upper, Keweenaw sedimentary rocks contain fragments of pre-Keweenaw metamorphic rocks; these could hardly have been carried into the basin by streams flowing outward from the center.

If the lavas flowed toward the margin of the basin, and streams depositing conglomerate beds flowed toward the center, we have an apparent paradox - one or the other would seem offhand to have flowed uphill. The paradox can be resolved if the floor of the basin was nearly flat, and if it was being more or less continuously warped downward by tectonic movement to form the basin. As long as filling by lava kept pace with downwarping, the lava surface would be essentially flat or slope very gently toward the margins (cf. Sandberg, 1938, p. 818, 820-821), and streams could not extend out into the basin. They would presumably be ponded at the margins (cf. Fuller, 1950, p. 67, and Pardee and Bryan, 1926, p. 15-16, on the Columbia River basalts), or be diverted to flow parallel to the margin of the basin. When extrusion of lava was interrupted for any extended period of time, however, continued downwarping would then produce a topographic basin into which streams could flow, depositing conglomerate beds. Conglomerate beds, therefore, represent interruptions in the steady accumulation of lava flows. It may be very significant that the first flow of lava above conglomerate beds, that is, the first flow after such an interruption, is very commonly a flow of extraordinary thickness (Broderick, 1935, p. 553-554); if the steady downwarping of the basin was more or less compensated isostatically by lava filling the basin, the longer such compensatory filling were postponed during an interruption, the greater might be the outpouring that terminated the interruption.

Although in a general way the present tectonic basin probably coincides with this ancient basin of accumulation, the margins of the first are not everywhere parallel to the margins of the second. In the Michigan copper district, the present strike of the beds is northeast, but the flank of the old basin of accumulation seems to have had a more easterly trend here. Several criteria suggest this more easterly trend.

(1) Though reliable data are scarce, the best available evidence indicates that major stratigraphic units generally increase in thickness down the dip (Butler and others 1929, pl. 20, provides the best example), as would be expected in a basin. If this thickening is more or less normal to the basin margin, lines of equal thickness, or isopachs, should be more or less parallel to the basin margins. Figure 3 shows the general orientation¹ of isopachs at two places; the symbol at Calumet is based on the stratigraphic distance between the Allouez and the Calumet and Hecla conglomerates in the Calumet and Hecla mine; the symbol farther northeast represents the trend of lines of equal thickness of the Greenstone flow at the Allouez No. 3 mine.

A dike, apparently fed from the interior of the flow while it was still molten, cuts the upper

1. All the orientation features of Figure 3 have been corrected for the present dip of beds; they are shown with the orientation the features would have if the beds were tilted back to the horizontal.

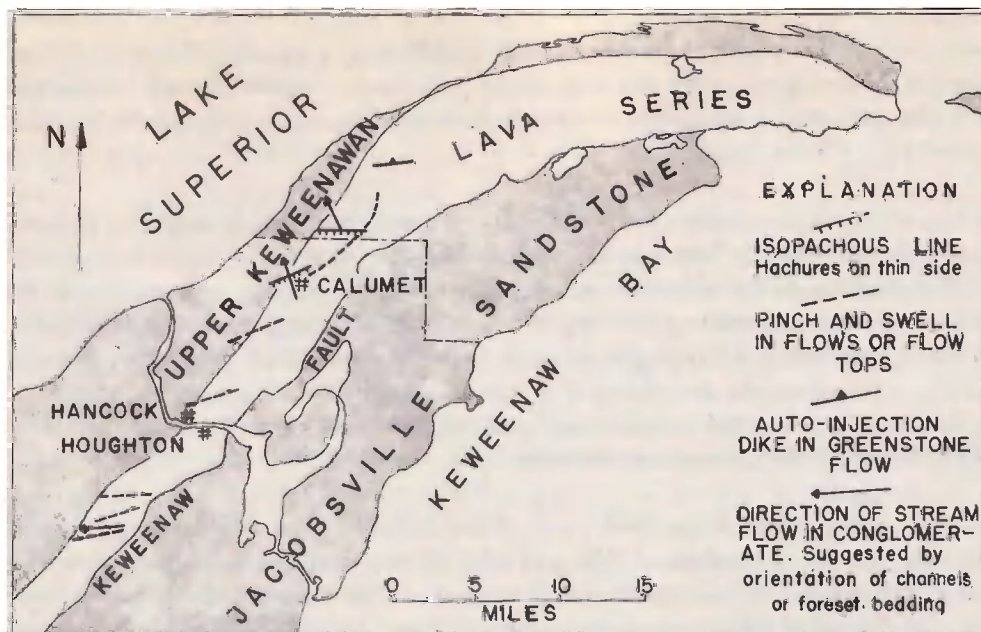


Fig. 3 - Features suggesting orientation of ancient margin of the Keweenaw basin

part of the Greenstone flow 9 miles northeast of Calumet. This dike is at a place where the Greenstone flow thins abruptly from over 1000 feet to less than 500 feet (Davidson and others, 1955), and seems to be more or less parallel to the axis of thinning; it is here assigned the same significance as an isopachous line, though the apparent parallelism may be just a coincidence.

(2) Another feature, here called "pinch-and-swell", has the same general east-west orientation. The fragmental tops of individual lava flows are typically thicker in some places than in others, as has been described at some length by Butler and others (1929, p. 31-32). An amygdaloidal flow top can range in thickness from less than 5 feet in the thin places to over 60 feet in the thick. An isopach map of a given amygdaloidal flow top, plotted in the plane of the top, might show either irregularly interspersed patches of thick and thin fragmental amygdaloid or highly elongate bands of thick amygdaloid separated by parallel bands of thin. The widths of individual bands of thick or thin flow top range from a few tens to a few hundreds of feet, and their length may be measured in thousands. These alternating bands of thick and thin amygdaloid are presumably primary features that originated as the lava flowed.

The orientation of elongate patches of thick and thin fragmental amygdaloid (pinch-and-swell) can be measured locally where the patches happen to be well exposed in accessible mine workings, but the evidence for their orientation at most places is indirect. Thickness of fragmental amygdaloid is at least one important factor affecting the location of ore shoots within the major deposits; the thicker parts of a copper-bearing flow top are generally more favorable than the thinner (Butler and others, 1929, p. 109, 192, 200-201, 219), and lean or barren streaks that are controlled by thinness of the flow top are conspicuous on slope maps and grade maps of some mines (Butler and others, 1929, pls. 39-49). Though for many reasons it would be most hazardous to use a grade or slope map as a faithful representation of the distribution of thick and thin fragmental amygdaloid, most large and prominently elongate rich and lean streaks probably reflect differences in thickness (pinch-and-swell) where they are not related to faults or crosscutting veins.

The orientation of pinch-and-swell of flow tops as inferred from slope and grade maps is shown in Figure 3. Assuming that this structural feature formed during flow of the lava, one would

it to be either a feature that lies parallel to the direction of flow or perpendicular to it. The general parallelism of the pinch-and-swell with the two isopachous lines is apparent, so it is assumed that the pinch-and-swell lies perpendicular to the direction of flow of lava, and generally parallel to the margin, or "shoreline", of the basin.

(3) The three arrows in Figure 3 show the direction of stream flow as suggested by primary features in certain conglomerate beds interbedded with the lavas. The arrow north of Calumet represents the direction of flow of the streams that deposited the Houghton conglomerate as shown by imbrication of pebbles and foreset bedding (White, 1952). At the Allouez No. 3 mine, where these measurements were made, the Houghton conglomerate attains thicknesses of more than 25 feet along an axis striking slightly west of north, and thins to a foot or less within 1500 feet to the east and west of this axis. This axis is presumed to coincide, more or less, with the direction of flow of the stream or streams that deposited the conglomerate bed.

Similar axes can be drawn parallel to thick parts of the Calumet and Hecla conglomerate in the Calumet and Hecla mine (Butler and others, 1929, pl. 38, "Plan showing thickness of lode"). The arrow west of Calumet represents the orientation of these axes. The absolute direction of stream flow - whether north-northwest or south-southeast - has not been established beyond question in the Calumet and Hecla mine, and the workings are inaccessible at present, so the head of the arrow may conceivably be shown at the wrong end; the head is shown at the north-northwest end by analogy with the arrow for the Houghton conglomerate because the lens of Houghton conglomerate at the Allouez No. 3 mine is in many detailed respects a small-scale replica of the lens of Calumet and Hecla conglomerate at Calumet.

The arrow southwest of Houghton represents the direction of stream flow shown by foreset beds in the Baltic conglomerate at the Champion mine. The direction of flow here seems to have been nearly at right angles to the direction at the other two localities. At the other two localities, the direction of flow is normal to isopachs, and is presumed to be normal to the basin margins. The direction of flow at the Champion mine would thus seem to have been parallel to the basin margin, and may represent a stream diverted along the edge of a lava flow that spread out from the center of the basin.

To sum up the evidence afforded by primary features of the lava flows and conglomerate beds, these features have two distinct trends at right angles to one another (Fig. 3), one slightly north of east and the other slightly west of north. These features can be logically related to the orientation of the ancient basin margin or "shore lines", and indicate that the margin trended slightly north of east in the area of the Michigan copper district. The present strike of the rocks is northeast, diagonally across the trend of the ancient margin, so we may infer that the rocks northeast of Calumet, for example, represent more central parts of the ancient basin of accumulation than the rocks southwest of Houghton. The useful application of these orientation data will be discussed after consideration of the gross structure of the basin as a whole.

Structure of the Keweenaw Basin

Tangible evidence for the configuration of the Keweenaw basin is only fragmentary. The Keweenaw rocks are completely buried by younger sediments in the vicinity of Minneapolis and farther southwest, and perhaps also in parts of the peninsula between Lakes Superior and Michigan (Fig. 1). East of Ashland, Wisconsin, the whole central part of the basin is covered by the waters of Lake Superior, and even the rim is under water in over 95 percent of the area east of the longi-

tude of Keweenaw Point (40 miles east of Calumet). Attempts to determine the shape of the basin, therefore, must be based primarily on extrapolation from the attitudes of the rocks in the relatively small proportion of the whole area where they are exposed. When magnetic and gravimetric data are available for the whole region, particularly the area covered by Lake Superior, our present guesses can be considerably refined.

The general attitude of bedding is known in all the areas where middle and upper Keweenaw rocks are exposed (Fig. 1). In places like the copper district and a few others it is also possible to measure locally the rate at which the dip flattens toward the center of the basin. West from the longitude of Keweenaw Point, therefore, cross-sections can be constructed with some degree of control on both sides of the basin. In drawing sections, one has some latitude in the selection of curves used to connect the dips on opposite flanks. One can, as one extreme, assume that the dips flatten rapidly toward the center of the basin, and that the beds are horizontal over most of the basin, beginning just a few miles in from the upturned margins of the basin; this construction gives a minimum depth for the structural basin. At the opposite extreme, one might assume that the curvature is more or less evenly distributed across the entire width of the basin; this construction gives a maximum depth for the structural basin. The second extreme - uniform distribution of curvature - is demonstrably in error in the copper district, where not only the dip but also the rate of flattening (rate of decrease of dip) generally decrease toward the center of the basin.

Another rough limit is set by the known thickness of the Keweenaw rocks; the lavas of middle Keweenaw age are probably of the order of 20,000 feet thick in the copper district², and these are overlain by at least 15,000 feet of sedimentary rocks of late Keweenaw age. The minimum depth of the base of the lavas in the center of the basin is therefore of the order of 35,000 feet, and may be greater if the stratigraphic units thicken appreciably toward the center of the basin, as they seem to do.

Within these various limits, the most reasonable constructions that can be made suggest that the base of the lavas lies somewhere between 35,000 and 50,000 feet below sea level in the middle of the basin.

By drawing sections across the basin at intervals, assuming some particular type of curvature, one can develop a structure contour map that shows the shape of the basin. Figure 4 shows such a structure contour map; this particular example is based on the assumption that the sharpest curvature is on the south limb, where the dips are steepest, and gives almost a minimum depth - the horizon contoured lies 15,000 feet or more above the probable base of the lava series. The general shape of the basin is about the same if other assumptions are made, and the principal difference introduced by these other assumptions is in the absolute depth. The general position of the deepest part is not materially changed. This is a logical consequence of the fact that the dips are gentler on the north limb than on the south - this asymmetry makes the deepest part lie nearer the southern limb almost regardless of the type of curvature assumed.

2. Over 15,000 feet of lava are exposed in a single section in the Delaware quadrangle (Cornwall, 1954), a little east of the main part of the copper district, and here, as in the copper district proper, an unknown but probably large thickness of lavas at the base of the middle Keweenaw is cut out by the Keweenaw fault.

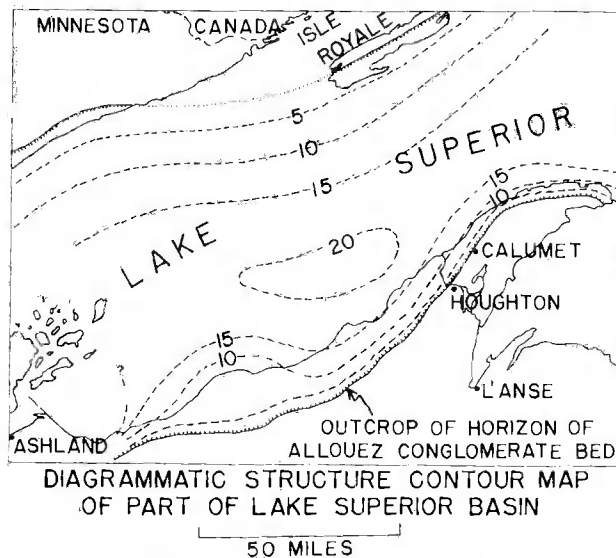


Fig. 4 - Contours in thousands of feet, represent the approximate depth below sea level of the horizon of the Allouez conglomerate; this bed is probably at least 15,000 feet above the base of the lava series over most of the contoured area.

The principal chance for error in a construction like Figure 4 lies in the possibility that there are important faults or reversals of dip out in the basin. Little can be done to evaluate or attack this particular problem without geophysical data in the area covered by Lake Superior.

Figure 5 is a highly simplified and locally modified version of Irving's map (1883, pl. 28)

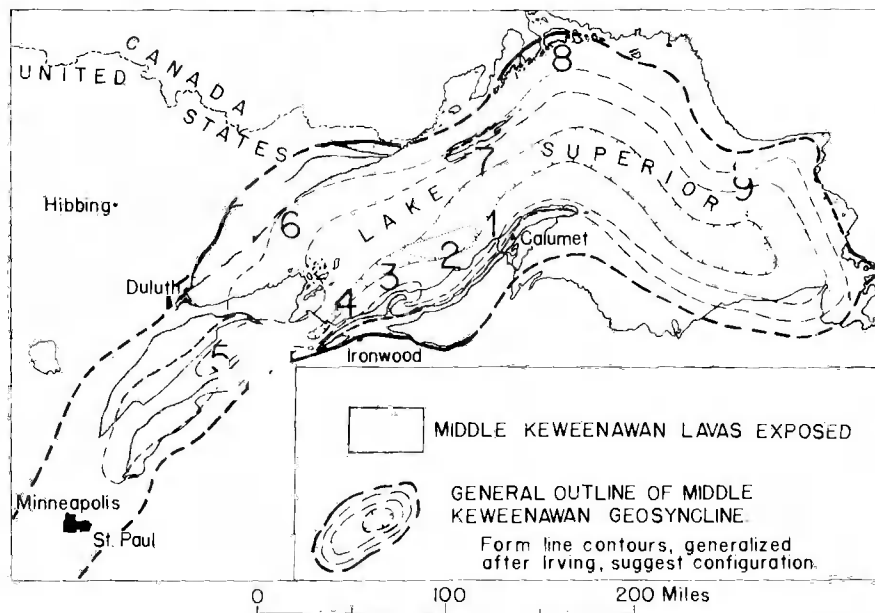


Fig. 5 - Form-line Contour Map of the Lake Superior Basin Northeast of Minneapolis. Numbers refer to areas mentioned in text.

showing the general configuration of the whole basin or geosyncline northeast of Minneapolis³. The heavy line outlining the area of lavas of middle Keweenawan age has been added. Though the interval between Irving's form lines represents stratigraphic thickness rather than vertical depth, these lines are virtually synonymous with structure contours where the dips are gentle. The most central line (deepest contour) of Figure 5 is taken from Irving's map without modification, except for a little smoothing at the east end; the oval area outlined by the dotted line is the area enclosed by the 20,000-foot contour of Figure 4, reproduced here to show the general correspondence. The form lines at the east end of the basin are, of course, based on very scant data.

Metamorphism in Depth

We have no first hand evidence to tell us what modifications, if any, deep burial in the center of the basin may have induced in the Keweenawan rocks, particularly the lavas. The present thermal gradient at Calumet is remarkably uniform to a depth of 5,488 feet, and averages $18.1 \pm 0.23^\circ \text{C/km}$ (Birch, 1954, p. 19). Extrapolating this gradient to depths of 35,000 to 50,000 feet suggests that the present temperatures at those depths may be somewhere in the vicinity of 200° to 285°C . If the lavas accumulated fast enough to preserve some of their original magmatic heat within the pile, temperatures in depth may well have been considerably higher in the late Keweenawan or early Paleozoic time than they are now. Temperatures of the order of 300°C probably characterize the higher grade parts of the green schist facies, if not actually the epidote-amphibolite facies.

The fragmental tops of many of the lava flows must originally have been rather loose, rubbly aggregates. After burial, their open spaces were presumably filled with ground water, and this water would be carried on downward as the lavas became ever more deeply buried. One can only speculate about the ultimate fate of this water and the permeable rock containing it when it was carried downward into a region where the lithostatic pressure was of the order of 2700 - 4000 atmospheres, and the temperature between 200° and 300°C , or higher. Some of the water would certainly combine with the rock minerals to form hydrous metamorphic minerals such as chlorite and perhaps actinolitic hornblende. The porous fragmental flow tops would be least partially crushed. The combination of crushing of the rock and heating would presumably drive some of the contained water toward the surface along the relatively open channelways afforded by the fragmental flow tops and conglomerate beds.

If we make the assumption, without attempting here to further bolster it with arguments from theoretical and experimental work on hydrous systems, that this water of essentially metamorphic origin was the principal agent of native-copper deposition in the middle Keweenawan rocks, we can develop from this assumption a logical structural reason for the location of the principal copper deposits.

Location of the Copper District

Perhaps the most interesting feature of Figure 4 is the position of the deepest spot. In any given bedding plane or flow top, the shortest path to the surface from this deep spot would lead to an area

3. A large positive gravity anomaly suggests that the syncline, with its associated lavas, extends southwest into central Kansas, where it abruptly terminates (Thiel, 1956, pl. 1).

at the southwest end of the copper district proper, which ends about 10 miles southwest of Houghton. If water of metamorphic origin were driven directly up the dip by heating and crushing in this deep spot, the maximum amount of water should emerge in the vicinity of and just southwest of the mines on the Baltic amygdaloid (Fig. 2), with decreasing amounts farther southwest and northeast. It is considered highly significant that all the important and most of the minor native-copper mines of the Lake Superior region are within 25 miles, horizontally, of the oval area bounded by the 20,000 foot contour in Figure 4. Less than 2 percent of the native copper from the region has come from beyond this 25 mile limit.

Within this area of major production, there is notably asymmetric geographic distribution of the producing mines. As noted above, the shortest path up the dip from the deepest spot would reach the surface 10 or 15 miles southwest of Houghton, at the southwest end of the copper district proper. The productive mines northeast of this point of emergence have yielded over 97 percent of the native copper produced in the region, whereas those to the southwest have yielded less than 2 percent. This proportion may be changed as exploration finds new deposits or as lower-grade ores are mined in the future, but it is nonetheless a remarkable difference, and one that requires explanation. The following explanation of the asymmetry is suggested.

Earlier paragraphs described certain primary features oriented parallel to the basin margin. These include a structural feature here called "pinch-and-swell", consisting of elongate patches in which the thickness of fragmental material in certain fragmental flow tops is appreciably greater or less than average. In the mines of the copper district, this linear element seems to be typically oriented nearly east-west (Fig. 3). In terms of permeability, the pinch-and-swell structure should make a flow top notably anisotropic - flow of solutions in a given flow top should be far easier in an east-west direction than in a north-south. Solutions moving up the dip from the deep spot shown in the center of Figure 4, therefore, would be continually steered off towards the east in their upward passage, producing the copper district proper where we now find it, rather than farther southwest, more nearly up the dip from the deep spot.

To the extent that this explanation is correct, the lack of parallelism between the present strike of the rocks and the strike of the ancient basin margin is an important element leading to the localization, and perhaps even the existence of the Michigan copper district. Where the ancient basin margin and the present strike of bedding are parallel, the trend of the pinch-and-swell structure would not have a component parallel to the dip of the bedding, and up-dip movement of solutions would be relatively inhibited; flow should take place more readily, under the same hydrostatic pressure, where the pinch-and-swell rakes up the dip.

Summing up, two structural conditions may govern the very limited distribution of native copper deposits. First, the copper district proper is very close to, and almost up the dip from a particularly deep part of the Lake Superior basin. Second, the copper district lies on the limb of a major indentation in the flank of the Lake Superior basin (see Fig. 5), in a place where the present margin is not parallel to the margin of the old basin of accumulation. Primary structural features like the pinch-and-swell structure rake up the dip in this area, providing conduits leading from the deep spot to the surface. In places where the present and original basin margins are parallel, as they may be elsewhere, channels governed by the pinch-and-swell might be far less favorably oriented; these places would capture a smaller amount of the solutions moving out from the bottom of the basin.

It should be emphasized at this point that the enrichment of the Michigan district in copper is only relative; as was pointed out in the introduction, there are minor amounts of native copper in

the lavas all around the Lake Superior basin. In many places enough copper has been found to encourage extensive prospecting. In addition, the amygdaloids and conglomerates are filled with secondary minerals throughout the basin, just as they are in the Michigan district. So mineralizing solutions have apparently moved upward and outward in all directions from the deeper parts of the basin⁴. The Michigan district seems to be unique only in that it may have captured more mineralizing water from the deepest parts of the basin than other areas - enough more to make the deposits commercial. As one possibility, more water may actually have flowed through the productive amygdaloids of the copper district than through those of other areas because of the favorable system of channelways. Or, as another possibility, the water that flowed through the rocks of the copper district may have contained more copper than elsewhere because it came from the deepest part of the basin, where the most crushing and metamorphism presumably occurred.

Deposits in Other Parts of the Basin

If channelways leading efficiently to deep spots in the Lake Superior basin are the chief factor in forming ore deposits, the chances for deposits in other parts of the basin can be at least roughly appraised. We can look first for other places in the region where the pinch-and-swell structure in flow tops rakes diagonally down the dip towards a deep spot. The type of information needed to definitely establish the trend of the pinch-and-swell structure can only come from rather extensive underground exposures, so outside the copper district one must depend on indirect evidence.

The copper district lies on the west flank of a major indentation in the present basin (Fig. 5). The form lines that define this indentation in Figure 5 are arcs, and the trend of the pinch-and-swell structure in the copper district can be approximated by chords of these arcs. This is perhaps to be expected if the indentation is not a feature of the ancient basin of accumulation, but is a later feature of tectonic origin - the trend of features like the pinch-and-swell that are presumed to be parallel to the ancient basin margin should have a course that follows the gross configuration of the basin, unaffected by the indentation.

A basis therefore exists for inferring an orientation of the original basin margin, and of the pinch-and-swell structure that seems to be parallel to it, where other indentations are superposed on the broadly arcuate form of the basin as a whole. Two such indentations appear on Figure 5, one just west of Michipicoten Island (Area 9) and another at Isle Royale (Area 7). Chords across the arcs in the form lines at Michipicoten Island strike northwest, and at Isle Royale they strike east-northeast. Channels with these orientations at these places would not, apparently, rake down into particularly deep parts of the basins. Solutions would have to cross the inferred trend of channels at both places to reach the surface from the deepest adjoining part of the basin. So in respect to channelways governed by pinch-and-swell, at least, the ideal conditions of the Michigan copper district do not seem to be repeated in any other place where middle Keweenawan rocks are now exposed at the surface. The most promising place for a repetition of the ideal condition is on the east flank of the indentation which bears the copper district on its west flank - unfortunately this

4. The ubiquitousness of the native copper and its associated secondary minerals in the lavas throughout the area of the Lake Superior basin - an area over 400 miles long and 100 miles wide - is an important reason for looking to some process of regional extent, such as is suggested here, rather than to local intrusive bodies, as a source for the copper and associated minerals.

area is well covered by Lake Superior. In one other area, about 45 miles west of Ironwood (east end of Area 5, Fig. 5), channelways probably rake down the dip, but the structure of the basin in this area is too little known to permit an estimate of the relative depth of the basin into which such channelways might lead.

Proximity to deep spots is the second basis for search for other favorable areas. Southwest of the copper district proper, in an area 15 to 40 miles southwest of Houghton, there are a number of mines which have produced over 5 million pounds of copper apiece, even though the total production from this area is less than 2 percent of the total for the region. This indicates that commercial deposits can be found even where channelways controlled by the pinch-and-swell structure may not be favorably oriented. This area lies directly up the dip from the particularly deep spot in the center of Figure 4, so proximity to a deep spot alone may give some promise of productive deposits. This makes worthwhile a general appraisal of other parts of the Lake Superior basin in terms of simple proximity to deep spots, neglecting the factor of the channelways.

Even a crude structure contour map such as Figure 4 or 5 shows that because of the asymmetry of the basin, the deepest spots are probably down the dip from the places where the dips at the surface are steepest. If the dip on one side of the syncline is 10 degrees, as it is along most of the Minnesota shore northeast of Duluth (Area 6, Fig. 5), the trough of the syncline is probably closer to the southern shore, where the dips of the lava flows are everywhere steeper. So in a very rough way one can conclude that the steeper the dip, the better the chance that a given area is close to a deep spot. Other things being equal, furthermore, the basin is probably deeper in places where it is wide than where it is narrower. Using dip and width of the basin as our main criteria, therefore, we may roughly appraise the promise of individual areas around the basin.

In the area 15 to 40 miles southwest of Houghton (Area 2, Fig. 5), the lava flows dip between 45 and 70°. This area, which has produced over 1 percent of the copper from the region, is probably second only to the copper district proper in terms of future promise.

Between this area and Ironwood (Area 3, Fig. 5), the dips are gentler, and the normal homoclinal dip toward the basin is interrupted by the Porcupine Mountain dome or anticline, 30 miles northeast of Ironwood. Only the uppermost lava flows of middle Keweenawan age are exposed at the surface in this anticline, and the core of the fold is rhyolite (Butler and others, 1929, p. 47, 50 and pl. 14). This whole area in and south of the Porcupine Mountain uplift would seem to be distinctly unfavorable for important near-surface copper deposits in amygdaloidal flow tops and associated conglomerate beds.

In terms of steepness of dip alone, the most favorable place in the region is north and northwest of Ironwood (Area 4, Fig. 5) where the dips are nearly vertical. Another factor complicates the evaluation of this area, however: A little farther west, in Area 5 (Fig. 5), both the north and south limbs of the Lake Superior syncline are separated from the center of the basin by thrust faults that repeat the middle Keweenawan section (Fig. 1). The fault shown along the northern boundary of the lavas of middle Keweenawan age west of Ashland is called the Douglas fault, and the fault separating the two slivers of the lavas 10-40 miles southwest of Ashland is called the Lake Owen fault (Aldrich, 1929, p. 125-126). The Douglas fault divides the north limb into two belts, in both of which the rocks dip southeast. In the same way the Lake Owen fault divides the south limb into two belts, in both of which the rocks dip northwest. These faults effectively separate the outer belts from the center of the Lake Superior syncline. Exposures are very poor in the area of younger sandstones east of Ashland. If the Lake Owen fault continues farther northeast, the lavas north of Ironwood may not be physically continuous with those in the center of the syncline, and the favorable

conditions are not fulfilled.

In Area 5 (Fig. 5), south and southwest of Duluth in Douglas and Bayfield Counties, Wisconsin, both limbs of the Lake Superior syncline have dips ranging from 30-45° (Grant, 1901, p. 21). Although these dips are of favorable steepness, the syncline is rather narrow here, so the maximum depth of the lavas may not be much more than 25-30,000 feet. This is distinctly less favorable than the areas farther east, where the basin is much wider and probably deeper. A number of showings in Wisconsin have been explored by small prospect shafts, but none have developed into mines.

Along the Minnesota shore (Area 6, Fig. 5), the rocks dip between 10 and 15°. The dips are even gentler around Nipigon Bay (Area 8). These are the least favorable parts of the Lake Superior basin on the basis of dip.

On Isle Royale (Area 7, Fig. 5), most of the lavas dip between 15 and 25 degrees (Lane, 1898, pl. 1). This area is more favorable than any other on the north shore, but is less favorable than most of the south shore.

At the east end of Lake Superior and on Michipicoten Island (Area 9, Fig. 5), dips locally exceed 40 degrees. Information on the east end of the basin is extremely sketchy, because so much of the Lake Superior syncline is covered by water, but unless there are unknown structural or stratigraphic complications, this area should be more favorable than anywhere along the north shore, including Isle Royale. It may well be more favorable than the Wisconsin area (Area 5), though explorations do not seem to have been very successful to date (see Thomson and others, 1952, p. 10-11).

To sum up, the basis for appraisal used here suggests that the most promising area outside the copper district proper is the area southwest of it (Area 2), extending to a point some 40 miles southwest of Houghton. The area north of Ironwood (Area 4) may be even more favorable, but its promise is clouded by the possibility that it may be separated from the deeper parts of the syncline by a fault. Michipicoten Island (Area 9) and the areas in Wisconsin (Area 5) on both limbs of the syncline south of Duluth are next in order of favorability. There is one small area 45 miles west of Ironwood, on the south limb of the syncline, that is a more favorable prospect than the rest of Area 5 because of the possibility that the pinch-and-swell structure may rake diagonally up the dip there. Isle Royale (Area 7) is probably less promising than any of the areas mentioned above, but distinctly more promising than the areas of gentle dip on the north shore in Minnesota and Canada.

Acknowledgments

A speculative essay of this sort necessarily draws on the work, some published and some unpublished, of many people. So far as I know, I am solely responsible for the particular juxtapositions of fact and theory presented here, but individual elements have come from many sources. I am much indebted to my colleagues in the U. S. Geological Survey's study of the Michigan copper district, particularly Henry R. Cornwall and Richard E. Stoiber, for the contribution their researches along different lines have made to development of the ideas expressed here. I owe special thanks to Dr. Thomas M. Broderick of the Calumet & Hecla Inc., not only for his willingness to share with the Survey party his unequalled knowledge of the geology of the Keweenaw series, but also for the challenge his well-founded advocacy of a magmatic origin has kept before us.

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COPPER MINERALIZATION AT THE WHITE PINE MINE ONTONAGON COUNTY, MICHIGAN

by

John R. Rand

(Abstract)

The White Pine orebody lies in gently-dipping laminated to massive shaley siltstones at the base of the Nonesuch formation of Upper Keweenawan age. Fine- to coarse-grained sandstone lying within and immediately below the ore column is generally not of commercial interest, although locally such sandstone may be quite strongly mineralized, primarily with native copper. Copper mineralization over most of the known orebody consists of an extremely fine-grained dissemination of chalcocite, with native copper occurring in amounts of secondary importance; bornite, pyrite, and chalcopyrite occur in minor or trace quantities. Native silver is present in sufficient quantity to be of commercial interest.

Within a 20 foot ore column, the heaviest mineralization is restricted to four distinct lithologic units with an aggregate thickness of about six feet. A significant amount of copper occurs in two additional units with a total thickness of about four feet. The remaining units are only slightly mineralized. The four units carrying the heavy copper mineralization are dark gray to black, thinly laminated shales or siltstones, with some fine-grained sandy zones in two of the units. All other units in the column are medium gray or lighter in color, or are red or brown, and range lithologically from thinly laminated shale through laminated or massive siltstone to sandstone with or without shale laminae.

The striking association of copper with specific lithologic units over a wide area suggests that mineralization occurred essentially contemporaneously with sedimentation in a restricted shallow basin, and that the chemical environment in which certain beds were deposited controlled precipitation of copper from the overlying waters. The copper is considered to have been derived originally from the Lower Keweenawan Portage Lake Lava Series, released by weathering and oxidation into surface and ground waters.

For a detailed description the reader is referred to White, Walter S. and Wright, James C., "The White Pine Copper Deposit, Ontonagon County, Michigan:" *Economic Geology*, Vol. 49, No. 7, pp. 675-716, November, 1954. - Ed.

COMMENTS ON PRECEDING PAPERS

by

T. M. Broderick

I think we should first discuss the source of the copper.

Mr. J. R. Rand: Copper is an original constituent in the lavas about the Lake Superior district, and by weathering and erosion of these lavas copper could be oxidized and liberated into ground water or surface water for the purpose of eventually going to form the deposits in the muds and clays of the present shales. It is not necessary to erode an ore body but merely to break down a large volume of rock which contains a small amount of copper.

Dr. Broderick: True enough, both White and Rand agree on the source of the copper being the small dissemination in the lavas. Some years ago I very carefully sampled "traps" in this district as we had them exposed from top to bottom in hundreds of drill holes; I did not do the sampling in hundreds of drill holes but rather picked out places where the sampling through several of the flows could be made very accurately. I had chemical analyses made; the Geological Society of America gave me a grant for this study which was mainly on differentiation of the flows and I came up with an average copper content of these traps of 1/100 of a percent. If anybody could sample them any better, I would like to see it done. Dr. Goldich of the University of Minnesota Laboratory used those same samples for a more exacting study of minor and trace elements and he checked that amount. Now I had recently gone through Washington's tables¹ and as I suspected the copper content of these traps was not at all unusual; just recently I wrote again to Dr. Goldrich and asked him about the latest figures that he had seen and been able to assemble on the average copper content of rock and we find that the copper content of these traps is still rather low. He gave me average figures, quoting: the content of copper in igneous rocks in general, .007% average and in basaltic rocks in general, a recent figure .0085%. Steiger found 0.0155% copper in a composite of 71 Hawaiian lavas. Michigan lavas contain less than that. The greenstone flow has .012 and, if you do not like taking a flow that does not contain an ore deposit, the Kearsarge flow has .009, just under the 1/100th of a percent. So I do feel irritated with references to the copper content of these lavas to explain an unusual district. Other than that, we are in pretty good agreement; the deposits are epigenetic, we agree, not speaking of the White Pine, but in general the deposits are epigenetic - they are formed by ascending hydrothermal solutions and there was a structural control of some sort. I would think of the structural control as both introducing or allowing the copper to be introduced into the channelways at depth and Dr. White has this structural control as indicating where the flow of solutions would take place. We both agree that on the way up there would be deflection of solutions by barrier conditions of various sorts. Now I think that there is considerably more than a fortuitous conjunction of affairs envisaged by White if some other origin is to be considered. That is, the same conditions in depth that would cause this metamorphic exhalation of solutions, might be the explanation that I am looking for as to how and where solutions from some magmatic source got into the lavas. I would think that the deeper the part of the section involved, the more likely there would be to be a tongue of some underlying intrusive that we like to call upon to furnish these solutions. Now how about

1. Washington, H. S., "Chemical Analyses of Igneous Rocks, 1884 - 1913." U. S. Geological Survey Prof. Paper 99, 1917.

this underlying intrusive? There are some who do not like to think of a gabbro as giving off much water because they think of it as a comparatively dry melt. We do have one tongue of this Duluth gabbro which is the handy one to call upon. We have one protrusion of it here at Mount Bohemia and it is thoroughly altered, uranitized, and it has an association of chalcocite fissures around so that it is competent to give off solutions which bear copper. In recent years in the Duluth gabbro itself there has been a study of the sulphide content and it is sufficient for the several governmental geological surveys and bureaus to do a lot of sampling along the base for copper and nickel, and several companies have gone in there and had respectable drilling campaigns. Large sums of money apparently have been and maybe still are being spent so far as I know. This puts the Keweenawan in a sort of metallogenetic province. The epoch started in the late Huronian and extended through the late Keweenawan. I have written Dr. Marsden of Duluth, Minnesota, regarding the age of the Sudbury norite; I did not know but that we could make it late Keweenawan but I guess not. He says that it is post-Huronian and pre-Keweenawan or words to that effect; so it is pretty close to Keweenawan. And in the Sudbury area you have the differentiation of that norite giving you the red-rock facies, and you have the copper and nickel, and in the center of the basin you have the lead-zinc differentiation. In Point Mamainse, north of Sault Ste. Marie, Ontario, an exploration is now going on trying to develop commercial ore and they succeeded in doing it in cross fissures in the Keweenawan which contain chalcocite. In the Copper Mine River area, Northwest Territories of Canada, there are again basaltic lava flows and there are wide cross fissures that in places are very rich in copper in the form of chalcocite. I am making the point that in this metallogenetic province native copper with associated chalcocite is a widespread thing. While genetically the White Pine situation may be a very attractive tree to look at, I am trying to see the bigger woods and it is pretty hard for me to take some interleaved deposits, inter-larded deposits, here in a shale with chalcocite, here in sandstone with native copper, here again in another shale with chalcocite, and pull them apart and say there is a syngenetic origin for one and an epigenetic origin for the other.

In discussing objections to a hypogene epigenetic origin for copper in shale at White Pine, the points are made that had they been epigenetic the nose of the anticline would be a natural collecting dam, that the chalcocite deposits should have followed up that nose, and that they should be rich just underneath that pitching anticlinal nose. Well, there was considerable structural readjustment after those Nonesuch shales were deposited around the Porcupine Mountains; they are turned up vertically and I guess almost overturned in places. Once you get away from the local disturbance around the Porcupine Mountain uplift, the dip of the shales becomes normal, 10 to 12 degrees. I do not see why you will not allow me to just have that little post-ore folding there in view of this steep upturning of the beds around the Porcupine Mountain fault only a couple of miles away.

I have pointed out some of the things on which as "defender of the faith" I still want to base my thinking. It is along the lines announced long ago by Irving when he pointed out the native copper in sediments, conglomerates, shales and sandstones, amygdaloids, cross-fissures and chalcocite in cross fissures and in the Nonesuch shale, and said that any acceptable explanation for these deposits must explain them all. Consequently I am looking very critically at anything that deviates from that. Maybe I will have to change my mind but I have not been induced to do so yet on the basis of anything that has been presented.

I am giving up the idea of presenting comments on this series of papers as they are presented; I have just written a brief announcement in Economic Geology referring to the fact that I am going to do so; I feel that I would like to defer my written presentation until the major portions of these articles by the United States Geological Survey appear in print. I find that it is very profitable because the longer I wait the less I have to criticize.

COPPER DEPOSITS OF THE LAKE SUPERIOR REGION²

Sir: In 1946 I and my associates (1) published a paper in this Journal bringing up to date the facts and deductions of the Calumet & Hecla geological group concerning the Keweenaw copper deposits of the Lake Superior region. This paper included a discussion of origin and reiterated a concept long recognized as fundamental by various geologists including Irving, Van Hise, Leith and Steidtmann and the Calumet & Hecla group, namely, that a theory to be acceptable must explain all of the deposits of the district. These include the native copper deposits in amygdaloids, sediments, and fissures, and the associated sulphides, of which chalcocite is in great predominance, likewise in amygdaloids, sediments and fissures. In addition are the associated deposits of copper nickel and cobalt arsenides and antimonides, largely in cross fissures.

The theory of the Calumet & Hecla group, formulated in the early twenties, still seemed to be the only one that satisfactorily explained the facts.

Over a decade ago, a group from the United States Geological Survey started a study of the district and they are presenting a series of papers in which the origin of the copper deposits is treated. They do not share the belief that one mode of origin must explain all of the several types of deposit. Their papers, presented already (2), propose several modes of origin including both syngenetic and epigenetic and they have not yet treated the most important deposit thus far mined, the Calumet conglomerate, nor the mass copper, chalcocite and arsenide fissures.

I have already discussed (3) the treatment of origin as given in the Cornwall papers published in 1951. I wish to discuss the more recent U.S.G.S. papers but in order to make it more definite that the evidence thus far presented does not lead me to abandon the idea of a single origin for all the occurrences, I prefer to postpone the discussion until a larger number of their series has appeared.

Friends in teaching say they have a problem in that students show a tendency to accept the latest material published and I realize that this is only natural. As soon as the Cornwall-White paper on "Native Copper Deposits" and the Stoiber-Davidson paper on "Mineral Zoning" appear, I shall try to publish some comments promptly. My discussion even then will be handicapped because a convincing presentation includes a treatment of the Calumet conglomerate and the mass copper, arsenide and chalcocite deposits in fissures. The U. S. Geological Survey treatment of these, I understand, will not appear for some years but I do not feel that I should wait that long for at least a preliminary comment on the papers listed (2).

In the meantime, students and others are referred to our 1946 paper (1) and my 1952 discussion (3). In these papers they will find that I have anticipated and commented upon most of the arguments which are being advanced for other explanations of the origin of these deposits.

In addition to this discussion of origin which I hope to present as soon as a few more

2. Reproduced from Economic Geology Vol. 51, No. 3, with the permission of the Editor.

of the Survey preliminary papers appear, I hope later to review the results of their entire project in the district. A start has been made on publication of their results of underground mapping in the mines and of quadrangle folios with the usual factual matter presented in such media. A local study of details of sedimentation led them to conclusions as to the source of the materials involved which are different from those hitherto regarded as most likely from evidence obtained on both sides of the Lake Superior syncline. It is hoped that before the Survey publishes further on this subject it will send in some specialists on processes of sedimentation and on significant characteristics of lava flows to study the broader aspects of the problem not only in Michigan but all around Lake Superior since the matter of location of the source of Keweenaw lavas and sediments is of fundamental importance. As stated by White, the determination of the source of the sedimentary material and "of the direction in which the ancient streams flowed is essential to a reconstruction of the physiography of the Keweenaw basin of deposition . . . (which) in turn may prove helpful or even necessary to the geologic search for new copper deposits" (4). Perhaps before the final publication of conclusions, the evidence afforded in the openings of the Calumet conglomerate mine will again become accessible for study.

I feel that my review of the topics of the survey other than those connected with the origin of the copper deposits had better be postponed until the final publication is out. An earlier discussion would be premature and would not be occasioned by the feeling of urgency offered by the debatable character of the topic of origin. In my final review I shall express appreciation for the completion of a long and tedious task, carried out with persistence and faithfulness and which at last provides the district with a set of useful topographic and geologic maps.

T. M. Broderick

Calumet, Michigan
December 21, 1955

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POSTSCRIPT³

Since the foregoing was submitted for publication, it has been announced that Dr. White would present a paper "The regional geologic setting of the Michigan native copper district" at an "Institute on Lake Superior Geology" to be held at Houghton, Michigan, May 11 and 12. He has very kindly sent me an outline of his paper and it presents a treatment of origin of the deposits including source of copper, source of solvent, broad structural controls and other features. Any discussion of the ideas on genesis being presented in the series of U.S.G.S. papers should certainly await the publication of this latest one by White, in addition to those by Cornwall and Stoiber referred to above.

Dr. White: I want to make only one point at this time. Dr. Broderick spoke of the .01% copper content of Keweenaw lava as though this was the source without any intermediate process. I think I should say that he himself pointed to one possible clue to this problem of getting a 100 to 1 enrichment. This is approximately 100th of the concentration that now forms an ore deposit so we have to look to some process or processes that will give us concentration of roughly 100 to 1. Dr. Broderick found in his study that he referred to earlier that the individual flows were quite notably differentiated and he pointed also to the fact that one of the constituents that tended toward enrichment at the top was copper itself. I think that this may give us a clue to at least a substantial fraction of this 100 to 1 concentration that we are looking for. If, for example, the copper content of the massive flow that he sampled is .01 or .007, it may well be that this represents somewhat less than the average original content of copper in the flow itself. As he himself points out, some of this copper tends to work its way to the top, enriching the top and by the same token depleting the central portion of the flow. If the tops are enriched only by a factor of 2 or 3, say .02 or .03, we would have a good start toward 100 to 1 enrichment. This reduces the factor from 100 to 1 to say 50 to 1, maybe even down as low as 25 to 1. This is a very hard thing to get hold of because it is almost impossible to sample a flow top, as I think we all realize, and be sure that we are dealing with this enrichment which we can postulate took place at the time the flows were extruded. I am on thin ice as well in suggesting what the figure might be, but I do think that this initial concentration in the parts of the lava flow which are the porous flow tops if in reaction with the contained water, might yield copper to a solution in sufficient concentrations to form the hydrothermal solutions that we all agree form the ore deposits.

Mr. Rand: On the basis of Dr. Broderick's .01% copper it would require an area of traps 30 miles square to be eroded 12 feet deep in order to supply the 6 billion pounds of copper considered to be known in the White Pine orebody. This erosion and transport do not involve movement of placer copper; it is a matter of oxidizing copper, taking it into solution and then carrying it, presumably in ground water, into or onto the flat basin area where muds are being laid down. It may be carried out over the muds in the surface waters or it may be carried beneath the muds in the ground water and in the sands underlying the muds. The movement of copper from the waters into the muds may take place essentially at the same time as the copper arrives over or under the muds or it may take place at some time after consolidation of the muds into rock.

Dr. J. W. Gruner (University of Minnesota): How does it happen that there is so little sulphur associated with the copper ores here if they are of regular hypogenetic origin? Ordinary copper

sulphide ores are very high in sulphur. In this region we have a very low sulphur content, relatively speaking of course, and this has rather bothered me for some time because the chemistry of these deposits evidently is different from the chemistry of the regular sulphide deposits.

Dr. Broderick: Of course that is one of the big problems, why the copper is native and not sulphide. Without going into the history and details there are two obvious answers that might be considered; one is that the solutions that deposited the copper were different from those that brought them in at Butte, Morenci, and other places, and the other is the rock into which those solutions were introduced. If you examine the assays of the Butte batholith and of the monzonites and allied rocks in which the porphyry coppers are deposited, you will find that the iron content is very low. Total iron I believe is less than 2%. The total iron in the amygdaloids and in the conglomerate deposits in Michigan is from 6 to 9% and a large part of that iron is in the ferric state. Proceeding from there, if the iron was a precipitant, does it show any effects of having entered into a chemical reaction when the copper was deposited? It is a matter of common knowledge amongst those who have worked in these deposits that in certain zones, over a vertical range of thousands of feet around the copper, there is an alteration of ferric iron. The rock is red normally and around the copper is a halo of bleached material and that bleached material has been sampled and assayed; polished sections have been studied running across the boundary of the bleached and unbleached and it is low in iron. Little needles of hematite have been absolutely removed so that iron has entered into that reaction. Removal of iron is therefore associated with the deposition of native copper. As a further clue, the iron that does remain in some of these altered areas is much higher in the ferrous state than in the surrounding rock. If you have 4% ferric iron and 2% ferrous in the normal amygdaloid in the zone around the copper those ratios will be reversed - it will be much higher ferrous and lower ferric. Chlorite will be formed which has iron in the ferrous state so that the deposition of copper in certain parts of the zonal column, not the stratigraphic column, is associated with the reduction and removal of iron. Now if iron was reduced it means something was oxidized and we threw the ball to the chemists and asked them, "Supposing that we had copper-bearing solutions coming in here of the sort that deposited sulphide elsewhere, what might happen to the sulphur? Could it react with the ferric iron, reduce it, and go out of the system as a soluble sulphate, leaving native copper?" That work was taken up in the laboratory of the U. S. Geological Survey and a paper was put out by R. C. Wells.⁴ If you will go back and refer to that bulletin you will get this story that I have just told you in brief. In summary, one answer to the question is that the solutions were the same as those which deposited copper in the porphyries but they hit a different rock, a rock that had oxidizing possibilities.

Dr. G. M. Schwartz (University of Minnesota): I suppose I might start by saying that I am probably the oldest timer of all because I worked in the district before Dr. Broderick, and probably before Dr. White was born and I would like to make two or three comments, because I find myself in agreement with both men, in part, and in disagreement with both, in part, and incidentally I might say that, for thirty-five years since I left this district, I have worked mainly in the Keweenaw in Minnesota. I was very much interested in Dr. White's comment as to why we do not have copper deposits in Minnesota to amount to anything. I further say that I think his is the best explanation I have heard.

I would like to point out on the problem of getting the copper out of the basalts that in Minnesota

4. Wells, R. C., "Chemistry of the Deposition of Native Copper from Ascending Solutions." U. S. Geological Survey, Bull. 778, 1925

at Susie Island, for example, there was a very nice copper vein with calcite, bornite, chalcopyrite and pyrite which is below the flows. Now I will grant Dr. White that the mineral-bearing solution possibly could have leaked out to the side, or downward, or something of that sort but I have a sneaking suspicion that it did not. I think that there is still a good argument for a hydrothermal origin rather than the old idea of lateral secretion which is essentially of course what Dr. White is proposing and is, incidentally, popular for many other deposits at the present time.

In regard, however, to the shale, I had a good look at that when I was fortunate enough to be called upon to examine the work in connection with the White Pine loan and I must say that there it is a lot easier for me to imagine the copper in the shale having been deposited with the shale, in other words being syngenetic. So there I would disagree with Dr. Broderick and agree with Dr. White and Mr. Rand. It does seem to me, however, that we are asking an awful lot of these weathering solutions to concentrate this minute amount of copper out of these flows and get it all in one place. There again I think that it is a little easier to imagine that the copper which is in the White Pine deposit probably came from the weathering of some of the copper deposits and if I understand the geologic history correctly I think this is entirely possible.

I would like to have either Dr. White or Mr. Rand comment on this. Of course we might even consider that there was a direct contribution to the water of copper from hydrothermal sources. This would be essentially going back to Van Hise and Leith's explanation of a possible origin of the iron in the iron formations. These are the points that have occurred to an old timer on this problem and I think it just keeps us going around more or less in a circle on how to explain these things.

Dr. White: I would like to make one comment in answer partially to Dr. Schwartz and partially also to Dr. Broderick. This has to do with uniformitarianism. Must we explain everything with the same set of rules? We have in this Keweenaw province an area of 50,000 square miles or more underlain by Keweenaw rocks. For an area of crystalline rocks this is substantial part of the earth's crust. If we assume that ore deposits can be formed as we have suggested, does this preclude this area from being cut here and there by veins of magmatic origin? This is pretty hard to pin down but I cannot feel the same compulsion that others seem to share that we have to explain everything by exactly the same set of circumstances. The deposits are different; the White Pine deposits are about as unlike any of the lode deposits as one can imagine. The arsenide veins that cut some of the lodes are quite different from the normal types of veins which cut the lodes. I do not personally see any reason why we have to explain all these things by exactly the same set of rules when the area involved is so large.

Dr. C. H. Burgess (Bear Creek Mining Company): It seems to me that the percentages of copper contained in the igneous rocks of various kinds, as Dr. Broderick read to us, indicates that both in "traps" and in granite that might have differentiated from them are very small. They are of the same order of magnitude and therefore the production of a copper deposit depends upon the efficiency of concentration. In that regard the explanation of the White Pine by Messrs. White and Rand is somewhat in the framework of the pyrite and marcasite in the black shales of coal measures. I wonder if sulphides in coal measures must also have a hydrothermal origin.

Dr. J. W. Gruner (University of Minnesota): The explanation that Dr. Broderick offered I had already read but I do not understand whether the solutions were acid or basic. Basic solutions do not bleach or leach iron at all; however basic solutions dissolve copper quite readily. Of course acid solutions both bleach and carry copper. That I think is one of the fundamental questions we have here.

Dr. Broderick: Regarding sulphur and organic matter I cannot say very much, but I can take Dr.

Burgess out into the bogs and stir up hydrogen sulphide. I do not think that there are any lava flows or igneous rocks around those bogs.

I do want to say something about the adequacy of a large volume of rock with a small percentage of some constituent for furnishing concentrations. It is an easy matter to sit down and figure how many cubic feet or yards or miles of rock containing 1/1,000 or 1/1,000,000 or 1/10th of a percent will, if you could get that all together, form deposits much richer, but the entire process studied in its entirety seems to carry rather some unlikely implications. We picture these lavas as being exposed, weathered and eroded, and nearly everything going into solution. Along with the copper, the zinc, lead and cobalt components will enter into solution. Let us imagine these traps being subjected to that process not over one season but certainly over centuries and maybe hundreds of centuries. Weathering goes on and the copper, lead, zinc, cobalt, etc., are carried by streams down wherever they go; weathering is not just in the vicinity of the White Pine basin, it proceeds all along the Keweenaw Peninsula and all around Lake Superior. Now at some time and at some place in this area of hundreds of miles being eroded during thousands of years of time a sudden opportunity presents itself and you get this deposit. The White Pine deposit is contained within a relatively few feet and is said to contain 300 million tons of rock carrying over 20 pounds of copper per ton; that is 6 billion pounds and it is only partly explored. This whole district in the hundred years that it has been mined has only produced 10 billion pounds. Here we are asked to believe that a minor episode in the erosion, weathering and solution of rock containing less than 0.01% of copper that have proceeded over the thousands of years and throughout the thousands of square miles of Keweenaw lavas around Lake Superior, suddenly, in a small fraction of the area and during a relatively few of the seasons involved has resulted in the precipitation of a deposit containing nearly as much copper as the whole district has produced to date. That is a difficult thing for me to understand.

Mr. H. W. Pfeffer (ARASCO Exploration Company): I do not know this district very well but I would like to mention an area in Nova Scotia which has certain similarities to White Pine. There we have Carboniferous rocks that are mostly red beds but in some small spots within the red beds are sandstones, conglomerates and shales. The shales are grey to blackish and they contain carbonaceous matter, usually remnants of wood, etc. Associated with these beds are nodules, sheets and disseminations of chalcocite. To the south of this area are the Copper Cliff Mountains which contain some pyrite and a little chalcopyrite in various spots throughout the volcanics. It appears from the way the Late Pennsylvanian rocks were laid down that the source was from that area and it seems quite likely that the copper must have come from there. There is no evidence whatsoever of intrusion into the Carboniferous rocks; the features are definitely sedimentary. One can visualize water carrying in solution copper sulphate in minute quantities and running off into this area of sediments and percolating through the sandstones, and then the copper sulphate reacting with the carbonaceous matter. Actually the occurrences are very similar except for quantity. These grey rocks lens out so that economically they are not of interest but in their manner of occurrence and chemistry they are very similar to White Pine.

GEOLOGY AND MINERAL DEPOSITS OF THE MANITOUWADGE LAKE AREA*

by
E. G. Pye

Introduction

In 1931, the Manitouwadge Lake area was surveyed for the Ontario Department of Mines by Dr. J. E. Thomson, now Assistant Provincial Geologist; and on his geological map, published in 1932, he noted an occurrence of gossan and sulphide mineralization at the site of the now famous Geco mine¹. But despite this it was only recently that any interest was paid to the discovery. This may be owing to the commonly held opinion that "greenstone" belts of small area do not lend themselves to the occurrence of large mineral deposits - the favourable prospecting area at Manitouwadge Lake is only about 35 miles square. It may also be because of the highly metamorphosed condition of the rocks - many prospectors consider that schists and gneisses are unfavourable to ore deposition. In any event, the area was avoided until as late as 1947, when the sulphide deposit at Manitouwadge Lake was first staked. But even at that time, it was difficult to arouse interest in the discovery; and after two years, the prospector, Moses Fisher, was compelled to let his claims lapse because of failure to attract a mining company to undertake development.

In 1953, two prospectors, Roy Barker and William Dawidowich of Geraldton, Ontario, decided to visit the area. Upon relocating the sulphide deposit, with which they were much impressed, they decided to stake. The sulphide deposit was examined by W. S. Hargraft, consulting mining engineer, and upon his recommendation, the property was quickly taken up by General Engineering Company, Limited; Consolidated Howey Gold Mines, Limited; and H. W. Knight and associates on a partnership basis. Diamond drilling in August and September indicated the possibility of a copper-zinc-silver ore body. Geco Mines, Limited, was incorporated in October, and it was not long before the results of further drilling indicated a deposit of such importance that the biggest staking rush in the history of Ontario, and one of the biggest in the history of Canada, was precipitated.

Location of Area, Means of Access

The Manitouwadge Lake area forms a small but very important part of the Heron Bay - White Lake region along the north shore of Lake Superior. As shown in Fig. 1, it lies about midway between two transcontinental railways, the Canadian National Railways line on the north and the Canadian Pacific line on the south; it is 170 miles east-northeast of the Canadian Lakehead, and 200 miles northeast of Houghton, Michigan.

* Published by permission of the Provincial Geologist, Ontario Department of Mines.

1. Thomson, Jas. E., "Geology of the Heron Bay - White Lake Area," Ont. Dept. Mines, Vol. XLI, pt. 6, pp. 34-47 (with map No. 4i), 1932.

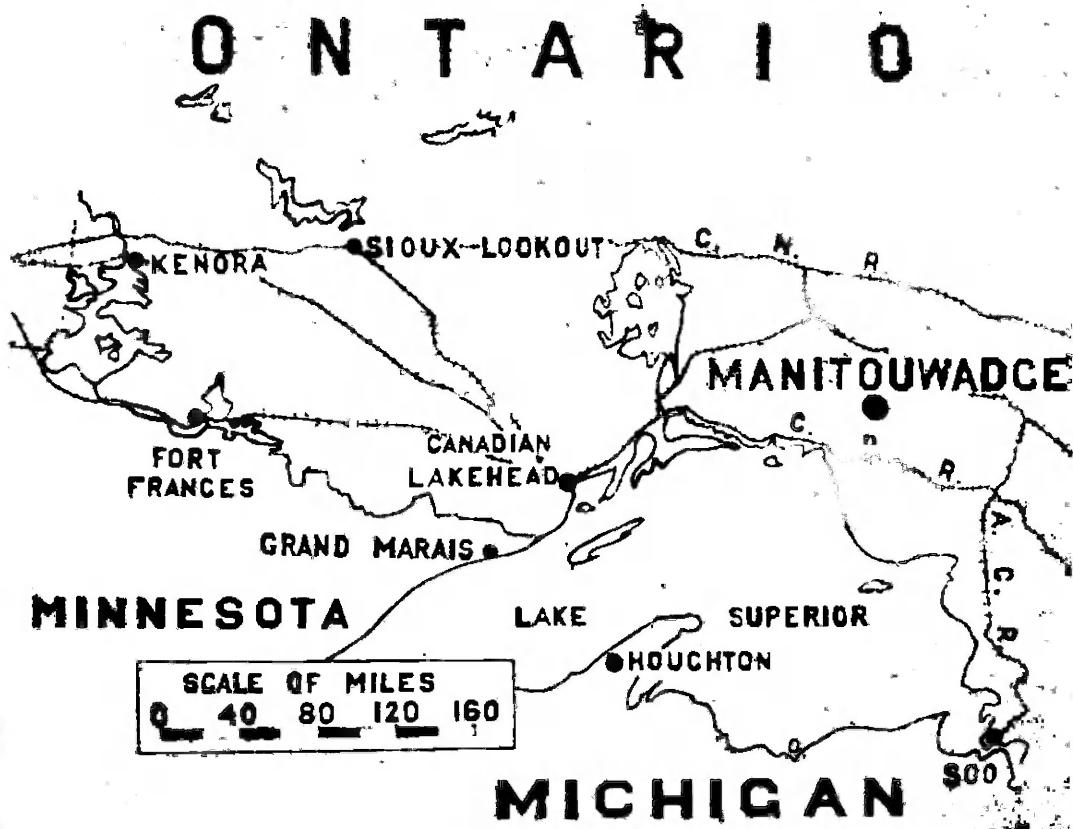


Fig. 1. Key map showing location of the Manitowadge Lake area.

The area is accessible by an Ontario Department of Mines access road connecting Manitowadge Lake with the Trans-Canada highway along the north shore of Lake Superior; by a spur railway line built south from Hillsport by the Canadian National Railways; and by a second railway line, built north from Hemlo by the Canadian Pacific Railway.

General Geology

All the consolidated rocks exposed in the Manitowadge Lake area are of Precambrian age. They have been divided into three main groups:

- (1) A system of closely folded and intensely metamorphosed volcanics and sediments, which, together with horizons of amphibole - biotite gneiss and banded iron formation, are believed to be of Early Archaean age;
- (2) An assemblage of igneous rocks, of post-Early Archaean and possibly of Algonian age; and
- (3) Diabase dikes, which have been correlated tentatively with basic intrusives of Keweenawan age exposed around Lake Nipigon and along the northwest shore of Lake Superior.

The areal distributions of these principal groups of rock formations are shown on the generalized geological map of the area (Fig. 2).

Early Archaean

Volcanics: A prominent series made up largely of hornblende schist is exposed south and east of

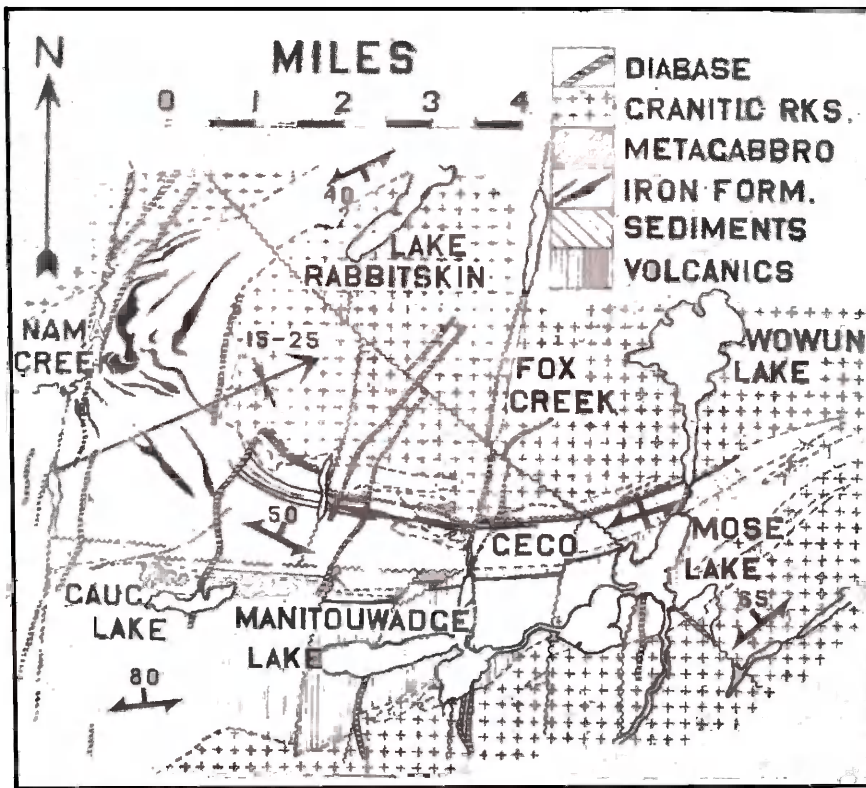


Fig. 2. Generalized geological map of the Manitowadge Lake area.

Wowun Lake. It forms a well-defined belt, up to and possibly exceeding two miles in width, which extends from this locality southwest to Manitowadge Lake, and thence westward across the southwest corner of the map area. Two varieties of hornblende schist are present. One shows little evidence of banding; the other is characteristically finely laminated and resembles a thin bedded sediment in structure.

Excellent exposures of the non-laminated hornblende schist are found in the west part of the belt. In places where shearing has not been too intense, vestiges of original pillow structures can be seen. The pillows are somewhat irregular in shape and do not permit satisfactory top determinations. But their presence is significant, for they indicate that the hornblende schist is of volcanic origin. In consideration of the mineralogical composition - the typical schist consists of about 50 percent hornblende with lesser amounts of andesine and a little quartz, sphene, and magnetite - it is probable that the rock is the metamorphosed equivalent of original basic lava.

Thin horizons of laminated hornblende schist separate the lava flows. They are particularly well-developed in the vicinity of Manitowadge and Mose lakes. The rock itself is similar mineralogically to the variety just described except that, at the expense of plagioclase, quartz is an essential rather than an accessory constituent. A further and more striking difference, of course, is the thin bedded structure - black layers of material rich in hornblende alternate with grey layers rich in plagioclase and quartz. These layers range from a small fraction of an inch to several inches in thickness. The laminated hornblende schist is found in places to contain lenticular fragments of greenstone, from less than an inch to six inches in length and up to about three inches in thickness. The two characteristics - stratification and fragmental structure - indicate that the original rock was a tuffaceous sediment deposited subaqueously during the period of volcanism.

Sedimentary Gneisses: As the north margin of the volcanic series is approached, well-developed

horizons of sedimentary gneisses are found to alternate with bands of hornblende schist. These increase in both number and thickness to the north so that, within a short distance, the series gives way to one in which the principal ferromagnesian mineral is biotite. Four principal varieties of sedimentary gneisses have been recognized. They are biotite gneiss, quartz-oligoclase-biotite gneiss, quartzite, and quartz-microcline gneiss.

In view of the evidence presented by petrologists to the effect that clay minerals combine to form chlorite and sericite, and that these in turn combine to form biotite during metamorphism², it is thought that the biotite gneiss, the quartz-oligoclase-biotite gneiss, the quartzite, and the quartz-microcline gneiss are the altered equivalents of shale, argillaceous sandstone, quartz sandstone, and arkose, respectively.

Amphibole-Biotite Gneiss: In many places throughout the series the sedimentary gneisses are found to be interrupted by lenticular masses of amphibole-biotite gneiss of dark colour, coarse to very coarse granularity, and striking appearance. This rock is made up largely of anthophyllite, hornblende, and biotite, with small amounts of quartz, oligoclase, and magnetite. Red garnets are also commonly present. They occur as large porphyroblasts, ranging from about one-half inch to two inches or more in diameter, and in places make up 25 percent of the rock mass. The amphibole-biotite gneiss is frequently found to grade, by disappearance of amphibole and, when present, also of garnet, into typical biotite gneiss. Because of this it is considered to be of sedimentary origin - it may represent the highly metamorphosed equivalent of a calcareous, chloritic grit or basic tuffaceous sediment that was developed at the same time as the enclosing rocks. It is included with the sedimentary gneiss on the generalized geological map.

Iron Formation: Commonly intimately associated with the amphibole-biotite gneiss is a peculiar banded rock. This banded rock consists of layers of coarse-grained quartz, from a fraction of an inch to a foot or more in thickness, alternating with equally thin or thinner layers of one or more of amphibole schist, garnetiferous amphibole-biotite schist, and a very coarse amphibolite. In the field it has been variously termed quartz-chlorite rock, quartz-amphibole rock, quartz-amphibole-pyroxene rock, and iron formation. Since the rock is distinctly banded, since the schist or amphibolite layers contain disseminated crystals and thin seams of fine granular magnetite, since individual horizons can be traced by dip needle and magnetometer, and since these horizons are very persistent and follow the folded pattern of the sedimentary gneisses, it is thought that "iron formation" is the most appropriate term.

Post-Early Archaean (Algonian?)

Basic Metaintrusives: Small lenticular bodies of metagabbro are found in a number of places within or close to the belt of volcanic rocks. These bodies have intrusive relations with the Early Archaean formations, but are themselves cut by granite and pegmatite. For the most part they consist of a medium-to coarse-grained rock made up of about equal amounts of dark-green hornblende and plagioclase, with small amounts of biotite, quartz, and magnetite. This rock is generally quite massive in the outcrop.

Granitic Rocks: The most abundant igneous rock found in the Manitouwadge Lake area is biotite

2. Harker, Alfred, "Metamorphism, A study of the Transformations of Rock Masses," Methuen & Co. Ltd., London, pp. 45-61, 1950.

granite gneiss. Together with massive granite, migmatite, and pegmatite, it occurs in three principal localities: (1) the extreme southeast corner of the area; (2) the extreme northwest corner; and (3) the whole of the northeast quarter. The granitic rocks to the northwest and southeast are believed to represent a single large mass, in which the Early-Archaeon rocks form a deeply infolded inclusion; those in the northeast quarter of the area are believed to represent a satellite of the main mass, which has been localized along the major synclinal axis (see Structural Geology).

Associated with the granite gneiss, migmatite, and the medium-grained, massive, intrusive biotite granite, and cutting the Early Archaeon formations, are dikes and sills of pegmatite and aplite. The pegmatite is of three ages. It occurs as: (1) dikes which cut metagabbro inclusions in, and which are themselves truncated by, the massive biotite granite; (2) irregular bodies which grade into, and hence represent a phase of, the massive biotite granite; and (3) dikes which cut the massive biotite granite. Some of the pegmatites are pre-ore in age, and on the properties of Geco Mines, Limited, and Willroy Mines, Limited, they were instrumental in the localization of the ore deposits.

Algonkian

The youngest rock exposed is diabase. The diabase forms a number of narrow, but fairly persistent north-south dikes, some of which are localized along transverse faults (see Fig. 2). In that these dikes cut sharply across all the other consolidated rocks, including the various granitic rocks, it is thought that they are of Algonkian or Late Precambrian age. It is possible that they could be correlated with similar rocks, of Keweenaw age, that crop out to the west of the area in the vicinity of Lake Nipigon.

Structural Geology

Folding: The rock type described as iron formation is the only one that occurs in sufficiently distinct and persistent horizons to be useful in outlining the structural geology. Examination of the generalized geological map of the area shows that, in the vicinity of Wowun lake on the east, the iron formation and the gneisses strike southwest and dip vertically to steeply north. Proceeding westward to Fox creek and the Geco mine, however, the formations assume an east-west strike; and still farther west, midway between Fox and Nama creeks, they strike northwest and dip 50° N. Finally, at the west side of the map area, the formations assume first a northerly strike and then double back on themselves to strike northeast again. They delineate a large trough or synclinal fold, which dip measurements indicate to be asymmetrical and overturned to the north. Other dip measurements, at the nose of the fold, indicate a plunge to the northeast of from 15 to 25 degrees. In the eastern part of the area, lineation and drag folds indicate a steeper plunge of about 40 degrees.

Faulting: After the major folding, the Manitouwadge Lake area suffered a series of disturbances that resulted in the development of a large number of faults. These faults are of three types: (1) longitudinal or strike faults, which more or less parallel the formations along the south limb of the syncline; (2) transverse faults, which strike in a general north-south direction; and (3) diagonal faults, which strike northwest, obliquely to the other faults. All are represented in the field by deep linear depressions in the topography.

An example of a major strike fault is the Agam Lake fault, which strikes due west, from north of Manitouwadge lake to almost the west boundary of the map area, just north of and roughly parallel to the belt of volcanic rocks. This fault is pre-ore in age, and is represented by a wide zone of graphitic schist, in places mineralized with pyrite and pyrrhotite. The magnitude and direction of

movement along this break have not been determined. However, the fault appears to truncate a number of pre-ore, right-hand transverse faults, and at the same time, appears to be terminated by the north-south, post-ore, left-hand Fox Creek fault.

At least three periods of movement are thus indicated. A possible fourth period of disturbance may be responsible for the fault that extends diagonally across the area from northwest to southeast. In regard to this fault, the offsets shown by the rock formations are of interest. In the northwest section of the area, the formations dip rather flatly to the southeast. Here the displacement was left-hand, or east side to the north. In the southeast section of the area, the formations dip about 65° to the northwest. Here the displacement was right-hand, or east side to the south. To the east of the Geco mine, the formations dip vertically. Here the formations have been traced across the fault to Wowun lake without any great apparent offset. Such anomalous conditions can be explained satisfactorily by assuming that the displacement along the fault was mainly vertical, and that the relative movement was up on the west side. South of Mose lake, a diabase dike was localized along this diagonal fault. But the diabase has been brecciated. Further, north of the Geco mine, the fault cuts and offsets two diabase dikes. In view of these facts and the simple vertical displacement indicated, it is thought that the two or more movements represented occurred in Late Precambrian time.

Mineral Deposits

All the important mineral deposits discovered to date are sulphide replacement bodies. Their locations are shown in Fig. 3. They strike and dip parallel to the formations that contain them, and have been found in or closely associated with either iron formation or a variety of sedimentary rock. A determination of the lead isotope ratios of a sample of galena, from one of the occurrences, by mass spectrometer is reported by J. T. Wilson of the University of Toronto to indicate an age of $2,600 \pm 120$ million years³. According to Wilson, the indicated age is close to that of leads found in the Golden Manitou and Barvue deposits in Quebec and the gold ores of Timmins in Ontario. The lead from Manitouwadge lake, and those from the other deposits, are all much older than the Sudbury nickel-copper ores, which are believed to have been formed in Late Precambrian time. In view of this, it is reasonable to assume that the ore minerals were deposited during the period of granitic intrusion, and that they are of Late Archaean or Algoman age.

Deposits in Iron Formation: Sulphide replacement deposits in iron formation have been found on the properties of Lun-Echo Gold Mines, Limited, about the nose of the Manitouwadge syncline, and Willroy Mines, Limited, on the south limb of the syncline.

As mentioned previously, the iron formation is a banded rock, in which layers of quartz alternate with layers of amphibole schist, garnetiferous amphibole schist, or coarse-grained amphibolite. In the replacement deposits found in this rock, the metallic sulphides heal fractures in the quartz and occur as either masses or disseminated crystals and grains replacing the minerals of the schist or amphibolite layers. Where massive replacement has occurred, the deposit is a strikingly banded one, in which layers of sulphides alternate with layers of mineralized quartz. On the other hand, where disseminated replacement has occurred, the sulphides appear to be localized along planes of foliation, which they accentuate.

3. Wilson, J. T., personal correspondence.

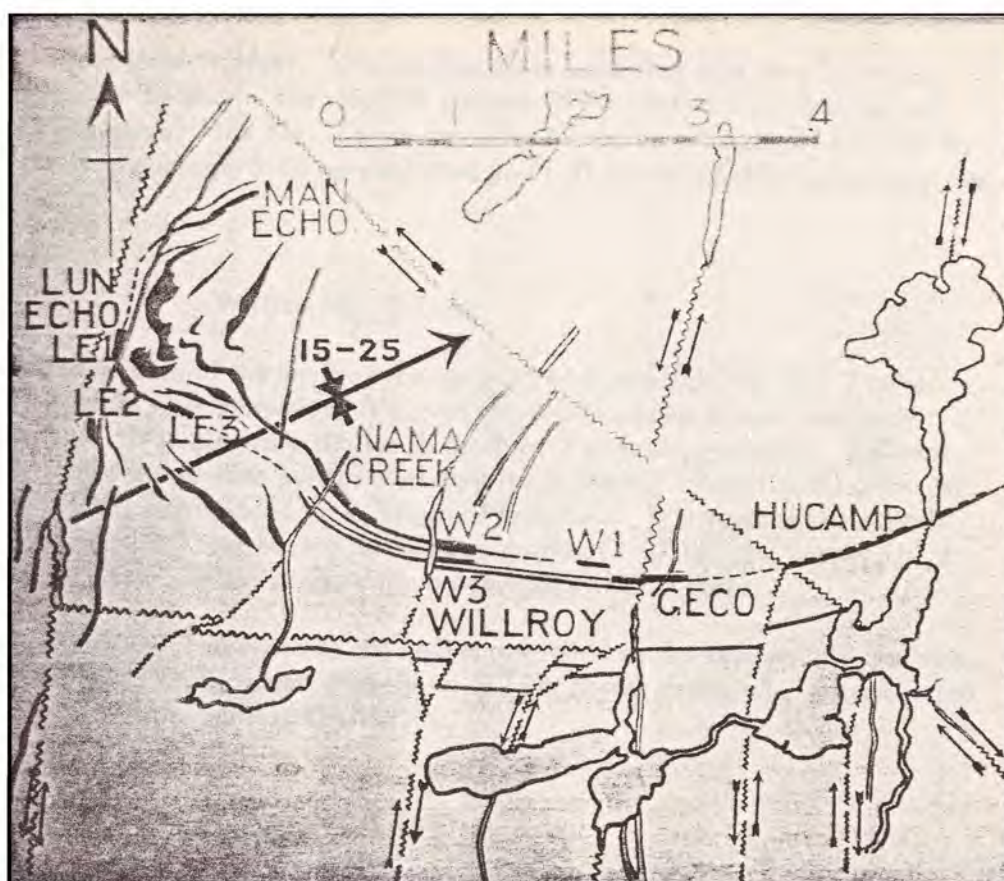


Fig. 3. Surface plan of the Manitowadge Lake area showing the locations of the more important mineral deposits.

The principal sulphide present is pyrrhotite. It is invariably accompanied by considerable pyrite, subordinate amounts of sphalerite and chalcopyrite, and in some cases also by galena. The replacement deposits in iron formation may thus contain values in copper, lead, and zinc. Silver is also usually present, and adds to the over-all value. Some of the deposits tend to be lenticular and of small extent. On the Lun-Echo property, for example, three of them have been thoroughly tested by diamond drilling. In each, commercial grade material, across widths up to and exceeding 25 feet, was indicated. But none of the deposits was found to have a length greater than 500 feet, and each of the three was found to decrease in width and grade with depth. In contrast to the Lun-Echo occurrences, two deposits, located on the Willroy property, appear to be sufficiently rich and large to make ore. These are known as the No. 2 and No. 3 ore zones. At the present time a vertical 4-compartment shaft is being sunk as a prelude to their underground development.

Willroy No. 2 Zone

The No. 2 zone lies 200 feet north of the shaft at the surface. It strikes N. 80° W. throughout the greater part of its length, and dips from about 70° N. to vertical. Near the west extremity, however, it curves sharply to assume a more northerly strike and a relatively flat dip to the northeast. It is a continuous horizon of mineralized iron formation, bordered on the north by garnetiferous amphibole-biotite gneiss and on the south by slightly sericitized biotite gneiss. The mineralization consists principally of pyrite, with pyrrhotite, sphalerite, and galena, and minor amounts of chalcopyrite. The sulphides are concentrated close to the south side of the iron formation horizon

across widths ranging from 7 feet to over 15 feet. This section forms somewhat of a core in the ore body, and both to the north and to the south, the sulphide content of the host rock diminishes and the material drops rapidly below grade. The No. 2 zone has been traced for a length of 800 feet by surface drilling, and is reported to average 5.88 percent zinc and 1.71 ounces of silver per ton across an average width of 19.6 feet.

Willroy No. 3 Zone

The No. 3 zone lies 500 feet south of the shaft at the surface, and parallels the No. 2 zone closely in attitude. Again, near its west extremity, it curves sharply to assume a more northerly strike and a somewhat flatter dip. It is also very similar to the No. 2 zone in character. But here the principal sulphide is pyrrhotite rather than pyrite; chalcopyrite is present in significant amounts; and galena is absent. The zone has been traced for a length of 1200 feet. It is reported to contain, to a vertical depth of 700 feet, 719,000 tons having an average grade of 1.27 percent copper, 10.3 percent zinc, and 1.5 ounces of silver per ton across an average width of 31.5 feet.

Deposits in Sedimentary Gneisses: Two types of ore bodies are found in the sedimentary gneisses, and may be classified as disseminated replacement deposits or as lode fissure deposits⁴. Disseminated deposits occur on the property of Willroy Mines, Limited.

Willroy No. 1 Zone

The No. 1 ore zone on the Willroy property is also a body of disseminated ore. Near its west extremity it trends northwest and dips 45° - 50° N.E. However, throughout the greater part of its length of 1900 feet, it strikes roughly east-west and dips 70° N. to vertical. The ore body ranges up to about 50 feet in width. It lies within the central portion of a horizon of highly sericitized, porphyroblastic quartz-feldspar-biotite gneiss, and consists of crystals and grains of metallic sulphides disseminated throughout the host rock. The pyrite has no preferred orientation. But the chalcopyrite and pyrrhotite, as well as occasional stringers of quartz, tend to occur as individuals elongated parallel to the foliation of the gneiss. Because of this orientation, the chalcopyrite and pyrrhotite also tend to be concentrated in thin layers and streaks, with the result that, in drill cores, narrow sections rich in copper alternate with sections poor in copper. The sphalerite, in part at least, replaces the pyrrhotite. A feature of particular interest is the fact that the ore body is paralleled along its north side by a band, about 15 feet in thickness, of white, crenulated quartz-sericite. This schist, unlike the less altered gneiss, is only sparingly mineralized and is extremely low grade. The Willroy No. 1 ore body is estimated to contain, to a vertical depth of 500 feet, 796,000 tons grading 1.5 percent copper, with low values in zinc and silver⁵.

Geco Ore Body

The Geco ore body is exposed about 600 feet south and 1800 feet east of the Willroy No. 1 zone, and from here extends eastward for a horizontal length of 2,650 feet. Like the Willroy No. 1 zone,

4. Bateman, Alan, M. "Economic Mineral Deposits," John Wiley & Sons, Inc., N.Y., p.III, 1942.

5. Hooka, Eric, Chief Geologist, personal communication.

it lies within the horizon of highly sericitized quartz-feldspar-biotite gneiss, which is bordered on the north by garnetiferous amphibole-biotite gneiss and biotite granite, and on the south by quartzite. It is a lode fissure rather than a simple disseminated replacement deposit. As shown in Fig. 4, it can be divided conveniently into three sections: the West, Central, and East.

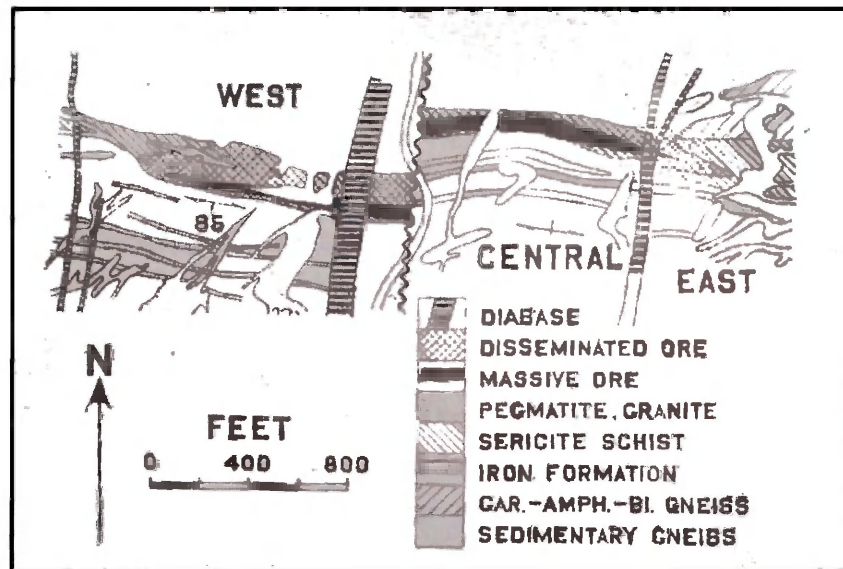


Fig. 4. Surface plan showing generalized geology in the vicinity of the Geco ore body (modified after company plans).

The West section of the ore body lies west of Fox Creek. It has a length of 1,200 feet at the surface, ranges up to 220 feet in thickness, and rakes to the east at about 40 degrees. In part it is in every respect similar to the Willroy No. 1 zone, and consists of highly sericitized gneiss mineralized with metallic sulphides, chiefly pyrite and chalcopyrite, and cut by occasional quartz stringers. But here the sulphides replace the host rock outward from a narrow, tabular core of massive ore made up of pyrite and sphalerite, with considerable pyrrhotite but relatively small amounts of chalcopyrite. This core occurs near the south wall of the ore body, within a few feet of the sericitized gneiss - quartzite contact. It decreases in width and tends to pinch out both to the west and with depth.

To the east, the West section is cut off sharply by the Fox Creek fault, so that east of the creek, the extension of the ore body lies approximately 250 feet to the north. This extension, or Central section, extends eastward from the fault for a distance of 850 feet, to a point where it is truncated sharply by a zone of north-south diabase dikes. Near the surface the middle section has an average width of 58 feet. Like the West section, it consists of a core of massive sulphides, chiefly pyrite and sphalerite. This is enclosed by an envelope of iron, copper, and subordinate zinc sulphides disseminated throughout sericitized gneiss. But here the core is much wider than in the West section, and the envelope of disseminated material is narrower and, in places, below ore standards. Near the surface, the ore of the Central section is thus rich in zinc but poor in copper. With depth the core of the ore body decreases in width and tends to tongue out, whereas the bordering disseminated ore increases in width and grade. The net result of this is a gradual transition from a high-grade zinc and low-grade copper ore near the surface, to a high-grade copper and low-grade zinc ore at depth. This deep ore, rich in copper but containing low values in zinc, is identical in character to that found in the West section of the ore body, and there is little doubt that it represents the eastward extension of the West

section down the general rake of the ore body.

As mentioned above, the Middle section of the ore body is truncated by a zone of north-south diabase dikes. The East section of the ore body lies east of these dikes and extends for a horizontal length of about 600 feet near the surface. It is identical to the central section in character, except for three features: (1) both the core of massive sulphides and the envelope of disseminated ore are narrower and tongue out eastward; (2) the core of massive sulphides attains its maximum thickness of about 50 feet at a depth below the surface of 700 feet, and pinches out upwards; and (3) at the east margin of the zone of diabase dikes, the core is represented by massive pyrrhotite and pyrite, and sphalerite does not become an important constituent until a depth of about 500 feet is reached. The East section, at or close to the present erosion surface, thus represents the upper limit of the east-raking ore body.

The Geco ore body has been tested by diamond drilling to a vertical depth of 1300 feet. To this depth, the three sections are estimated to contain 15,227,251 tons of ore having an average grade of 1.76 percent copper, 3.48 percent zinc, and 1.77 ounces of silver per ton⁶.

Mineralization and Paragenesis

The principal ore minerals in all the known deposits are chalcopyrite and sphalerite. Galena is often also present, and is particularly prominent in the Willroy No. 2 ore zone, but nowhere does it occur in sufficient quantity to be of economic importance. Silver is present in every deposit. It has not been recognized as such. Assaying of samples from the Geco ore body indicates that high values in copper are usually accompanied by high values in silver, and the thought has been expressed that the silver is present in solid solution in the chalcopyrite⁷. A qualitative spectrographic analysis of chalcopyrite from the Geco ore body indicated the presence of tin, which may also prove to be of economic importance⁸.

Associated with ore minerals in all the deposits are quartz, in small veinlets, pyrite, and pyrrhotite. Small amounts of cubanite and marcasite have been found. The paragenesis, as given by Langford⁹ for the Geco occurrence, is as follows:

- (1) formation of pyrite;
- (2) fracturing and introduction of quartz;
- (3) formation of pyrrhotite;
- (4) formation of chalcopyrite, overlapped in part and followed by;
- (5) formation of sphalerite; and
- (6) formation of galena.

The presence of ex-solution textures of sphalerite in chalcopyrite and of chalcopyrite in sphalerite indicates that the Geco ore minerals were formed at high temperatures, and that the deposit, according

6. The Northern Miner, April 5, p. 41, 1956

7. Langford, F. F., "Geology of the Geco Mine in the Manitouwadge Area, District of Thunder Bay, Ontario," Unpublished M. A. thesis, Queen's University, Kingston, Ontario, 1955.

8. Op. cit.

9. Op. cit.

to Lindgren's¹⁰ classification, is of the hypothermal type¹¹. This conclusion follows from the work of Buerger¹², who points out that chalcopyrite unmixes from sphalerite at temperatures of 350 to 400° C, and from the work of Edwards¹³, who states that sphalerite unmixes from chalcopyrite at temperatures of 500 to 600° C.

Structural Controls of Ore Deposition

One of the most interesting aspects of geological survey work is speculation as to the reasons why ore deposits are where they are after the ore deposits have been discovered and partly developed. Such speculation, in the hope that it may prove useful to further exploration, will constitute the balance of this paper. The structural controls of ore deposition in the Manitouwadge Lake area may be considered under two headings: major controls, and minor controls.

Major Controls

The major controls over the deposition of the ores were the folded structures and certain pre-ore faults.

Folded Structures: In regard to the folded structures, dip determinations, and measurements of lineation made apparent by the parallel alignment of elongate biotite flakes and prismatic crystals of amphibole, indicate a regional plunge of the formations to the northeast. This plunge ranges from 15 - 25° in the west section of the area to about 40° in the east section. Of interest is the fact that the rake of all the known ore bodies or mineralized zones, and in the case of the Geco ore body, also of the zonal arrangement of sulphides, is in the same direction and at the same angle as the plunge of the formations.

Pre-Ore Faults: One of the most interesting features of the area is the localization of the Geco and Willroy No. 1 ore bodies along a very persistent horizon of sericitized quartz-feldspar-biotite gneiss. At the Geco mine, this horizon is cut by north-south dikes of pegmatite, which are terminated abruptly by the massive sulphide core of the ore body and do not appear in expected positions on the other side of the core. This indicates that the massive sulphides were localized in a fault zone, and that this zone served as a channelway, along which the hydrothermal solutions, that effected the sericitization of the gneiss and the deposition of the ore minerals, actually migrated.

At first consideration, it would appear that this fault zone, which is post-pegmatite in age, was developed after the formation of the major syncline. But the horizon of sericitized gneiss has been traced continuously across the area for a distance of 4 miles, and throughout this length it is everywhere conformable to the folded unaltered sediments enclosing it. Because of this, and because the alteration indicates the presence of a continuous channelway during the epoch of mineralization, it

10. Lindgren, W., "Mineral Deposits," McGraw-Hill Book Co. Inc., N. Y., 1933.

11. Langford, F. F., op. cit.

12. Buerger, M. W., "Unmixing of Chalcopyrite from Sphalerite," Am. Mineral., Vol. 25, pp. 534-538, 1934.

13. Edwards, A. B., "Textures of the Ore Minerals," Aust. Inst. of Min. and Met., Melbourne, Australia, 1947.

It is concluded that the sericitized gneiss represents a bedding fault that was deformed with the other rock formations during the regional folding.

The other ore bodies or mineralized zones in the area do not occur along persistent horizons of altered rock. Nevertheless, it is thought that they also may have been localized along folded bedding faults - faults that were of limited lateral extent and were formed as parallel structures merely subsidiary to the "break" represented by the sericitized gneiss. In this regard, it is to be noted that mineralized zones containing pyrite and pyrrhotite have been found in numerous localities throughout the area, but that it is only close to the horizon of sericitized gneiss that such zones contain any significant amounts of copper, zinc, or silver.

Minor Controls

The minor features which are known to have exerted some influence in the localization of the ore bodies are: (1) intrusive-sediments contacts; (2) local curves or bends in the formations; and (3) the presence of flat-lying bodies of granite pegmatite.

Intrusive-Sediments Contacts: Examination of Fig. 4 shows that the Geco ore body lies within sericitized gneiss, which is bordered to the north by biotite granite and by garnetiferous amphibole - biotite gneiss. Where the sericitized gneiss is bordered by the granite, the best widths and values in copper have been found. On the other hand, where it is bordered by the garnetiferous amphibole-biotite gneiss, both to the west and to the east, the widths and metallic content decrease, and even the sericitic alteration becomes weak. It would thus appear that the contact, between the granite and the sericitized gneiss, localized the structural adjustments that provided the open spaces necessary for the migration of the ore-forming fluids and the deposition of the metallic sulphides.

A second example, illustrating the effect of intrusive-sediments contacts on the localization of ore, is found in the Willroy No. 3 zone. Here the mineralization lies in a band of iron formation. This iron formation, and the sulphide mineralization within it, have been traced for 2300 feet. But the zone only attains ore grade where, over a length of 1200 feet, the iron formation is bordered along its footwall side by a narrow, sill-like body of pegmatite.

Local Curves or Bends in the Formations: A second minor but nevertheless important control over the localization of the ore bodies was the presence of local curves or bends in the formations. As shown in Fig. 4, the formations in the vicinity of the Geco ore body strike roughly east-west for a considerable distance, and dip vertically to steeply south. Near the west boundary of the area represented, however, the horizon of sericitized gneiss assumes a strike of N. 55° W. and a dip of 65° to 75° N. E. The ore body occurs where the sericitized gneiss strikes east-west and has a vertical or near-vertical dip. Similar conditions are found on the Willroy property. Here there are three ore bodies, all of which trend roughly east-west, and all of which terminate westward at points where their respective host rocks curve sharply to assume northwest strikes and flatter dips.

The reason for the localization of the four ore bodies, along the east-west portions of their favourable host rocks, close to points of deflection in attitude, is found at the Geco mine. It was mentioned previously that the massive sulphide core of the ore body is localized along a fault zone which truncates bodies of pegmatite. In the sericitized gneiss adjacent to the massive sulphides numerous drag folds have been mapped. These drag folds are of two types: one type is "Z" - shaped in plan and is compatible with the major Manitouwadge syncline; the other type is "S" - shaped in plan and hence is a "reverse" structure incompatible with the major fold. Such "reverse"

drag folds have been found only in the horizon of sericitized gneiss, and it is logical to assume that they are expressions of the movement which culminated in the post-pegmatite faulting. They plunge at about 40° E., and indicate that the block of ground north of the fault moved down and to the west. A relative displacement of this type would result in the development of favourable open spaces along the steep-dipping portions of the fault zone. Thus, as pointed out by Newhouse,¹⁴ if one portion of a fracture surface dips steeply, and the other portion has a lower angle of dip, and if the hanging wall moves relatively down, the hanging wall will ride on the flat-dipping portion as a supporting surface. This will separate the hanging wall from a footwall along the steeply-dipping portion of the fracture surface to form an opening.

Presence of Flat-Lying Bodies of Pegmatite: The third minor control over the localization of the ore bodies in the area was the presence of small, flat-lying bodies of pegmatite extending across horizons of favourable host-rocks. At the Geco mine, the north-south pegmatites that are truncated by the massive sulphide core dip at flat angles, in places eastward, in other places westward. These pegmatites are typically massive, pink, unaltered varieties. But, within a foot or two of their contacts, they are somewhat sericitized, and display fractures healed by metallic sulphides. According to Walter Clarke, chief geologist of Geco Mines, Limited, the disseminated ore in the sericitized gneiss tends to improve in grade as the contacts of these flat-lying bodies are approached. Similar pre-ore pegmatites cut across the ore zone at the Willroy No. 1 ore body. As each of the two pegmatites are approached from below, an increase in the width and/or grade of the ore body is apparent. Because of this it is thought that the flat-lying pegmatites served as relatively impermeable barriers, which inhibited the migration of the ore-forming fluids and thus effected sulphide deposition in the sericitized gneiss at or close to their contacts.

Conclusions

Exploration and development work at the various properties permits tentative acceptance of certain valuable conclusions about the mineralization in the area. These facts are as follows:

- (1) The mineral deposits are of Archaean age and may be related genetically to the granitic rocks.
- (2) All the known mineral deposits are replacement deposits, either disseminated or lode fissure in character, and occur in either iron formation or sedimentary gneiss.
- (3) The mineral deposits were formed at high temperatures, and may be considered as representative of Lindgren's hypothermal class.
- (4) The deposits are controlled in their attitudes by the major folded structures, and rake flatly eastward parallel to lineations.
- (5) They lie within a pre-ore folded fault zone that is represented in the field by a persistent horizon of sericitized quartz-oligoclase-biotite gneiss, or they lie within smaller, parallel structures close to the horizon of sericitized gneiss.
- (6) All the important ore bodies are found where the formations strike roughly east-west, and adjacent to and east of places where those formations curve sharply to assume a northwest strike and relatively flat dips to the north.
- (7) Two ore bodies, the Geco and the Willroy No. 3, are localized along the contacts between granite or pegmatite and their respective favourable host rocks.

14. Newhouse, W. H. "Structural Feature Associated with Ore Deposits," in *Ore Deposits as Related to Structural Features*, Princeton University Press, Princeton, N. J., p. 17, 1942.

(8) In two cases, at the Geco mine and in the Willroy No. 1 ore body, flat bodies of pegmatite served as relatively impermeable barriers, which inhibited the migration of the ore-forming fluids and effected sulphide deposition in the host rock at or close to their contacts. It is of interest to note that in several localities in the area, the horizon of sericitized gneiss has been found to disappear beneath outcrops of flat-lying pegmatites. Such occur at west end of the Geco ore body, in the extreme north-west corner of the Willroy property, and again between the Nama Creek and Lun Echo properties. In each of these places favourable ore structures may exist. But it seems unlikely that sulphide bodies can be located beneath the pegmatites by geophysical methods. Rather, it is concluded that successful exploration will necessitate detailed geological mapping, to determine the approximate location and trend of the sericitized gneiss beneath the pegmatites, followed by expensive diamond drilling.

THE BLIND RIVER, ONTARIO, URANIUM AREA*

by

S. M. Roscoe

The development of a major uranium mining field near Blind River, about 100 miles east of Sault Ste. Marie, Ontario, has doubtless been watched with considerable attention by those connected with the mineral industry here in the Lake Superior region. This new mining district is very different from any other mining district in Canada. It is, in many respects, more like an oil field than a mining area. From a geologist's point of view this has had several interesting effects. Probably more than in older mining areas, the services of numerous well-trained geologists are recognized as indispensable not only in controlling exploration work but also in helping to maintain profitable production from known ore-bodies. Most of the mining geologists, coming from other mining areas, have had the stimulating experience of having to re-orient their thinking from an emphasis on structure to an emphasis on stratigraphy and on concepts of sedimentation. Interesting also is the keen interest workers in the area have in problems of genesis – that is: are the deposits syngenetic or epigenetic? An important by-product of the Blind River discoveries is the promise of a wealth of new geological data pertaining to Huronian rocks in the region north of Lake Huron.

The Blind River uranium deposits are in pyritic quartz-pebble conglomerate beds within and near the base of Huronian sedimentary rocks. They are very similar to the gold-uranium deposits of the Witwatersrand in South Africa.

The first discovery of this type of uranium deposit was the Pronto, near the shore of Lake Huron about 10 miles east of Blind River. The uraniferous conglomerate at Pronto was found at the base of a sequence of quartzite and other sedimentary rocks which unconformably overlies granite and greenstone. This discovery triggered intensive prospecting activity throughout the region in 1953. The search was concentrated along the contact between Huronian and pre-Huronian rocks. A number of deposits similar to the Pronto were soon discovered in basal Huronian rocks in the Quirke Lake - Elliot Lake sector about 25 miles northeast of Blind River. All of the important uranium deposits discovered to date in the Blind River area (other than the Pronto deposit) are in this sector.

Numerous other occurrences of radioactive conglomerate have been found in other parts of the region, but in most of these the radioactivity is due principally to thorium. Possibilities of finding uranium deposits in these other areas, however, cannot, by any means, be considered exhausted.

General Geology

In the Quirke Lake - Elliot Lake sector, the Huronian rocks are folded into an open syncline

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which plunges gently to the west. The belt of sedimentary rocks preserved within the syncline is about 9 miles wide and about 5,000 feet thick in the central part (Fig. 1).*

Pre-Huronian Rocks

The pre-Huronian rocks, where overlain by Proterozoic formations, are principally greenstones invaded by granodiorite. These basement rocks are overlain with unquestionable unconformity by the Huronian sedimentary rocks. Immediately beneath the unconformity, in most places, the basement rocks are altered in a manner very suggestive of a weathering profile. The altered zones show gradations upwards from normal basement rocks into highly sericitic rocks which are interpreted as residual deposits, or paleosols formed prior to deposition of the Huronian sediments. This residuum is thickest - locally up to 50 feet thick - where it overlies granitic rocks. It seems probable that such deeply-weathered zones were extensive over the pre-Huronian surface and provided the source of detrital material for the basal Huronian sediments.

Huronian Sedimentary Rocks

The Huronian sedimentary rocks of the North Shore of Lake Huron region were divided by Collins (1925) into a lower, Bruce series and an upper series called the Cobalt series. The Bruce series was divided from bottom to top into: the Mississagi formation - mainly quartzite; the Bruce Boulder conglomerate; the Espanola formation - limestone and greywacke; and the Serpent quartzite formation.

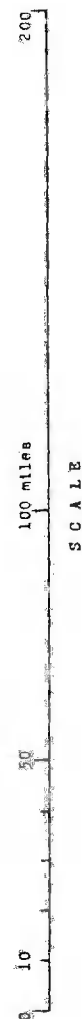
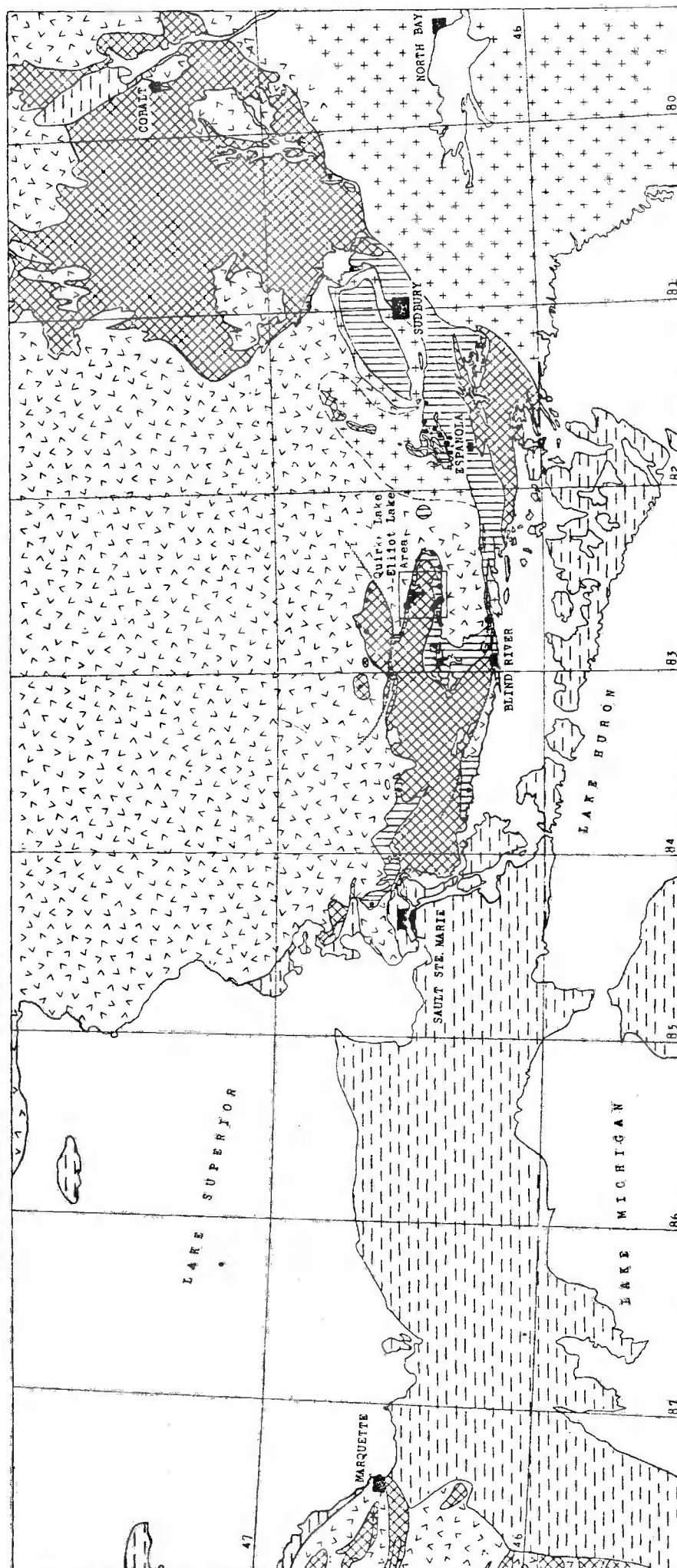
Numerous drill-holes have now provided much more detailed information on the succession in the Quirke Lake - Elliot Lake sector than was obtainable from the original surface mapping. Stratigraphic correlations are very important in exploration for uranium ore in this area, so it seems very desirable that some of the rock-stratigraphic units be redefined in the light of these new data. It is proposed that the Huronian rocks be divided into groups on the basis of cyclic repetitions of boulder conglomerate layers throughout the sequence. The Mississagi unit is elevated from formational rank to group rank and its base is defined as the bottom of the lowermost boulder conglomerate. The Elliot group, below this boulder conglomerate, is subdivided into two formations, the Matinenda formation and the Nordic formation. (Table I).

Matinenda Formation

The Matinenda formation contains all of the uranium deposits of the area and will be described in some detail. It is not possible within the scope of this paper to describe other stratigraphic units. These are illustrated diagrammatically on the accompanying composite columnar section. The following general features shown on the diagram might be noted in passing: The succession is characterized by layers of boulder conglomerate, each overlain by fine-grained sedimentary rocks which are in turn overlain by coarse grained, clastic sedimentary rocks. Both the Elliot group and the Mississagi group thicken rapidly to the south and also show a pronounced decrease in grain size in this direction. Note also that the Mississagi group overlaps the Elliot group in the northern part of the area. Such

* Unfortunately it is not possible to reproduce more of the author's maps in this publication. The reader is referred to the bibliography. - Ed.

DISTRIBUTION OF "HURONIAN" ROCKS IN THE REGION NORTH OF LAKE HURON



- Palaeozoic and Keweenaw rocks
- Granite, Granitic gneiss, Basic intrusive rocks (Sudbury complex), may include some older granite (1)
- "Huronian" sedimentary, volcanic, and metamorphic rocks.
- Lowermost "Huronian" sedimentary, volcanic, and metamorphic rocks.
- Granite and Greenstone. + include some younger granite (4)
- Fault
- Group of radiometric occurrences

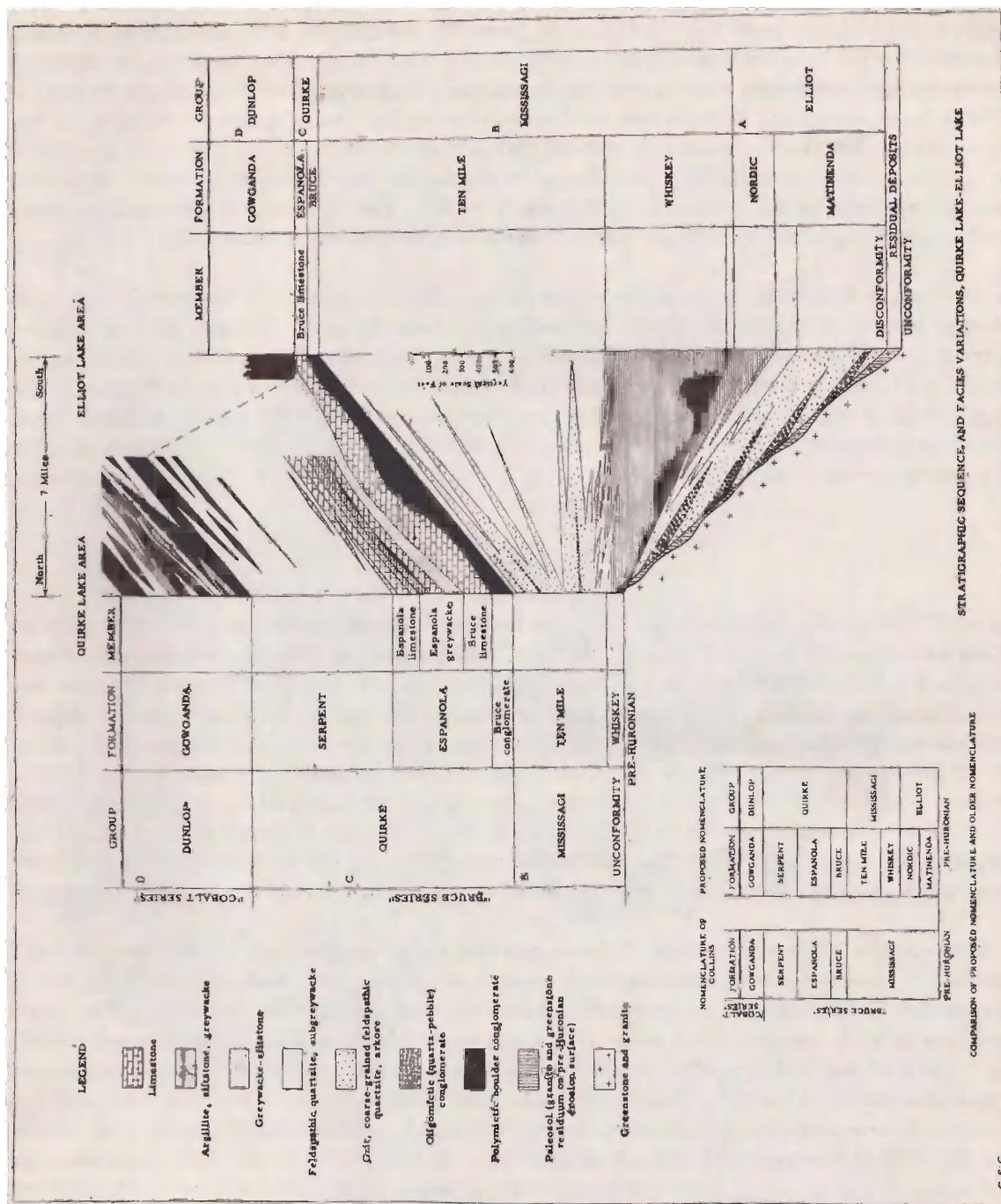


Table I

overlaps towards the north of lower formations by succeeding higher formations is characteristic of the Huronian succession throughout the region.

The Matinenda formation is composed of coarse-grained, clastic rocks including: quartz grit, feldspathic quartzite, arkose, and quartz-pebble conglomerate. These rocks are poorly bedded and poorly sorted, for the most part. Torrential cross bedding, seen on all outcrops of the formation, shows dips which were originally southeast to east (prior to folding). The formation shows pronounced local variations in thickness as well as a general regional thickening from north to south (0 to 700 feet). These local variations in thickness are believed to reflect the original topography of the pre-Huronian surface. The thicker parts can thus be interpreted as representing filled valleys, while adjacent thinner portions overlie hills and ridges on the buried pre-Huronian surface. Isopach maps show these valleys and ridges to have a southeasterly trend. The formation is believed to have been of alluvial origin, deposited by streams which flowed in a southeasterly direction.

The Matinenda formation is distinctly radioactive. The radioactivity, apparently due mainly to monazite and zircon, is highest in coarse-grained pyrite-bearing beds. Closely packed quartz-pebble conglomerate is particularly pyritic and radioactive, with the radioactivity due to disseminated high-grade uranium minerals - brannerite, uraninite and 'thucolite' - as well as due to thorium in the more ubiquitous monazite and zircon. The thickest, coarsest-grained, most closely packed and most uraniferous conglomerate beds are found in relatively thick parts of the formation - that is, within or overlying pre-Huronian "valleys".

Uranium Deposits

Two such "valley" structures contain most of the uranium ore deposits discovered to date in the area. One extends southeastward from the Algom-Quirke mine and contains ore deposits along a length of about 5 miles which include the Algom-Quirke deposit, the Consolidated Denison deposit, the Spanish American deposit, the Zenmac deposit, the Panel deposit, and the Can Met deposit. The other extends northwestward from Algom's Nordic mine and contains ore deposits along a known length of about 4 miles which include the Nordic deposit, the Lake Nordic deposit, the Milliken Lake deposit, and the Stanleigh deposit. Algom's two mines are approaching production with plants that will have a combined capacity of 6,000 tons per day. Denison is constructing a 5,700 ton plant; Can Met, a 2,500 ton plant. The other companies mentioned are either sinking shafts or have announced plans to sink. Pronto is in production with a plant rated at 1,250 tons per day capacity.

Thicknesses of ore zones are about 10 feet, and individual ore sections up to 32 feet thick have been reported. The ore deposits most typically consist of interlayered beds, one to three feet thick, of quartz-pebble conglomerate, conglomeritic quartzite, and pebble-free quartzite. The selection of the sections of such conglomeritic zones which are to be mined must be carefully controlled by sampling. Some of the highly pyritic conglomerate layers contain several tenths of one per cent U_3O_8 , and rare seams, a fraction of an inch thick, may contain up to several per cent U_3O_8 . Conglomeritic quartzite contains less uranium than the highly pyritic conglomerate, and pebble-free quartzite contains only very small amounts of uranium. In places, however, such quartzite contains a very high uranium content associated with pyrite along seams which follow cross-bedding planes. The ratio of thorium to uranium varies widely. In quartzite and pebbly quartzite it is about 3 to 1. In most ore deposits it is less than 1 to 1. In general, pyrite content, uranium content and thorium content all show close relationships to sedimentary features but show no clear cut relationship to features such as folds, faults, or contacts of diabase dykes. Places have been discovered, however, where uranium values appear to cut across sedimentary contacts and where rocks, not normally very

radioactive, contain ore where they are in contact with rich conglomerate.

Pyritic Quartz-pebble Conglomerate

The ore conglomerate contains pebbles of quartz, a few chert and jasper pebbles, and, very rarely, pebbles of argillite, greenstone, and granite. Pebbles are from 1/4 inch to 2 inches in diameter, and fairly well sized within individual layers (Fig. 2). They are moderately rounded and, in the



Fig. 2. Hand Specimens of Pyritized Conglomerate from, left to right; Pronto Uranium Mines, Ontario; Algom Uranium Mines, Ontario.

richest conglomerates, are tightly packed. The matrix contains abundant grains of pyrite, poorly-sorted granules and silt-sized particles of quartz and feldspar, and small plates of muscovite, sericite, chlorite, and epidote.

The poorly sorted matrix of the conglomerate was probably not greatly modified by diagenetic processes. Secondary quartz is found at the rims of some quartz pebbles. Overgrowths are found on a few quartz and feldspar grains and a little carbonate is present in the matrix of some conglomerate samples. It is difficult, however, to distinguish between secondary minerals of authogenic origin and those related to later metamorphism and hydrothermal alteration.

The conglomerates and adjacent rocks have been markedly deformed, probably concomitantly with folding and thrust faulting in the Huronian rocks. The following effects of such deformation are observable in thin sections: undulatory extinction in quartz grains; fractures with displacements; rotation of grains; and comminution of matrix material. The crushed rocks have been re-healed by secondary quartz, mica, chlorite and other minerals. Serrated boundaries between grains and granular texture within pebbles are common. Much of the pyrite has clearly crystallized or has been recrystallized subsequently to the deformation. Some of the uranium mineralization is also post-deformation in age.

Most of the uranium in the ore is within grains of an amorphous, or metamict, material. This material contains abundant inclusions of anatase and gives an X-ray powder diffraction pattern similar to that of anatase; after strong heating, it gives the pattern of brannerite - a uranium titanate - as well as an anatase pattern. This material is therefore referred to as 'brannerite', although it cannot be considered certain that it was ever in the form of crystalline brannerite. The 'brannerite' occurs as discrete rounded grains and also as irregular intergrowths with pyrite. Uraninite is abundant in some ores and is found as angular to subangular grains. Brecciated uraninite grains have been noted. 'Thucolite', a uraniferous hydrocarbon, is common along fractures in the ores and also in rocks a considerable distance away from ore conglomerate beds. Pitchblende has been reported. Monazite and zircon, abundant in most ore samples, occur as rounded grains of detrital origin. Radioactive epidote (possibly allanite) and radioactive titanite have also been noted.

Marcasite occurs in place of pyrite in some ores. Pyrrhotite and chalcopyrite are common, particularly in conglomerate at the very base of the Matinenda formation. Magnetite has been reported associated with pyrite. Cobaltite has also been identified. Galena is common. Molybdenite is found along slip planes in adjacent country rocks. Sphalerite is commonly associated with thucolite and carbonate in veinlets. Trace amounts of gold, silver, chromium, nickel and vanadium are also present in the ores.

Origin

Our knowledge of these deposits is still far too incomplete to allow any forceful advancement of a theory of their genesis. It might be interesting, nevertheless, to give a brief summary of the more credible hypotheses of origin which have been advanced.

The placerists suggest that the original quartz-pebble gravels contained hematite, ilmenite, magnetite, rutile, titanite, epidote, pyrite and other sulphides, monazite, zircon and many other heavy minerals, including uranium minerals (possibly 'brannerite' and uraninite). Subsequent diagenetic and metamorphic processes effected a certain amount of solution, redistribution, and recrystallization of constituents with little change in bulk chemical composition or addition of new

elements other than sulphur. Large quantities of the latter are, of course, required to convert iron oxides to pyrite.

The most serious criticism raised against this theory is that uranium minerals, particularly uraninite, are very unstable under weathering conditions and could not possibly have survived to become important constituents of the gravels. The most resistant radioactive minerals, such as monazite, contain much more thorium than uranium. Such minerals are also the most abundant radioactive minerals in most granitic rocks, which most commonly have a thorium-uranium ratio of about 3 to 1. If it be granted for the moment that it is unlikely that there were in the source area any large bodies of rock which contained resistant uranium minerals in greater abundance than thorium minerals, then it seems unlikely that extensive placer deposits which contain more uranium than thorium could have been formed. It is necessary, therefore, to consider possible mechanisms whereby the conglomerates could become enriched in uranium relative to thorium. Hydrothermal solutions or ground water, for example, may have dissolved uranium from adjacent country rocks and re-precipitated it in conglomerate; thorium might, at the same time, have been removed from the conglomerate.

The hydrothermalists, seizing with glee upon the fact that the placerists are forced to admit that huge quantities of sulphur must have been added to the conglomerates, suggest that the relatively minute quantities of uranium in the conglomerates were introduced in the same manner, probably at the same time and probably from some deep seated source, rather than from adjacent rocks or from surficial waters.

This later hypothesis requires that the conglomerates were preferred exclusively to all other rocks and structures as hosts for the introduced uranium. Such a preference could be attributed only to a much greater permeability or much more dilatant condition of the conglomerates as compared to other rocks at the time of the postulated uranium mineralization. Prior to consolidation, the quartz-pebble gravel with its poorly-sorted matrix was probably not greatly more permeable than overlying and underlying sands. It is difficult to evaluate how the relative permeabilities of the two rock types might have been changed by diagenesis, by cataclastic deformation and by metamorphism.

Most of our present knowledge of these uranium deposits is of a qualitative nature. Quantitative data on mineralogy, chemical composition, structural relationships, ages of mineralization, and so on, may resolve the problem, but a consideration of the length of time that the same problem has been argued in South Africa would warn us against expecting a speedy solution to the problem of origin of the Blind River Uranium ores.

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Discussion

Dr. A. W. Jolliffe (Queen's University, Kingston, Canada): I would like to comment very briefly on this paper. One thing that I think the speaker did not emphasize that is worthwhile stressing is that here is an unusual deposit with some hundreds of millions of tons worth something in excess of a billion dollars. That is not just a pious hope; it has been blocked out and a great deal of the ore has already been sold. So here is one of the great deposits of all time and it was found by a geologist, Mr. Franc. R. Joubin. The staking that followed the initial find was entirely guided by a geological map prepared by the Geological Survey of Canada - Dr. Collins' original map of this area made in 1924. I think that point is worth stating; perhaps Dr. Roscoe did not want to stress it because he is a member of the Geological Survey of Canada himself, and I know from talking with the people who are developing these mines how great a contribution they feel that geology in general, and the Geological Survey of Canada in particular, have made to the development of this amazing camp.

Dr. J. W. Gruner (University of Minnesota): If we could imagine that the Colorado Plateau were metamorphosed as the Bruce series is we might get something similar to the Bruce series and to the Blind River deposits but there would be certain differences which would be very marked in the Plateau. We have no thorium whatsoever and of course that is one reason why the Plateau deposits are easy to explore because thorium does not interfere with any of the radiometric counting. We would also have another difference - that would be the presence of organic-plant trash as they call it out there. This is fossil material which of course would not be present in the Bruce series. But one thing we would have that would correspond to the thucolite, except for the thorium, would be asphaltite. The largest deposits on the Plateau are associated with this supposedly oil-derived, asphaltic hard material which you call thucolite in Canada. The clastic nature of the brannerite which I have seen in microscopic sections has been compared with the clastic grains of uraninite in the Witwatersrand. However that is the greatest objection, as you all know, to epigenetic hydrothermal origin of these deposits, if these clastic grains exist. If they are really clastic grains we must change our ideas of the climate of the Precambrian because uraninite is not stable, we are sure, under the present conditions of oxygen in the atmosphere.

Mr. Wm. Belobraidich (Oliver Iron Mining Division): I understand that airborne magnetics were flown over the area. Was there any significant correlation between the magnetics and the orebody itself?

Dr. Roscoe: No, there was none whatsoever; even scintillation airborne surveys have not been outstandingly successful in the area. They in general simply show outcrop areas of the Matinenda formation or other radioactive formations and the aerial-magnetic surveys show diabase dikes and gabbroic bodies in basement rocks. There has been some thought of attempting to trace basement structures by use of magnetic information with the view that the basement structures would have a bearing on the topography of the basement floor and one might be able to get some clues about drilling in that manner, but nothing successful has been done that I know of.

MAGNETIC PROSPECTING FOR IRON ORES

by

W. George Wahl

Iron-rich minerals forming ore deposits can be detected by all of the commonly used geophysical techniques except those based on radioactive decay. If the necessary geophysical contrasts exist, iron ore deposits can be mapped by electromagnetic, resistivity and self-potential surveys. Gravity surveys have outlined non-magnetic ore bodies but magnetism is the natural field force most commonly measured in the geophysical prospecting for iron ores.

In general it may be stated that either iron ore deposits or the iron formations from which the deposits are derived are magnetic. This is true of the deposits in Michigan, Minnesota, Labrador, Quebec, and Ontario, but not of the Steep Rock and Michipicoten, Ontario, and Wabana, Newfoundland districts.

The increased competition for new iron ore deposits caused by the depletion of reserves has forced instrument modifications and changes in field procedures which would speed up the mapping of magnetic data. Interpretive techniques had to be devised which would satisfy the demand for a rapid appraisal of magnetic anomalies.

The field and interpretative methods and instrument modifications which will be discussed encompass the whole range of magnetic instruments from the first geophysical tool, the compass, to the latest, the airborne magnetometer.

The compass is being used more and more as a reconnaissance geophysical tool because of its portability and ease of operation. The type of compass commonly owned by the prospectors can be used to gather data on the direction of the horizontal component of the magnetic force. If sufficient care is used, the results obtained can map magnetic deposits in great detail. The least a compass survey can accomplish is to delimit the area for more involved surveys.

The compass may be used as a geophysical tool by measuring the azimuth of a line at fixed intervals across the area to be mapped. Pacing along surveyed property boundaries, claim lines, or picket lines will give sufficient control for this type of mapping.

The local magnetic deflection may be plotted by arrows pointing in the direction taken by the compass needle. Figure 1 shows the results obtained by measuring the azimuth of north-south claim lines at 200 foot stations across an iron formation. This illustration shows that traverse lines 1/4 mile apart will map an iron formation in sufficient detail to enable certain deductions to be made as to the location and size of the causative body. In this particular case, the data show that the iron formation reaches its greatest width towards the east side of the area mapped. This survey showed that the formation had a large potential volume and minable width. Prospecting in the area outlined by this survey uncovered an iron formation of sufficient promise to warrant further work. The compass survey, besides delimiting the area to be covered by a magnetometer survey, also shows the direction which the traverse lines should take to yield the most informative results.

The data obtained on a compass survey may be shown in another manner. If the amount of deflection from regional magnetic north is computed and if a negative value is assigned to those deflections which are east of regional magnetic north and a positive value to those deflections west of regional magnetic north, the data may be contoured. The contoured results will show approximately the location, length, and width of the causative body. The depth may also be approximated. A line drawn along the crest of the positive and negative anomalies will mark the extreme outside limit of the magnetic deposit. These lines will also tend to define the length of the causative body. The zone across which the greatest rate of change occurs marks the axis of the magnetic body and also gives an indication of the depth of burial.

The dip needle is another reconnaissance geophysical tool which will return excellent results if properly used. The lack of control on the survey, misorientation and improper leveling are in direct relationship with the care exerted by the operator. It has been found that a spot bubble on the face of the instrument will be a great aid in orienting the dip needle in a strong magnetic field. It can be shown that if the needle is counter-balanced so as to come to rest in a position normal to the earth's magnetic field the instrument is much more sensitive to small changes in that field. The confusion of positive and negative values, which are actually at odds with the normal conception of up and down can be eliminated by reading zero when the north-seeking end of the needle points vertically up, 90° when horizontal and 180° when pointing vertically down.

A Schmidt-type magnetometer is by design a delicate instrument of great sensitivity but cumbersome to use. Magnetometers have been or are being designed which will speed up the mapping of the data in the field. The null type, torsion magnetometers which do not have to be oriented or leveled and which have a great range of values are a step in the right direction.

A practical solution to the time-consuming practice of changing auxiliary magnets in the Schmidt type instruments is to increase the size and weight of the sensitivity screw so that the scale constant is increased to around 400 or 500 gammas per scale division. It has been observed that little information is lost by using such a large scale constant when the results have to be contoured in 5000 gamma intervals.

A detailed interpretation of magnetometer results obtained on a closely controlled survey will describe the causative body as to location, depth, length, width and approximate grade or susceptibility. This is time consuming but the results obtained are usually sufficient to enable a conclusion to be drawn as to the relative worth of the causative body.

The following interpretative techniques have been devised which will rate the relative significance of magnetic anomalies on a preliminary appraisal of the magnetic data.

Location: The causative body is directly below the peak of a magnetometer anomaly.

✓ Depth: The depth can be approximated by measuring the horizontal distance between points where isomagnetic lines of equal intensity are evenly spaced and closest together.

Area: The size of the causative body can be approximated by sketching a line which joins the points of zero curvature around the anomaly.

Grade: The relative grade or susceptibility of a magnetic body can be determined by comparing the intensity per unit area of its anomaly with other anomalies of the same shape in the immediate area. A discussion of this technique together with illustrations is presented later on in this paper.

An airborne-magnetometer survey is the most rapid method by which large areas can be mapped. The unit cost is low and the accuracy of the data obtained on a well controlled survey is equal to that

obtained by the most sensitive ground instruments.

In Canada airborne-magnetometer maps are available at relatively low cost from several government agencies. These maps show the magnetic data as mapped at the flight elevation and along certain flight lines. The data are contoured and as a result the placement of isomagnetic lines between the flight lines is interpreted. This causes some of the discrepancies encountered when comparing the results of a ground survey with those found on an airborne map. It is mere chance that a flight line passes directly over the peak of an anomaly. During a field examination the area between flight lines on either side of the peak of the anomaly mapped should be investigated. In some areas the lack of identifiable ground control causes some errors in the plotting of data. It is therefore advisable to cover additional ground to insure the adequate mapping on the ground of the cause of the anomaly found by the airborne-magnetometer survey. No additional work such as drilling or test pitting should be based on the results of an airborne survey alone.

When examining a magnetic trend on an airborne sheet it may be observed that the peak values are not constant. This may be caused by a differing tenor of magnetite along the strike of the formation, by thickening and thinning of the formation, by differences in depth of the burial of the formation, by different flight elevations on adjacent flight lines, or by combinations of any of the above.

Any interpretation of airborne magnetometer data must be made with a realization that the intensity varies inversely as the square of the distance and that closely spaced anomalies on the ground may resolve into one anomaly at the flight elevation. All interpretative techniques apply equally as well to airborne data as they do to ground data.

The intensity per unit area method of comparing anomalies is especially useful when examining an airborne magnetometer survey. This consists of recording the intensity of an anomaly and dividing by the surface area of the anomaly. Comparison should only be made between anomalies of the same shape and depth of burial. For example, in the vicinity of Marmora, Ontario there is a 7,000 gamma positive anomaly found over the magnetite deposit now being mined by Bethlehem Steel Company, (Fig. 2). Approximately 10 miles northeast of Marmora another 7,000 gamma anomaly is located which is caused by a basic intrusive carrying about 5% magnetite, (Fig. 3). The anomaly over the magnetite deposit has approximately 10 times the intensity per unit area of the other anomaly. It may be assumed that magnetite comprises 50% of the mass causing the Marmora anomaly. This approximates the average grade of iron (35%) as shown by drilling.

Anomalies whose causative bodies are at different depths of burial can be evaluated in a like manner. It is assumed that the intensity varies inversely as the square of the distance. Figures 2 and 5 show the Marmora anomaly as mapped at 500 feet terrain clearance. Figure 4 shows the anomaly mapped at 5,000 feet terrain clearance.

The following formula can be applied:
$$\frac{\text{distance squared} \times \text{intensity}}{\text{area}}$$

$$\text{Figure 2} \quad \frac{(500)^2 \times 6,700}{16,000,000 \text{ sq. ft.}} = 104$$

$$\text{Figure 4} \quad \frac{(5,000)^2 \times 140}{50,000,000 \text{ sq. ft.}} = 70$$

Figure 5 $\frac{(500)^2 \times 4,100}{14,500,000 \text{ sq. ft.}} \approx 70$

The discrepancy in the above results is caused by the inability of the airplane to duplicate the flight paths. The results are sufficient to show that the method has merit.

In comparing anomalies by this method only those anomalies of similar shape should be compared. Great discrepancies can result if long linear anomalies are compared to circular anomalies. Differences are also great when linear anomalies trending north-south are compared to east-west trending anomalies.

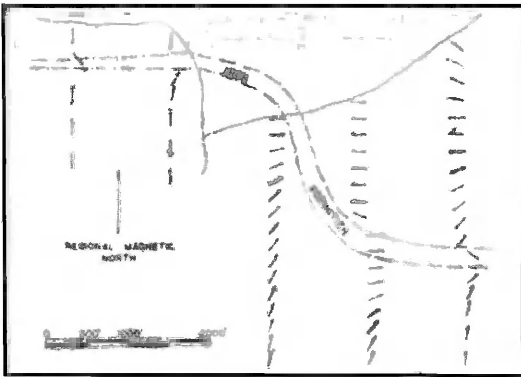


Fig. 1. Compass survey across iron formation.

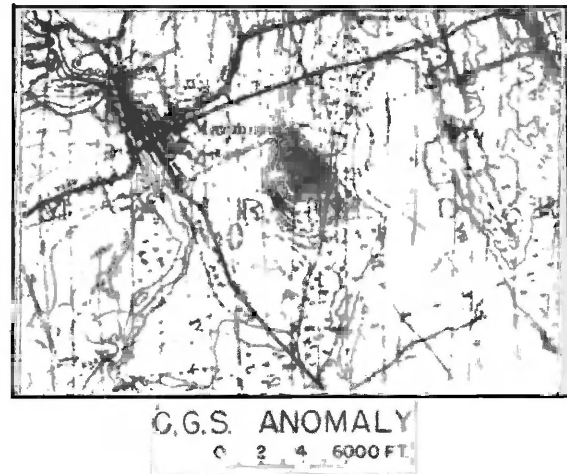


Fig. 2. Seven-thousand gamma anomaly at Marmora, Ontario.

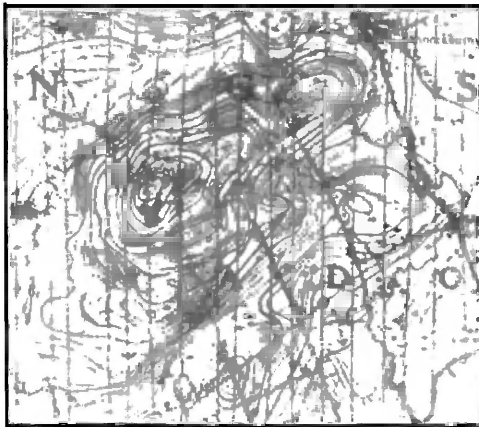
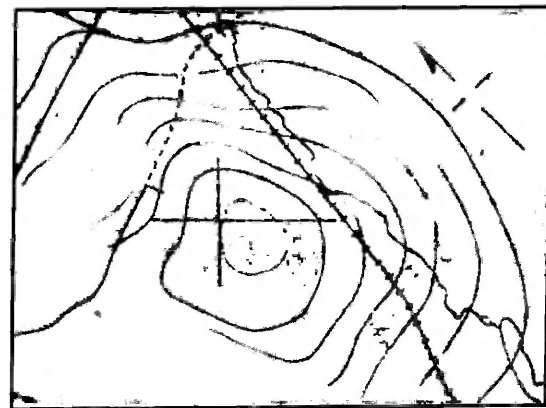
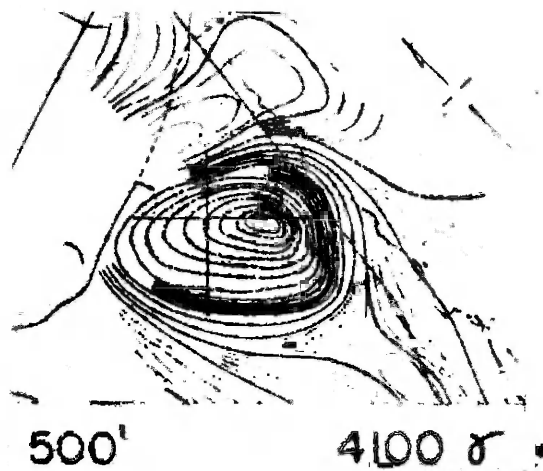


Fig. 3. Seven-thousand gamma anomaly ten miles northeast of Marmora, Ontario.



5000' 140'

Fig. 4. Marmora, Ontario anomaly at 5,000 feet clearance.



500' 400'

Fig. 5. Marmora, Ontario anomaly at 500 feet clearance.

RELATIONSHIP OF GRAVITY TO GEOLOGICAL STRUCTURE IN MICHIGAN'S UPPER PENINSULA

by

L. O. Bacon

Introduction

Gravity measurements were begun in the Upper Peninsula in 1950 in an attempt to determine the relationship between gravity variations and known geological structure, the final purpose of the work being to increase our knowledge of major geologic structures which in the most part lie hidden beneath glacial drift in the western half of the peninsula or beneath the Paleozoic sediments of the eastern half of the peninsula. This paper is a composite of work carried out by the writer and that of four students who investigated selected areas as part of their graduate programs.

The area which was covered is shown in plate I. The Upper Peninsula of Michigan comprises an area of about 17,000 square miles.

Station density varied considerably, a total of 4000 stations being occupied; however, station density varied from approximately one per square mile in the Iron River mining district to as little as one per township in the eastern end of the peninsula. In almost all cases stations occupied were along existing roads which in some areas are not very plentiful.

Field Work

The gravity measurements were made with a Worden geodetic instrument which has a very low instrumental drift rate.

Probable error in determination of latitude of the stations was ± 0.1 mile. The majority of the stations occupied were U. S. Geological Survey or U. S. Coast and Geodetic Survey bench marks or along Michigan highways where elevation control was better than ± 1 foot. In areas where few bench marks were available, elevations were obtained by altimeter, using a station microbarograph to monitor air pressure fluctuations. Elevations determined by altimeter have a probable error of ± 5 feet in much of the area. Some elevations determined in this manner may be in error by ± 10 feet.

Topographic corrections were made for a limited number of stations; and such effects at other stations probably do not exceed 0.2 or 0.3 milligal, since the area is not rugged. Effects of curvature of the earth are of the order of 0.3 to 0.6 milligal, depending upon elevation of the station. Indirect effects are essentially constant over the area covered. In view of the above probable error, it is believed that the precision of the reduced data is of the order of ± 1 milligal.

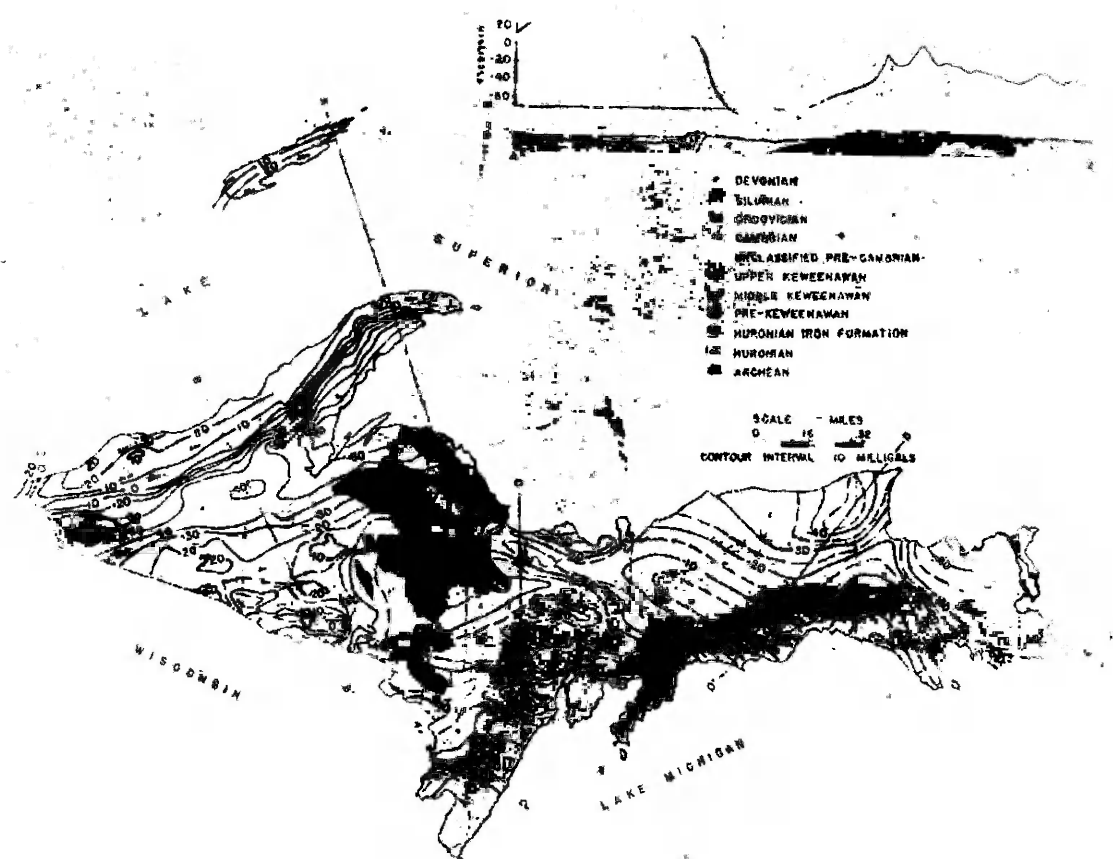


Plate I. Gravity-geological map of Upper Michigan.

All stations values are calculated relative to the pendulum station at Iron River¹, having a Bouguer value of -5 milligals.

Plate I shows the gravity data of the Upper Peninsula contoured at a 10 milligal interval with the 5 milligal contour indicated in part of the area.

1. Numbers refer to bibliography at end of paper.

Geology is taken from the Geologic Map of the Upper Peninsula of Michigan² and is somewhat generalized for the purposes of portrayal. The Huronian iron formations are shown, not primarily because they in themselves are deemed so important for their contribution to the gravity picture but primarily as a marker horizon; it is quite obvious, however, that upper Huronian sediments in synclinal structures do produce positive Bouguer anomalies.

Major gravity anomalies occur in the Keweenaw Peninsula associated with the middle Keweenaw lava flows. Other anomalies in the western half of the peninsula are generally associated with Huronian synclinal structures. A broad regional gravity anomaly exists in the eastern half of the peninsula.

On the Keweenaw Peninsula gravity values vary from +10 milligals along the north side of the peninsula to -70 milligals about 16 miles to the southeast along the southeast side of the peninsula. The contact between the sandstones and the flows is a fault. This is a fairly steeply dipping reverse fault having a throw generally considered to be the order of a few thousands of feet. A conservative estimate, from calculations based upon the observed gravity data, is a throw of the order of 12,000 feet, using a density contrast of 0.48 between the Keweenaw flows (density 2.86) and the sandstone (density 2.38). The very large gravity anomaly of the order of 100 milligals is strikingly similar in appearance to the mid-continent gravity high through Wisconsin, Minnesota, Iowa and Kansas.^{3,4}

At the western end of the Upper Peninsula the major feature is still the anomaly associated with the Keweenaw flows. However in the northern portion of the area a gravity terrace occurs on the flank of the anomaly. This is in the Porcupine Mountain region and is associated with the acid intrusives, granites and felsites which invade the area.

The Huronian iron formation in the western end of this area is the iron-producing Gogebic range. The Huronian sediments here do not give rise to any pronounced gravity effect, a fact which may be attributed in part to lack of sufficient gravity stations as well as the narrowness of the band of sediments, which dip steeply northward between the Keweenaw flows to the north and the Archean granites to the south. There is, however, a warping of the gravity contours produced by the flows to the north and the less dense Archean rocks to the south.

The south central area is almost entirely underlain by Precambrian sediments. The Upper Huronian sediments which occur in synclines such as the Iron River-Crystal Falls district of the Menominee range produce positive gravity anomalies because of the density contrast of about 0.3 between the Upper Huronian sediments and the surrounding Pre-Cambrian greenstones. Calculations indicate that the syncline which comprises the Iron River-Crystal Falls district has a depth of the order of 6000 feet. The deepest mines in the area extend downward only about 2000 feet.

To the west of this district occurs a gravity anomaly which is about of the same order of magnitude. In a paper by Wyble and the writer in 1951⁵ the probable presence of a Huronian sedimentary basin in this area similar to the one to the east was postulated. There are no outcrops in the area, and seismic refraction surveys have indicated that glacial drift is from 60 to 300 feet in thickness. Drilling on a magnetic anomaly at the south edge of the gravity anomaly in 1955 encountered an amphibolite.⁶ This may be responsible for the gravity anomaly, although the writer does not believe that the limited work done is adequate to discount the original postulation.

The gravity anomaly associated with the Marquette Iron Range, which is a synclinal structure somewhat similar to that of the Iron River-Crystal Falls district, has a maximum of 12 milligals in a surrounding field of -20 milligals. Calculations of the depth of this basin gives a figure of the order

of 8,000 feet.

Between these two synclinal basins lies a dome-shaped structure roughly 15 by 20 miles in extent. This structure is called the Amasa Oval after a nearby village. The core of this structure is Archean granite which gives rise to a negative anomaly of approximately 10 milligals with respect to the surrounding area. The offset of the negative anomaly may well be only apparent, as there is an extensive area which has not a single gravity station in it. Contouring of the area was done on the basis of the data available. In general there are positive anomalies associated with the synclinal structures which contain the Upper Huronian sediments.

The Menominee district shown to the south and east of the Iron River-Crystal Falls region does not produce any pronounced gravity effect. The beds here dip to the south, and their east-west trend is reflected in the warping of the gravity contours.

Magnetic measurements have traced the east-west belt as far eastward as Escanaba on the shores of Lake Michigan where a gravity high of -11 milligals within a surrounding -35 milligals exists. Actually, this gravity high lies to the north of the eastward extension of the Menominee Range; the writer believes that it is due to either a synclinal basin containing Upper Huronian sediments or a topographic high on the Precambrian surface, which at Escanaba lies about 800 feet beneath the surface. The anomaly may be a combination of both the above possibilities. A few magnetic stations in the northeast corner of this gravity anomalous area outlined a magnetic anomaly of about 10,000 gammas.

To the south of the Menominee Range the gravity values decrease rapidly and are probably due to the thickening of the Paleozoic sediments as well as to the presence of granitic basement.

The gravity values in the eastern half of the Upper Peninsula are in the area covered by Paleozoic sediments. The major gravitational anomaly is the one associated with the Marquette iron formation and the broad gravity high extending to the southeast across most of the eastern half of the peninsula.

A number of smaller local anomalies are evident either as closed contours or as warping of the gravity contours. These are evidently a reflection of either the structure or the topography of the Precambrian basement below the Paleozoics. The area is now undergoing active exploration by one of the mining companies.

Returning to consideration of the broad southeast-trending gravity and magnetic anomaly, we observe that it practically disappears where the Paleozoics thin out to nothing, that is, where the Archean rocks crop out, which suggests that the negative values to the north and south are caused by thick accumulations of lighter sediments.

As we go eastward, the anomaly increases in magnitude. The few exposures of Paleozoic rocks have dips generally towards Lake Michigan, except in the northern part where the rocks on the north side of the anomaly dip to the north toward Lake Superior. This fact seems to indicate that this anomaly may be a reflection of the ridge or dividing line between the two basins. This is supported in part by deep drilling in the eastern end of the peninsula.

Farther to the east we observe primarily only the continuation of this anomaly, which seems to continue across the straits of Mackinac into lower Michigan where it probably merges with the gravity high extending nearly the length of the Lower Peninsula. There is also a swing of the anomaly due northward, indicating that the positive anomaly extends perhaps across the eastern end of Lake

Superior. This northward trend seems to tie in with some of the dense lavas exposed along the north and east shores of Lake Superior in Ontario.

There is a definite possibility that it is a continuation of these lavas which produces the anomaly running down through the Lower Peninsula of Michigan. The anomaly through the eastern Upper Peninsula and down through the Lower Peninsula is strikingly similar to the mid-continent gravity high which extends from the western end of the Lake Superior basin down through Minnesota, Iowa, Nebraska and Kansas. This latter anomaly is considered to be caused by a basic rock within the basement complex.

Conclusion

We see that the gravitational picture can be very complex in the region where Precambrian rocks are near the surface. The dense iron-bearing synclinal formations produce positive gravity anomalies, and much information can be obtained about major structural features from gravity investigations.

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Discussion

Dr. W. S. White (U. S. Geological Survey): If you were to complete your profile between Isle Royal and the Keweenaw Peninsula by extrapolation, do you think it would produce a gravity high or a gravity low?

Mr. Bacon: I would expect the Bouguer gravity anomaly to be larger in magnitude; however there might be a trough near the center due to thickening of the Upper Keweenawan sediments.

Dr. White: This large anomaly supports the contention as outlined in my paper on the source of the lavas and mineralizing solutions. Would not the apparent lack of such an anomaly near the eastern end of Lake Superior preclude the presence of Keweenawan lavas in this area?

Mr. Bacon: Not necessarily. The indicated low gravity values in the eastern end of Lake Superior may be due primarily to the thickening of the Lake Superior sandstone.

GEOLOGICAL FACTORS AFFECTING BENEFICIATION OF LAKE SUPERIOR IRON ORES

by

M. E. Volin

The geologist finds it convenient to classify formations according to mineral constituents, origin, texture, color, and many other significant features. In evaluating his discoveries or expectations for discoveries towards reaching a decision on how far to pursue his exploration objectives, the geologist applies some general cut-off factor related to the economics of utilization of the ore minerals, be it grade, metallurgical response, or a combination of many such things. Thus he brings to bear an appreciation of the principal problems involved in converting his potential raw material into a marketable product.

The mineral dressing engineer who receives the samples sent by the geologist is singularly interested in their response to his techniques of beneficiation methods. He assumes that the samples represent the average character of a mineralized body of significant size, and it is his objective to find an economic way to recover the minerals in a useful form. Some of the geological records may be helpful to him in guiding his first estimate of how the mineral dressing problems can be attacked; the degree of usefulness will depend on the geologist's understanding of the problems in applying the beneficiation processes.

Our panel subject may seem somewhat of a departure from the theme of geological exploration, but in proposing this subject it was my hope that the discussions would emphasize some of the geological information about the Lake Superior iron formations that can be of interest to the mineral dressing engineer and would point out factors that the geologist can bring into clearer definition as a help in attacking the mineral dressing problems. Exploration is an initial and very important phase of building and maintaining mineral enterprises, but the successive phases in reaching production are a series of logical steps in overcoming interrelated problems. The best possibility of success is teamwork by people who are experts in their particular lines but are informed on all the phases, and the need for this kind of coordination is more apparent as the problems become increasingly complex.

The changes that have taken place in iron ore mining in Minnesota set a pattern for this industry in the Lake Superior region. We have seen the production picture change from all direct-shipping ores to increasing tonnages of beneficiated ores from larger and more complex plants until today we have the first huge taconite plants. This same trend with some different characteristics is underway here in Michigan, and it is being hastened by the competition from premium grade imported ores. As the low-grade iron resources come more and more into the picture, it is evident that a greater degree of teamwork between geologists and mineral dressing engineers is needed to resolve the problems of utilization. Just as the geologist has developed classifications of the iron formations to aid his search for ore, the mineral dressing engineer needs classifications of the formations, or other resource segments, in terms of metallurgical response. The geologist can provide a lot of information helpful in dealing with the mineral dressing problems. The need for this sort of approach was pointed out as long ago as 1933 by Dr. T. M. Broderick, then research professor at the Michigan College of Mining and Technology, in his AIME publication entitled "Application of Geology to Problems of Iron Ore

Concentration."¹¹

We have for speakers men who have worked on the many problems of the Lake Superior iron ores and have an appreciation of the complex character of the low-grade resources. Each has been closely associated with the particular phase of the subject he will present. Although our discussions will largely be concerned with the Michigan iron formations, we are fortunate in having two of our Canadian neighbors here to tell us about the problems of the siderite ores in their locality; their information should be helpful to us in appraising the possibilities of the Michigan siderites.

Panel

GEOLOGICAL CHARACTERISTICS OF MICHIGAN IRON ORES AFFECTING BENEFICIATION

by

Alan T. Broderick

(Abstract)

The amenability of an iron-bearing rock to beneficiation by physical methods depends principally on its mineralogy and grain size. In the case of sedimentary iron formation, these features were determined by events in geological history which can be conveniently divided into three periods.

During the sedimentation-diagenesis period the original mineralogy and texture were established in response to the sea bottom and pre-lithification environment. If the principal iron mineral were magnetite in coarse enough grains, the amenability of the rock to magnetic concentration was established then without any later geological process being necessary. If, on the other hand, the principal mineral were hematite rather than magnetite, the formation would not be workable today without the grain-coarsening effect of metamorphism because the fine grind necessary for liberation is too fine for the flotation process. In some very restricted areas the siderite in carbonate-facies iron formation is pure enough to be of possible interest as a source of sintering ore. Silicate-facies rocks, since the iron in them is chemically bound to silica, cannot be made to yield a desirable product by physical methods regardless of the grain size. The grains of pyrite in sulfide-facies rocks are too fine to be upgraded by known physical methods.

During the metamorphism period, the iron minerals adjusted to the new environment by increasing in grain size and/or by forming new minerals. In centers of high-grade metamorphism (garnet zone and above) the hematite and magnetite in iron formation of the oxide facies were so increased in grain size that the rock was made amenable to beneficiation by flotation. Under intense metamorphism, silicate, carbonate, and locally oxide facies rocks alter to coarse grunerite and are therefore not treatable physically. There is no appreciable volume of sulfide-facies rock in high-grade metamorphic areas in Michigan.

During the oxidation period, the hematite of the oxide facies rocks was not altered. Magnetite altered to martite. The carbonate-and-silicate-facies rocks, particularly in low-grade metamorphic areas, were profoundly altered. If the carbonate and silicate layers simply oxidized in place with little or no addition of iron, the result is a banded rock containing layers of earthy hematite and/or goethite which is not treatable by gravity or flotation methods. However, magnetic roasting may be applicable. If, on the other hand, iron moved during the oxidation period and locally enriched the

iron layers sufficiently, the result is a rock made up of bands of hard, dense direct-shipping grade material alternating with lean cherty or argillaceous layers. Some of this type of formation can be and is being treated by gravity methods in Michigan.

Table I shows graphically the relationships between the products of these three periods of geologic history.

In order of decreasing tonnage available in significant widths at ledge in Michigan, the geological types of iron formation are listed below. Where a beneficiation plant is in operation or has been contemplated, it is listed with its type.

- | | |
|--|--|
| 1. Oxidized/Low-grade metamorphic/Carbonate and silicate facies | Book Mine, Iron County |
| 2. Unoxidized/Low-grade metamorphic/Carbonate and silicate facies | |
| 3. Low-grade metamorphic/Oxide facies | Empire Mine, Marquette County |
| 4. Unoxidized/High-grade metamorphic/Silicate facies, silicated carbonate and oxide facies | |
| 5. High-grade metamorphic/Oxide facies | Humboldt, Republic Mines,
Marquette County
Groveland Mine, Dickinson
County |
| 6. Unoxidized/Low-grade metamorphic/Sulfide facies | |
| 7. Oxidized/High-grade metamorphic/Silicate facies, silicated carbonate and oxide facies | Ohio Mine, Marquette County |

Minerals resulting from OXIDATION	Minerals resulting from METAMORPHISM (Biotite Zone & Below)	Principal Mineral in SEDIMENTATION and Diagenesis Facies	Minerals resulting from METAMORPHISM (Garnet Zone & Above)	Minerals resulting from OXIDATION
Specularite	← Specularite (3)	← Hematite → ↳ +SiO ₂ →	Specularite (5)* → Grunerite →	Specularite Hem. & Lim.
Martite	← Magnetite (3)*	← Magnetite → ↳ +SiO ₂ →	Magnetite (5) → Grunerite →	Martite Hem. & Lim.
Hem. & Lim. (1)*	← Siderite (2)	← Siderite → +SiO ₂	Grunerite (4) →	Martite (7)* Hem. & Lim.
Hem. & Lim. (1)*	← Silicates (2)	← Silicates →	Grunerite (4) →	Martite (7)* Hem. & Lim.
Limonite	← Pyrite (6)	← Pyrite →	Pyrite & Pyrrh. →	Limonite

* Existing & contemplated beneficiation plants in Michigan

Numbers show approximate order of decreasing volume available at ledge in Michigan.

Table 1

THE RELATIONSHIP OF DIAGENESIS, METAMORPHISM
AND SECONDARY OXIDATION TO THE CONCENTRATING
CHARACTERISTICS OF THE NEGAUNEE IRON-FORMATION
OF THE MARQUETTE RANGE

by

G. J. Anderson and Tsu Ming Han

Introduction

Over the past few years all of the major mining companies in the Lake Superior District have been focusing a great deal of attention on methods and techniques to beneficiate the large low-grade reserves of iron formation distributed in this area. The Cleveland-Cliffs Iron Company has conducted extensive research on the Negaunee Iron Formation of the Marquette Range, and as a result have three properties in operation and a fourth which will be developed within the next few years. We have found that microscopic studies have played an important part in this research and have contributed considerable information to the development of the low-grade ores. These studies reveal that the methods and degree of concentration are governed by the geological processes to which the primary iron formation was subjected. The purpose of this report is to discuss the various types of iron formation produced by these processes and their concentrating characteristics.

There have been at least two major theories regarding the origin of the iron formation. The earlier of these proposed a single-facies theory which suggests that all the iron was deposited as iron carbonate. A recent theory by Dr. Harold James may be considered a multiple-facies theory in which he proposes primary sulfides, carbonates, silicates and oxides. We are not advocating any particular theory; however, according to the information we have derived from our studies, we feel that we are in position to make some suggestions. We have found that the iron in the iron formation was largely deposited as iron carbonate which has been completely re-crystallized. There are virtually no sulfides present on the Marquette Range, so we cannot consider this type. There are iron silicates present in large quantities, but we believe they have probably formed by diagenesis of the carbonate iron formation plus fine clay and/or fine clastics. This is suggested because the silicates are intimately associated with fine clastic sediments and the plates penetrate into carbonate grains and replace clastic materials. A large portion of the iron formation is in the form of magnetite chert which may be formed either by the diagenetic replacement of the carbonate iron formation or by the diagenetic recrystallization of the primary magnetite iron formation, if it is present as Dr. James has indicated.

There has possibly been some primary hematite and magnetite deposited locally, but they are present in very minor quantities. The hematite is usually associated with clastics and occurs as sub-microscopic plates or grains. The magnetite is usually associated with chert and carbonaceous materials and occurs as irregular sub-microscopic grains.

In summary, the information that we have available suggests that the iron formation, to a large extent was primarily deposited in the form of iron carbonate with some clastics, followed by diagenetic

and metamorphic processes, and then subjected to secondary oxidation.

The mineralogy and mineral grain disposition of several samples from the Marquette Range are described below exemplifying the various types of iron formation.

Types of Negaunee Iron Formation

A. Diagenetic Iron Formation – Direct Magnetic Separation

1. Magnetite-chert with some carbonate
2. Magnetite-silicates with carbonate chert
3. Magnetite-silicates with clastics
4. Cherty magnesium-iron carbonate

B. Oxidized Iron Formation – Magnetic Oxide Conversion

1. Martite-chert
2. Martite-clastics
3. Goethitic hematite-chert
4. Goethitic chert

C. Metamorphic Iron Formation – Froth Flotation

1. Specular-hematite-chert with or without sericite
2. Magnetite-chert with some chlorite and locally garnet
3. Grunerite with chert magnetite or garnet

General Description and Concentrating Characteristics of the Various Types of Iron Formation

A. Diagenetic Iron Formation – Direct Magnetic Separation

The metallurgical characteristics of this type of iron formation are governed by the magnetite content, magnetite size, and mineral association.

1. **Magnetite-Chert with some Carbonate** – The results of our studies which included both microscopic and metallurgical testing have shown that this material has the most favorable concentrating characteristics. The reasons for this are the simple mineral composition, uniformity of grain size, and sharp boundaries between the magnetite and the chert, Fig. 1.

2. **Magnetite-Silicates with Carbonate Chert** – Our studies have shown that this material can be concentrated, but is not as favorable as No. 1 because of the presence of fine silicates and finer magnetite which necessitate longer grinding for liberation. The magnetite is more closely interlocked with the gangue minerals, Fig. 2.

3. **Magnetite-Silicates with Clastics** – In this material the magnetite is not uniform in size some being as coarse as -65 mesh and some as fine as a few microns, Fig. 3. As a result, this material is treatable, but yields a low percentage iron recovery with a high mineral loss in the tailings in comparison with No's 1 and 2, due to the loss of fines embedded in the matrix.

4. Cherty Magnesium-Iron Carbonate - A large part or the total of the iron in this material is tied up in the form of carbonate, Fig. 4. The magnetite can be liberated when present, but generally the percent iron recovery is extremely low and the iron loss in the tailings is great.

B. Oxidized Iron Formation - Magnetic Oxide Conversion

The metallurgical characteristics of this type of iron formation are governed by the degree of oxidation, particle size, mineral texture, and the mineralogy.

1. Martite-Chert - Microscopic and metallurgical studies have shown that this material appears to be the most favorable for concentration by magnetic oxide conversion because of uniform crystal size and sharp boundaries between the martite and chert, Fig. 5.

2. Martite-Clastics - Studies have shown that this material is moderately favorable and that the martite can be concentrated; however, a large part of the iron is tied up as hematite in the matrix of the clastics, Fig. 6. As a result, the percentage of iron recovery is comparatively low and the iron loss in the tailings high.

3 & 4. Goethitic Hematite-Chert and Goethitic Chert - Studies have shown that, at the present time, this material is undesirable for beneficiating by magnetic oxide conversion. This is due to the irregular forms, the fineness, and softness of the mineral particles, Fig. 7. As a result, the concentrates always contain an appreciable amount of silica and there is a considerable iron loss in the tailings.

A microscopic statistical sampling study on the -65, + 100 mesh portion of the oxidized iron formation samples from one of the Cleveland-Cliffs Iron Company drill holes has been conducted. The results are indicated in Plate I which reveals the concentrating characteristics of the materials in this particular hole.

C. Metamorphic Iron Formation - Froth Flotation

The metallurgical characteristics of this type of iron formation are related to the crystal size of the minerals and the mineral assemblage.

1. Specular Hematite-Chert with Sericite - The specular hematite in this material occurs as fairly oriented plates ranging from as coarse as 48 mesh and as fine as a few microns, Fig. 8. This material is the most favorable for concentrating by froth flotation because of good liberation of the ore particles and the fact that a very high grade concentrate can be obtained by grinding to approximately -65 mesh.

2. Magnetite-Chert with some Chlorite - Because this material is coarse-grained, Fig. 9, it can be treated by standard flotation methods or magnetic separation, but at our operating properties, it is being treated only by flotation.

3. Gruneritic Rock - This rock varies from pure grunerite to magnetite-grunerite, and grunerite-chert, Fig. 10. Locally, garnet appears as one of the chief constituents. This material is not economically treatable at the present time, based on the magnetite content; and it is not favorable for flotation.

A correlation has been made between the mineral assemblages of the metamorphic iron formation

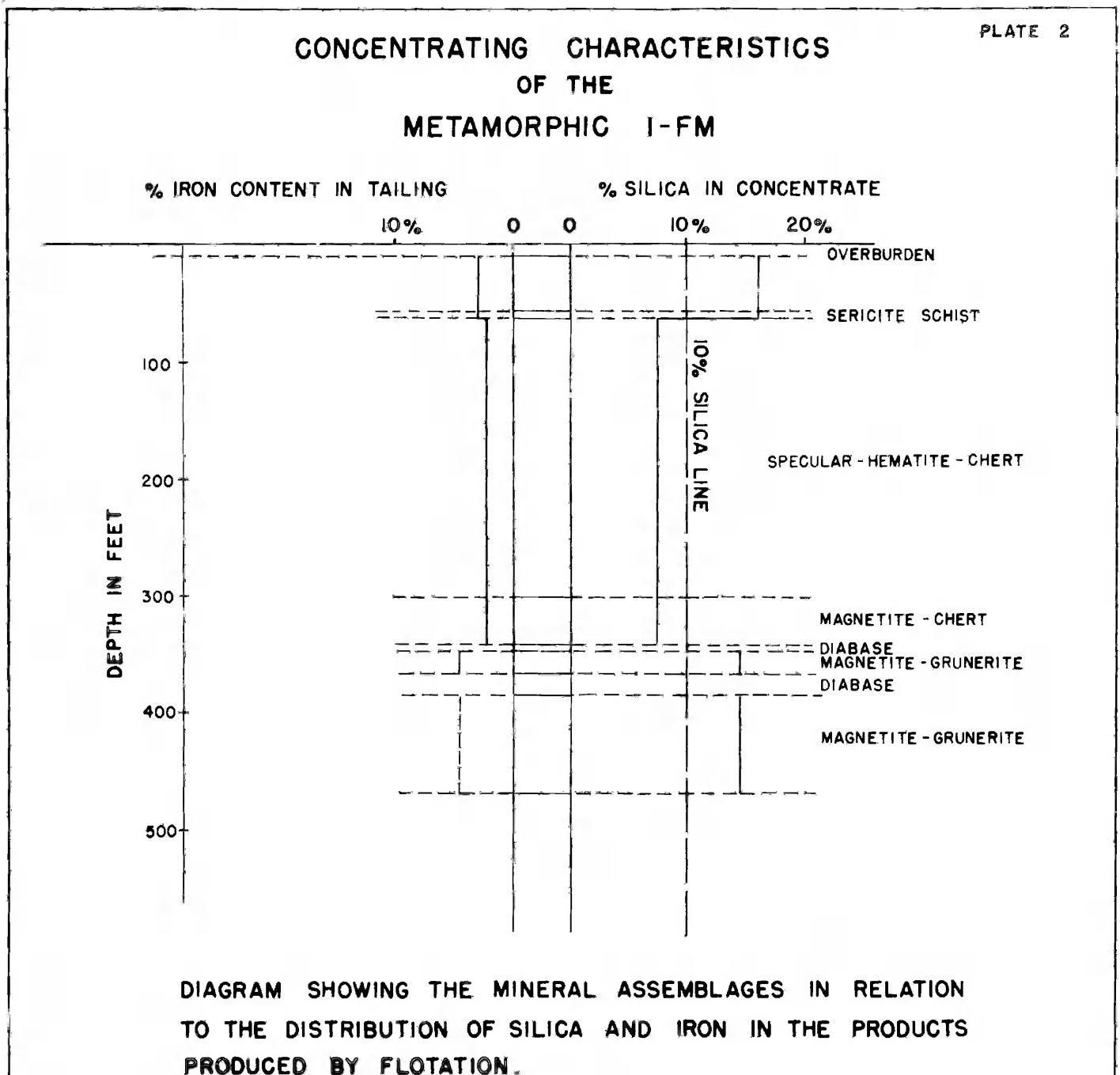
DEPTH IN FEET	OVERBUNDEN	MATERIAL CLASSIFIED (STANDARD GRINDING)		% SILICA IN CONC.		MICROSCOPIC SAMPLING									
		MOST DESIRABLE		DESIRABLE		UNDESIRABLE		MOST UNDESIRABLE		METALLURGICAL CHARACTERISTICS OF THE OXIDIZED NEGAUNEE IRON-FORMATION					
		— 5 - 10		— 10 - 15		— 15 -		MARQUETTE RANGE							
		TYPE OF MATERIAL IN %								CHARACTERISTICS OF THE MATERIAL		METALLURGICAL RESULTS EXPECTED			
		CHERT	MEDIUM GRAINED MARTITE - CHERT	COURSE GRAINED MARTITE - CHERT	FINE GRAINED MARTITE - CHERT	HEMATITE - CHERT	GOETHITE - CHERT	MARTITE - GOETH. CHERT							
30		MARTITE - CHERT	36	61				3		PARTLY OXIDIZED MEDIUM GRAINED MARTITE (325M + 400M)	DESIRABLE				
100		GOETHITE - CHERT	34	5				82	1	GOETHITE IS FINELY INTERLOCKED WITH CHERT	MOST UNDESIRABLE				
140		MARTITE - CHERT	21		77			1	1	INTENSIVELY OXIDIZED COARSE GRAINED MARTITE (100M - 325M)	DESIRABLE				
140		MARTITE - GOETH. - CH.	40		30			15	15	SAME AS 104'-130' EXCEPT MORE MART. CH. & MART. GOETH. CH.					
160		MARTITE - CHERT	34		61		3	1	1	SAME AS 130'-140' EXCEPT IT CONTAINS MORE HEMATITE - CHERT AND GOETHITE - CHERT	UNDESIRABLE				
160		MARTITE - GOETH. - CH.	40		24	3	9	15	14	SAME AS 140-145					
180		MARTITE - CHERT	35		63		1	1		MARTITE IS FAIRLY COARSE - GRAINED (200M TO 400M) AND INTENSIVELY OXIDIZED	DESIRABLE				
200		MARTITE - CHERT	31		47	21		1		TWO EXTREME SIZES OF MARTITE 100M TO 400M AND - 400M					
220		MARTITE - GOETH. - CH.	48		9	20		22		SAME AS 180'-210' EXCEPT IT CONTAINS GOETHITE					
220		MARTITE - CHERT	31		26	42				SAME AS 180'-210'					
220		MARTITE - GOETH. - CH.	33		5	28		6	18	SAME AS 180'-210' EXCEPT IT CONTAINS GOETHITE					
280		MARTITE - CHERT	28		31	40			1	TWO EXTREME SIZES OF MARTITE 100M TO 400M AND - 400M	UNDESIRABLE				
340		MARTITE - CHERT & HEMATITE - CHERT	43		30	5	24			MARTITE CHERT MIXED WITH HEMATITE CHERT					
360		GOETHITE - CHERT	50				10	60		GOETHITE & SOME HEM. ARE FINELY INTERLOCKED WITH CHERT	MOST UNDESIRABLE				
380		MARTITE - CHERT & HEMATITE - CHERT	31		33		36			HEMATITE CHERT MIXED WITH MARTITE CHERT	UNDESIRABLE				
380		HEMATITE - CHERT & GOETHITE - CHERT	42				25	33		HEMATITE AND GOETHITE ARE FINELY INTERLOCKED WITH CHERT	MOST UNDESIRABLE				
420		MARTITE - CHERT & HEMATITE - CHERT	31		31		36			HEMATITE CHERT MIXED WITH COARSE GRAINED MARTITE CHERT	UNDESIRABLE				
440			29		43		26			COARSE GRAINED MARTITE CHERT MIXED WITH HEMATITE CHERT	DESIRABLE				
460		HEMATITE - CHERT & GOETHITE - CHERT	46		1		36	7		HEMATITE & GOETHITE ARE INTIMATELY INTERLOCKED WITH CHERT	MOST UNDESIRABLE				
480		MARTITE - CHERT	24		64	9				MARTITE SIZE RANGES FROM 65M TO 325M	MOST DESIRABLE				

in one of The Cleveland-Cliffs Iron Company diamond drill holes and their actual metallurgical test results obtained from the Cleveland-Cliffs Iron Company Research Laboratory. The correlation is diagrammatically illustrated in Plate 2.

Conclusion

In reviewing the types of iron formation it may be concluded that the diagenesis and metamorphism are constructive processes of ore beneficiation while secondary oxidation is not a favorable process.

NOTE: The term "chert" mentioned in this paper optically is a fine-grained to medium-grained quartz which was re-crystallized from chert by diagenetic and metamorphic processes to various degrees.



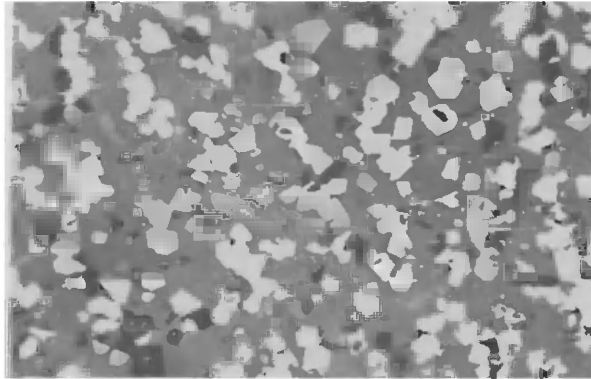


Fig. 1 - Magnetite-chert with some carbonate. 125x. Polished Section. Magnetite, white; chert, grey; carbonate, light grey; and pits, black.

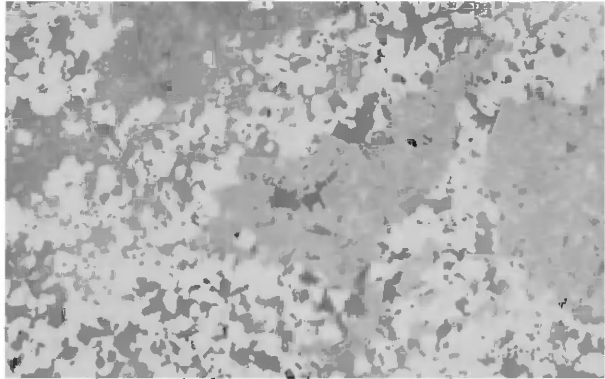


Fig. 2 - Magnetite-carbonate-silicate. 125x. Polished Section. Magnetite, white; carbonate, light grey; silicate plates, grey; and pits black.

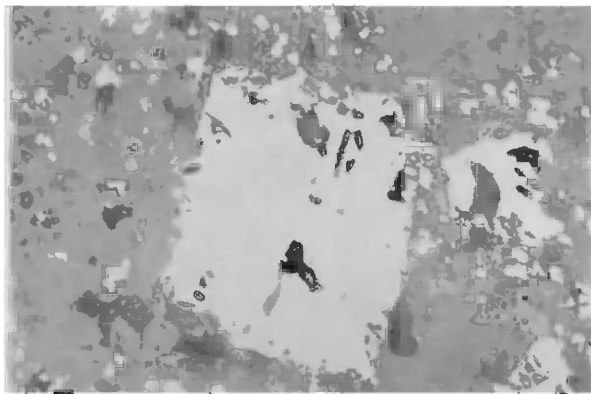


Fig. 3 - Magnetite-clastics. Polished Section. Magnetite, white; gangue (quartz, chlorite, etc.) grey; and pits, black.

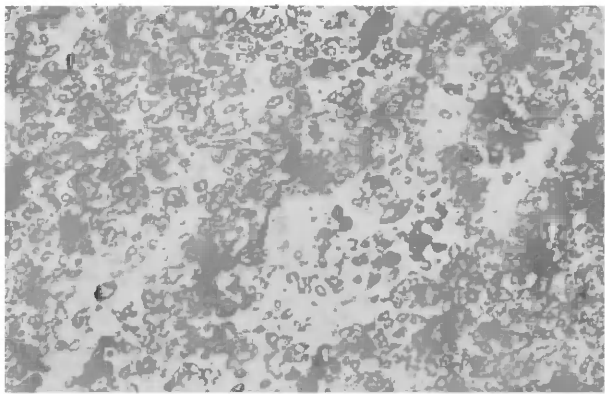


Fig. 4 - Cherty magnesium iron carbonate. 200x. Thin Section. Carbonate, granular grey; and chert, white.

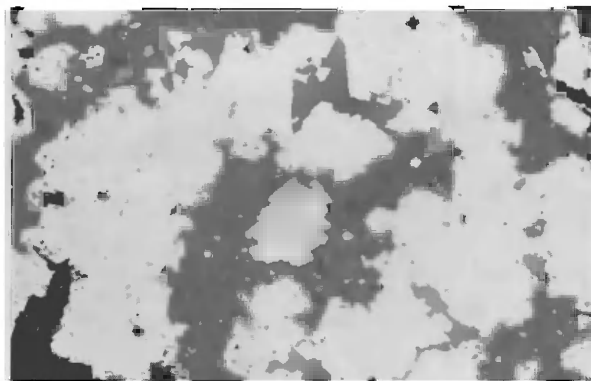


Fig. 5 - Martite-chert. 125x. Polished Section. Magnetite remnants, greyish white; martite, white; chert, grey; and pits, black.

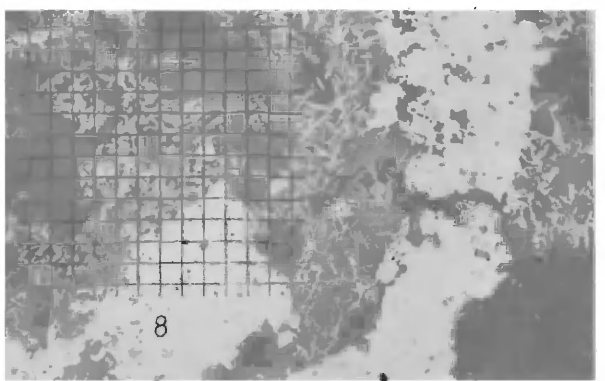


Fig. 6 - Martite-clastics, screen openings: -400 mesh. Polished Section. Magnetite remnants, light grey; martite and hematite, white; gangue, dark grey; and pits, black.

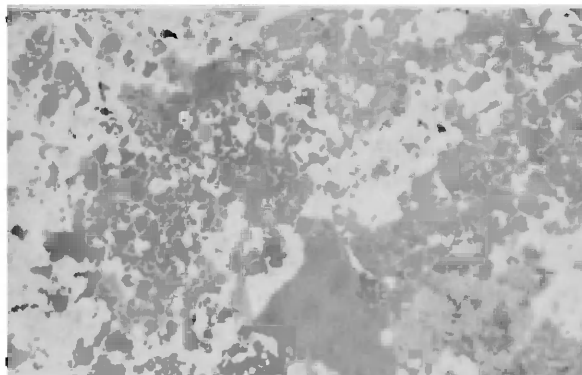


Fig. 7 - Hematite-goethite-chert. 125x. Polished Section. Hematite, white; goethite, light grey; gangue, dark grey; and pits, black.

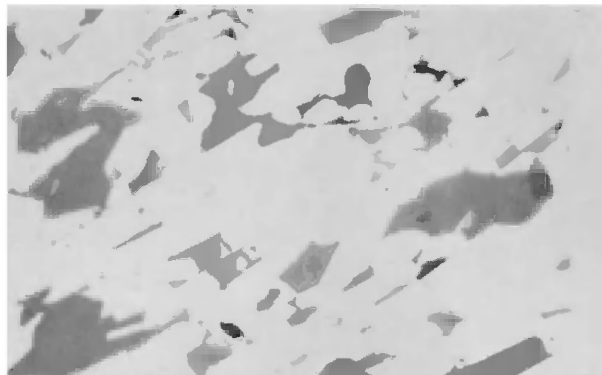


Fig. 8 - Specular hematite-chert. 125x. Polished Section. Specular hematite, white; gangue, grey; and pits, black.

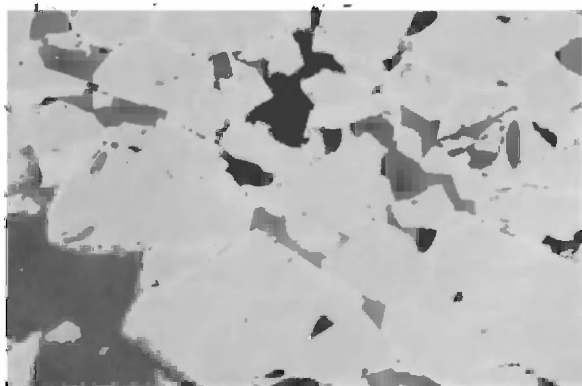


Fig. 9 - Magnetite-chert. 125x. Polished Section. Magnetite, light grey; martite, white; gangue, grey; and pits, black.

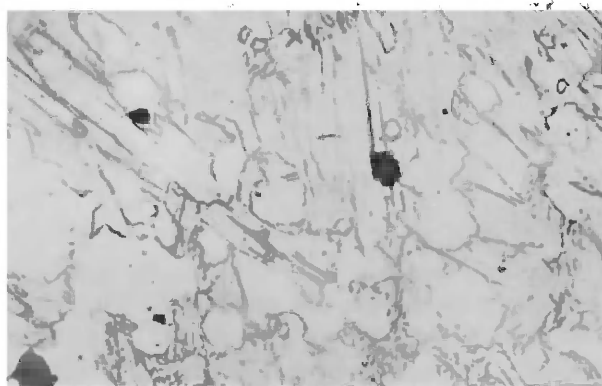


Fig. 10 - Grunerite-chert, 100x. Thin Section. Grunerite, grey; chert, white; and magnetite, black.

THE NATURE AND BENEFICIATING PROPERTIES

BY MICHIPICOTEN SIDERITES

PART I - DISTRIBUTION AND NATURE

by

A. M. Goodwin

Distribution

A principal iron formation of the Michipicoten district extends in faulted segments from the Helen Mine northeastward to the vicinity of the Algoma Central Railway, a total distance of 11 miles. From west to east the individual segments are, a) Helen - Victoria - Alexander - presently producing 1.4 million tons annually; b) Siderite Hill - presently being prepared for production; c) Lucy; d) Ruth; e) Josephine - a former producer of hematite ore; and f) Bartlett - representing a reserve of siderite ore, Plate 1.

Structure

The iron formation is situated on the south limb of an east-west trending syncline which, at the Helen Mine, rakes eastward at 60 to 70 degrees. The limb has been overturned. Thus, the formation dips southward yet tops are to the north. Northerly trending, vertical faults and flat thrust faults are common. Offsets on the vertical faults, which are generally east side to the north, range up to 2 miles and on the flat thrusts in the order of 200 feet.

Stratigraphy at the Helen Mine

The iron formation is enclosed in volcanic rocks. Basic volcanics typically overlie the iron formation and acid volcanics typically underlie it.

Overlying basic volcanics

The basic volcanics overlying the iron formation have the appearance of normal pillow andesite. Pillow structures are well preserved and consistently indicate tops to the north. The contact between basic volcanics and underlying iron formation is generally abrupt.

Iron Formation

The iron formation consists of the following ternary succession in descending order, Fig. 1.

Top	Banded chert member
	Pyrite member
Bottom	Siderite member

Banded Chert Member: This member ranges in thickness from 200 to 1000 feet and averages 500 feet. It consists of thin-bedded chert interbanded with siderite, pyrite, and magnetite. Local zones of graphitic chert contain up to 14 percent carbon. In contrast to other Precambrian iron formation, jasper is negligible.

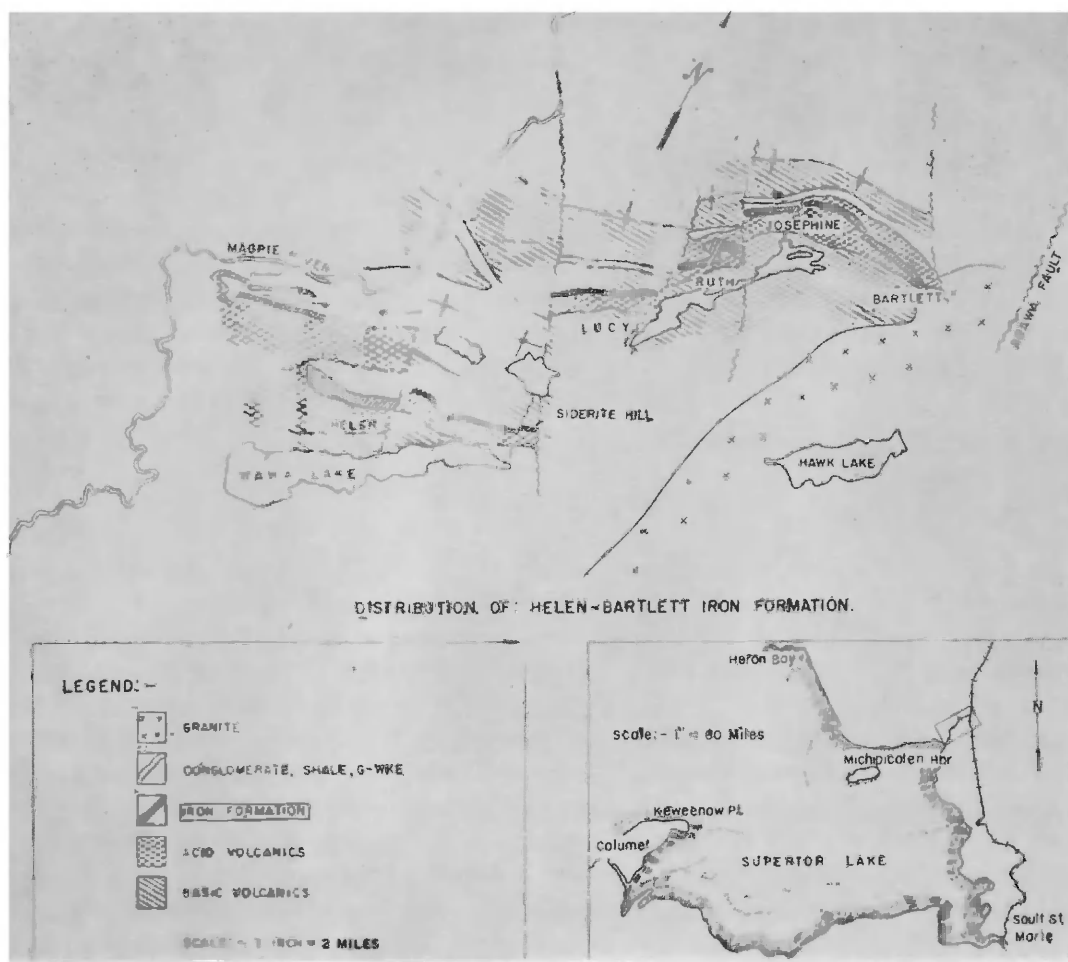


Plate 1 - Distribution of Helen-Bartlett Iron Formation.

Pyrite Member: This member is consistently located at the contact between chert and siderite. It ranges from 10 to 50 feet thick and consists of mixed pyrite, siderite, and chert. The member increases in thickness and purity towards the west end of the range. Sulphur has a marked limiting effect on the sintering process as will be described later.

Siderite Member: This member averages 200 feet thick within the limits of present mining. There are variations in thickness of considerable magnitude as a result of faulting and original thickening and thinning. The siderite, for the most part, is of massive, uniform structure. It contains variable siliceous impurities which are present either as, a) evenly disseminated grains and patches of chert, or b) relatively thick, uniform chert zones. One such zone in the Victoria mine, called the Central Silica zone, ranges in thickness from 10 to 60 feet. It is formed of relatively coarse grained, essentially structureless chert. A persistent zone of banded chert typically separates siderite from the underlying acid volcanics. It is 5 to 15 feet thick and is similar in appearance to the main banded chert member. It contains considerable amounts of argillaceous impurities.

Two principal diabase dykes transect the ore body. The siderite adjacent to the dykes has been partly altered to magnetite. The zone of alteration ranges in thickness from 10 to 50 feet. Magnetite presents certain beneficiating problems as will be described later.

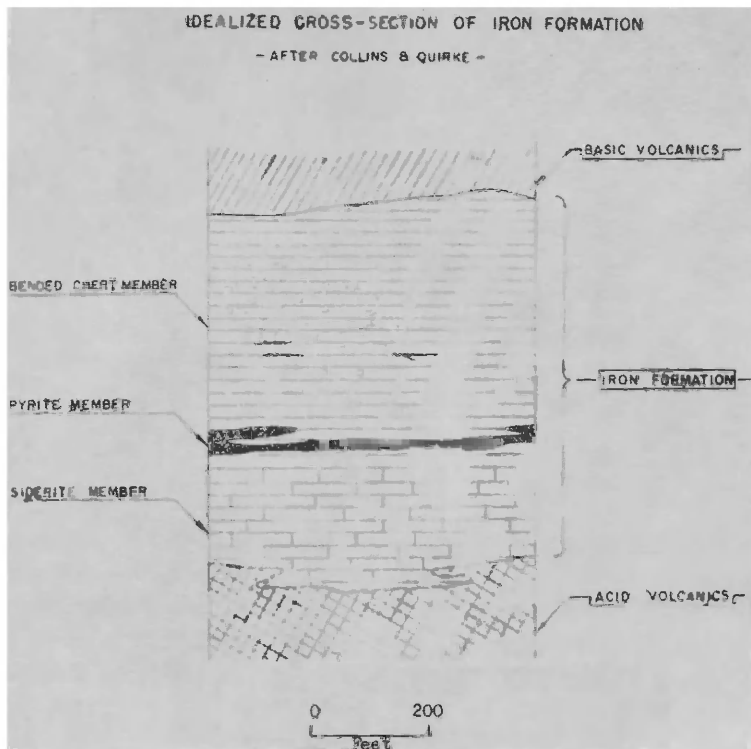


Fig. 1 - Idealized Cross-section of Iron Formation.

Chemical Composition

Table 1 illustrates the chemical composition of a) average siderite, b) siderite-magnetite complex

ALGOMA ORE PROPERTIES, LIMITED Jamestown, Ontario

	A	B	C
SiO	5.26	3.40	6.56
AlO	0.82	1.65	0.16
Fe	36.7	43.8	40.2
Mn	2.20	2.30	1.44
MgO	6.31	6.67	2.44
CaO	3.10	3.88	0.20
S	1.74	0.79	22.9
Ignition Loss	25.32	10.22	29.20

A. Siderite ore. D.D.H.U-3-57; 960-970 ft.

B. Siderite-magnetite ore alongside diabase dyke. D.D.H.U-3-56; 930-940 ft.

C. Pyrite-bearing ore. D.D.H.U-256; 680-690 ft.

Table 1 - Analyses

alongside diabase dykes, and c) pyrite-rich siderite. The table illustrates, 1) the sintering action of

diabase dykes, 2) the abundance of magnesium in the ore relative to calcium, 3) negligible aluminum, 4) the manganese content. The ore is essentially a self-fluxing, manganese-bearing iron carbonate.

Wall-Rock Alteration in Underlying Volcanics

The chemical and spectrographic characteristics of wall-rock alteration in the underlying volcanics are being investigated at present. Alteration consists essentially of the addition to the volcanics of iron, manganese, magnesium, sulphur and carbon dioxide, together with the removal of silica and calcium. The degree of alteration increases upwards through the underlying volcanics and is most intense in the 100 - foot interval below the iron formation. There are also lateral variations in intensity away from the area of the present mine working.

Origin

The available evidence indicates that the iron formation originated in a submarine, volcanic environment. Iron, manganese, sulphur, and carbon dioxide are considered to represent products of fractional crystallization which occurred toward the end of a volcanic cycle. Acid volcanics likewise represent end products of the same fractionation, hence their persistent stratigraphic location beneath the iron formation. The iron formation is considered to have formed at the chemical plane on the sea floor where ascending, acid groundwaters of volcanic origin came in contact with alkaline to neutral sea water. The broad, horizontal chemical plane separating these two contrasting chemical environments is considered to have resulted in formation of the ternary succession which is so characteristic of the iron formation. In this manner banded chert was deposited as a chemical sediment on the sea floor. Siderite and pyrite members formed largely by replacement of basal portions of the banded chert member; replacement was controlled by increasing pH and decreasing pressure as the sea-water environment was reached.

THE NATURE AND BENEFICIATING PROPERTIES
OF MICHIPICOTEN SIDERITES
PART II - BENEFICIATING PROPERTIES

by

D. R. Dorrance

Introduction

At the Helen Mine, the ore is beneficiated by two processes, namely heavy-media separation and sintering. All the ore is sintered, but that part which will not make sinter grade is first put through the sink-float plant. The cut-off between sinter grade and sink-float grade is between 7.5 and 8.0 percent SiO_2 . The sink-float operation will be described first.

Sink-Float Operation

The sink-float operation consists of separating minerals of different specific gravities by immersing them in a medium of high specific gravity. Minerals having a higher specific gravity than the medium will sink and those of lesser gravity will float. Siderite has a specific gravity of 3.60 and the gangue has a specific gravity of 2.40 and 3.10. By using a gravity of 3.30 a separation is made of ore and gangue. The heavy media used consists of finely ground ferrosilicon suspended in water. The ferrosilicon has a dry specific gravity of 6.9 and contains approximately 15 percent silicon.

The ore brought up from underground is minus 4 inches in size and is stocked on either low-sulphur or high-sulphur piles. The ore is further reduced to 1 1/2 inches by a system of screens and crushers in the sink-float plant. It is then subjected to intensive washing in order to remove all fines. In the separators the gangue material floats to the top bath and discharges out the end through a chute. The sink material sinks to the bottom and is raked ahead by means of a spiral to the head of the separator where it discharges onto screens. The excess medium is drained off to a 20-foot thickener. The underflow from the thickener is pumped to a 48-inch Dings magnetic separator where the ferrosilicon is reclaimed.

Specific gravity determinations are taken on the separator every half hour. The specific gravity is kept around 3.30. Samples of the feed, sink, float and sands are taken each shift. The plant handles both high and low sulphur ores and makes a good separation.

The ores high in magnetite give the most trouble because the magnetic fines cannot be cleaned out of the ferrosilicon and they then lower the specific gravity. The maximum magnetite that can be handled is 15 percent. Ores in which silica and pyrite are intimately mixed present a problem since the relatively heavy pyrite causes siliceous rock to sink.

Sintering Operation

The sintering operation consists of roasting siderite in order to drive off carbon dioxide and induce oxidation, thereby producing a high grade sinter ore in a physical form suitable for furnace feed. Roasting is accomplished by putting crushed ore and coke on oil-fired sintering machines. High ignition temperatures result in dissociation of siderite. The gases are withdrawn by forced air drafts.

Ore is brought from the Helen Mine to the sintering plant by means of an aerial tramway 15,000 feet long and by railroad cars. The tram carries approximately 3,600 tons per day and the railroad about 2,500 tons per day. The ore is transported by a system of conveyors to crushers and screens to produce a 1/4-inch feed. The feed to the sintering machines is made up of a mixture of screened siderite ore and screened coke. Proportioning of the components is done at each individual sintering machine. The operator controls the rate of flow from the bins to a pelletizer where water is added. Mixing of the feed must be done so that an intimate blending of ore, coke and moisture is obtained; in addition, the mixing should be done so that the mixed feed is thoroughly aerated and is in such physical condition that maximum porosity is obtained. The mixed feed is fed to the machines through reciprocating swing chutes. The finished sinter is dumped over bar grizzlies into bins and thence to railway cars.

Maximum permissible limits in the sinter are SiO_2 - 11.20 percent; S - 0.100 percent. In order to stay within these limits, the feed must not contain more than 7.90 percent SiO_2 and 4.0 percent S. Considerable care must be exercised both in mining and beneficiating to remain within these limits.

Discussion

Mr. Volin: The information in all of these papers is very gratifying to me. To have this subject included in a purely geological symposium was somewhat of a concession but I think we can see that geology ties up with beneficiation processes and of course the two of them go together in order to achieve the final result of bringing a property into production.

DISTRIBUTION OF TRACE ELEMENTS IN SOIL FRACTIONS

by

D. H. Yardley

Geochemical prospecting is a relatively new scientific tool in the search for hidden ore deposits. It is so new that more papers have been published in this field since 1951 than in all preceding years.

An investigation of some aspects of geochemical exploration was begun near Ely, Minnesota in late 1953. The test area is near the Kawishiwi River along the basal contact of Duluth gabbro with Giant's Range granite, Fig. 1. Funds for the study have been provided by the Graduate School of the University of Minnesota and the Minnesota Institute of Research.

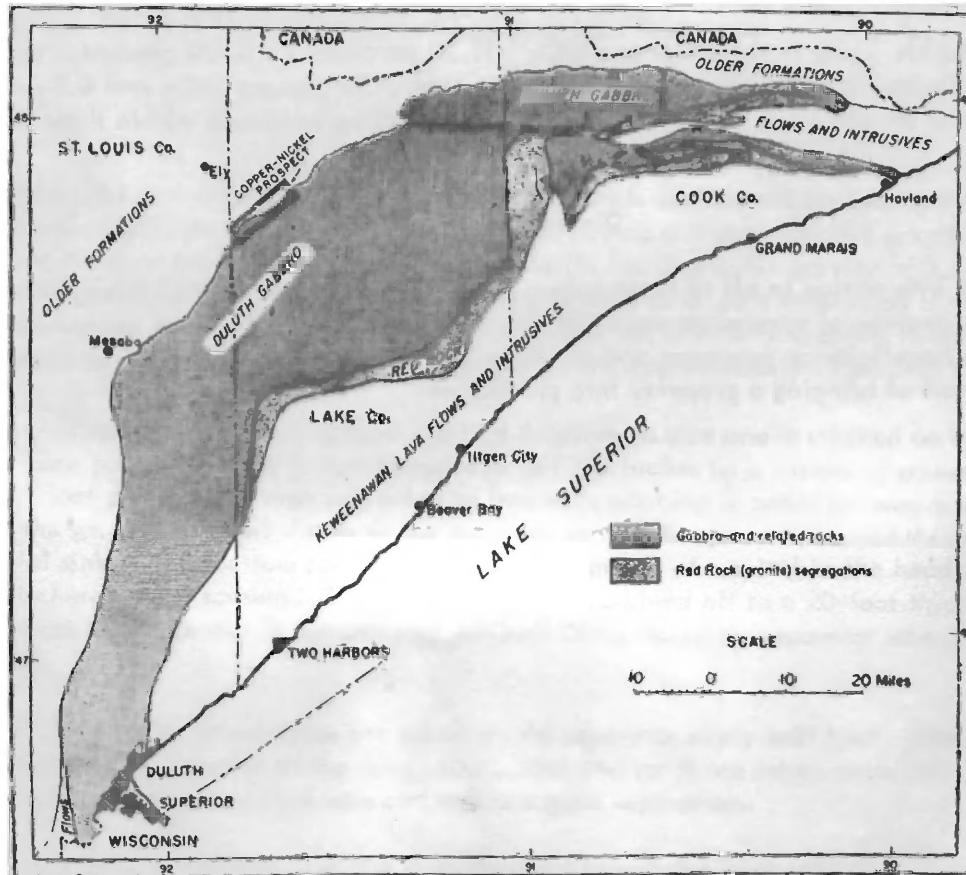


Fig. 1 - Index map, and outline of the Duluth Gabbro (after Schwartz & Davidson).

The primary object of the investigation to date has been to obtain data on the distribution of trace elements in glacial materials in northern Minnesota. It was felt that such data would demonstrate whether or not soil samples would reflect the presence of a known mineralized zone below glacial till and some idea might be gained regarding the pattern of distribution to be expected in soils with a

similar climatic history and of similar origin.

To date the study has concerned itself with data on the distribution of Cu and Ni in glacial soil.

Summary of Geology

The Duluth gabbro is one of the world's largest basic intrusives and has been defined as a lopolith (4)*. It intrudes rocks which range in age from Keewatin to middle Keweenawan. Within the test area the gabbro is in contact with granite except for short sections where the gabbro is in contact with remnants of iron formation. Sulphide mineralization occurs very near and parallel to the basal contact of the gabbro for a distance of several miles. Schwartz and Davidson (10) have described the geologic setting of the mineralization and noted that the sulphides occur at the base of the thickest part of the gabbro.

The sulphides occur disseminated in all the silicates and also as small interstitial masses but are most abundant in the plagioclase. A few tiny veinlets of sulphide are present but these may be deuteric. The sulphides found include chalcopyrite, cubanite, pentlandite, pyrrhotite and minute amounts of bornite. The sulphides are reported to be syngenetic (10, p. 702), (11).

The ratio of Cu:Ni is about 4:1. This ratio of copper-nickel content is based on analyses of samples from various outcrops. The average of seven surface samples (10, p. 702) is 0.57% Cu and 0.13% Ni. The average of 29 grab and chip samples from about 12 outcrops was 0.59% Cu and 0.17% Ni. The average for 30 surface samples obtained from 20 different 40-acre tracts (11) is 8.72% Fe, 0.44% Cu and 0.11% Ni. The average content of the above 66 samples is 0.53% Cu and 0.14% Ni, a ratio of 3.8:1.

Test Procedure

The chromograph method (13), which was used for all tests, makes use of a reaction between the metal being tested for and special reagent paper to form a colored spot. The colored spot obtained is compared to colored spots prepared from samples of known metal content. The chromograph enables one to apply a fixed volume of test solution to a fixed area of reagent paper under a fixed suction head. The variable is the amount of metal present in the test solution.

Sample Treatment

The dried soil samples were screened, a 0.1 gram portion fused with 0.5 grams of potassium bisulphate flux, the fused product digested in 13% sodium citrate solution, diluted to 5 ml and filtered. The pH of the filtrate was then adjusted to > 8.5 and 0.2 ml used in the chromograph for the Ni test. The pH of a portion of the remaining filtrate was adjusted to 4.5 and 0.2 ml used for the copper test. Demineralized water obtained from a Barnstead Bantam Demineralizer was used for diluting and for cleaning equipment. Reagents were purified with dithizone solution where necessary and procedures carefully standardized so that the only variable would be the heavy metal content of

* Numbers refer to bibliography at the end of paper.

the samples. When it was necessary to prepare new reagent paper, new standard color spots were prepared so that any variation in the strength of the reagent paper would tend to cancel in color spot comparisons. All standards were made up using blank soil from the test area.

pH Discussion

Repeat tests by chromatographic analysis in the early stages of the investigation often failed to check. Quantitative variations of 50% and occasionally more were common. Nickel tests on slightly basic test solutions would sometimes be blank or very low and show a very definite color on a repeat run; less often erratic copper tests were encountered.

A series of tests on known samples, and on made-up samples, was run for Ni and Cu for a range of pH values. These samples contained Ni, Cu, and Co ions known to be present in anomalous parts of the test area. Table I illustrates the intensity readings of one series of colorimetric spots on test solution containing 500 ppm of Ni, and 500 ppm of Cu.

Table I

Ni		Cu	
<u>pH.</u>	<u>p.p.m.</u>	<u>pH.</u>	<u>p.p.m.</u>
7.0	0	3.0	500
7.2	75	3.0	500
7.5	200	4.0	500
8.2	300	4.2	500
8.5	400	4.5	500
9.2	400	4.8	500
9.5	425	5.4	450
10.	425	6.2	400
11.	425	6.7	300
		7.0	300
		7.2	500
		7.5	1500
		8.8	2000

The results demonstrate that reproducible results can be obtained within the general accuracy limits of $\pm 30\%$ for the method, over a pH range of about 8.5 to 11 for Ni and 3 to 5.5 for Cu. Table I also shows that for either metal tests run at a pH of 5.5 to 8.5 are not reliable.

The high Cu readings at pH ≥ 7.2 can be explained by precipitation of Cu, Co, and Ni by rubeanic acid reagent in ammoniacal solution (13, p 3). The low readings at pH 5.4 to 7 are perhaps related to the pH of 5.3 (2, p 79) at which cupric Cu tends to precipitate as hydroxide or basic salt from dilute solutions. Leach (7) used this explanation in interpretation of hydrogeochemical tests for Cu near Butte, Montana.

The tests demonstrate that the pH of the test solutions is very important and that a standard pH within the ranges given above should be used when testing field samples. This point, perhaps, has

not received sufficient emphasis in the literature, although the chromographic procedure used by the Geochemical Section of the U. S. Geological Survey does adjust the pH to the desired range.

Sampling Procedure

Sampling was carried out along five north-south traverse lines across the gabbro-granite contact. Insofar as possible, samples were taken at 100 foot intervals. The surface soil samples were taken at an average depth of about one foot which was below the high-humus surface layer and into clean till.

At some sampling points, samples were taken at each foot of depth down to bedrock in order to obtain data as to vertical distribution and distribution below swamps. An auger and a Swedish type peat sampler were used in sampling down through swamp materials; casing was used where necessary. A hand auger-drill was used in taking samples in till.

Areal Distribution Contours and Profiles

Plotting of Cu, Ni, and Co content in contour form (Fig. 2) shows that anomalous amounts of

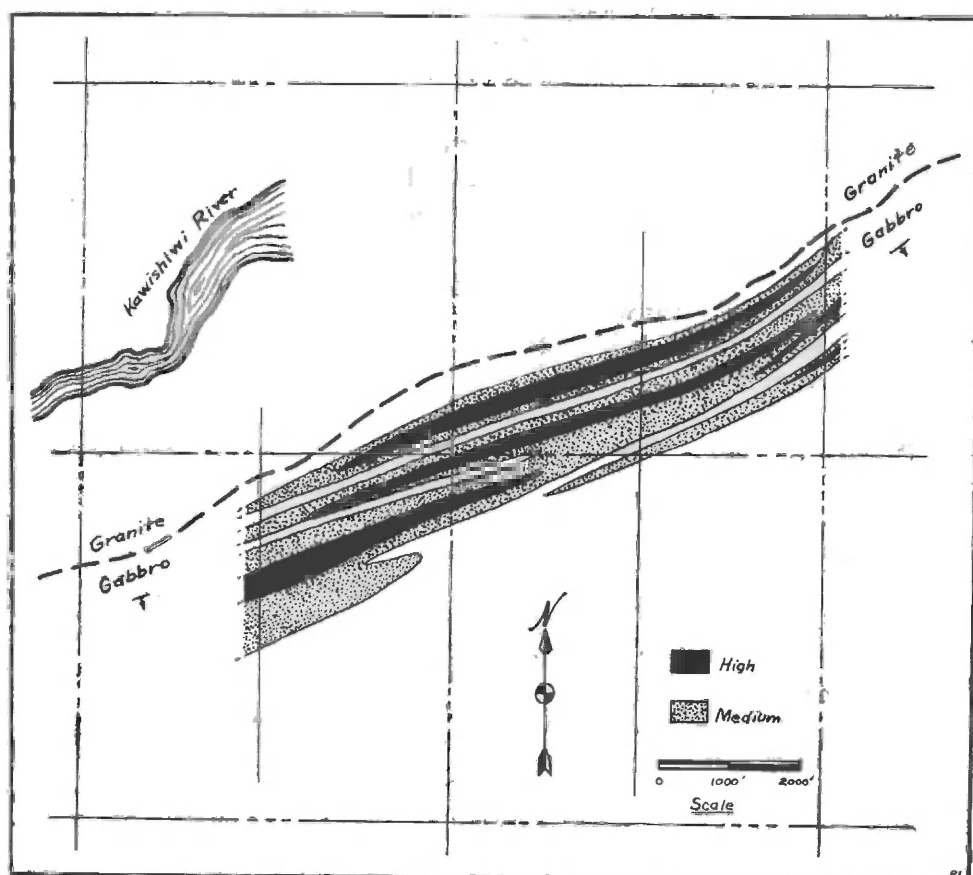


Fig. 2 - Total Cu, Ni, & Co, in glacial till - Ely District, Minnesota.

these metal ions occur in till over and closely adjacent to mineralized areas of the gabbro. Contouring nickel content alone, or the copper content, outlines the same target area. Contours of the copper

content provide a more distinct anomaly than nickel because of the higher copper concentration.

The position of the northern boundary of the anomaly implies that the mineralization is parallel to but not quite at the base of the gabbro. This is confirmed by 3 Bureau of Mines drill holes (3).

Distribution by Soil Size

Testing of soil samples for any geochemical campaign involves a decision whether the sample should be screened, and if screened what soil fraction should be selected for testing.

The glacial overburden in the area displays a wide range of particle size. For this reason it was necessary to select the soil fraction which most likely is representative of the true heavy-metal content. The finer soil fractions generally are to be preferred in soil sampling, because sulphides would tend to weather to finer size (6, p 530).

Exceptions to this general rule do occur. Sergeev (12, p 46), comparing the tin, tungsten, and chromium contents of -1mm. fractions with 5mm. and coarser sizes in the part of the halo nearest the deposit states, "The content of the valuable element is approximately the same in both. In places, however, the coarser fraction contains somewhat more of the valuable element. Lean samples (a remote or the train part of the halo) have a lower content of the valuable element (down to zero) in the coarser fraction, although its concentration is stable in the finer fraction. It may be concluded that dispersion takes place chiefly at the expense of the finer materials." And also, "Remembering that halos of saline genesis are characterized by secondary compounds less directly related to the massive rock, the advantages of observing the halos in the fine deluvial fraction become evident. Such samples provide a reliable expression of the dispersion halo in its largest spatial development."

Sergeev refers to elements which are resistant to chemical weathering and are dominantly residual in nature. Ground-up coarse fractions which contain one or more large pieces of ore mineral would test high in metal. However, even those elements which occur in resistant minerals conform to the general rule in the train part of a halo.

A factor which also favors the selection of the fine soil fractions, in addition to the tendency of sulphides to weather to finer sizes, is the probability that transportation of heavy metals by capillary solutions may be important in the formation of some geochemical halos, and capillarity would be most effective in materials within the finer size ranges. Bischoff (1, p 58), provides some indirect support for this view, "Gravel and coarse sand on the contrary proved very unfavorable, probably because of rapid drainage," and "The depth of favorable overburden through which ground water would bring appreciable quantities of heavy metals to surface was surprising. The practical maximum overburden is now considered to be 30 to 50 feet for clay and 20 to 30 feet for fine sand." Bischoff also noted a blanketing or masking effect of sand and gravel ridges.

Distribution in Soil Fractions

The much greater number of soil particles in a unit weight of fine materials would be much more likely to include some particles of mechanically derived ore mineral than would the coarser fractions. The finer sizes also provide a much larger total surface area and so could absorb more metal ions from percolating soil solutions. Thus the finer materials would tend to "fix" relatively larger amounts of metal ions; we might say that they have a larger total adsorptive capacity and so would be much more

likely than the coarse fractions to reflect the presence of anomalous concentrations of trace elements.

Samples were sieved through a 9 mesh screen and some were sieved into three sizes, +9 mesh, -9+80 mesh, and -80 mesh. Stainless steel screens were used to avoid possible contamination. Tests on blank samples of cleaned St. Peter sand before and after screening showed no contamination from abrasion of the screen. The screens used were all Tyler screen scale.

Table II compares the metal content of the +9 mesh and -80 mesh fractions from ten sample locations. The +9 mesh material was crushed in an agate mortar before fusion.

Table II

Nickel p.p.m.		Copper p.p.m.	
+9 mesh	-80 mesh	+9 mesh	-80 mesh
0	0	30	5
0	5	0	7
0	15	10	25
0	250	5	375
0	100	5	250
10	100	5	300
0	120	25	400
50	160	50	350
0	70	5	250
10	10	5	15
<u>70</u>	<u>830</u>	<u>140</u>	<u>1977</u>
Approximate percentage detected in +9 mesh fraction:		Nickel = 8%	
(compared to -80 mesh fraction)		Copper = 7%	

One can conclude that for all practical purposes the heavy metals do not occur in the +9 mesh soil size, at least for the concentration ranges shown.

Table III is a comparison of the nickel content of -9+80 mesh and -80 mesh soil fractions. Although the -9+80 fraction contains a distinctly lower proportion of nickel, about two thirds as much, the anomaly would not be missed by testing only the -9+80 mesh fraction.

A comparison of the Ni content for 30 samples on a parallel traverse showed that the -9+80 fraction averaged 62% as high as the -80 fraction. Again the anomaly was obvious, using either soil size. It seems reasonable to conclude that a mixture of the two sizes (all the -9 mesh material) will give dependable results for field comparisons.

The preceding figures show that for most field work the finer soil sizes are more indicative of geochemical anomalies. To confirm this view a study was made of samples known to contain appreciable quantities of Cu and Ni. The samples were screened to six products and five chromatographic analyses were made for Ni and five for Cu. Agreement of analytic results was best in the finer size samples.

Fig. 4 illustrates the distribution; in each case the p.p.m. of metal is the arithmetic mean of five analyses.

Table III

Comparison of Nickel content of -80 mesh soil fraction and
-9+80 mesh fraction. 100 foot sample spacing. Line 5
Nickel p.p.m.

<u>-9+80 mesh</u>	<u>-80 mesh</u>
0	0
10	20
0	0
0	0
10	0
300	400
250	500
300	300
75	100
350	400
100	150
70	150
400	700
0	75
<u>1865</u>	<u>2795</u>

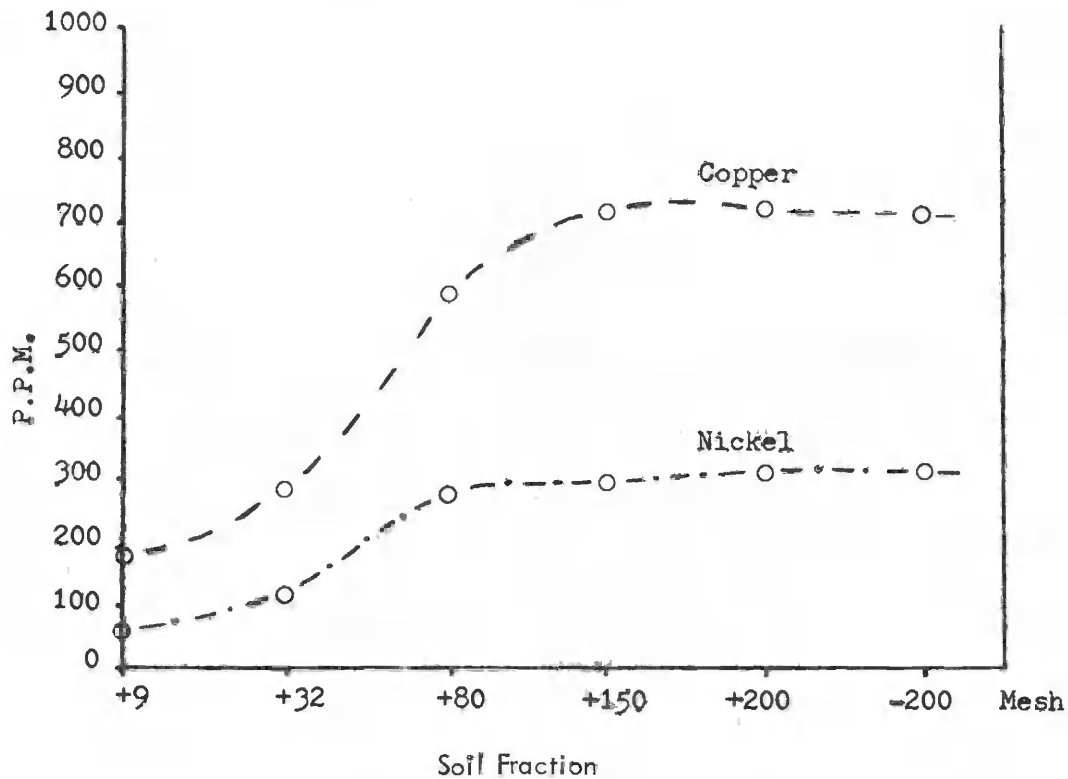


Fig. 4 - Cu and Ni Distribution. Average of 4 samples, 5 tests per soil fraction for each sample. (Each point represents 20 determinations.)

The notable feature is that there is an increase of metal content with decreasing soil size in the coarser materials, but for the -80 mesh and finer fractions there is no increase, but rather a roughly equivalent metal content. The only exception to the above trend was one sample of "rubble-like" material consisting of more than 50% of +32 mesh size. In this case the +9 mesh material tested substantially higher than the -9+32 size. The normal trend applied for the fractions smaller than 32 mesh.

Certain general conclusions which may be drawn from the above tests are:

1. -9 mesh material would be satisfactory for most field work but samples of only -80 mesh material will give more reliable results.
2. Use of -80 mesh soil is to be preferred where anomalies of small magnitude might be expected.
3. The levelling off of metal content in the sizes smaller than -80 mesh shows that nothing is gained by any attempt to screen to a size finer than 80 mesh.
4. There is no general distribution relationship between metal content and available surface area of the finer particles of soil. This is significant in any consideration of the processes by which trace elements move and are fixed in soils.
5. Tests of distribution of metal in various soil sizes should be carried out as a preliminary guide in new sampling areas.

A pertinent question is whether the 0.1 gms. of soil used in a test is representative of the several grams of soil in the field sample? Or, stating the problem another way, "Is it necessary to use any special methods of mixing to insure that the test portion is representative of the whole sample?" Repeat tests show that sample results can be reproduced within the limits of accuracy of the method without any formal mixing other than that inherent in screening. The accuracy is sufficiently high so that there appears to be no danger of not detecting an anomalous metal content through failure to mix the samples formally.

In addition, the test sample is as representative of the field sample as the field sample is of its area of influence. Hawkes and Lakin (5, p. 291) compared ground and quartered bulk samples of 500 gms. with grab samples of 5 gms. and concluded that "there is no significant loss in accuracy of data by substituting grab samples for bulk samples".

Scooping of Samples

All samples tested in this investigation to date have been carefully weighed on an analytical balance. However, a volumetric scoop designed to provide about 0.1 gms. of soil adds to the speed and ease of field methods for testing soils. Use of a scoop is recommended by several authors and has been found to give satisfactory field results.

The variation in soil sample weight when a scoop is used rather than a balance has been considered by Huff (6, p 531). Huff found that the error caused by scooping ranges from 3 to 11 per cent and averages about 7 per cent in any one area.

Table 4 is a comparison of scoop weights for soil samples from the Ely district. The variation of weight for scoops of a particular soil size is small and is well within the accuracy of the test method. However, there are significant weight differences between equal volumes of different soil fractions from the same sample, and also between the same soil fractions from separate areas.

Although the study is not comprehensive the results do indicate that scooping samples can lead to

TABLE 4

Weight, in Grams, of Soil Sample Fractions
Measured by Using a Volumetric Scoop

Location	Mesh	No. of Samples	Weight (grams)			Std. Deviation		2 x Std. Deviation	
			Max.	Min.	Mean	Grams	%	Grams	%
Line 5 8+00S	-9	40	0.138	0.123	0.130	0.003	2.3	0.006	4.6
	-9+80	40	.132	.115	.125	.005	4	.010	8
	-80	40	.109	.095	.101	.005	5	.010	10
Line 2 8+00S	-9	40	0.169	0.145	0.158	0.006	3.8	0.012	7.6
	-9+80	40	.151	.127	.138	.007	5.1	.014	10.2
	-80	40	.130	.114	.120	.004	3.3	.008	6.6

rather large variations in weight of sample with consequent variations in computed metal content. If a scoop is used for sample measurement one should check the mean weight of the soil size fraction selected for the different soil types encountered. Then if necessary a correction factor can be applied to the computed results.

Anomalous metal contents are often so much greater than background content that a correction factor for scoop weights usually can be ignored in field work. However, where the anomalous content may be of small magnitude the possible error due to using a volumetric scoop could be significant.

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TRENDS IN GEOCHEMICAL EXPLORATION

by

H. E. Hawkes

The art of mineral exploration is at the present time passing through a period of revolutionary development. In the brief ten years since the war, radically new techniques of appraising ground for the possibilities of buried ore deposits have not only been perfected but have demonstrated their effectiveness by contributing to the actual discovery of new deposits. Whereas in the past, mineral discovery almost invariably started with the work of the independent and often untrained prospector, the new methods now available make it possible for large, well-capitalized exploration companies to carry out their own programs of primary exploration. The result has been an acceleration in discovery rate comparable with the increase in discovery of petroleum reserves with the development of advanced geophysical methods in the two decades before the war.

Two outstanding features characterize the coming-of-age of mineral exploration techniques. The most spectacular of these is the perfection of technical methods of mineral reconnaissance of large tracts of unexplored ground by observations from aircraft. The airborne magnetometer, first of the low-unit-cost reconnaissance methods, has been credited with the discovery of a substantial number of our new deposits of magnetic iron ore. Airborne radiometric techniques have been applied widely in exploration for uranium. More recently, airborne electromagnetic surveys have been effectively used in detecting electrical conductors, a few of which already have led to the discovery of large deposits of basemetal sulfides. Air photographs are now generally used as a guide in interpreting regional geologic structures that may make favorable conditions for the emplacement of ores. The outstanding characteristic of all airborne surveys is extremely low cost per unit area, even though the over-all cost of equipment and operation may seem higher than that of the more conventional methods.

The other new development in mineral exploration is the diversity of exploration techniques that is now commonly brought to bear on each individual problem. Whereas conventional exploration has been guided primarily by outcrop search and geologic study, followed immediately by drilling, the tendency now is for independent appraisals of a tract of ground by several or many methods - geological, geophysical and geochemical - and the synthesis of the indications from all methods in the interpretation of the economic possibilities.

Geochemical methods of mineral exploration are playing an important part in the evolution of our mineral exploration techniques. The purpose of this paper is to point out the kinds of contributions that can be made by geochemical techniques to exploration with special emphasis on application in the glaciated terranes of the Canadian Shield.

A "geochemical" method of mineral exploration is a method based on mapping variation in the chemical composition of some naturally occurring material, and the interpretation of the resulting chemical pattern in terms of possible mineralization in the vicinity. The chemical elements measured are most commonly the ore metals themselves, present usually only in trace amounts; the material sampled may be rock soil, stream sediment or water, glacial deposits, or vegetation.

Geochemical Reconnaissance

Probably the oldest method of locating bedrock ore, other than by simple outcrop search, is the panning of stream gravels for resistant heavy minerals such as gold, and the tracing of the trail of increasing values upstream to the bedrock source. More recently the waters of streams have been sampled and analyzed for traces of metals as a method of determining the existence of metalliferous deposits upstream. A similar pattern can be traced by sampling sediments collected from stream channels for traces of "exchangeable" metal (metal that is in equilibrium with the water, and hence that can be dissolved in weak chemical reagents). In all these methods, one sample, properly chosen and properly analyzed, either mineralogically or chemically, will tell the prospector how much of a chance he has of finding an orebody in the area drained by the stream. These potentially are methods of mineral reconnaissance of very considerable power.

Within the last three years, geochemical reconnaissance based on determinations of the exchangeable "heavy metal" (mainly zinc) content of stream sediments has been applied on a large scale to exploration in New Brunswick and the Gaspé Peninsula of Quebec. This method has, or soon will be, described in detail in the literature (Bloom, 1955; Hawkes and Bloom, 1955 and in press). The present discussion, therefore, will be limited to a brief summary of the principles and operation of the method.

Sampling consists of collecting a number of small samples of stream sediment at sites selected on the basis of optimum coverage. Experience has shown that the chances of missing an important zinc-bearing deposit is relatively slight if samples are taken within two miles downstream from the deposit. Common practice is to collect four samples at each site, two from the sedimentary material in the active channel of the stream, and two from the flood plain within a few feet of the active channel. Samples should be collected in non-contaminating containers, such as aluminum tins or waterproof envelopes, and brought back to field headquarters for analysis. One or two ounces of sample is ordinarily adequate.

Samples are prepared for analysis by drying and sieving to minus 80 mesh, and discarding the coarse fraction that does not pass through the sieve.

Analysis is by a technique described by Bloom (1955), in which a standard volume of the sample is shaken with a cold aqueous solution of ammonium citrate to which is added a solution of the reagent dithizone in xylene or toluene. Exchangeable zinc, and to a lesser extent lead and copper, in the sample is dissolved in the aqueous citrate solution, and then reacts with the dithizone to give a color change that is quantitatively proportional to the amount of metal extracted. The xylene solution of zinc-dithizone is a brilliant red, in strong contrast to the green of the original dithizone solution. Where insufficient zinc is present to react with all the dithizone available, the resulting color is a mixture of green and red, the hue of which depends on the relative amounts of unreacted dithizone and the zinc-dithizone complex. By selecting one of these intermediate colors, such as gray, for a standard endpoint, it is possible to determine the quantity of zinc extracted from the sample by adding barely enough dithizone solution to the system to reach the gray endpoint, and then recording the total volume of dithizone solution added. This test requires only very simple equipment that can, if desired, be packed as a compact kit for field use.

Interpretation of the data is facilitated by plotting the values for exchangeable metal directly on a posting map. In the absence of significant concentrations of metallic mineralization in the drainage basin above a sample site, the sample will ordinarily contain less than 4 parts per million of exchangeable metal. Samples containing over 10 ppm exchangeable metal may be considered a promising

indication, depending on the size of the stream and the general geologic environment. Samples containing over 40 ppm are strongly anomalous.

Follow-up of the most promising indications is carried out most conveniently by carrying a portable chemical test kit, and making the tests on the spot without drying or sieving. The original sample site should be revisited, and freshly collected sediment tested again to make sure that the high values were not due to contamination or to a local source of metal of no significance. Then, the trail of increasing metal values should be followed upstream to determine as far as possible the source area.

Sediment analysis for exchangeable metals apparently outlines the same geochemical patterns as water analysis. It has distinct advantages over the water analysis in that the analytical technique is much easier and more reliable, the metal content does not fluctuate with the weather, dry stream beds can be sampled, and samples can be stored for future reference.

Both methods, of course, have many limitations. All they can tell is that an unusually rich source of metal exists in the area upstream or upslope from an anomalous metal indication in the stream. They rarely lead to the exact location of the source, which must be determined by some other method. They also do not tell whether the source is a high grade deposit, or a broad zone of disseminated metal of no economic value. They cannot obtain a response from a deposit that is not undergoing active oxidation and leaching, such as might occur beneath a lake or swamp. However, even though these methods may miss some deposits, and give strong indications from disseminations of no value, they provide the prospector with extremely valuable ore guides at a very low cost per area covered.

Geochemical Methods in an Integrated Exploration Program

Although geochemical reconnaissance has certain serious shortcomings and ambiguities, the data of airborne magnetic and electromagnetic surveys also are fraught with uncertainties in interpretation. Geological mapping, furthermore, can only point out areas where, by analogy with areas of known mineralization, ore ought to occur.

In detailed work in areas of glacial cover, geochemical soil anomalies are commonly associated with bedrock ore; unfortunately, the anomalies are many times displaced for considerable distances downslope or down-glacier from the suboutcrop of the ore. Still more unfortunately, strong geochemical soil anomalies have been found and mapped in areas of no important mineralization, where the source is weakly disseminated metal scattered through a large volume of rock. Geophysical patterns in detailed work can be equally ambiguous, though in different ways. Geology again can only tell where the ore ought to be, not where it is.

Because of this complex of uncertainties, it has become common practice in Canadian exploration work to prepare a series of maps as transparent overlays, each one of which shows the targets indicated by one particular method. Then the localities where the greatest number of target areas overlap is considered for more detailed exploration. The purpose of the entire schedule is the narrowing down of target areas for the final and most expensive phase of exploration, the diamond drilling. The cost of one wasted drill hole could often pay for a very considerable amount of preliminary reconnaissance or detailed exploration work.

Mention might be made of a few actual examples of such integrated exploration programs in the Bathurst District of New Brunswick:

- (1) Airborne electromagnetic surveys were used for primary reconnaissance; electromagnetic

anomalies were checked on the ground by geochemical soil surveys; localities where both methods showed anomalies were drilled.

(2) Primary reconnaissance was by airborne electromagnetic surveys; anomalies were checked on the ground by both geochemical soil surveys and gravity surveys; where both ground methods showed anomalies, the localities were drilled.

(3) Primary reconnaissance was by geochemical stream sediment analysis; anomalous areas were detailed with geochemical soil surveys and ground electromagnetic surveys; localities showing both electromagnetic and geochemical soil anomalies were drilled.

(4) Areas for airborne electromagnetic surveys were selected on the basis of regional geochemical patterns indicated by stream sediment surveys; anomalies were checked on the ground by geophysical methods.

Geological studies accompanied all of the above programs. It should be mentioned that a number of other exploration schedules have been successfully applied in the Bathurst District that did not include the use of geochemical methods.

Future Trends in Geochemical Exploration

Geochemical methods of exploration, like geophysical methods, are at the present time going through a period of rapid development in which new or improved methods are continually being developed and successfully applied. At the moment, there is no sign that this sharp upward trend is starting to level off. However, it is still possible to make a few guesses as to what the future may hold in store.

There is every reason to suppose that methods of geochemical reconnaissance based on analysis of stream water or sediment for metals other than zinc can be developed. Particular mention might be made of copper, molybdenum, and uranium as being particularly hopeful. The sampling and analysis of sediments from the bottom of fresh-water lakes shows promise as a means of locating sources of metal in the surrounding country; this would be particularly attractive in the Canadian Shield where aircraft can land on lakes, and samples can be taken without beaching the plane.

Studies of the fine-grained fraction of glacial till holds some promise as a method of appraising the possibility of mineralization up-glacier from the sample site. Additional experimental work on the movement of metals from a source in the bedrock up into transported cover such as glacial moraine may lead to more reliable interpretation of geochemical soil anomalies in glaciated terrane.

The most important trend in geochemical exploration is a human one. More and more geologists are becoming familiar with geochemical methods of ore finding, and are learning what these methods can and cannot do. More than ever before, exploration geologists are able to view these new techniques in their proper perspective with respect to the other available tools, and can integrate them into well-balanced exploration schedules.

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Discussion

Dr. J. W. Gruner (University of Minnesota): Are there any interfering ions in this ion-exchange work?

Dr. Hawkes: In the first place, it is well to remember that what you measure with the Bloom Test is the group of elements that react with the reagent, dithizone. The principal metal is zinc, but the group also includes copper, lead, cobalt, mercury, and platinum, etc. As for interferences, you run across samples on which the method will not work and where you never know exactly why. Such effects can result from excesses of iron and manganese which are known to interfere with the dithizone reaction.

Mr. M. P. Walle (Minnesota Department of Conservation): Has any geobotanical work been done in New Brunswick?

Dr. Hawkes: I think that only a very small amount of experimental geobotanical work has been done in New Brunswick. The reason that the geobotanical method has not been more widely used is that you can usually find the same patterns by soil sampling, and with much less effort than you can with plant sampling.

Mr. Neil B. Ivory (University of Minnesota): Would geochemical methods be useful for detecting deposits under the lakes by dispersion of metals into the lake-bottom sediments or water?

Dr. Hawkes: This question opens up a field that we know very little about. On the surface of it, you would say "No", but yet the fact is that you do find strong anomalies in some lakes that must be due to mineralization lying beneath the lake-bottom sediments. There are two possible ways that this could come about: one is that metal-rich glacial material derived from the pre-glacial outcrop, is deposited around the lake, then leached by modern ground water and the extracted metal deposited in the lake bottom; the other explanation is that perhaps solution and migration actually do occur in the reducing environment under the lake even though we can visualize no mechanism whereby this could take place. That is not answering your question. I am sorry, I wish I could because I would like to know the answer myself.

Dr. W. S. White (U. S. Geological Survey): What has been done with respect to water flowing into swamps and water flowing out of swamps?

Dr. Hawkes: Undoubtedly swamps do have an effect similar to lakes in precipitating metal. This effect, however, is not as universal or striking as you would expect. Ordinarily, metal-rich waters will retain most of the metal content on their way through a swamp. You cannot say the same of lakes; you do find strong anomalies in waters going into the lakes, that are absent in the water draining the same lakes. My hunch is that the effect in the lakes is due to plankton that scavenge the metal and then die and collect at the bottom; you do not get this condition in swamp waters. Water that filters through the muck of swamps would at first undergo a change in composition but in the course of time the metal content of the muck would come up to an equilibrium value, and then nothing further would happen. One limnologist some years ago published an account of the variation in copper in a glacial lake in Connecticut: he found that the copper content was distributed in three ways -

one was ionic copper, another copper in living organisms (plankton), and the third was copper in dead organic material. The limnologists have technical names for all of these. Depending upon the time of year, the weather, the sunshine, and the composition of water entering the lake, the ratios between these three kinds of copper varied tremendously. The content of ionic copper in the lake was much more a measure of the season than of the copper content of waters entering the lake. Incidentally, he found that the ionic copper content of the inlets went up by a factor of 10 in the middle fall when the leaves were rotting.

Dr. Gruner: Has any work been done on peat with respect to the concentration of heavy metals?

Dr. Hawkes: Yes, there has. Empirical work has shown that peat does absorb just about every metal. The agricultural people are also concerned about this same problem as muck farms are very valuable for raising certain kinds of produce. While I can say that a lot has been done, I would not dare try to summarize it here. In general, muck serves as a trap for trace metals. There was one muck farm in New York State adjoining a zinc-bearing Silurian dolomite formation; the zinc leached from the surrounding rocks accumulated in the muck until in spots the dry weight of the muck was as much as 16% zinc oxide; some of the ashed samples contained nearly 100% zinc oxide.

In reply to a question from the floor I would say that "heavy metals" refers to a group of minor elements that react with the reagent dithizone. This reagent is most sensitive for zinc which is also the metal that is most likely to be in the stream sediment in major quantities. In our work the only other metals that were present in sufficient quantities to give a positive response were copper and lead; excesses of copper over zinc can be distinguished by the different color of copper-dithizone complex. I am sure you realize that in most ore deposits, metals go together in characteristic groups. Thus if you have a nickel deposit you will probably find copper; if you have a silver deposit you will probably find lead and zinc. Hence even with a method that measures only copper, lead and zinc you can get an indication of the majority of ore types. There are, of course, a good many you may not be able to detect, as for example high-grade silver deposits, tungsten, columbium, tin, etc.

Dr. Yardley: I wish to call attention to a paper on "Prospecting for Bog Covered Ore by Means of Peat Investigations" by Dr. Martti Salmi of Finland*. It presents some very interesting data in connection with peat and muck and the effect of humic acid on their fixing powers. Trace elements in these organic materials are multiplied by 7, 8 and as high as 20 times that of clay minerals; they are a very powerful fixative agent. We have done a little work in northern Minnesota on this and we do find anomalies at a depth of 3 or 4 feet, that is considering the vertical profile. The shape of these apparently reflects whether it is essentially a transported anomaly or a non-transported anomaly. That work has not gone very far yet, but there is a little information on these peats.

Dr. Gruner: Dr. Yardley mentioned humic acid. Now there is some information on humic acid available from investigations that are being conducted by the Chemical Engineering Department of the University of Minnesota. I got hold of some of it the other day and I thought I would try to see whether I could absorb uranium with this pure stuff because peat absorbs uranium very rapidly. I got a negative result with humic acid.

Dr. Dutton: One phase of geochemical prospecting that Dr. Hawkes did not mention is in drill holes. Would you tell us something about it, Dr. Hawkes?

* Reference 9, p. 85.

Dr. Hawkes: Several of the oil companies, one in particular that I know of, are using geochemical logs for stratigraphic correlations of their holes. They find that by analyzing for particular elements (I am not sure which ones they are, but I think there are four that have been found useful) and plotting the values on vertical sections, they can get very good drill hole correlations just as you do with electric logs, gamma ray logs or other types of geophysical logs. They take very large numbers of samples and feed them through an instrument known as a quantometer or automatic spectrograph. The samples are poured in at one end, and the analytical data comes out on punched tape at the other end. Something like this might be helpful in the Iron Ranges of Lake Superior where you want to correlate, or even find out whether you have, a stratigraphic section in the sequence. Some work of this kind has, in fact, been done on titanium.

Dr. Dutton: Dr. Hawkes refers to some work in the Cuyuna district in Minnesota. In this area the iron formation, which is primarily interbedded siderite and chert, or silicate and chert, lies between slates and siltstones. The question arose as to methods for distinguishing sediments that were younger than iron formation from those older than iron formation. In a bulletin of the Minnesota Geological Survey, resulting from a cooperative investigation of the Cuyuna by the Federal and the State surveys, several of 12 or 15 chemical analyses have an exceptionally high content of TiO_2 for sediments; some of these analyses ran as high as 2%. The samples with high TiO_2 were in what was presumed, on the basis of the mapping done in the mines, to be hanging-wall materials. Dr. M. Fleischer of the Geochemical and Petrology Branch in Washington was asked whether or not it was likely that the titanium content would be sufficiently persistent and sufficiently characteristic that it could be used for stratigraphic purposes. He replied that he did not know actually, but it so happened that some of the chemists in the Branch had just perfected a field test for titanium and they were interested in trying it. Two chemists came to the Cuyuna district and in three days made 75 determinations. The determinations can be made in 10 minutes from the time the sample is selected and the cost is 10 cents. In three days they were able to show that there was a very diagnostic split in the titania values for the iron formation, for the rocks below the iron formation, and the other rocks above. The iron formation was the lowest of all three - less than a 1/2%. The rocks below the iron formation were approximately 1 to 1 1/2%, and the rocks above the iron formation 2% or more than 2%. This has been a most useful tool in working in the Cuyuna district inasmuch as within the vicinity of the mines, the only exposures of bedrock are in the pits themselves. There has been much drilling but unfortunately most of it has been churn drilling so only cuttings are generally available. Mr. R. G. Schmidt of the U. S. Geological Survey has run thousands of titania determinations on cuttings and it has been a tremendous help to him in tracing out the stratigraphic sequence in areas between mines and from that the structure in the Cuyuna district. The general method of this field test for titanium was published in Economic Geology*.

I think that other things of a similar nature might very well be used. The matter of trace elements for stratigraphic purposes is a tool of which as yet we do not recognize the full potentialities and it is simply a matter of trying to find techniques which are sufficiently perfected that they can be used readily in the field. An offshot of this titanium test came from one of the Oliver Mining Company's geologists and concerned the rapid determination of iron content in a sample. In the titanium test a reagent is added to put the iron into solution so that it does not mask the color by which the amount of TiO_2 is determined. In a field test for iron the general procedure is similar, but this decolorizing reagent is omitted. The sample solution is diluted a proper amount in accordance with having calibrated a photographic light meter with chemically analyzed samples. The photographic light

*Shapiro, Leonard, and Brannock, W. W.: A Field Method for the Determination of Titanium in Rocks, Econ. Geol. Vol. 48, No. 4, pp. 282-287, 1953.

meter is then used to determine the amount of iron in the digested sample at the same dilution. This is a quick, easy method for field determination of iron.

A member: How accurate is that?

Dr. Dutton: I would be inclined to say within 10% accuracy but I am not sure.

APPLIED PHOTOGEOLOGY

by

W. Warren Longley

(Transcription)

In the beginning I should mention that Aero Service Corporation, Philadelphia, Pennsylvania, is sponsoring this talk, and affiliates of that company, Knox, Bergman and Shearer of Denver, Colorado, have assisted me in preparing some of my material.

I wish to discuss the general field of Photogrammetry and procedure followed in the Denver office in interpreting photographs. Most people know the value of aerial photographs for geological purposes, but few are familiar with the detailed procedures from the photography through to the final geological report. I regard it as a serious matter that so few geologists recognize what can be accomplished in Photogeology. I find this is true not only with the general public, but with my associates in the field of Geology as well; and it is particularly annoying that at times I am not able to convert my own students who are studying Photogeology. I shall, therefore, mention some facts in order that you may recognize the many uses of aerial photographs, and then I want to discuss in detail the problems of photo-interpretation in the Canadian Shield. It should be pointed out that geological interpretation of aerial photographs in the Canadian Shield, including western Upper Michigan, is quite different from that in most sections of the oil areas of this country.

In regard to photogrammetry, all branches of interpretation depend on the quality and character of the initial photographs, and for that reason we must have good coverage and good photos in our initial work.

Insofar as the historical development of photography in geology is concerned, I believe that some of the early efforts were made in the Canadian Rockies where horizontal photographs were taken from one mountain peak to another and in that way some aid was given to geological mapping. As time progressed we find that our first true aerial photographs were taken during World War I. Following that, the equipment and techniques developed during World War I were applied, and in the late twenties and early thirties extensive use was made of oblique photos. Oblique photos can still be used to a certain extent in aiding geological investigations, but they do not have the advantage of the verticals.

My first work with vertical aerial photographs was in 1936. From that time on the quality of the photographs and the techniques have been improving. I should mention here that Aero Service Corporation has been among the pioneers in the field of aerial photography and photogrammetry. I might make here a distinction usually recognized by geologists: photogrammetry is primarily the compilation of various kinds of maps as contrasted to geological interpretation. Most geologists do not like the tedious work of photogrammetry - they prefer having maps prepared for them and then proceeding to the geological study. Aero Service Corporation works primarily in the photography and photogrammetry fields. In their organization they now employ over 800 people and conduct projects in photogrammetry and photogeology throughout the free world.

In photogrammetry, there are several problems to be considered and one of most importance is that the photographs must be adapted to the job in mind. There are many varieties of photography, of lenses, cameras, and final pictures, and in all of these one cannot do a proper job unless the proper photographs are available. For instance, if you want to make a planimetric map of a city, photographs taken with a long focal-length lens at considerable height would be most satisfactory. If you want to work on geological interpretation and wish vertical control, then you need photographs taken with a short focal-length lens. The lens most frequently used in this country has a focal-length of six inches. The focal-length of the lens has an influence on the pictures, and one should know what lens is best for a particular job.

Reconnaissance

In general reconnaissance work one wants a rapid coverage of the ground. Photography will be used in studying only major ground features. For such general reconnaissance there are several things we can do, one of which is to take vertical photographs on a scale of about one to 60,000 or one to 70,000. Taking vertical photos at that scale means that the airplane must be fairly high. When I first started work in photography and photo-interpretation, such photographs would not have been possible because the planes could not fly high enough. Another thing one can now do for this general reconnaissance coverage is to use a so-called tri-met camera system in which three photographs are taken simultaneously - left, right, and along the axis of flight. In that way it is possible to get a wide coverage in a single flight that is quite satisfactory for reconnaissance work. Another system being used for a wide coverage is low oblique. This is at an angle of about 12° that is rectified to the vertical plane for study. Thus, in general reconnaissance there are several choices - the vertical photographs, of a scale around 60,000 or 70,000, the tri-met system, or the low obliques.

Detailed Reconnaissance

In so-called detailed reconnaissance a different problem presents itself. Detailed reconnaissance yields excellent photographs for geological study. In this work a common practice is to employ scales of around one to 20,000, possibly one to 40,000, or occasionally around one to 15,000. One to 15,000 represents roughly 4 inches to the mile. On a photo of this scale, using a magnifying stereoscope, one should be able to see a log across a creek and to pick out individual trees and objects of that kind. Using a scale of one to 40,000, only the major structural features will appear. The photo-interpreter, therefore, must know the general situation, must know his objective, and know precisely what scales are most adaptable. Of course, it is the problem of the photo-expert to appraise any land area or any particular geological region and to advise what photographs will do the best job toward the desired objective. Detailed reconnaissance can also be done by enlarging photos, such as one to 60,000, but direct photographs are much better.

Detailed Surface Mapping

Now we come to another stage - that of detailed surface mapping. Detailed surface mapping is used in many engineering projects and also around a mine or mining project. For instance, in mapping for petroleum, usually the project will deal with hundreds of square miles. In mine mapping it might be a matter of a few square miles, and for these we might be using scales down to one to 1,000. The problem involved here, with photographs on a scale of one to 1,000, is that the vertical control will require the use of some of the more complicated photogrammetric devices, such as the

Kelsh Plotter, Multiplex, Autograph, or Planograph, but with suitable photographs and the proper equipment one can get very detailed maps. Also, with stereoscopic study there are many features that the trained photo-interpreter can recognize.

It must be realized, of course, that photographs do not solve all the problems of geology. Geological field work must accompany the photo interpretation in order to obtain the best results. That is to say, geological problems not solved in the photographs must be solved in the field, and that again leads to the objective of the job. There are many photographic interpretation projects in which the interpreter never leaves his office. The interpretation may be excellent, but one might say that for the best quality map the geologist should do detailed field checking. The photographic interpretation is merely a means whereby a much better final map will be produced at a fraction of the cost of ground mapping.

Films

Many new developments in the past few years have served as aids to photogrammetry. Panchromatic film is now being used which has a much greater latitude than film available a few years ago. Interpretation can be much more specific from this film, and I suspect we will find many improvements in film over the next few years. Infra-red is another film which has been used extensively in aerial photography in recent years. Infra-red film has some very decided advantages, particularly in forest survey work in some sections of the country. The primary advantage is where one wants to make a distinction between deciduous trees and conifers. If one wants to recognize species, infra-red is not as satisfactory as panchromatic film. I want to emphasize that because in some sections of Canada the ability to distinguish between deciduous and coniferous trees is very significant in interpreting geology, and a sharp contrast is obtained by using infra-red. Infra-red is also important when working in swamp areas, because the ground moisture is more apparent when photographed with infra-red film than with other films.

The branch which I believe is presently receiving the greatest research attention is color photography. Color film for the usual 9" x 9" photograph is several times more expensive than panchromatic film. In a newer development, attention is focused on 55 millimeter film, and most of you are familiar enough with color to know that because of the "grain" one can use much smaller negatives of color than of black and white for the same final quality of picture. Interest is generated here, for in studying many geological features with color, detail obtained cannot be matched by black-and-white photography. I believe, therefore, that color photography in Geology has a great future.

Some places where color differentiation may have a particular advantage are around metal deposits, particularly those of hydrothermal origin. It might be said on theoretical grounds that there should be extensive rock alteration around hydrothermal deposits. An increase in certain metal constituents in the soil should be reflected in the vegetation. It is believed that the different soil conditions and different metal constituents have an influence on vegetation. It can be demonstrated that certain species of vegetation do absorb greater amounts of certain metals than other species. An area of primary research now is related to the effect of unusual soil on the initiation of the growing season and on early or late ripening. Another very significant factor is autumn coloration. If any great strides along these lines are to be made, it must be recognized that photography must be done at very specific seasons, and we hope that we can make some very significant contributions along this line.

Control

Also to be considered is the control of aerial photography. Any one using vertical pictures taken many years ago undoubtedly has been annoyed by flight strips going apart and coming together and by all kinds of gaps and irregularities. Through the application of radar principles we have developed procedures whereby it is possible to control a flight line. In trackless country a flight line can be laid out by radar which the airplane can follow specifically to get complete coverage and avoid the weaving for which the pilot cannot be blamed. Adding some shoran principles, we can determine the instantaneous position of the airplane, and I believe at the present time with some of our procedures we can spot our airplane position within 25 feet, and the position of the photograph center within 75 feet. Thus, when necessary, not only can we fly very straight parallel lines, but we can determine the precise relative position of the individual photos. With this principle we have tremendous potentialities for precise mapping which, of course, can be used directly with our geological work.

Magnetics

In connection with geological interpretation, we have new additions in other branches. The airborne magnetometer has contributed very greatly to photo interpretation, and new electromagnetic airborne equipment promises a revolution in magnetic work. Involved with the electro-magnetic work is a wide range of possible applications. This airborne instrument work is just now in its infancy, and I am sure that over the next few years we are going to find tremendous applications of it as an assistance in photo interpretation.

Commercial Photogeological Evaluation Methods

Although various applications of photogeologic evaluation are used in ground water geology, hard rock geology, soil analysis and general geology, the major percentage of photogeological evaluation conducted today is directed towards oil exploration. The following discussion, therefore, focuses upon the principal method used today in compilation of data from the stereoscopic examination of air photographs for purposes of oil exploration.

Consulting geological firms that specialize in photogeological evaluation are not equipped to compile air photograph coverage. They depend upon commercial and governmental agencies such as Aero Service Corporation and the Commodity Stabilization Service as a source for air photograph coverage. These agencies also offer mosaic coverage.

Initial Procedures

A three-fold operation initiates a photogeologic evaluation: Geological research, indexing and filing, and base-map construction. Geological research is conducted throughout the project area. This research is aimed towards the compilation of all geological data available from the literature both as regards structural geology and stratigraphy. Inasmuch as the entire geological evaluation must be based upon criteria observable on air photographs, any aid in the way of published field data facilitates the photogeological evaluation. While research is being conducted, the air photographs, mosaics and other materials used in the analysis must be properly indexed and filed. This routine task is important for the smooth operation of a photogeological evaluation. The third

process, initiated at the inception of a project, is the construction of base maps and accrual of control data for subsequent use in the drafting processes intimate to the final photogeological map compilation.

If aerial mosaics are not available from either governmental or commercial agencies, the photogeological firm must be prepared to construct mosaics. Mosaic construction, initiated prior to the geologic interpretation of air photographs, must be completed prior to geological evaluation so that the photos used for mosaic construction can also be used for geological interpretation.

Photogeological Evaluation

Upon conclusion of research, indexing and filing, the photogeological interpretation of the air photos is commenced. This geological study, the most important phase of photogeological evaluation, consumes a majority of the total time expended. In an area of considerable size the photogeological evaluation proceeds on 15' quadrangle increments. Each 15' quadrangle is assigned to a geologist for photo interpretation. After the geologist annotates every other air photograph and ties the photogeological interpretations within flight lines as well as between flight lines, the annotated photographs are submitted to a second geologist who studies the area to ascertain validity of the initial geological interpretation. At the termination of this geological evaluation, all of the final map data, except for the land network and drainage, are shown on the air photographs. These data include structural geology, stratigraphy, and culture.

Mosaic Posting

The posting of mosaics is a common step between the annotation of the air photographs and compilation of geological data to a land network. Either semi-controlled or controlled mosaics at a scale of 1/48,000 or 1/63,360 are used in this process. Mosaic annotation is not made directly on the mosaic emulsion surface. Thin acetate overlays, affixed to each mosaic, receive the pencil annotations. This method has two direct advantages: one, the acetate has a uniform surface that is amenable to pencil annotation, and two, upon completion of the acetate annotation, a preliminary print can be made from the annotated acetate for an early examination of the photogeological results. Cartographic draftsmen transfer data shown on air photographs to aerial mosaics.

At the completion of geological interpretation and mosaic annotation, a set of preliminary maps printed from the acetate overlays is available to the client. At this time a geological field check of the photo evaluation is conducted. The field check is not aimed towards making a field map out of the photogeological evaluation, but rather to confirm the stratigraphical identification of rock units as well as questionable structural interpretations. All field derived data are shown on the aerial photographs, the aerial mosaics and on the final maps.

Drafting Procedures

Where photogeological evaluations are used in oil exploration, it is mandatory to orient the geological data with respect to sections, townships and ranges. Hence, compilation of photogeological maps is inseparably related to land network identification.

During the geological evaluation of air photographs, section line fences and roads as well as prominent cultural detail are identified, and these control data are recorded on the pictures and

annotated on the mosaics. A fair density of control is, therefore, available for orienting geological patterns with respect to the land network when the drafting stage is approached. If control data are scarce, various literature is used to further control identification. This literature includes topographical sheets, General Land Office plats, County Highway planning maps, and township plats. If mosaic construction is of average quality, an imperial linen base map tracing is placed over the annotated mosaic, and geological data are traced on the imperial linen in ink. The control established prior to drafting is used to orient the base map over the annotated acetate. After the map is completely drafted in ink, a geological and cultural legend and title are affixed thereto. The final map is colored with printer's ink and prepared for submittal. A photogeological report that sets forth the salient features of the evaluation plus conclusions in regard to oil exploration is prepared to accompany the final photogeological map.

The Canadian Shield

I will now go on to the next stage, that of particular applications of photogeology to the Canadian Shield. In oil areas one usually finds erosion in a satisfactory stage; the most ideal circumstance for photogeology is the mature stage of the erosion cycle, together with arid conditions. In the Canadian Shield there is a general cover of glacial till. Combined with this in many areas is a heavy timber cover. Consequently, conditions for photo interpretation in the Canadian Shield are somewhat undesirable, but there are many things that can be done. Insofar as metal deposits are concerned, we recognize a relationship between these deposits and certain kinds of igneous rocks; we also recognize the relationship between metal deposits and fault and shear zones. This means that if we can make some distinction between rock types and detect fault and shear zones, we have made a contribution toward the ultimate goal in hard-rock geology of finding a mineral deposit.

Another situation I should mention is the great scarcity of outcrops. When we start our photo-interpretation, therefore, we have to rely on slight relief and on drainage. On the photographs the only things we have are color tones and textures. Using stereo photos, the primary features to be searched for are linear structures on the upland areas, linear segments in streams, and also any linear distribution of the vegetation. Steeply dipping faults and shear zones have a rather linear expression, while low-angle faults do not have a true linear expression and will be more curved.

In regard to vegetation, it is possible by careful analysis to recognize whether there is a deep or thin covering of soil; a thin one is helpful at times. If all one can do is pick out shear zones, why not pick them out on the ground and save trouble? I might point out one example on which I worked: I knew that there should be a strong fault zone going through a certain area, and I knew within a mile where it should be. When I first went to the field, I did not have air photographs, and I searched that place back and forth for over two weeks trying to pick up the fault zone which I knew should be there. On the ground I could not find it because of till, low relief, and timber. I finally got the photographs and within five minutes of studying them I was able to pick up the fault zone; there could be no question of its location, and one could trace it through the area. The point that I want to bring out is that many features can be seen and traced on the photographs that cannot be seen on the ground.

In Precambrian areas careful topographical representation is significant because slight changes can mean a change in rock type. Of prime importance in Precambrian mapping for mineral deposits is complete delineation of sedimentary belts and lava belts, and their relationship to the surrounding igneous masses; minor changes in topography may show up these characteristics. Of course, detailed topographical expression can be worked out only with instruments such as the Kelsch Plotter, but even form-line sketching or contour-line sketching can be a tremendous help in presenting geological

features. Another significant feature is the drainage. In initial geological work a very detailed plotting of all streams is helpful, because even though till covers the bed rock, the stream distribution and the stream pattern may be significant in interpretation.

In the Precambrian areas such as I have worked on, the field checking procedures are far more extensive than in ordinary petroleum work. This means that it is necessary to have a photo interpreter in the field with a crew for ground checking and with some liaison between field crew and office men, the latter working with instruments that could not be carried out in the field, e.g., the Kelsch Plotter. The Kelsch Plotter is one of the plotting devices that has proved its accuracy and simplicity in recent years and is regarded as one of the more significant of the instruments in geological work.

In regard to Canadian work, in summary and conclusion, I can just say that it is a difficult job; many geologists express the opinion that the details of geology cannot be worked out from photographs. It is my opinion that a tremendous contribution can be made by photography, and at the present time with the use of the airborne magnetometer, we have an additional field. Recently I was rechecking one of my field jobs after airborne magnetic work had been done, and in several places where I was still in doubt after detailed photo study and field checking, I was able to settle the problems without question from the results of the airborne magnetic work. By combining airborne magnetometer work with photography, we are in a position to get a rather detailed map -- one from which we can select the more favorable areas for subsequent exploration. I believe that the application of these procedures will result in geological information, I should say rather than maps, many times more complete than has been available without the photographs, particularly with the additional information from magnetometer work. I believe that the careful application of these procedures will lead us to some new mineral deposits more readily than we have been finding them.

In regard to discovering mineral deposits, the previous speaker employed a rather difficult method of approach. The way I have suggested is equally difficult and, of course, it will be recognized that this work that I have taken up will be preliminary to such work as he has suggested in geochemistry. A significant factor in the discovery of a Gaspé, Quebec, copper deposit was the easy way that I suggest you all try. One geologist who used his head more than his feet walked in to see my chief at that time, Dr. I. W. Jones of the Quebec Department of Mines. He just said, "I want a copper deposit, a large deposit of low-grade ore. Where is one?" Dr. Jones turned to him and told him where to go in Gaspé to look for it, and there it was waiting. For many years Dr. Jones had done much mapping in that region. Most geologists thought that there were no mineral deposits of importance south of the St. Lawrence River in Quebec, and few had looked there; so when the gentleman came along, it gave Dr. Jones an opportunity to tell him where there really was some copper, and this information led to the discovery. I suggest, therefore, that you try that way first, and if it does not work, you will have to resort to photogeological work along with geochemical work.

Discussion

Dr. H. E. Hawkes, Jr. (Massachusetts Institute of Technology): In what way does photogrammetric work have an advantage over what the geologists have been trying to do otherwise for some time?

Dr. Longley: I can give an example applying detailed photogrammetry to the geologic interpretation. Around 1946 I mapped the Bachelor Lake area in the Province of Quebec and showed the prospectors where the ore was. I did a rough contour job using form lines which helped considerably, but I was criticized because, as the detailed work around the mines showed, the elevations did not check with mine, and the engineers said my map was not accurate. It was not intended to be

accurate. Had that same job been done with a Kelsch Plotter or Multiplex, for example, it would have been a far superior map and would have been of far more help to the mining engineer in his operations and also helped in geological interpretations. Photogrammetry would have yielded a superior map to the one I was able to produce by the routine procedure of photo interpretation. For the geologist making up a map in critical areas, there would be considerable advantage to a detailed map made by the more precise mapping instruments. That was the only place I did run into severe criticism because my map was not good enough. To the people using the maps, the form lines were interpreted as contour lines and they proceeded accordingly.

The general situation is that physiography is very important in the interpretation and presentation of geological features. Detailed mapping of surface features, such as can be done with a Kelsch Plotter or Multiplex, provides an excellent physiographic base to aid in the geological interpretation and presentation.

MODERN TECHNIQUES OF PHOTOGEOLOGY AND PHOTOGRAMMETRY IN NATURAL RESOURCE DEVELOPMENT

by

John C. Bayless

Aerial photography has come a long way since the days following World War I when Talbert Abrams helped pioneer aerial surveying and the cameraman hung over the side of the cockpit with a hand-held camera. Today, a military jet can photograph for reconnaissance purposes a 490-mile strip across the United States in less than four hours. But photography and photogrammetry for geologists and engineers are long past the reconnaissance stage and have become precise tools and desirable components of nearly all mapping operations. The aerial camera is the modern surveying instrument in the search for minerals and fuels to support our national economy.

The principal value of aerial photographs is that detailed maps can be made from them. The photogrammetry of overlapping pairs of aerial photographs for quantitative data is so perfected that virtually no ground detail is too small to be measured and plotted. Applications in the fields of natural resource development, engineering planning, and area mapping are almost without limit.

Photogrammetrically plotted maps are an important supplement to aerial photographs as contact prints because, in plotting, the radial distortion of scale and displacement of images on the photograph due to tilt or relief has been rectified to an orthographic projection. Thus accurate distances and directions can be measured. Topographic contours or control points for structural contours in absolute elevations are often plotted. For field work in densely vegetated areas or in areas with only faint geologic clues, an accurate topographic map has distinct advantages in locating oneself on the photograph and in the field.

A geologic map in the full meaning is a geologic contact map with topographic contours. By relating contacts to contours a detailed interpretation is best accomplished. Reconnaissance contact maps are usually prepared by transferring the pattern of formational outcrops from individual photographs onto photographic mosaics. Geologic maps are compiled by photogrammetric plotting using stereoprojection equipment.

The production of geologic maps by photogrammetric methods effects savings by reducing the number of supplemental control points which must be obtained by ground survey. In addition, when higher altitude photography is used, the increased area covered by each model, and the fewer models required with less time spent setting up and joining detail between models, result in savings in stereocompilation. From the viewpoint of the photogeologist, stereoprojection instruments partly solve the problems of relating or transferring geology to base maps. These instruments also combine stereoscopy in orthographic projection with the ability to make many measurements more easily than those he now makes on the ground.

The trend today is for specialized teams of photogrammetrists to work with teams of photogeologic

interpreter specialists to produce geologic maps.* Such joint operations bring together the planes, laboratories, photogrammetric instruments, plotting techniques, field operations, reproduction processes and technical and professional staffs to provide an integrated interpretation and mapping program. This seems to be a reasonable approach to applying two specialized techniques to the expanding requirements for geologic mapping and the need for more detailed mapping.

Planimetric maps can be constructed by geologists or engineers from aerial photographs using a system of radial-line plotting based on the usual surveying principles of intersection and resection. These methods are not very accurate and most photogrammetrists and engineers, who are concerned with precision mapping, consider them to be of reconnaissance value only.

Greater accuracy is obtained by using stereoprojection plotters. The development of new first-order plotting instruments has hastened the adoption of Kelsh and Multiplex photogrammetric instruments by geologists by making available these less elaborate plotters which today generally have a supporting role in mapping for precise engineering projects. A Kelsh stereoscopic projection plotter is shown in Figure 1. Projectors are mounted above a plotting table in such a way that they exactly duplicate, on a reduced scale, the altitude, tilt, and position of the aerial camera at each picture station along the flight line. Working in a dark room the operator sees a three-dimensional image of the topography. By means of a small tracing table which can be moved freely on the plotting table, he traces the ground plan, controlled by known ground stations and corrected for tilt, radial distortion, and scale.

Topographic contours can be plotted by using a floating dot in the stereoscopic image of the topography and some known ground elevation control points. The operator can set the dot correctly at elevation control points and, using the contour scale selected, move the dot and tracing table along the given contour, automatically tracing the line on the map.

The principles of photogrammetric mapping also apply to structure contouring. If a topographic contour map is not to be prepared, the geologist selects on aerial photographs evenly spaced points along the formation or marker bed boundaries to serve as structure contour control points. He pin-pricks them through the photograph and identifies each on the back. Depending upon the scale, 15 to 30 points per square mile are selected. The photogrammetrist determines the elevations and sometimes the coordinates of these points so that the geologist can then contour the structure on a key bed. Such methods may be three to four times faster and also are more accurate than plane table mapping.

In recent years a trend has developed toward the use of special photography flown to suit the needs of given projects. It is often cheaper to fly new photography correctly designed than to attempt to use older photography designed for some other purpose. The best opportunity to save money and time is at this point. For example, when Kelsh plotters are used with a 5X projection enlargement ratio, 1:60,000 photography can be plotted directly to 1:12,000 map scale. Three to five 1:60,000 photographs cover the area of about thirty 1:20,000 photographs, the usual available scale. The use of this small-scale photography may save one-half to two-thirds the plotting time, some flight costs, and considerable ground control.

On the other hand, there is also a demand for new large-scale photography. Stratigraphic and

* Abrams Aerial Survey Corporation, Lansing, Michigan is affiliated with Doeringsfeld, Amuedo and Ivey, Denver, Colorado for integrated photogrammetry and photogeologic interpretation.

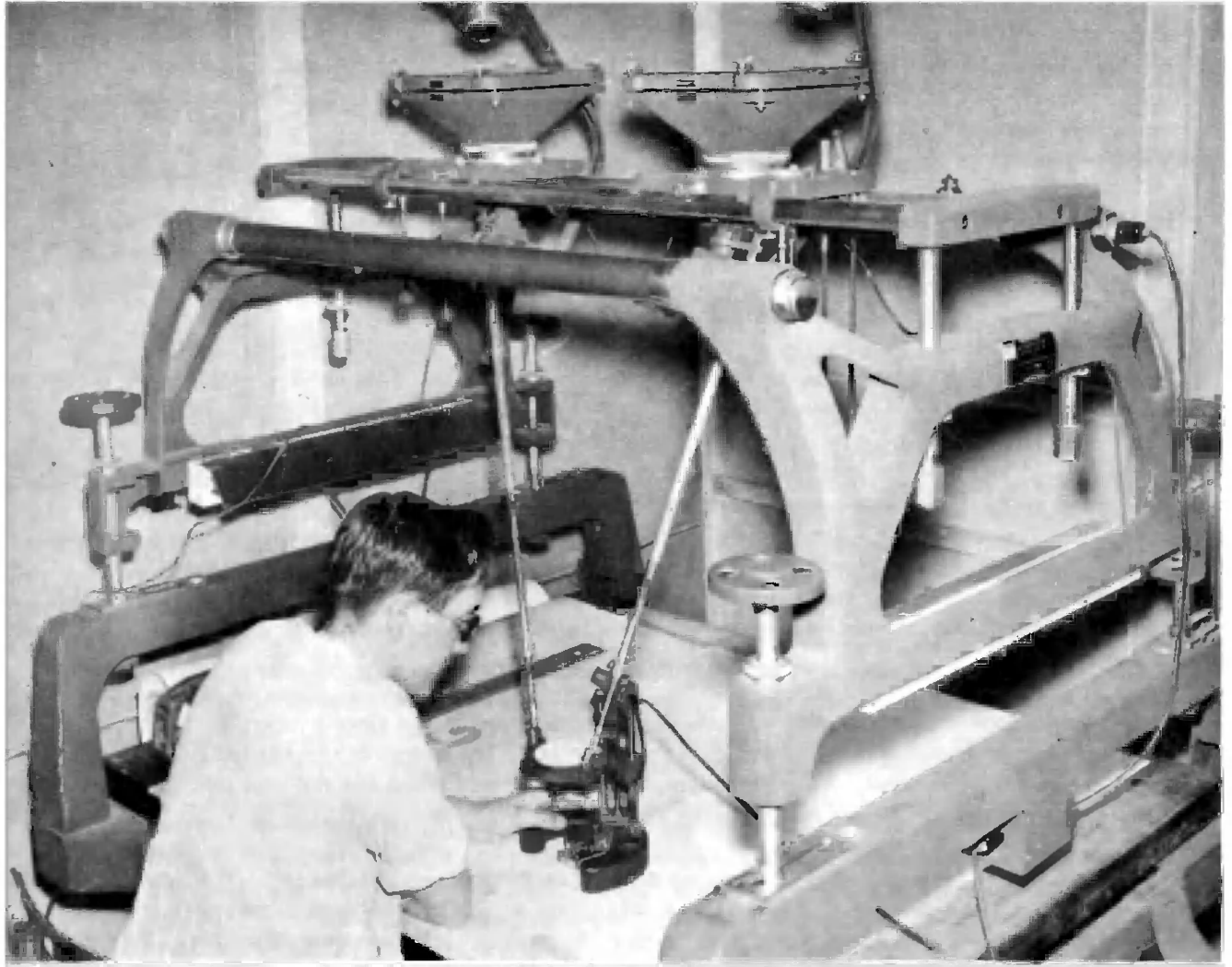


Fig. 1. Kelsh type stereoscopic projection plotter. Spatial model is created by projection of 9" x 9" glass diapositives made from aerial photographic negatives. Tracing of ground plan and measurement of altitude are accomplished by a tracing table which rolls over the manuscript with a pencil lead directly under the illuminated floating dot.

geomorphic columnar sections may be better interpreted from stereoscopic study at large scales. Columns showing hard layers and ridge makers are particularly useful to photogeologists. As in the case of precise structure contouring, thicknesses of stratigraphic units are best measured by photogrammetric techniques.

A convenient medium for speeding the work of the interpreter to the user is a reproducible photo-mosaic on the same scale as the contact prints. A recent development is printing the mosaic image on the under surface of reproduction linen. While viewed over a light table, the geology can be transferred to the clear top surface using a stereoscope and the original annotated contact prints.

If topographic and structure contour maps are also accomplished on linen at the same scale, these can be fitted and traced directly onto the mosaic. Topographic contours are usually traced on the back side over the mosaic while structure contours are drawn on the top side with other geology. The result is a photograph of the region and superimposed geology with contours which can be viewed separately or together. There is also the advantage of a durable drafting surface on which changes can be made without affecting the photographic image.

The historical principles of interpretation of geologic maps apply to the interpretation of aerial photographs. In the training of a geologist today it is difficult to determine which should be studied first because there are basic similarities, differences, and limits to each. Culture is shown in full detail on aerial photographs while the geologic map depicts only the landmarks considered essential by the mapper. The photograph indicates generally what is at the surface and the geologic map usually indicates an interpretation of bedrock beneath the mantle. However, in this latter regard, aerial photographs frequently reveal subtle tones, patterns, forms or relief which are keys to the bedrock or structure not evident to a person on the ground. Photographs when viewed as stereo-pairs under a stereoscope reveal relative relief while a geologic map compiled photogrammetrically has topographic contours which indicate actual relief as detailed as required. The fact is that modern geologic maps are likely to be based on the interpretation of photographs, and have been compiled photogrammetrically.

Photo-interpretation involves more than the identification of features. The interpreter supplements his direct observation by deduction and by visualizing obscure or hidden features with the guidance of previous experience and reasoning. This is an essential difference between photo-reading and interpretation. The value of the map increases with the degree to which the latter is applied. Both have a common starting point, the recognition of diagnostic features.

Many excellent examples of photogeology are in company files but generally are not available for publication. However, a good list of outstanding photographs has been prepared by the American Geological Institute as Report No. 5, 1951, and is a source of materials for training programs.

There are two basic phases of photogeologic interpretation. One is the mapping of rock types and formation units and the other is the determination of rock structure. Each of these is somewhat specialized in the several fields of economic geology but the objective in any case is the compilation of a geologic map.

Consolidated sedimentary rocks are recognized by their stratification which appears on photographs as banded outcrop patterns. If the beds are horizontal, the contacts will be horizontal and their surface traces will parallel topographic contours.

Beds that have been tilted and subsequently truncated by erosion crop out as belts. Where streams cross the outcrops a V-shaped pattern develops with the V's pointing in the direction of dip.

Folded beds are often expressed at the surface by belts which form parallel ridges and valleys, or looped and zigzag ridges with canoe-shaped valleys. Anticlines and synclines are differentiated through analysis of the dip of beds. If the stratigraphic sequence is recognized, anticlinal axes are located along the oldest beds exposed in the center. In a syncline the opposite is true.

Sedimentary rocks are distinguished on photographs mainly on the basis of stratification, and differentiated by comparative color and resistance to erosion. The latter are suggestive only. Color depends on the character of the rock and the vegetation it supports. Resistance to erosion depends not only on the physical and chemical characteristics of the rock but on the climatic environment as well. Limestone and dolomite, for example, are very susceptible to erosion in humid regions but frequently form ridges in arid regions. Pure limestone and dolomite are characteristically light but impurities produce darker colors. Frequently, distinctive horizon markers rather than formation units are selected to map structure even though the lithology may be unknown.

Extrusive igneous rocks are distinguished mainly by their surface irregularity, a ground plan

which suggests a mobile form, and association with vents such as cones or fissures. More recent flows are barren and usually dark in color. Geologically ancient lavas may not be recognizable except by a field check of lithology or structure.

Massive, intrusive igneous rocks usually appear to cut across stratified rocks with discontinuous contacts. Dikes are recognized on photographs by their linear form, group pattern and by their cross-cutting relations. Petrographic distinctions are rarely possible even though color tone is used to determine form and structure.

Joints and fractures are recognized by angular patterns in the drainage or by a grooved or striated appearance of the bedrock.

Faults are conspicuous where the outcrop pattern has been offset or interrupted. Fault traces unnoticed on the ground may be prominent on aerial photographs as linear boundaries between areas of contrasting vegetation and soil coloration. An escarpment and color contrast mark the line of a fault in igneous rocks in Figure 2.



Fig. 2 . Huronian lavas in upper part of photograph faulted down against intrusive igneous rocks in lower part, Marquette County, Michigan (Photography by Abrams Aerial Survey Corporation).

More widespread use of color photography is just around the corner for photo-interpretation. Where browns, yellows and greens may be diagnostic, details in rock strata, soils and vegetation may be lost because these colors photograph as about the same shade of grey on black-and-white photography.

Another advantage of color photography is that the eye can differentiate about 200 shades of grey in the tone scale between black and white. In contrast, there are about 200,000 different combinations in the color scale. Reds and whites, gradations in yellows, and even some gradations in whites can be seen on color photographs. Usually one cannot differentiate features depending on these color changes on black-and-white photographs. In this respect, color photography has been particularly useful in outlining areas of leaching around mineralized zones.

In the past few years it has been thoroughly demonstrated that bleaching and discoloration by hydrothermal alteration can generally be mapped more rapidly, effectively and accurately using color aerial photography than by ground methods alone.* In some areas blanket alteration up to four miles across has been mapped on color photographs and in others alteration effects limited to the immediate walls of ore bodies can be observed. Alteration mapping on color photographs is being used as a guide to uranium exploration on the Colorado Plateau.

Color photographs must be relatively large-scale to register adequate color separation suitable for alteration mapping. Where individual veins are to be delineated, photography should probably be 1" = 250' to 1" = 500'. Up to 1" = 1500' may be used for reconnaissance of mineralized areas. If stratigraphic boundaries, lateral variations, and structure are to be interpreted, scales as small as 1" = 2500' may be used.

Proper exposure and haze filtration are always critical in color photography. Colored acetate sheets can be used to correct some errors in color reproduction. Filter sheets are also useful in emphasizing certain colors for interpretation purposes.

The trend toward wider application of photogeology and photogrammetry in geologic interpretation and mapping is paying off in better maps at lower costs. The details of areas mapped are commercial secrets of the client. However, it is well known that most of the major oil companies and many mining companies are using these exploration techniques at an accelerated rate. As the integration of photogrammetry and photogeology gains momentum, increasing economies can be expected.

Many factors have conspired to make this a very brief discussion of the subject. The literature, such as "Photogrammetric Engineering" published by the Society of Photogrammetry, reports many of the newer applications. I will be very glad to correspond at any time on questions concerning the applications of modern photogeologic and photogrammetric techniques.

* Abrams Aerial Survey Corporation is affiliated with Colorado Exploration Company, Golden, Colorado for geological and geophysical contracting to the mining industry. The writer is indebted to that company for some data on interpretation of color photographs.

Discussion

Mr. R. A. Spencer (Consolidated Mining & Smelting Company): What are the costs of color photography as compared to black and white?

Mr. Bayless: Color aerial photography costs at least twice as much as black-and-white aerial photography. However, what is the cost of aerial photography? It is the sum of the costs of mobilization of a plane and crew, the film, and laboratory processing and is a function of scale, the size of the project, the geographic location and the contractor's estimate of the expected weather conditions. The latter is of particular import in color photography and the requirement for absolutely clear weather usually necessitates much longer stand-by times. Color film costs four times that of black-and-white film but the laboratory costs may be about the same if only color transparencies are delivered.

Very small color photographic projects of a few square miles in Michigan may cost about the same as black-and-white photography because of the high unit area mobilization for all small projects. However, black and white photography of medium size projects at 1:6000 scale costs \$60 - \$100 per square mile and color photography would be more than this. About \$20 to \$40 per transparency is a representative cost for vertical color photography. This does not appear at first consideration to compare favorably with "government" black-and-white photography which so many of you use. However, the usual government photography is at 1:20,000 scale and is contracted, for large areas, under very competitive conditions for \$3 to \$6 per square mile.

We are faced with similar problems when giving generalizations on costs of photogrammetry and stereo-plotting. Plotting of topographic maps may range from pennies to dollars an acre depending your scale, contour interval, content and relief of the areas. Ground control is hard to estimate until you know the availability and location of existing control and what must be done to bring it to the project area. Control can cost from 50 cents a square mile to 50 cents an acre.

Dr. A. W. Jolliffe (Queen's University, Kingston, Canada): It seems to me that these papers have stressed the geologic interpretation of aerial photographs. I think it should be noted that to some extent the photographs themselves are most useful in geologic mapping. I am speaking now from long experience in the northwestern part of the Canadian Shield where we have a lot of barren outcrop and not much overburden as in the area Dr. Longley referred to. Here it is very difficult to make interpretations despite good exposures and the abundance of linear features, and the chief use of the photographs is as an actual base for geologic plotting.

One other point in regard to Dr. Longley's procedures: We utilize every available piece of geologic information prior to the interpretation of the photographs and field check afterwards and I suggest that any geologic interpretation is just as accurate as these two necessary procedures. Again, on the basis of my experience, the use of photographs seems to me to be chiefly as bases for plotting. This is heresy to anybody who makes such extensive use of complicated photogrammetric apparatus but my point is this that the geology does not warrant too much in the way of detailed rectification of plotting. The radial-line method is of sufficient accuracy for most geologic maps.

Dr. A. M. Goodwin (Algoma Ore Properties, Limited, Canada): Are there examples in which the difference in cost between color photography and black and white is warranted in the finding of a mineralized area?

Mr. Bayless: There are indeed such examples and I am embarrassed for not being able to give you

the names of the districts. The work was done by an affiliate of our organization in some of the old Colorado mining districts. Some of the work was done around Aspen. There resulted a number of new discoveries that were identified by colors associated with leaching in areas that had been walked over for many years by field men who knew the geology.

Of course, there are other aerial survey companies besides those represented here today. A California firm has a large color contract in South America about which you may have read in the National Geographic Magazine. They showed recently in Chicago some of the color photography that was being done in a copper district. I cannot say whether or not they show anything that was not already known but they were or are photographing and presumably interpreting and mapping many square miles.

Color photography is one of those things that is looked upon highly by photogrammetrists. I found this when talking to the Atomic Energy Commission people in Grand Junction, Colorado. Photogrammetrists praised the technique though geologists thought black and white was serving their needs about as well on the Plateau. It may be a reluctance to accept something new. There is also the matter of higher costs. We are doing color photography, but I do not want to over sell color. As a matter of fact it is so "touchy" that we are very happy to work in black and white.

I should like to make a comment on radial plotting. I do not mean to belittle it. Certainly there is more radial-line plotting than any other type today by individuals and by mining companies with interpretation sections. Many of the things that I have talked about are on the verge of becoming more universally accepted. The use of stereo plotting instruments as a tool for geologists is something that is coming and developing fast. But it is certainly true that there are many projects in which the accuracy of simple radial control is quite satisfactory.

There is another trend that has not been mentioned thus far. That is the integrated program of natural resource development in which bed rock geology, soils, and forest and water resources are mapped for engineering planning and design and for exploitation. This program involves the work of many specialists. Projects of this kind are going on abroad, and similar work is being planned in this country too.

A question may be raised as to why foreign photogrammetric equipment is being used by many American aerial survey companies. Swiss, German and Italian instruments are all being introduced because they are more efficient and offer control extension capabilities.