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THE COPPER PROVINCE OF NORTHERN MICHIGAN, U.S.A.

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ABSTRACT

The late Proterozoic, Keweenawan strata of northern Michigan contain two principal types of copper mineralization, each at a distinctly separate stratigraphic position. Native copper occurs in amygdaloidal and fragmental flow tops and in reddish interflow conglomerates of the Portage Lake Lava Series. Chalcocite and combined chalcocite-native copper mineralization is found as fine-grained disseminations in basal portions of the Nonesuch Shale, a sulfide-bearing, organic-rich formation lying some 100's to 1 000's of metres above the Keweenawan lavas. An extensive red-bed conglomerate and a more local mafic to felsic flow pile lie stratigraphically between the Portage Lake Lava and Nonesuch strata. The Nonesuch mineralization of the White Pine area is also geographically centred some 60 miles southwest of the main native copper districts of Calumet and Houghton. Both copper types contain silver as a significant minor constituent.

Exploration and investigation of these two camps have taken place in large part as distinctly separate operations. The native copper ore, exploited almost continuously since 1844, occurs as irregular stratiform lodes at numerous stratigraphic levels in steep to moderately dipping beds. Many observations including those of mineral zoning, indicators of elevated metamorphic or hydrothermal temperatures, and ore controls related to relative permeabilities within and between stratigraphic units suggest that source-bed or magmatic concepts could best explain the origin of these lodes. On the other hand, the White Pine mineralization, exploited since 1954, is remarkably continuous and uniform in grade over an extensive area within strictly defined basal beds of the gently to moderately inclined Nonesuch Formation. It possesses all basic characteristics of a classic sedimentary deposit. Detailed studies in recent years have suggested, however, that mineralization of the Nonesuch may have resulted from an upward influx of cupriferous solutions which caused replacement of syndiagenetic iron sulfides and some accompanying precipitation of native copper in the presence of organic matter.

In past years concerted efforts by many individuals and organizations have produced a vast fund of information and interpretations concerning this famous copper province. Undoubtedly, a definitive solution to the occurrence and genesis of the Keweenawan mineralization will depend not only on further careful investigations at the local scale, but also on the discovery of additional regional guides such as those currently developing concepts resulting from stratigraphic and structural analyses throughout the Lake Superior basin.

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INTRODUCTION

The Lake Superior copper deposits are contained in an area known as the Keweenaw peninsula, a linear zone some 200 km in length along the south shore of Lake Superior (fig. 1). Within this region, late Precambrian Keweenawan strata have been successfully exploited for native copper, principally in basalts and conglomerates, for some 130 years; and for copper sulfide and lesser amounts of native copper in "black shales" for some 20 years. Copper is accompanied by important traces of silver in both geologic environments.

This mine production has quite naturally stirred much interest in other areas of Keweenawan rocks which occur around the present Lake Superior basin, and has resulted in a vast number of geologic studies and exploration programs throughout the immediate area and possible extensions of the Keweenawan copper province. The recognition in recent years of a probable Precambrian rift features has added new dimensions to current geologic concepts and economic studies in the basin.

This paper deals mainly with the nature of the Lake Superior copper mining camps and with regional aspects of the Keweenaw basin. Certain portions of the text result from the writer's personal studies and his continued interest in this highly intriguing metallogenic province, but obviously the majority of data and interpretations are borrowed from the careful work of many, many other students of the district. Hopefully, the credits mentioned will fully and accurately represent the contributions of a least the major pertinent studies; of course, the writer assumes responsibility for the present synthesis and his own interpretations.

KEWEENAWAN BASIN GEOLOGY

The Keweenawan strata (table 1) occupy an arcuate structural trough largely concealed beneath the present glacial Lake Superior and beneath flat-lying Paleozoic sediments along southwest and southeastward extensions of the basin. Nevertheless, good exposures are present around the rim of Lake Superior (fig. 1).

Animikean rocks (>1 650 m.yr.), including Lake Superior iron formations enclose the trough to the south and northwest. Archean rocks (>2 480 m.yr.) enclose it in turn on the south, north, northeast and northwest. Keweenawan intrusives and flows have been dated at approximately 1 050 to 1 200 m.yr. in age.

In general, the Keweenawan is divisible into a lower sedimentary sequence, a middle volcanic sequence, and an upper sedimentary sequence. The Lower Keweenawan is best exposed as a 200 m thickness of sediments known as the Sibley Series north of Lake Superior.

The Middle Keweenawan consists mainly of tholeiitic flood basalts and minor but important interflow red-bed conglomerates. The volcanics are composed of several hundred individual flows commonly measuring tens of metres in thickness and possibly attaining some 9 000 m in total thickness (White, 1968). They are known variously as the Portage Lake Lava Series and the South Shore Traps in the copper mining districts, as the North Shore Volcanics adjacent to the Duluth gabbro complex in Minnesota, and as the Osler Series in Ontario north of Lake

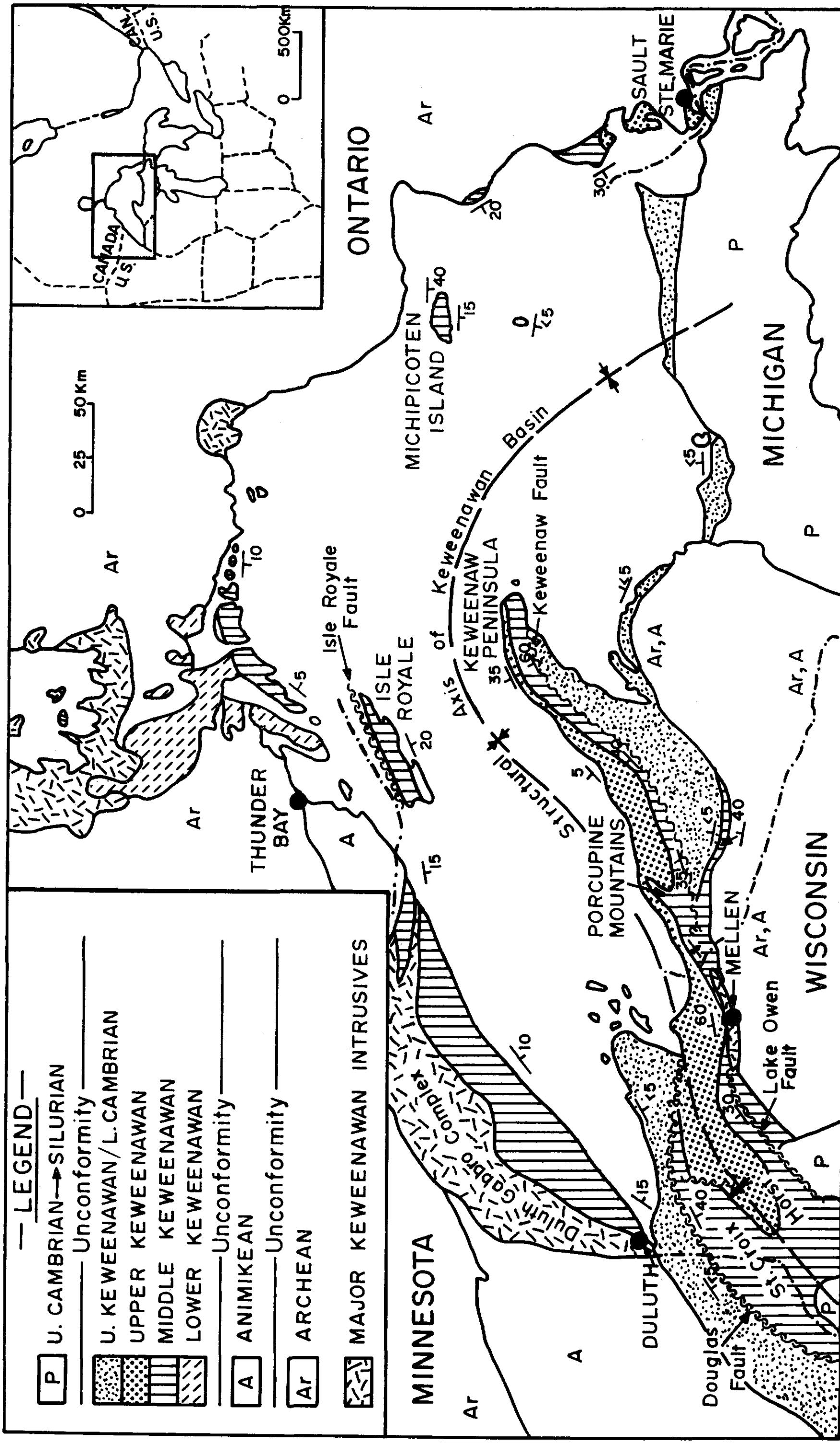

FIG. 1. — *General geology of the Lake Superior region (after Halls and West, 1971).*

TABLE 1. — *Stratigraphy of the Lake Superior Copper Districts*

Paleozoic	Upper Cambrian to Silurian	
	Unconformity	
Late Precambrian	Upper Keweenawan/ Lower Cambrian	Jacobsville and Bayfield Sandstones
	Upper Keweenawan	Freda Sandstone Nonesuch Shale
	Middle Keweenawan	Copper Harbor Conglomerate/ Unnamed Formation Portage Lake Lava Series/ North Shore Volcanics/Osler Series
	Lower Keweenawan	Sibley Series (on north shore)
	Unconformity	
Middle Precambrian	Animikie	
	Unconformity	
Early Precambrian	Archean	

Superior. Similar volcanics are exposed on Isle Royale and Michipocoten Island within the Lake, and at other minor localities around the lake.

A major projection of these mafic flows (fig. 2) has been made on the basis of a well-defined mid-continent gravity high trending southwest from Lake Superior to Kansas, and southeast beneath the Michigan basin (Muehlberger *et al.*, 1966).

Upper Keweenawan strata are composed predominantly of red-bed conglomerates and sandstones, and a relatively minor black shale section. The Copper Harbor Conglomerate was formerly considered as the basal non-volcanic unit of the Upper Keweenawan, but it has been found to contain local mafic flows and has been relegated to the Middle Keweenawan (White, 1972). The Upper Keweenawan now consists of the greyish Nonesuch Shale (approximately 200 m thick) and the overlying Freda Sandstone, a red-bed section, which may exceed 4 000 m in thickness.

An unnamed formation consisting of 0-2 500 m of mafic and felsic flows underlies the White Pine area. It has the form of a volcanic dome overlying the Portage Lake Lava Series and was buried by contemporaneous and/or subsequent onlap of the Copper Harbor Conglomerate.

The Upper Keweenawan is apparently overlain by the Bayfield and Jacobsville Formations which are probably laterally-equivalent, non-fossiliferous sandstones

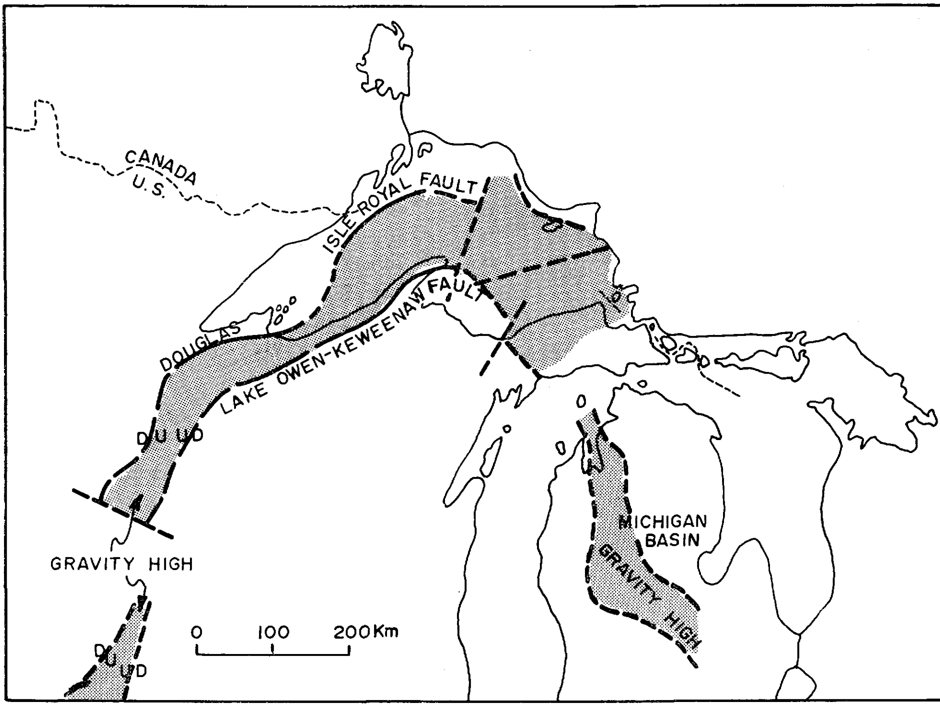

FIG. 2. — *Keweenawan mid-continental rift features (from Card* et al., *1972).*

located in Wisconsin and Michigan, respectively. These strata are in turn succeeded unconformably by fossiliferous Upper Cambrian beds. The Bayfield and Jacobsville Formations are generally considered lithologically more similar to the Freda Sandstone than to late Cambrian strata, and are commonly assigned to the uppermost Keweenawan, although a Lower Cambrian age is also possible. Seismic studies indicate that these sandstones probably form a thick friable sedimentary unit underlying most of Lake Superior (Halls and West, 1971).

The structure of the Keweenawan basin is dominated by an arcuate synclinorium filled by inward-dipping Keweenawan extrusives and sediments. White (1960*a*) draws attention to the increasing thickness of stratigraphic units toward the synclinal axis, and suggests that flows and sediments generally kept pace with subsidence of the basin. Bent pipe-amygdules in lavas suggest flow outward from the centre of the basin whereas current analysis indicate a northerly transport of sediments toward the basin. The total thickness of Keweenawan strata in the central part of the basin is estimated to be as much as 55-60 km on the basis of seismic studies (Berry and West, and Smith *et al.*, both *in* Steinhart and Smith, 1966).

Numerous moderate to steeply-dipping reverse faults parallel the north and south sides of the Keweenaw basin. The best known of these is the northward-dipping Keweenaw fault which forms the south boundary of the Michigan copper districts and separates the Portage Lake Lavas from the Animikie rocks and the Jacobsville Sandstone to the south. The Keweenaw fault probably continues toward the southwest along the Lake Owen fault in Wisconsin.

This southern system of boundary faults is complemented on the north side of the basin by the Douglas fault and its possible extension, the Isle Royale fault, interpreted from seismic investigations in the north-central portion of Lake Superior (Halls and West, 1971).

It seems clear that the Keweenaw basin represents a late Precambrian graben and horst structure with rapid infilling, followed by reverse thrusting during late stages of rift adjustment. The exposures of Keweenawan strata north and south of the lake have been tilted gently to moderately, even steeply, toward the basin axis during these late movements.

A local anticlinal flexure (Porcupine Mountain structure, fig. 1) with an accompanying northward-dipping thrust fault occurs on the south flank of the basin in the White Pine area (Hubbard, 1971). The Nonesuch Shale copper mineralization is contained in synclinal limbs of this structure.

Among intrusives of the Lake Superior region, the Duluth Gabbro complex (1 142 ± 25 m.yr.) is especially intriguing since (1) it dips from its exposed location on the north shore toward the Keweenawan peninsula, (2) it correlates closely in age with Keweenawan strata, and (3) it contains copper and nickel in large amounts. While it may be metallogenically attractive to postulate that the Duluth complex underlies the lake proper and gave rise to cupriferous ore solutions which ascended through strata of the Keweenaw peninsula (e.g., Butler and Burbank, 1929), gravity data now indicate that the complex must pinch out near the northern shoreline of the lake (White, 1966).

A smaller sill-like complex occurs at Mellon, Wisconsin at the probable junction of the Lake Owens and Keweenaw faults (fig. 1). It intrudes Portage Lake Lavas and possibly the Copper Harbor Conglomerate. Similarities in form and petrology to the Duluth Gabbro have long suggested a common origin for these two complexes.

Other intrusives of Keweenawan affiliation include the Logan sills and dikes of generally basaltic composition. These are especially common along the northwest shore of Lake Superior where they invade Lower and Middle Keweenawan strata.

Alkaline complexes occur northeast of Lake Superior along the north-northeast trending Kapuskasing subprovince within the Superior (Archean) province. A portion of these intrusives are distinctly pre-Keweenawan in age, but a younger group (approximately 1 050 m.yr.) appears to correlate rather closely with Keweenawan ages (Stockwell *et al.*, 1970).

NATIVE COPPER MINERALIZATION

The following descriptions of native copper in interbedded tholeiitic flows and red-bed conglomerates of the Portage Lake Lava Series along the Keweenawan Peninsula (fig. 3) are taken mainly from Weege and Pollock (1971), Weege *et al.* (1972) and White (1968, 1971*b*). Other sources are mentioned as appropriate.

The 200 or more flows of the Portage Lake Lava Series are chiefly amygdaloidal basalts, with lesser amounts of andesites and a few rhyolites. Individual flows commonly measure 30-50 m in thickness and are laterally continuous for tens of kilometres.

Some 20 conglomerate and sandstone horizons occur within the lava flows.

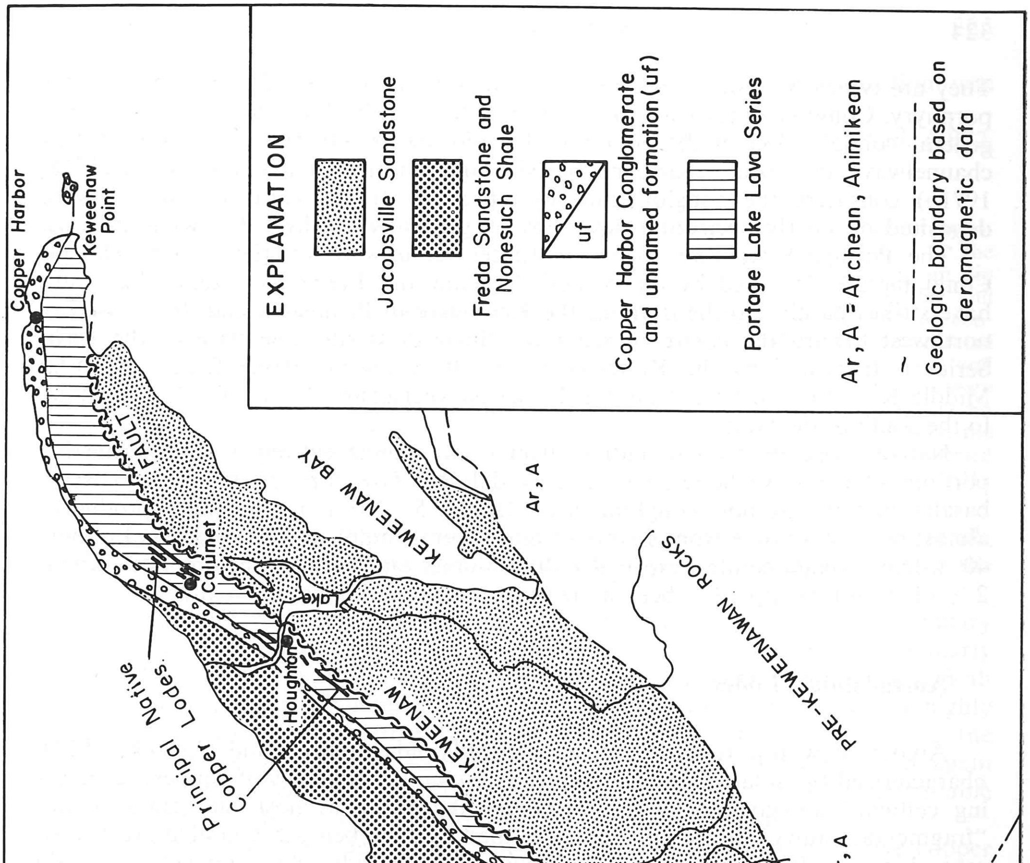

FIG. 3. — *General geology of the Keweenawan copper province of Michigan (after White, 1971b).*

They are typically felsic in composition and contain pebbles of quartz and felspar porphyry. Conglomerates make up some 3 to 8 % of the Lava Series and have the general configuration of discontinuous lensoid sheets. On the basis of identified channelways, crossbeds, coarse pebble size and imbricated pebbles, White (1968, 1971*b*) considers the conglomerate to represent stream sediments which were deposited on nearly horizontal flow tops by generally northward flowing streams.

The Portage Lake Lava Series is succeeded upward by the Copper Harbor Conglomerate, followed by the Nonesuch Shale and Freda Sandstone. All strata have strikes parallel to the trend of the Keweenawan Peninsula, and dip 20 to 75° northwest toward the centre of the Lake Superior basin. The base of the Lava Series is truncated by the Keweenawan Fault, a reverse strike fault separating Middle Keweenawan lavas from the Upper Keweenawan (?) Jacobsville Sandstone to the south of the fault.

Native copper and minor native silver occur almost entirely within permeable portions of the Lava Series, i.e., in amygdaloidal flow tops of otherwise massive basalts, and in interflow conglomerates. Of the 5×10^6 tons of copper produced, almost 60 % has come from six major and several minor amygdaloids, and almost 40 % from conglomerates, especially the Calumet and Hecla Conglomerate. About 2 % of the total copper has been mined from cross-cutting fissure veins.

Amygdaloidal Lodes

Among flow top types, "cellular" amygdaloids (Weege and Pollock, 1971), characterized by isolated vescicles, typically contain only traces of copper; "coalescing cellular" amygdaloids with interconnecting vescicles host one major mine; "fragmental" amygdaloids, apparently formed by flow beneath a chilled crust, host several major deposits; and "scoriaceous" amygdaloids, characterized by sandy infillings of fragmented flows, are mineralized at one stratigraphic horizon. Fragmental amygdaloids generally grade downward into non-fragmental amygdaloids which contain little or no copper values.

The thickness of lodes is naturally quite variable, but may commonly attain 3 to 5 m. The lateral configuration and dimensions are also highly irregular.

Conglomerate Lodes

Mineralization in conglomerate beds between basalt flows occurs in the form of lensoid sheets. In thick conglomerate sections, a noticeably greater proportion of copper is usually found close to the upper and lower contacts, and lower grade ore may exist at intermediate levels. In thin stratigraphic thicknesses, the entire conglomerate section may be well-mineralized.

Native copper in conglomerates is commonly but not everywhere associated with bleached rock in which the usual deep red color due to hematite has changed to a salmon-pink color. The chemical exchange responsible for this alteration apparently involves a partial reduction of ferric iron as well as some loss of iron.

Considerable exploration success has been realized in recent years (Weege and Pollock, 1971; Weege *et al.*, 1972) from careful analysis of stream channels and interpreted ore solution barriers within conglomerate beds. A fundamental factor in this success has been a conviction that the native copper mineralization was deposited from ascending hot aqueous solutions.

The barrier concept is clearly and concisely explained by Weege *et al.* (1972, p. 625):

> The most reasonable explanation for the form of many deposits lies in the barrier hypothesis, originally advanced by Graton, Broderick, and Butler in special reports to the Calumet and Hecla Mining Co. This theory visualizes the ore solutions as travelling up dip along certain amygdaloids and conglomerates with throughgoing permeability (Butler and Burbank, 1929). Inasmuch as the thickness and permeability of a given amygdaloid or conglomerate bed may vary enormously from place to place, flow tended to be concentrated along those pathways that afforded the least resistance to flow from depth to the surface, and tended to avoid relatively impermeable areas, which would thus act as barriers. Solutions were funneled by barriers of various types into the areas that are now mineralized.... Where no major barrier or constriction was present in a thick layer acting as a major channel way, the flow would not be concentrated, and as a result, small amounts of copper could be dispersed through a large volume of rock that would not be rich enough to mine (Broderick, 1931).

Contouring of conglomerate thicknesses at the Kingston mine (Weege *et al.*, 1972) clearly demonstrates a positive correlation of good ore with thinning of the conglomerate.

An important economic oreshoot was also located by recognition of tributary stream channels (the new Centennial No. 3-6 deposit) merging with the spectacularly large and rich Calumet and Hecla orebody which occupies the main channel. Both the main and tributary channels are characterized by greater thicknesses of highly permeable conglomerate relative to the more compact sediments bordering the channelways. The nonchannel sediments with fine-grained matrices would again serve as barriers, whereas the stream channels would behave as conduits suitable for ore solution transport as well as for interstitial mineralization.

To the writer's knowledge, all current concepts on genesis of the native copper lodes involve ascending hydrothermal solutions coming from deeper portions of the Keweenawan basin. Evidence of low grade alteration of mineralized flow tops, and the attractive possibilities of warm ore solutions at depth are principally responsible for the consensus.

Some authors (e.g., Butler and Burbank, 1929) point to the immense igneous activity indicated by the flows themselves and by the roughly contemporaneous Duluth gabbro. However, White (1968) notes the paucity of sulfur in the native copper lodes, and suggests that a mafic magmatic source would probably result instead in a characteristic copper sulfide mineralization.

Others (e.g., Stoiber and Davidson, 1959; White, 1968; Jolly, 1973) suggest that ore solutions were generated by metamorphism at depth and rose to mineralize permeable zones near surface. Jolly proposes that dehydration of the basalts under metamorphism involving epidotization at depth would leach much more than adequate quantities of trace element copper from flows; and that hydration of near-surface flows by the ascending, chloride-rich, metamorphic fluids producing typical pumpellyite and chlorite alteration would cause deposition of copper by simple over-saturation in the ore channels.

Hegelson (pers. commun., 1967; 1969) has offered another attractive explanation for reduction of copper to the native metal. His studies of metal complexes in aqueous solutions at elevated temperatures have demonstrated that simple complexes such as HCl and perhaps CuCl may exist as stable and appreciably soluble species at temperatures above approximately 300 °C. On cooling, the cuprous chloride complexes may disproportionate spontaneously into equal amounts of cupric chloride complexes (oxidation) and native copper (reduction). This process would provide for a 50 % efficient deposition of copper by reduction from ascending ore solutions.

Some sulfide mineralization occurs in a 15 mile segment of lower Portage Lake Lavas east of the principal native copper deposits (fig. 3). Studies by Robertson (1972) indicate a zonal distribution of copper-iron sulfides and a close association of mineralization with andesite dikes which also contain copper-bearing sulfides. A magmatic origin is favored although leaching of copper from flows at depth is not excluded.

NONESUCH SHALE MINERALIZATION

Since White and Wright's (1954) initial description of the White Pine mineralization, a large number of detailed studies and analyses have been carried out on the Nonesuch Shale, chiefly to define the nature, distribution and controls of mineralization. This section will attempt to summarize the principal findings and interpretations to date.

The White Pine copper mineralization (fig. 3) occurs mainly as sulfide and native metal disseminations within well-bedded, fine-grained clastic horizons at the base of the Nonesuch Shale. A very minor portion of mineralization is located in fractures considered to be post-ore in age.

In a typical vertical profile, a few inches or feet of underlying Copper Harbor Conglomerate may contain interstitial native copper and minor native silver of ore grade. The copper is found in diagenetically chloritized zones and intimately associated with organic particles. Hamilton (1967) suggests that these occurrences resulted from chemical reduction of initially reddish conglomerate by connate solutions which were pressed out of the overlying Nonesuch during compaction and carried soluble organic matter into the immediately underlying aquifer. Favorable reduction zones created in this manner would then be susceptible to native copper mineralization from cupriferous solutions circulating in the Copper Harbor Formation.

The overlying Nonesuch contains several widespread ore horizons in its basal section (for details, see White and Wright, 1954; White, 1968). Native copper, and again minor native silver, may accompany the more dominant copper mineral, chalcocite, in the lowermost beds, but upper mineralized horizons typically contain fine-grained chalcocite as the only ore mineral.

Disseminated chalcocite generally extends stratigraphically upward in ore or sub-ore quantities to a remarkably abrupt selvage surface, above which the beds are consistently pyritic. The selvage surface cross-cuts strata at gentle to moderate angles and varies in position from a few centimetres to about 15 m above the base of the Nonesuch within the mine area. Concepts of post-sedimentary mineralization from copper ascending at low temperatures into an initially pyritic, poorly consolidated Nonesuch Shale have been advanced and refined to explain the amounts, distribution, mineralogy and metal zoning in these strata (White, 1960*b*, 1971*a*; Brown, 1965, 1970, 1971; White and Wright, 1966; White, D. E., 1968).

Without attempting to recount all details of evidences gathered thus far, the principal features which nevertheless support the above hypothesis may be summarized as follows:

(1) Sulfide textures showing a systematic step-by-step replacement of syndiagenetic pyrite by Cu-Fe sulfides, and then Cu-sulfides within the narrow selvage zone; this feature is interpreted as a fossil mineralization front.

(2) Chalcocite nodules surrounded by hematic halos at several horizons *within* the ore zones, indicating probable replacement of iron-sulfide nodules, with consequent redeposition of iron as hematite.

(3) A statistically reasonable inverse correlation between the amount of copper deposited in lowermost ore horizons and the height of the selvage surface in the Nonesuch strata, strongly suggesting that approximately equal amounts of copper entered vertically into the Nonesuch across a broad basal area, and that little copper remained to mineralize higher beds where a greater proportion of copper was precipitated in thick or high grade ore beds at the base of the Nonesuch.

(4) Anomalous concentrations of minor metals (Cd, Pb and Zn) as sulfides directly above the stratigraphically undulating selvage zone; these metals are less sulfophile than copper and were presumably swept continuously upward before the mineralization front. Luppens (1970) has also found anomalous mercury concentration above the selvage surface.

Not all observations support the early diagenetic replacement model. For example, Jost (1968) discovered, and Rohrbacker (1969) confirmed, a mine locality in which a selvage of Cu-Fe sulfides of as yet uncertain configuration and dimensions occurs near the top of the Parting Shale unit and well below the top of the cupriferous zone proper. This feature could be the first indication that cupriferous and pyritic zones oscillated laterally with onlap and offlap facies of sedimentation as has been suggested to explain lateral oscillations on a larger scale in the Zambian Copperbelt deposits (Garlick, 1961).

Other investigations specifically intended to locate possible lateral oscillations of the selvage surface at White Pine (e.g., Brown, 1965, 1971) did not reveal such features. It is therefore not unreasonable to suggest that perhaps Jost's discovery represents an island of unmineralized shale within a cupriferous zone otherwise formed according to the concepts of the diagenetic replacement model. Rohrbacker (1971, pers. commun.) also found minute iron sulfide grains beneath the main Cu-Fe selvage, and consequently questions the copper-sulfide replacement model.

DISCUSSION

The above description of the Michigan copper province in Keweenawan strata illustrates the highly distinctive natures of two different, neighboring geologic environments which nevertheless contain remarkably similar copper-silver concentrations, almost to the exclusion of other normally associated base metals. Because there now exists rather substantial evidence that the native copper ores were derived from ascending, warm solutions, it is certainly very tempting to extend portions of this concept to explain the sulfur-dominated Nonesuch mineralization. No doubt this bias has influenced some investigations at White Pine, but not without some justification, for the majority of qualitative and quantitative data obtained thus far have generally reinforced this view.

In the absence of diagnostic evidence in favor of an original sedimentary origin for copper mineralization of the lower Nonesuch, the writer is presently inclined to support the iron-sulfide replacement hypothesis for the White Pine ore, and to view the two Michigan copper districts as resulting from closely related, ascending ore solutions. In the native copper district, copper and silver probably precipitated within the ore solution aquifer by saturation and/or reduction near surface. At White Pine, similar solutions again precipitated native metals, but the majority of copper precipitated as sulfides upon encountering the initially pyritic lower Nonesuch Shale. The temperature of deposition at White Pine was probably lower than in the native copper district; this may simply reflect the higher stratigraphic level of the Nonesuch and/or its geographic separation from the native copper regions. There may be no clear distinction in time between mineralization of the two environments.

The proposed cupriferous solutions for both districts may have been generated during still-active igneous events of approximately Middle to early Upper Keweenawan time, or to the more passive leaching of metals during de-hydration of flows at depth as adequately explained by Jolly (1973). The continued volcanism until just prior to Nonesuch Shale deposition as evidenced by flows in the Copper Harbor, and the apparent evolution of stratigraphically higher Middle Keweenawan flows toward more felsic compositions suggests that late stage volcanic volatiles may have emptied into subsurface aquifers or even onto surface in early Nonesuch time. The occurrence of a rather large felsic dome stratigraphically beneath the White Pine area is in fact surprisingly similar to the common association of base-metal massive sulfides with felsic volcanic domes in calc-alkaline volcanic sequences elsewhere (e.g., Sangster, 1972).

The lack of associated lead-zinc in abundance in the Michigan copper district argues against a differentiating calc-alkaline magmatic source, and suggest that a post-volcanic selective leaching process such as proposed by Jolly may be more reasonable. However, the recognition of essentially monometallic, copper-pyrite ores of volcanic affiliation in Cyprus (Hutchinson and Searle, 1971) and in Newfoundland (Upadhyay, 1973), for example, opens other avenues of speculation.

In fact, the copper-pyrite ores are now thought (Hutchinson, 1973) to be closely related to deep crustal or mantle sources from which contemporaneous tholeiitic flows emanate. Considering the immense volume and thickness of tholeiitic basalt in the Keweenawan basin, it is very tempting to draw parallel conclusions for the unique regional association of copper with basaltic volcanism in the Lake Superior district. Additional incentive for these broad concepts arises from the interpretation of the Keweenawan belt as a mid-continental rift which probably tapped mantle sources of magma material. Hopefully, a constructive balance of criticism among students of the Lake Superior copper province will lead to further refinement of these oversimplified concepts of Keweenawan metallogenesis.

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