

Institute on Lake Superior Geology



Proceedings

**40th Annual Meeting
May 11-14, 1994**

Michigan Technological University
Houghton, Michigan

Volume 40

**Part 5—Lessons from mining case histories:
West Menominee Range, Michigan**

By: Allan M. Johnson

40TH ANNUAL MEETING INSTITUTE ON LAKE SUPERIOR GEOLOGY

Volume 40 consists of

Part 1: Program and Abstracts

Part 2: Self-guided geological field trip to the Keweenaw Peninsula, Michigan

Part 3: Volcanic geology of eastern Isle Royale, Michigan

Part 4: Michigan kimberlites and diamond exploration techniques

Part 5: Lessons from mining case histories: West Menominee Range, Michigan

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Part 5—Lessons from mining case histories: West Menominee Range, Michigan

By: Allan M. Johnson
Department of Mining Engineering
Michigan Technological University, Houghton, Michigan 49931-1295

ITINERARY

7:30 am	Leave MTU from Memorial Union Circle
9:00	Arrive Iron River Area (NOTE: All times are EDT, but Iron County is Central Time Zone)
9:00-9:30	Isabella Mine - open pit/underground mine footwall slate and Riverton iron formation part of Dober Mine complex flooded pit (acid water)
9:40-10:30	Dober Mine and Iron River Old Stambaugh sewage treatment plant site open pit/underground mine acid drainage river diverted diversion structure in river synergetic pond system for treating AMD holding ponds
10:30-11:30	Cardiff Mine open shaft 1992 death (drowning of teen in flooded mine workings)
11:30-1:00	Iron County Historical Museum Caspian Mine Site, 1921 steel headframe (oldest in U.S.) boxed lunch on grounds - inside if inclement weather iron ore mining dioramas early life in Iron County logging museum also adjacent to Lee Le Blanc Art Center (memorial to renowned wildlife artist from Iron River)
1:00-1:30	Buck Mine Site acid drainage surface and underground sources
1:30-2:00	Smuggler Mine Old County Road 484 road cave-in, fatality
2:15-3:30	Homer-Wauseca Mine and Sherwood Mine Complex pumping pit for overburden dewatering site of USGS-MGS dewatering study in 1940's and basis for Theis' groundwater drawdown calculations sand filling raises mine subsidence
3:30-4:00	Cardiff Mine Headframe shallow underground mine
4:00-5:30	Return to Houghton

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INTRODUCTION

The Menominee Range of northern Michigan was a major producer of direct shipping iron ore for nearly a century. When the last underground mine on the Range ceased operation in 1978, it marked the end of an era. With the start of mining in the early 1880's, the district had gone through a full cycle from the start-up of mining through close-down. During this period over 200 million long tons of iron ore were produced and shipped from nearly 100 mining operations. This development and production spanned the time from when the United States advanced from an essentially rural-agricultural society through the industrial revolution and into the beginnings of the computer and space age. The location of the West Menominee Range in Iron County is shown in Figure 1.

HISTORICAL SKETCH

Iron ore mining was the impetus for the development of the Crystal Falls and Iron River centers of mining. Mining jobs brought miners and their families to the district, paid for the roads and railroads needed for shipping equipment and supplies in and the ore out to lower lake markets. Taxes paid by mining dollars built the cities and towns, including the schools, hospitals, police and fire departments, and attracted all the businesses that comprise thriving communities.

Ore produced from the Menominee Range mines was vital to the war effort of two World Wars and supported mining families and the families of the supportive service businesses for a number of generations for one century. Iron ore mining paid for the infrastructure of these two major population centers in Iron County just as mining has done in other areas of the Upper Peninsula.

During this century, great advances were made in mining and processing iron ore into steel. Early mining was done largely by human manual labor and horse transportation. Until the advent of steam, electrical, diesel and gasoline powered engines, mining was labor intensive and a highly dangerous occupation. The County Mine Inspectors' records are replete with injuries and deaths resulting from dangerous work in the ever-deepening underground mines. Deaths and injuries that ranged from rock falls, delayed blasts, timber support failures, runaway skips and trams, scalding steam from mine fires, suffocation from inadequate ventilation and noxious gases and other hazards including mine cave-ins and floodings.

In one tragedy, 27 men were killed one night on the 28th of September 1893 when the Mansfield Mine was suddenly flooded by an inrush of water through a failed shaft located adjacent to the Michigamme River in east Iron County. However, technological improvements in mining evolved during the tenure of the West Menominee Range resulting in highly productive and much safer mining methods by the time the last mine--the Sherwood Mine--ceased operations in 1978.

LESSONS FROM MINING CASE HISTORIES

There are many lessons that can be learned from such a rich history. For example, with the use of case histories, deficiencies in past mining practices and mine closure procedures that have resulted in current environmental problems, can be identified and studied. These environmental problems can be grouped into three areas: 1) mine subsidence; 2) mine water drainage problems; and 3) problems related to inadequate mine shaft sealing and capping practices.

Mine subsidence has been a problem in the district. In one instance, human life was lost because of sudden subsidence of a section of county road into a shallow slope of an old mining operation. Also, many mines in the Iron River area encountered acid waters during their operation and several continued to drain acid water when they became flooded. The acid waters flowed from the mines into the Iron River and eventually the Brule River system causing pollution problems. Because the Brule River marks the border between northeastern Wisconsin and the Upper Peninsula of Michigan, the residents of the two states are concerned with the problem.

There is one occurrence of human fatality resulting from falls into mine shafts in Iron County. This occurred at the Chatham Mine in Stambaugh in 1992. The presence of hundreds of shafts, some with deteriorating or inadequate protection in the form of seals or caps, remains a cause for concern.

These three basic environmental problems were investigated by the use of case histories. This field trip guide is structured to present information on these problems and to show how these problems have been addressed by the mining companies, local government entities, and the Michigan Department of Natural Resources, to lessen their impact on this mining district. The overall objectives of this project were: 1) to document deficiencies in mine closure procedures that have resulted in problems of subsidence, acid drainage or shaft sealing/capping failures; 2) to examine these problems and deficiencies and attempt to develop ideas on how they could have been prevented for their effects lessened by action taken prior to mine closure; and 3) to recommend these ideas as guidelines in mine closing procedures.

BACKGROUND

The Iron River-Crystal Falls mining district is located on the western Menominee Range in the southern part of Iron County in the Upper Peninsula of Michigan (Figure 1). The western Menominee Range forms a roughly shaped triangle, one leg of which extends between Iron River on the west and Crystal Falls on the east, a distance of about 20 miles. From the City of Iron River which is situated on the northwestern part of the range, the iron formation trends southeasterly towards the Wisconsin border which is about five miles to the south. The third leg of the triangle extends south of Crystal Falls paralleling and then crossing the Brule River into Wisconsin. The eastern part of the Range parallels the Menominee River on the Michigan side.

The topography is mostly rolling, varying from about 1300 feet to 1700 feet in elevation. The higher elevations are near Iron River, Michigan and as a result the drainage is generally to the southeast. The Iron River drains the western area southeasterly into the Brule River which forms the border between northeastern Wisconsin and Michigan. The Crystal Falls area is drained by the Paint, Brule and Michigamme Rivers which join, forming the Menominee River, which ultimately empties into Lake Michigan. The drainage is shown in Figure 2.

The area has been heavily glaciated and the soil is thick glacial drift consisting mostly of glacial till and outwash morainal sands and gravels. The area is mostly wooded with numerous lakes and streams that are abundantly supplied with water from rain and snow melt. The glacial overburden in the area is a prolific aquifer.

The climate is northern temperate with relatively short summers and a short growing season and the winters are cold and long.

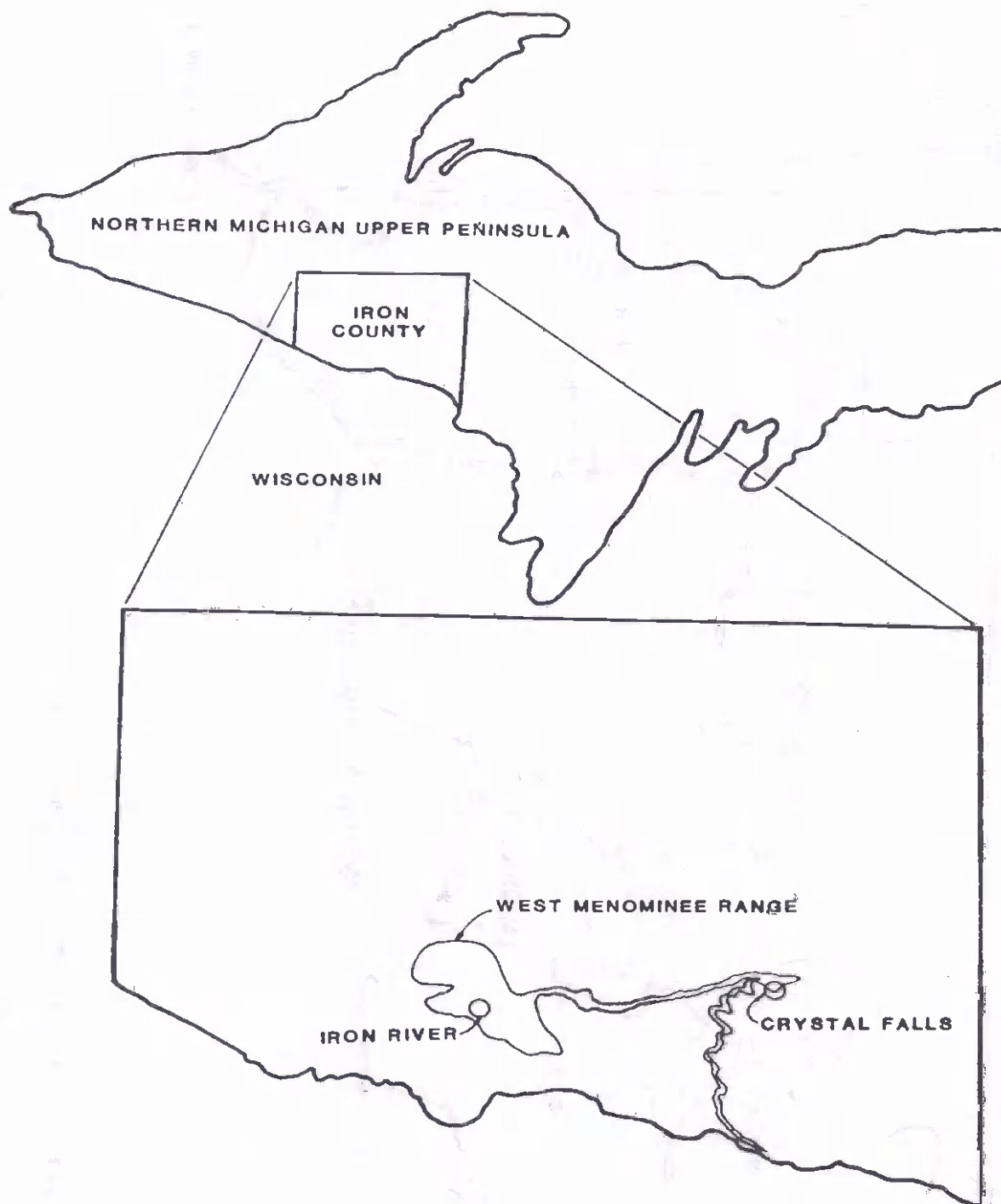


Figure 1. Location of the Cities of Crystal Falls and Iron River on the Menominee Range in Iron County, Michigan

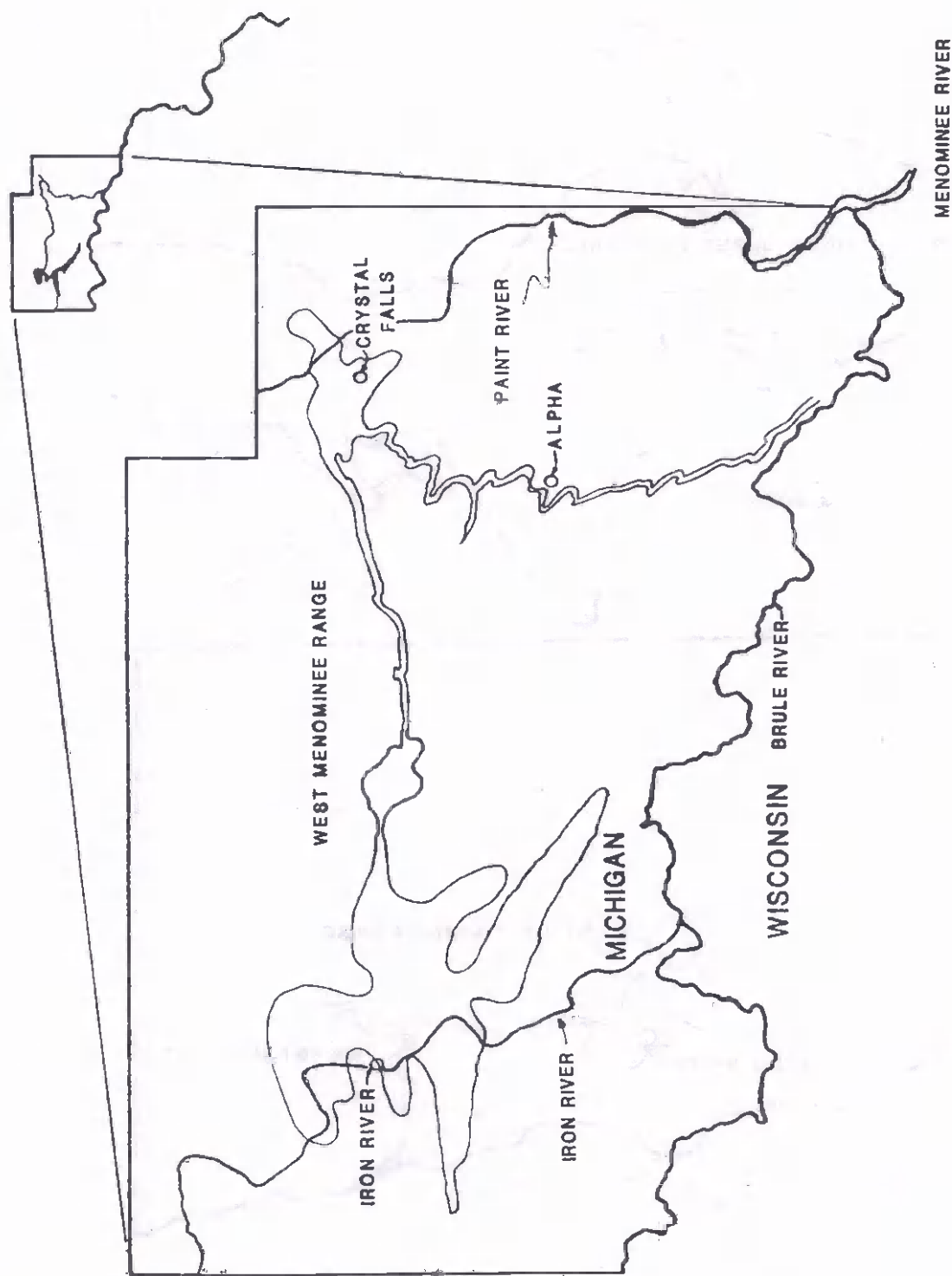


Figure 2. Drainage from the West Menominee Range

Geology

The west Menominee Range is comprised of a series of complexly folded sedimentary rocks of Middle Precambrian age. The strata are the five formations of the Paint River Group of the Upper Animikie Series. The bottommost unit is the Dunn Creek Slate which is some 1000 feet thick. The upper 50 feet of the Dunn Creek Formation contains the Wauseca member, a pyritic-graphitic slate. The Riverton Iron Formation overlies the Dunn Creek Formation and is in turn overlain by the Hiawatha Greywacke, which is as thick as 500 feet but is absent in some areas. The magnetic Stambaugh Formation and the Fortune Lakes Slate are the next higher units, respectively. More detailed descriptions of the rock units are presented in Table 1 and the generalized geologic relationships of the folded Paint River Group strata as it exists near Iron River, Michigan is shown in Figure 3.

Ore. The Riverton Iron Formation is not all ore. It consists primarily of thin-bedded siderite and chert. Ore occurs only in structurally favorable areas where deep weathering and oxidation has enriched the iron content of the rock. For the most part, the ore bodies are irregular in shape, size and attitude, but tend to lie in the troughs or along the flanks of steeply plunging synclines. The ore is usually continuous from depth to the bedrock surface. Laterally the ore may grade into unoxidized iron formation. Most of the mined ore has been extracted from tabular bodies that are 100 or more feet thick and hundreds to thousands of feet in vertical or lateral directions. The ore may vary between and even within deposits from a soft and hydrated form to very hard hematite ore. Generally the ore is described as a direct-shipping, old range, non-bessemer, high phosphorous ore. The ore from some mines is enriched in manganese.

TABLE 1

Rock Units in the Iron River-Crystal Falls District

Rock units in the Iron River-Crystal Falls district

		Rock unit	Estimated thickness (feet)	Remarks	
Pleistocene		Till, gravel, sand	0-425	Mantle more than 99 percent of area.	
Ordovician		Sandstone, dolomite	Unconformity 0-100	Flat-lying remnants of sandstone and dolomite in the southwestern part of the area.	
Upper Precambrian	Keweenaw Series	Silica rock	0-200	Massive cherty rock that probably represents silicified erosion surface on dolomite.	
		Dabase	Unconformity	Rare dikes. Unaltered; magnetic and inversely polarized.	
Middle Precambrian	Antrim Series	Granite and trachyte		Granite, medium-grained, massive; in eastern part of district only. Trachyte as sparse thin dikes.	
		Metadiabase and metagabbro		Chloritized, massive. Abundant dikes and sills, a few stocks.	
		Paint River Group	Fortune Lakes Slate	4,000+	Character known only for lower part of section, exposed in eastern part of district, where strata consist of gray slate, striped slate, sideritic slate, graywacke, and possible iron-formation. Most of unit not exposed or drilled within district.
			Stambaugh Formation	100	Cherty, laminated rock and massive chlorite slate, some graywacke. Many parts strongly magnetic.
			Hilawatha Graywacke	0-500	Massive, graywacke, commonly sideritic, and gray slate. Lowermost part commonly contains abundant chert fragments.
			Riverton Iron Formation	Minor unconformity 10-800	Thin-bedded rock, mainly chert and iron-rich carbonate where unoxidized. Includes some graphitic slate, also stilpnomelane beds and magnetite-rich beds in eastern part of district. Host rock for ore bodies.
		Dunn Creek Slate	400-1,500	In eastern part of district, unit consists of siltstone underlain by black cherty slate, sideritic slate, and chert-carbonate rock. In western part of district, unit is chiefly siltstone and slate. Uppermost part throughout district is graphitic pyritic slate (Wausaca Pyritic Member).	
		Baraga Group	Badwater Greenstone	0-15,000	Massive chloritized mafic volcanic rock, in part flows with ellipsoidal structure, in part tuffs and agglomerates. Some parts strongly magnetic.
			Michigamme Slate	6,000	Mostly interbedded slate and graywacke; in southeastern part of area were highly metamorphosed equivalents. Probably contains some ferruginous beds in uppermost part.
			Amass Formation	1,800	Principally martite slate, with layers of cherty iron-formation. Locally strongly magnetic.
	Hemlock Formation		6,000+	Mostly massive metabasalt, locally with ellipsoidal structures. Contains Bird Iron-Bearing Member (200 ft thick) 1,200-1,400 feet below the top of the formation. Both the greenstone and the Bird Member are locally strongly magnetic.	
	Chocoma Group	Saunders Formation	1,000(?)	Mainly massive dolomite. Exposed in only a few places in southern part of district.	
?	?	Greenstone in the Brule River area	Not known	Massive metabasalt, in part with agglomeratic and ellipsoidal structures. Some layers are magnetic.	

From James, et al., p.17, 1968

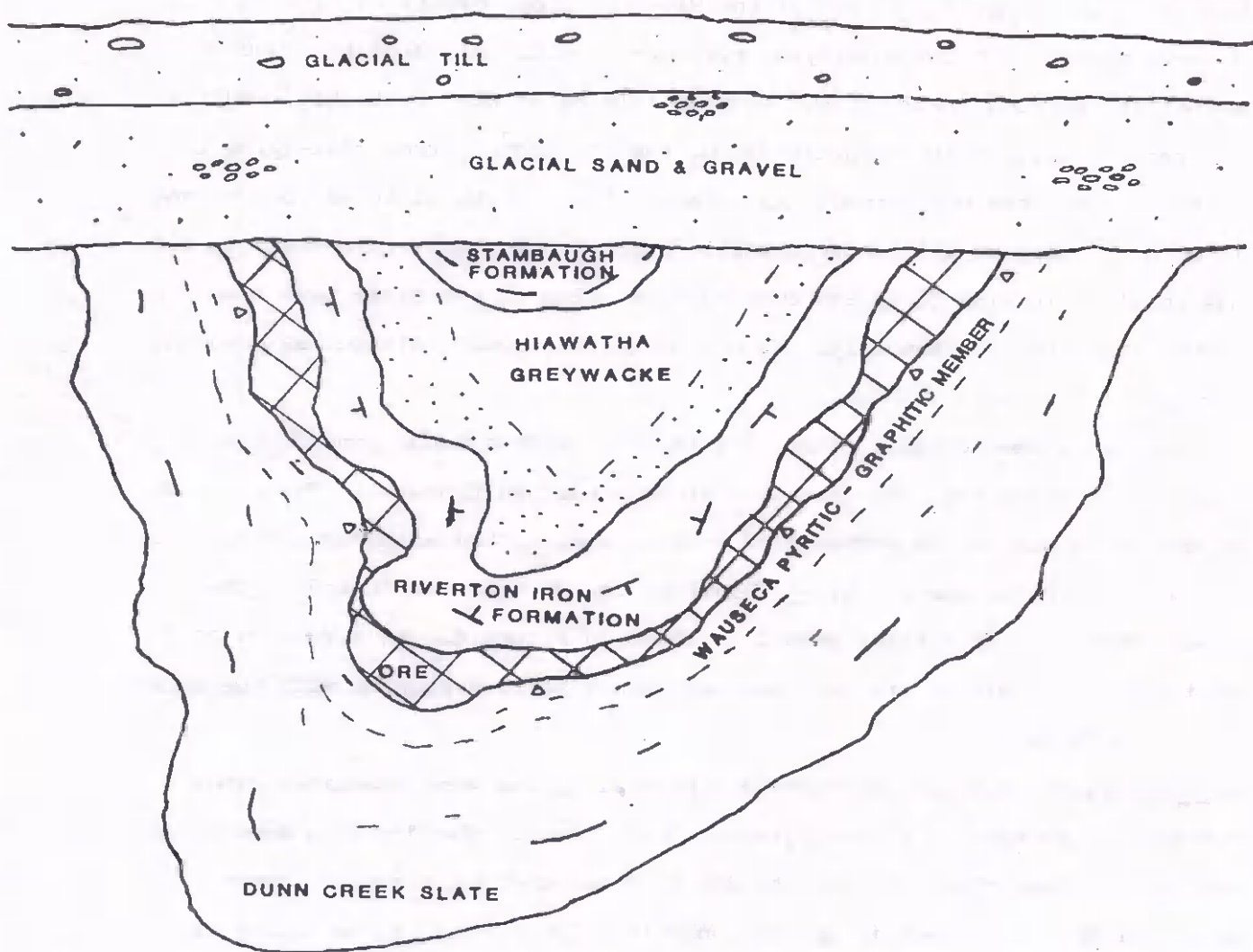


Figure 3. Generalized Geologic Relationships of the Folded Paint River Group Formations in the Iron River District

On the western end of the Menominee Range, near Iron River, the ore bodies occur in the basal part of the Riverton Iron Formation. They are in direct contact with the underlying pyritic-graphitic slate of the Wauseca member of the Dunn Creek Slate. Complex folding of the strata has resulted in great variations of the attitudes of the ore bodies, from flat-lying to vertical and often overturned. As a result the pyritic slate may be present in both the hanging wall and footwall. Exposure of the pyritic slate to air has resulted in mine fires and even surface piles of the slate have been known to ignite spontaneously. As a consequence, acid drainage has been an accompanying serious problem.

However, near Crystal Falls, the iron ore bodies occur some distance above the base of the iron formation along a perched footwall. The perched condition is due to the presence of a slaty member, the Raindrop Slate, which according to James, et. al (1968) is in the lower one third of the iron formation. This relationship is shown in Figure 4. As a result, acid drainage from mining operations has not been a serious problem with the mine near Crystal Falls.

Glacial drift. Bedrock exposures are rare along the West Menominee Range due to the presence of a thick glacial drift cover. The drift is locally as much as 300 feet thick, but 100 to 200 feet thicknesses are more common. Near Iron River, bedrock is exposed only in a few places in the valley of the Iron River and at the bottom of some surface subsidence pits. Exposures of the Riverton Iron Formation are also present along a thinly covered bedrock ridge which extends south from Crystal Falls.

The surface material in the Crystal Falls area is mainly outwash sand with smaller areas of terminal and ground moraines. In the Iron River area, the glacial cover varies but in the northern part, the Mineral Hills area,

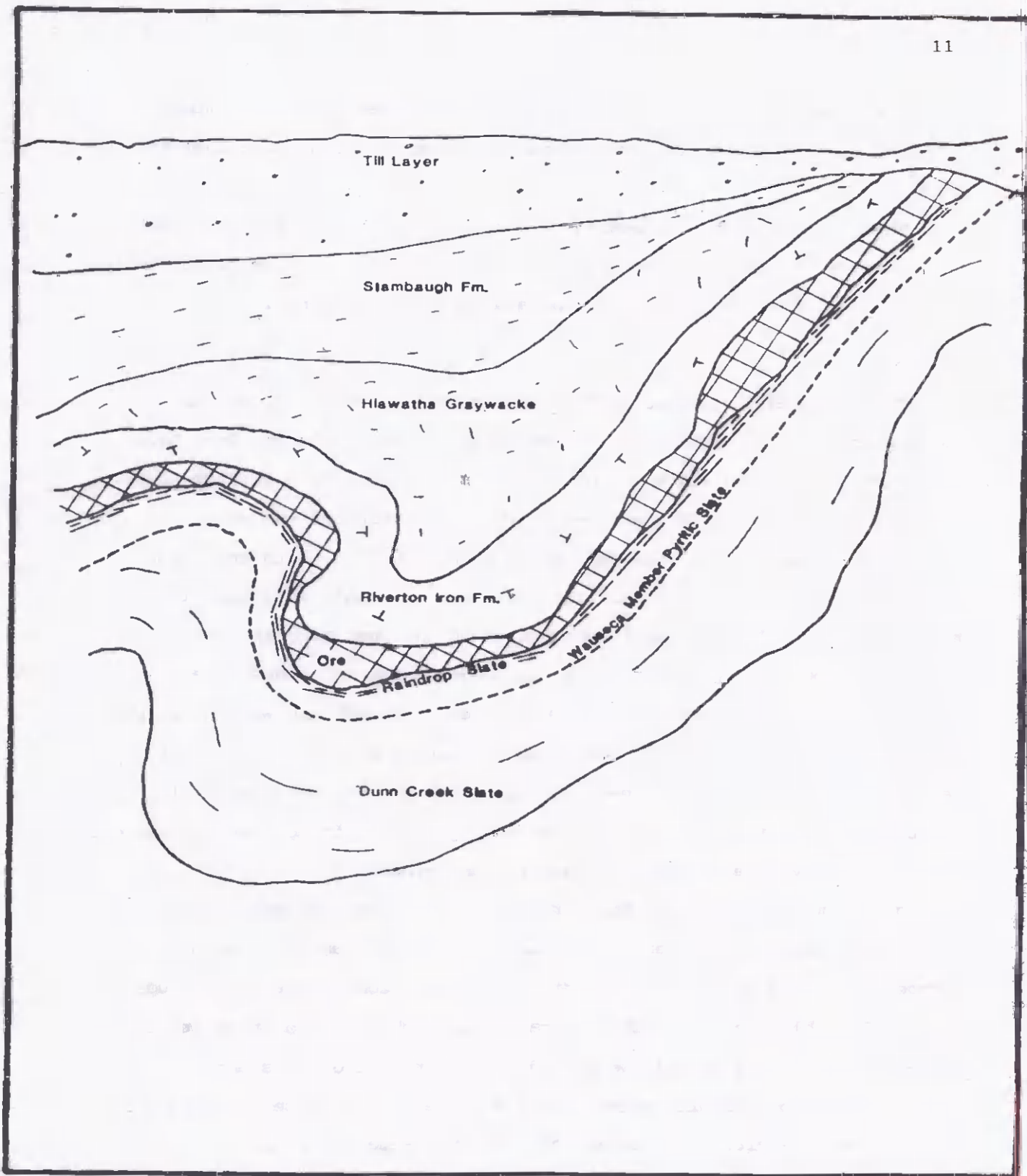


Figure 4. Stratigraphic geologic relationship in the Crystal Falls district.

the drift may be characterized as poorly consolidated sands with minor gravels overlain by a fairly continuous sheet of very competent boulder till.

The glacial drift is a copious aquifer, a condition which has greatly influenced mining activity and has resulted in problems with mine dewatering and drainage, drilling, shaft sinking and surface subsidence.

Mining

Iron ore was discovered in Iron County in 1851 by Harvey Mellen, a government surveyor. The find was made from an outcrop in the Iron River valley about one mile south of the present site of the City of Iron River. However, it was nearly 30 years before the first iron ore was mined. Mining did not start until 1882 when rail lines were brought to both the Crystal Falls and Iron River districts. The first ore shipments were made in the fall of 1882. All of the early production on the West Menominee Range came from small open pit operations where the bedrock was at or near the surface. With time, however, these mines became deeper and were developed into underground operations. Concurrent exploration and drilling activity resulted in the discovery of new ore bodies, many under thick glacial overburden. Vertical shafts were sunk through the drift adjacent to the ore bodies and they were developed as underground mines.

Underground mining methods. The vertical to near vertical and tabular shape of the ore bodies on the Menominee Range dictated the underground mining methods that were used in the district. The most common methods included top slicing, block caving, sublevel caving and sublevel and other stoping methods. The caving methods were used only where the ore was amenable to a caving operation. Stopping methods were employed in the more competent ore bodies. As a result, many surface pits which assume the shape

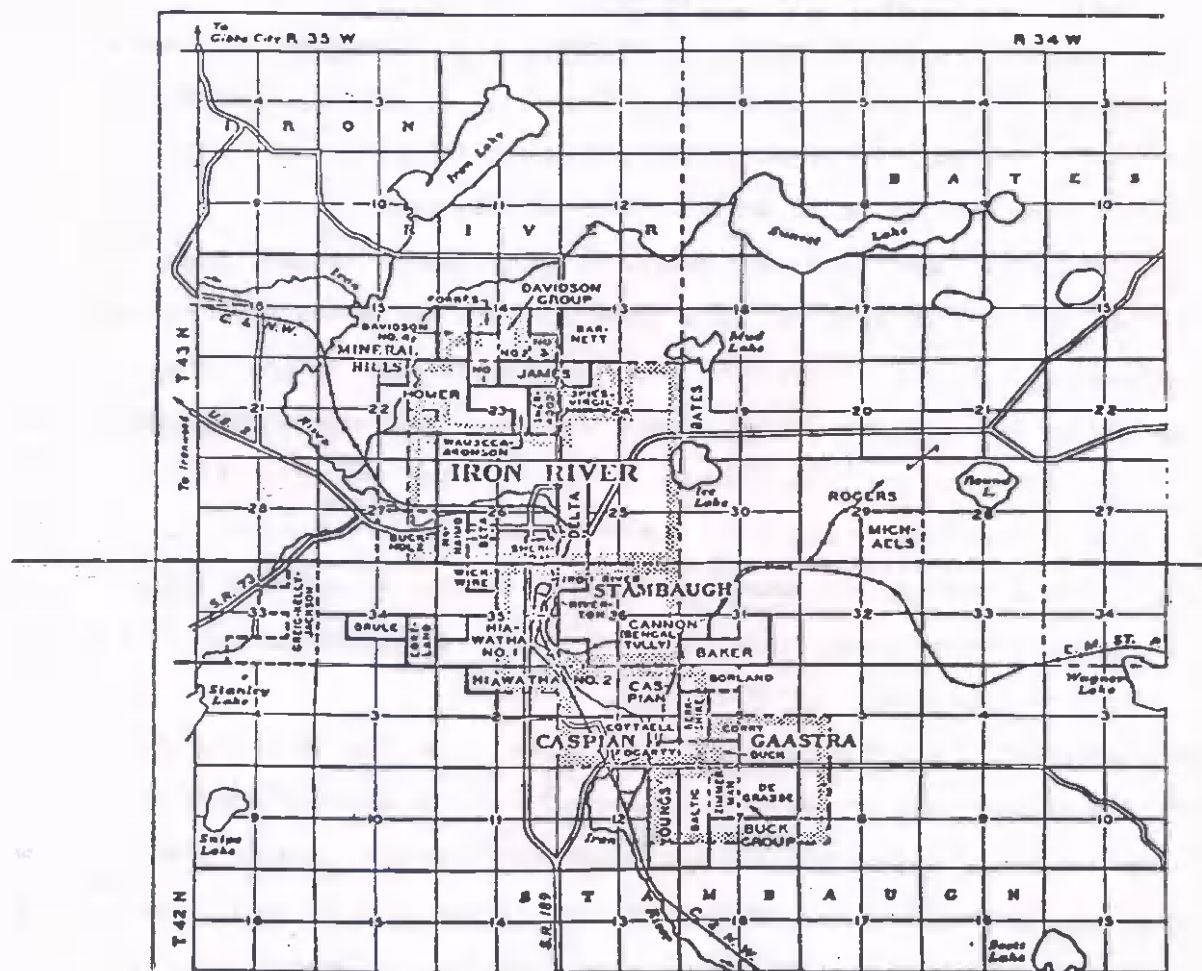
of the underlying ore body are present above the mines that employed caving and top slicing techniques. Large open stopes were produced in the more competent ore bodies and surface subsidence may or may not have occurred. Nearly all of the shafts that served the mines in the district are vertical. The only inclined shafts are those in several pre-1900 mines, and these shafts were at steep angles (70 to 80 degrees).

Ore. The ore mined was direct shipping and required little if any processing. For most mines, size reduction and screening were the only processing techniques employed. Ore washing was used at one mine and drying was required at another where the ore was wet. High manganese content was a characteristic of ore from a number of mines. The ores from this Range exhibited increasing concentrations of silica, phosphorous and sulfur near the footwall contact and sometimes also at depth. These impurities limited the depth to which some ore bodies were mined, although several of the mines operated to depths of over 2000 feet.

Mining operations and production. The mine properties were all 40-acre parcels or combinations of them. Most of the individual properties or "forties" had its own name and was under singular ownership. Records show a total of about 100 mining operations were at one time or another active in the district. Of these, 55 were in the Iron River district, or West Iron County, and 45 in the Crystal Falls district or east Iron County, the locations of which are shown in Figures 5 and 6, respectively.

As time passed, many of the mines were combined into groups and operated as a complex. In like fashion the originally diverse ownership was gradually consolidated into holdings of a half dozen large steel companies.

The Iron River district was active from 1882 until 1979, shipping a total of 147 million long tons of ore. Records for the Crystal Falls area



Source: Lake Superior Iron Ores Second Edition 1952

Figure 5. Map of Mined Properties in the Iron River District

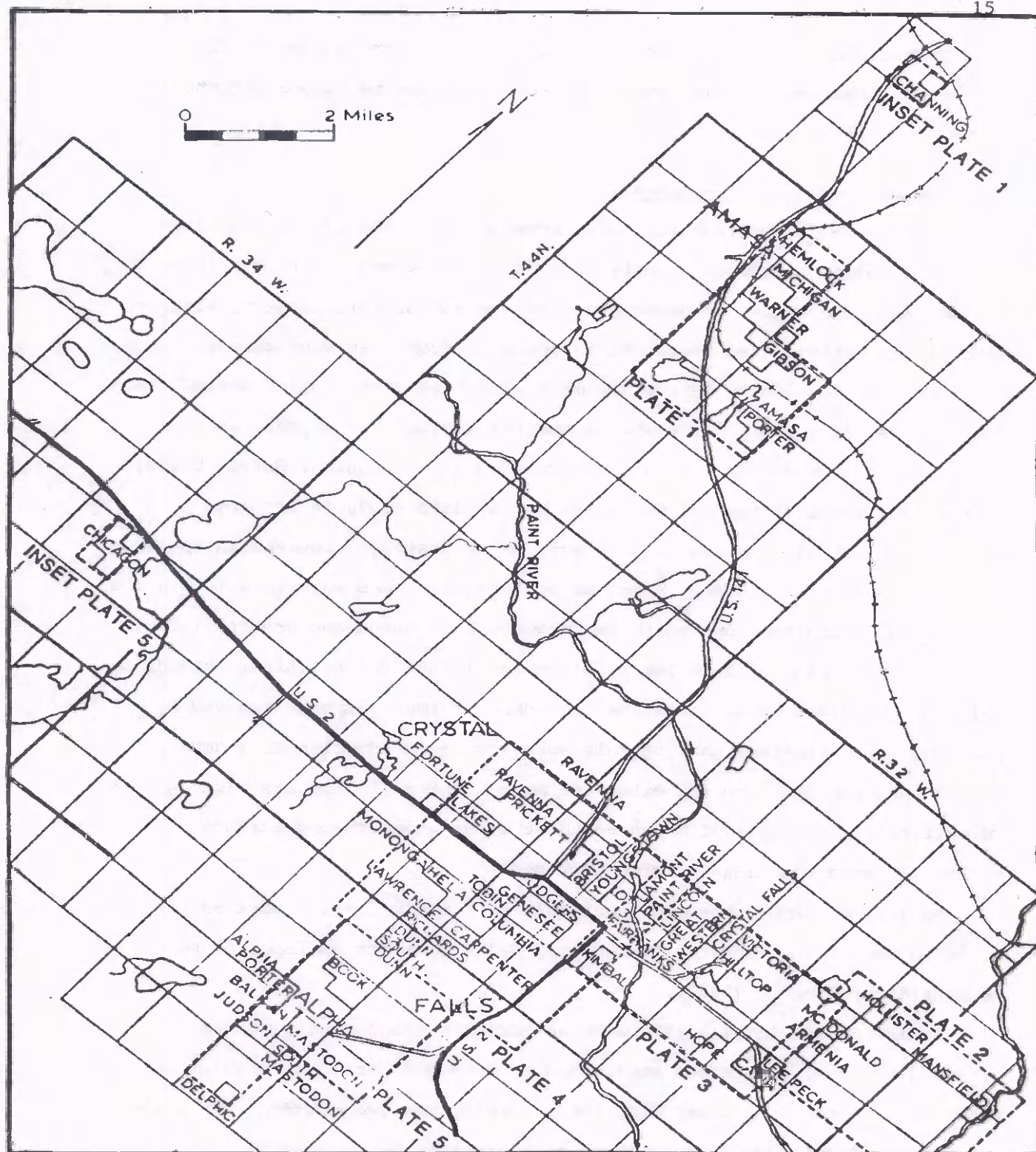


Figure 6. Mine and map plate locations in the Crystal Falls district, Menominee Iron Range.

show 59 million long tons of ore shipped from 1882 through 1969. The production from each of the mining operations in the two sub-districts are listed in Tables 2 and 3.

Previous Work and Acknowledgements

Experience gained from work done previously on closed mines in Iron County, Michigan provided not only much of the background for this research, but was also the basis for developing the concept of this project; i.e., studying the deficiencies resulting in problems from past mine closures with the intent of developing better and more effective mine closing procedures. The first study began in 1974 when a special legislative appropriation by the State of Michigan channeled funds through the Geological Survey Division of the Department of Natural Resources for a basic study on problems associated with mine subsidence and acid water drainage problems in the Iron River district of Michigan. A second appropriation was made to complete the work. These efforts resulted in two reports by Johnson and Frantti (1976, 1978) which addressed these two problems and identified practical methods by which the problems could either be corrected or their impacts reduced by planning. An important part of this work was the production of a detailed map showing the location and extent of mine openings in the district and the identification of critical areas — those areas where in-use surface structures were underlain by mine workings.

Additional funds were made available to perform similar work on the mines in east Iron County in the Crystal Falls district as reported by MacDonald and Johnson (1983).

Following the initial 1978 work an additional appropriation was provided to do more detailed studies on an acid mine drainage problem at the Dober Mine in the Iron River district. Pumping was recommended as a means to abate acid drainage in the 1979 report prepared by Johnson.

TABLE II

IRON ORE SHIPMENTS IN MICHIGAN THROUGH 1974
MENOMINEE IRON RANGE

IRON RIVER DISTRICT, Iron County		
Mine	Gross Tons	Years of Shipments
Baker	267,107	1909-1915
Bates	4,054,666	1915-1947
Beta	27,156	1886-1891
Brule	4,200	1936
Buck Group	21,653,499	1901-1962
Cannon	12,033,884	1910-1963
Caspian	6,623,320	1903-1937
Chicago	1,234,339	1911-1922
Cortland	52,148	1912-1914
Cottrell	75,134	1915-1916
Davidson Group	8,197,014	1911-1953
Davidson No. 4	128,599	1913-1921
Delta	95,759	1920-1925
Forbes	2,283,822	1913-1939
Hiawatha No. 1 and No. 2	22,162,905	1893-1967
Homer-Cardiff-Minckler	17,493,590	1915-1971
James	8,326,342	1907-1954
Nanaimo	373,765	1882-1908
Riverton Group	5,881,550	1882-1937
Rogers	2,907,375	1914-1942
Sheridan	116,299	1879-1909
Sherwood	12,536,031	1931-1974
Spies-Virgil	4,195,111	1912-1956
Wauseca-Aronson	15,364,448	1926-1929, 1940-1972
Wickwire	128,869	1911-1917
Youngs	802,751	1905-1928
TOTAL	147,019,683	

TABLE III

CRYSTAL FALLS DISTRICT, Iron County		
Mine	Gross Tons	Years of Shipments
Alpha	1,370	1903
Armenia	713,395	1889-1914
Balkan-Judson	4,441,799	1882-1935
Book	2,317,523	1943-1958
Bristol-Youngstown	14,804,805	1890-1934, 1950-1969
Carpenter	2,735,452	1914-1928
Cayla	44,492	1954
Crystal Falls	1,744,015	1882-1913
Delphic	33,770	1883-1896
Dunn	2,208,511	1887-1915
Fortune Lake	1,316,905	1953-1958
Great Western	2,296,739	1882-1925
Hemlock	2,125,756	1891-1919
Hilltop	98,202	1899-1919
Hollister	143,117	1890-1914
Hope	28,530	1892-1903
Kimball	35,757	1907-1915
Lamont	558,524	1889-1910
Lawrence	6,963	1920-1956
Lee Peck	2,844	1892
Lincoln	241,627	1891-1909
Mansfield	1,462,504	1890-1913
McDonald	30,289	1909-1913
Odgers	2,101,381	1916-1935
Paint River	382,078	1882-1913
Porter	733,327	1916-1927
Ravenna-Prickett	635,227	1911-1917, 1940-1943
Richards	534,448	1913-1927
South Mastodon	8,203	1887-1890
Tobin-Columbia-Monongahela-Genesee	13,523,289	1882-1963
Warner	<u>3,417,030</u>	1915-1934, 1951-1958
TOTAL	58,727,872	

SOURCE: Reed (1975)

From 1978 through 1982 the U.S. Bureau of Mines funded a study of the closing of the Sherwood Mine which was undertaken by an interdisciplinary team of investigators at Michigan Technological University. Subsidence monitoring performed during this project showed that four different subsidence mechanisms were active while the mine flooded. Hydraulically triggered subsidence and piping-induced subsidence were two new mechanisms which were observed to have wider application. This work has been prepared as reports by Johnson and Frantti (1982, 1983) and Johnson and Hodek (1983).

Although this report deals largely with mine related problems on the Menominee Range; problems with mine subsidence, drainage and shaft seals have cropped up in other mining districts in Michigan. Investigations of these occurrences in both iron and copper mining districts have provided additional insights and the experience gained from them have materially aided this work. Some of the ideas developed from these efforts were incorporated in a paper entitled "Hydrologic Considerations in Mine Closings" by Johnson (1983)

This work would not have been possible without the help and contributions of many others associated with both government and industry. Several of those who have made outstanding contributions are: Robert Reed, and Jack Van Alstine of the Geological Survey Division, and Joseph Bal of the Water Resources Division of the Michigan Department of Natural Resources; Alice Allen (ret), Jacob Frank (ret), and Charles Rhoades of the U.S. Bureau of Mines; Peter Korach, Reino Laine and Sulo Hiltunen, Iron, Gogebic and Houghton County Mine Inspectors, respectively; Robert Edwards (ret) of Inland Steel Mining Company and Burton Boyum (ret) of Cleveland Cliffs Iron Mining Company. Larry MacDonald of the Institute of Mineral

Research at Michigan Technological University deserves special mention for his invaluable assistance in the field on all of these projects and also his professional contributions to this research.

MINE RELATED PROBLEMS - INTRODUCTION TO CASE HISTORIES

Three basic types of problems associated with closed and abandoned underground mines are considered in this report; 1) mine subsidence 2) mine drainage and 3) the safety of surface openings, mainly shafts but also including pits. Each of these major topics is comprised of several subdivisions. These topics and their subdivisions are identified and briefly discussed in this section which is introductory to the case histories which follow.

Mine Subsidence

Three categories of mine subsidence have been recognized on the West Menominee Iron Range: 1) subsidence that occurs during mining activity 2) subsidence occurring shortly after the mine is closed and while it is flooding and 3) longer term subsidence. For the most part, the first category of subsidence is related to the use of underground mining methods that resulted in surface disturbance. These techniques include top slicing and caving mining methods. With these techniques the surface subsides with the extraction of ore. In top slicing the subsidence is almost immediate because mining is started near the surface. With the caving methods, surface subsidence is often temporarily delayed until the fracture zone reaches the surface. However, this type of subsidence usually poses no problems as its occurrence is expected and the surface opening conforms quite closely to the shape of the ore extraction area. Consequently, this type of subsidence is not of primary concern to this work. This leaves the remaining two categories of subsidence; 1) short term subsidence which occurs while the mine floods and 2) longer term subsidence. Each of these categories will be discussed separately.

Short term subsidence. Although it may seem initially that the only distinction between subsidence occurring during the period of mine flooding and subsidence that occurs at some later date is one of timing, this is not necessarily the case. Flooding of a mine may cause profound changes in the mine environment that may either trigger or result in subsidence activity. In fact, the period of flooding is probably the most critical period in which subsidence may occur. Water entering the mine as it floods can reduce friction between rock masses. Frictional forces that held faulted or jointed rock masses in position may become reduced to the point where adjustments take place. This mechanism may often be enhanced by processes that took place when the mine was operating. Minerals in these planes of weakness may have become altered by exposure to air and humidity in the mine. Examples are expandable clay minerals and sulfides and other minerals susceptible to chemical changes. Under certain conditions these reactions may cause expansion of susceptible minerals within planes of weakness and result in spalling and rock mass failure adjacent to the mine openings. Elevated hydraulic pressures from introduced water into the planes of weakness may also cause this type of failure.

Secondly, water has mass and as this mass is redistributed during flooding, differential loading of rock and soil masses may occur. If a delicate equilibrium exists between these masses and is upset subsidence may be the result. Steeply dipping shear zones along which previous subsidence has occurred are most susceptible to further movement caused by differential loading during flooding. Obviously the loss of friction by the introduction of water into these zones can be a mitigating factor.

Thirdly, water inflow into the mine through previously subsided areas, shafts and other openings to the surface may wash unconsolidated overburden

(sand, gravel, silt, etc.) into the mine void. This can result in surface (overburden) adjustments that may be quite extensive. Fourthly, under special conditions of mine flooding, piping activity may occur. Piping involves the development of a cavity or void in unconsolidated overburden above the bedrock interface as a result of sand transport by groundwater flow into the mine. Laboratory experiments on the piping mechanism were reported by Johnson and Hodek (1983) and piping induced subsidence activity at the Sherwood Mine was documented by them and by Johnson and Frantti (1983a, 1983b).

A fifth mechanism for triggering mine subsidence may occur when a mine becomes flooded. Great hydraulic forces can be generated within a flooded mine if sudden water displacement occurs from the fall of surface material into the mine or compression occurs by rock mass movement. The surging water can trigger new subsidence or reactivate movement in areas of previous subsidence. A documented case of this type of occurrence is described by Johnson and Frantti (1983a, 1983b) and is included in this report as a case history.

Long term subsidence. This category includes all subsidence that occurs following the flooding of a mine complex. It is a very broad category in the sense that no limit is placed on the amount of time required for subsidence to occur.

The mechanisms at work to create this type of subsidence include the ever present force of gravity, long term chemical and physical weathering of minerals and the triggering effect of earth tremors of natural or man-made origin. The latter could include shock waves caused by explosion or tremors caused by heavy machinery or traffic. If subsidence occurs in a flooded mine, the resulting hydraulic disruptions could trigger additional

subsidence.

Gradual sloughing of rock from the roofs of near surface stopes can result in the upward migration of the mined void until the surface fails. This is probably the most prevalent mechanism at work in long term subsidence. The delayed effect of long term subsidence and its unpredictability places this category of subsidence into one of great concern.

Mine Drainage

Two types or sources of acid mine drainage are recognized in the West Menominee Range; 1) acid water from underground sources and 2) surface sources of acid drainage.

Acid drainage is prevalent only in the extreme western part of Iron River area of the West Menominee Range. It occurs there because of the close proximity of the ore to the source of the acid -- the pyritic Wauseca member of the Dunn Creek slate. Oxidation of the pyrite in slate exposed in the mines produced soluble ferrous sulfates. When these soluble sulfates were dissolved in water, sulfuric acid was formed.

When operating, many of the mines in the Iron River district pumped acid waters into the Iron River causing highly visible pollution as the acid became neutralized and the dissolved iron and aluminum then precipitated to form insoluble compounds referred to commonly as "yellow boy".

With the cessation of mining it was believed that the acid drainage problem would cease to exist. However, acid drainage reoccurred at several of the mines when they flooded, and are a continual source of acid drainage.

Surface piles of sulfur bearing black slate are also the source for some acid drainage. Surface water and near-surface groundwaters leach acid from extensive black slate piles at one mine complex which is situated in

the Iron River valley. The acid water flows a short distance before entering the Iron River creating additional pollution. Case histories of both of these occurrences are presented in this report.

Safety of Surface Openings

This category includes all surface openings resulting either directly from mining activity (shafts, raises, open pits) or indirectly (subsidence pits, caved ground). It deserves special attention because of the great threat that these openings present to the public. The threat is magnified because of the attractiveness of these areas to the public and their general lack of understanding or concern for their danger.

Injuries or deaths occurring from the fall of individuals, especially children, into an inadequately protected mine shaft or surface pit probably creates more intense ill will and negative feelings toward the mining industry than any of the other categories. This threat is made worse because these areas provide a real attraction for the general public. Consequently, it is not out of place to give serious thought and consideration towards methods of effective and safe protection.

Case histories illustrate the various types of surface openings which were originally inadequate, or through time have become so. Included in the examples are shaft openings that are uncapped, some that are inadequately capped, and several that were well capped but have deteriorated either because of a poor selection of material or engineering that did not take into account the eventual deterioration that would take place. A distinction is made between shaft seals in bedrock and surface caps. Although the problems of providing adequate fencing and providing maintenance are not heavily emphasized they are obviously important, as is the need of providing surface markers for identification and a means to locate the shaft openings.

CASE HISTORIES

Short Term Subsidence Effects

In the previous section, short term subsidence was defined as those subsidence events that occurred during the time required for a mine to flood. A well-documented case history involving each of the five subsidence mechanisms which were proposed to be active during mine flooding was developed at the Sherwood Mine. These mechanisms included; 1) water lubrication of shear planes 2) water loading of fault blocks 3) overburden washing resulting in shear failure of sands 4) piping produced cavities in the overburden and 5) hydraulically triggered subsidence.

Setting. The Sherwood Mine is located about one mile north of the City of Iron River (see Figure 7). The mine opened in 1943 and was shut down in 1978. Total shipments through 1978 including some ore extracted from an adjoining property during the 1930's totaled 13.7 million long tons of ore.

Sub level stoping was the only mining method used at the Sherwood Mine. The main ore body was served by a vertical shaft depth of 1625 feet. The near vertical, tabular ore body had major development on the 400, 800, 1000, 1200, 1425 and 1625 levels (Figure 8). Thick glacial overburden is present at the Sherwood Mine. The thickness varies because of irregularities in the bedrock surface, but averages 150 feet. A 30-foot thick, well consolidated glacial till overlies poorly consolidated sands with lesser gravels. These relationships are shown in Figure 9.

The Sherwood Mine is part of a large complex of mines. It is connected with a shallower mine, the Virgil-Spies on the east and a deeper mine, the Homer-Wauseca on the west. Although these mines are interconnected and would flood as one, they were independently operated by other mining companies. Both of these adjacent mines had been shut down earlier — the

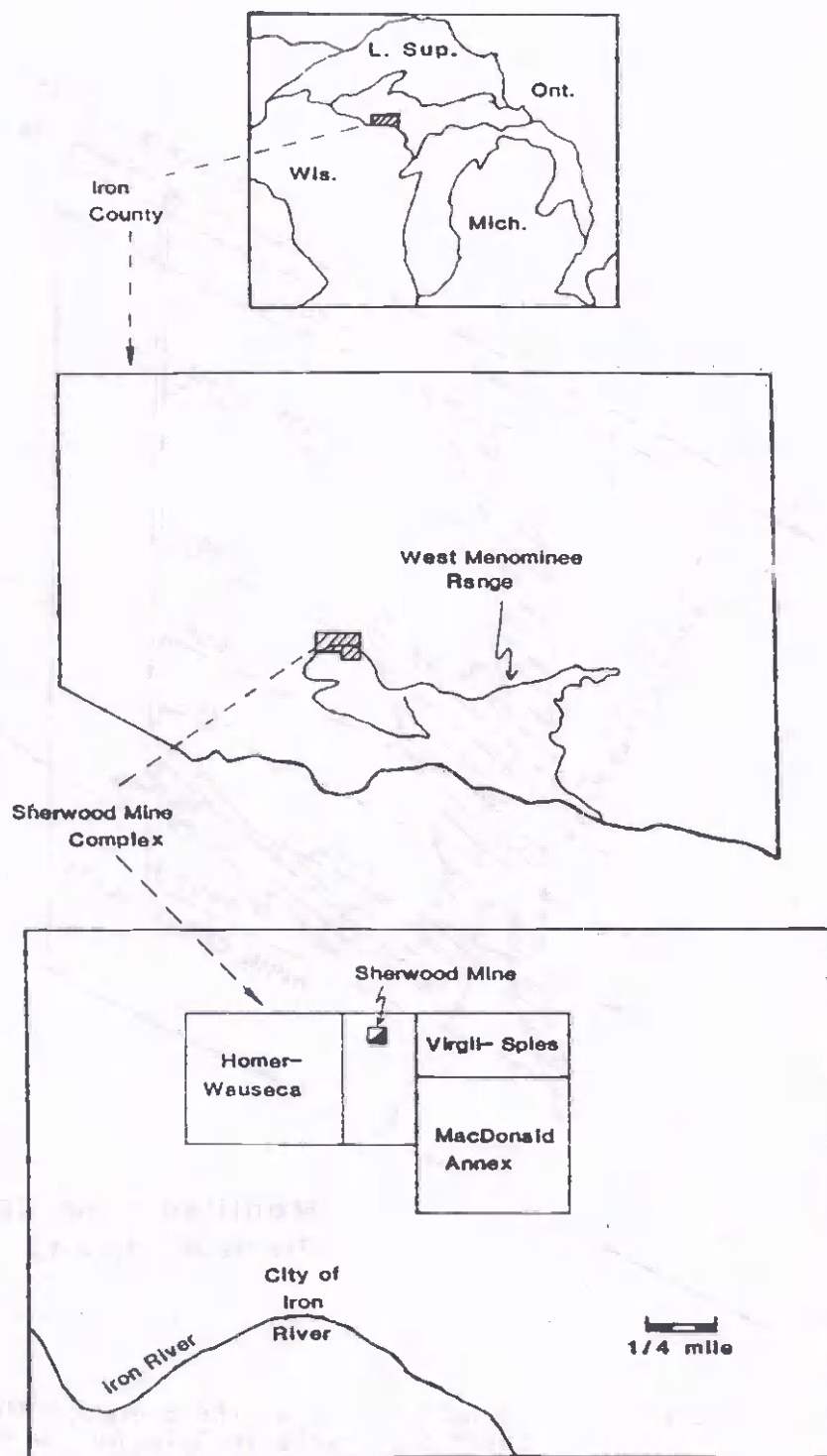


Figure 7. Location of the Sherwood Mine Complex in the Iron River District of Northern Michigan

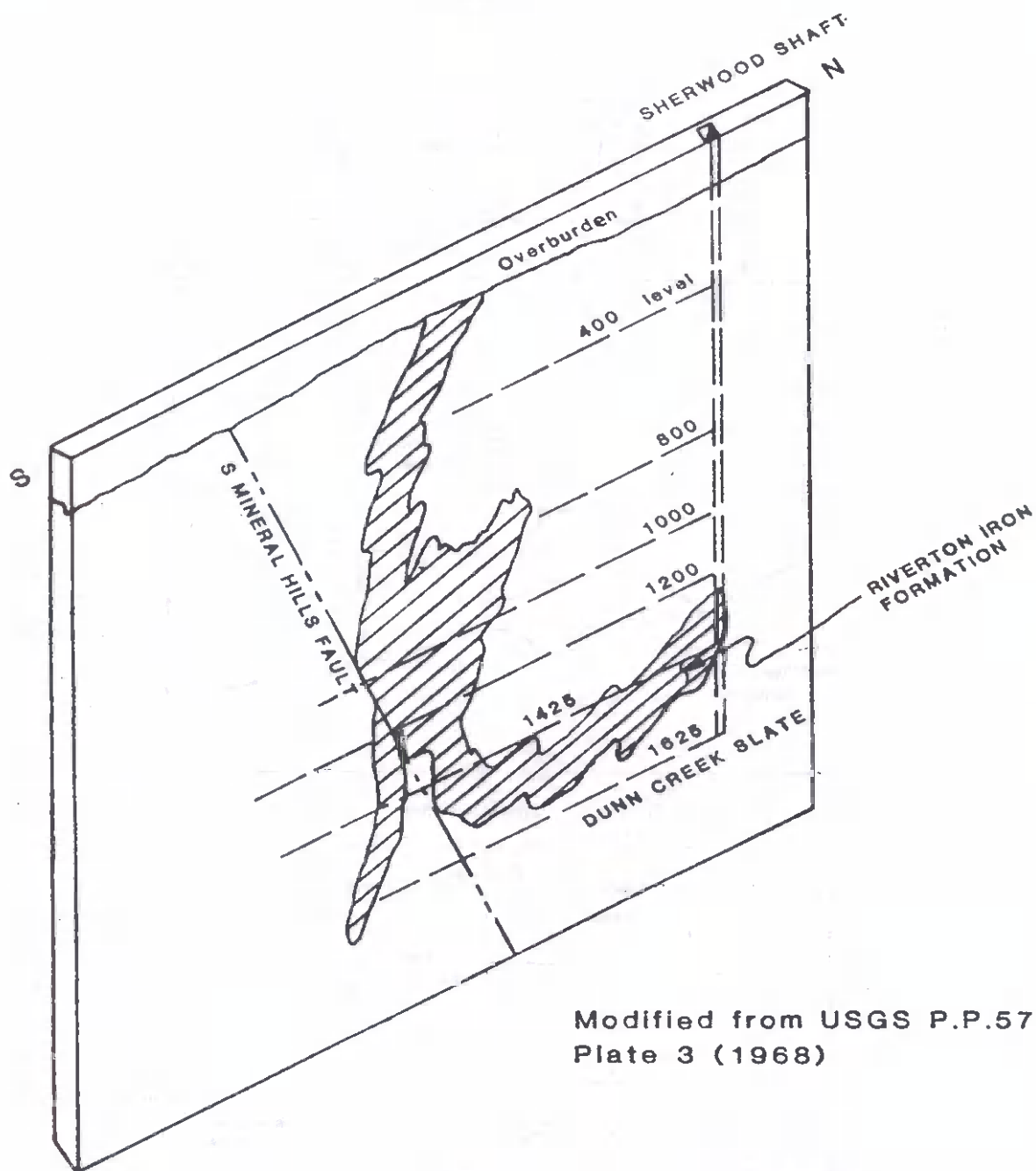


Figure 8. Isometric View of the Sherwood Mine Shaft and Levels in Relation to the Main Ore Body.

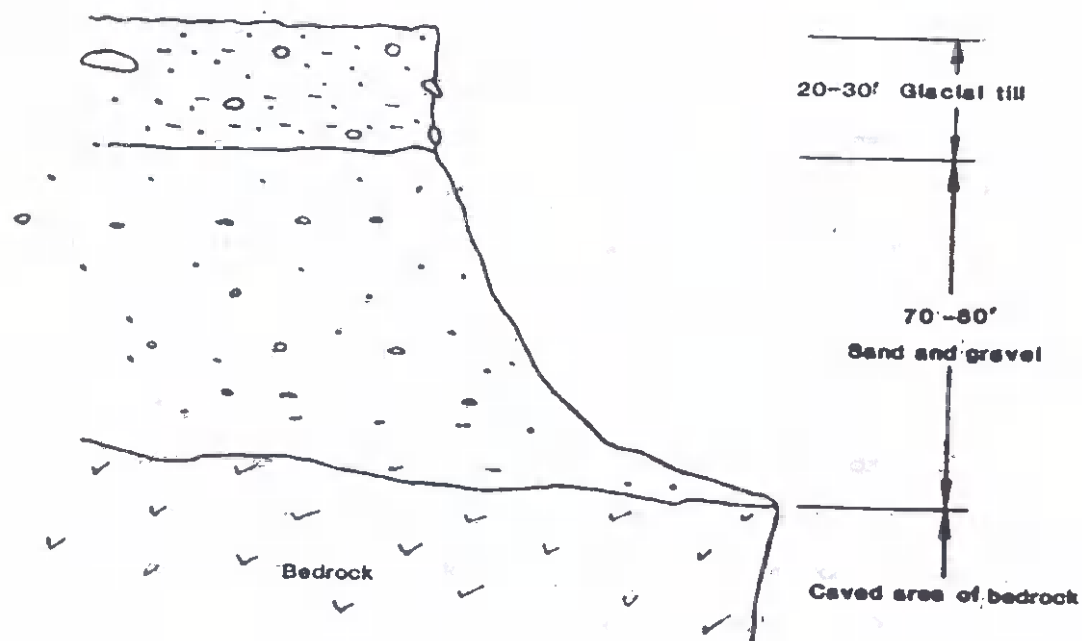


Figure 9. Generalized Profile of Glacial Overburden at the Sherwood Mine in the East Pit

Virgil-Spies in the 1950's and the Homer-Wauseca in 1968. The locations of these adjoining mines is shown in Figure 7.

The Sherwood Mine has had a rather long history of subsidence. Major stopes in the upper levels of the Sherwood Mine on both the east and west margins of the Sherwood property had caved to the surface. These cave-ins resulted in large deep surface pits in the thick glacial overburden. The West Pit caved in February 1956 and the East Pit caved to the surface in August 1964. The pit locations are shown in Figure 10. Also shown is a small pit located between the East and West Pits, known as the Central Pit. This 100-foot diameter pit appeared suddenly in February of 1967 following an explosive blast used to break up consolidated overburden being used for stope filling operations. The blast apparently triggered the collapse of a soil capping over an existing cavity in the overburden. This void had probably been formed either by piping or running sands, but a plug-type failure of a shallow stope may also have been responsible. A steeply dipping (70° south) east-west fracture developed in the Sherwood Mine during the Spring of 1966. By November of 1966 the fracture was evident on the 400, 800, 1000 and 1200-foot levels plus on the surface. The maximum displacement was three feet on the 1000-foot level as observed in a major crosscut drift.

Monitoring of post-mining subsidence. Monitoring systems installed at the Sherwood Mine prior to shut down included borehole extensometers in the steeply dipping fault zone within the mine, surface and underground acoustic emission sensors, a grid of surface subsidence monuments a piezometer network to monitor water rise in the overburden and water level measuring devices to monitor the flooding of the mine complex.

When the pumps were shut down in 1978, the mine complex began to

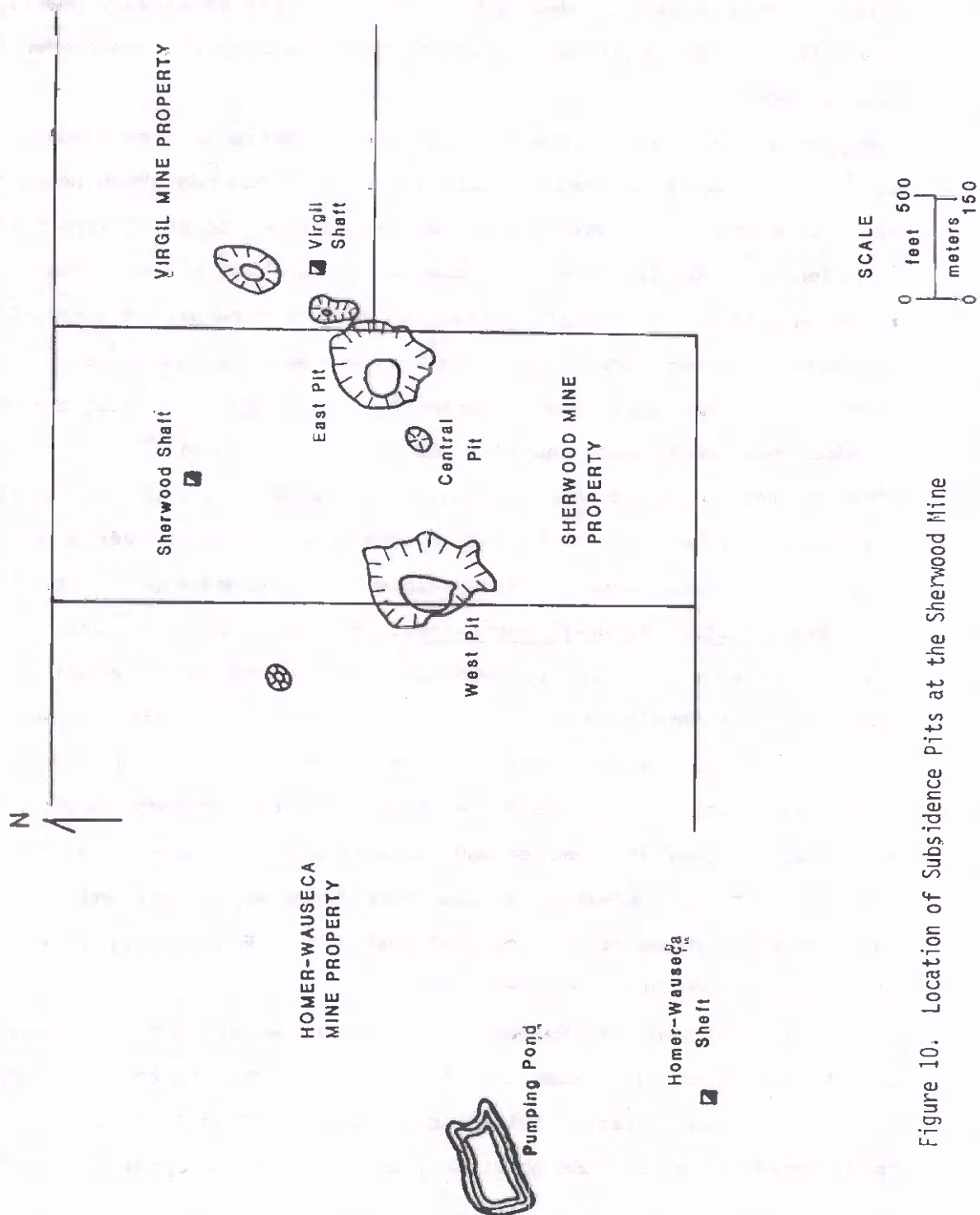


Figure 10. Location of Subsidence Pits at the Sherwood Mine

flood. The mine was flooded by mid-1981, in a period of 2.75 years. About one more year was required for groundwater levels in the overburden to equilibrate.

Subsidence. During the time required for the Sherwood Mine complex to flood, three different major subsidence events occurred which serve to illustrate the five subsidence mechanisms ascribed to short term post-mining subsidence. Included were 1) subsidence in the West Pit area which represents shear failure of overburden sands as a result of water flow into the mine, 2) broad surface subsidence as a result of rock mass movement from water loading and shear plane lubrication and 3) hydraulically triggered subsidence which in turn caused a previously formed soil cavity to suddenly develop into a subsidence pit with the collapse of the protective capping. This cavity is believed to have been caused by piping of overburden sands into a mine stope. Each of these events is described separately.

Shear failure in overburden sands. Beginning in late summer 1979, a little more than one year following shut down of the mine, a small subsidence pit developed in sand fill in the West Pit. The pit was circular, about 30 feet in diameter and 10 feet deep. A month and one half later, additional subsidence caused the pit to become much larger. It now was about 100 feet in diameter and 40 feet deep and cone-shaped. Several days later the pit underwent another subsidence adjustment and was enlarged to 200 feet in diameter and about 60 feet deep. Figures 11, 12 and 13 illustrate these three subsidence events.

It is believed that following the rise of water in the overburden above the Sherwood Mine that water flow into the mine through the pit area washed sand into the incompletely filled stopes below. This loss of sand from the "plug" consisting of sands previously washed into the opening in the top of

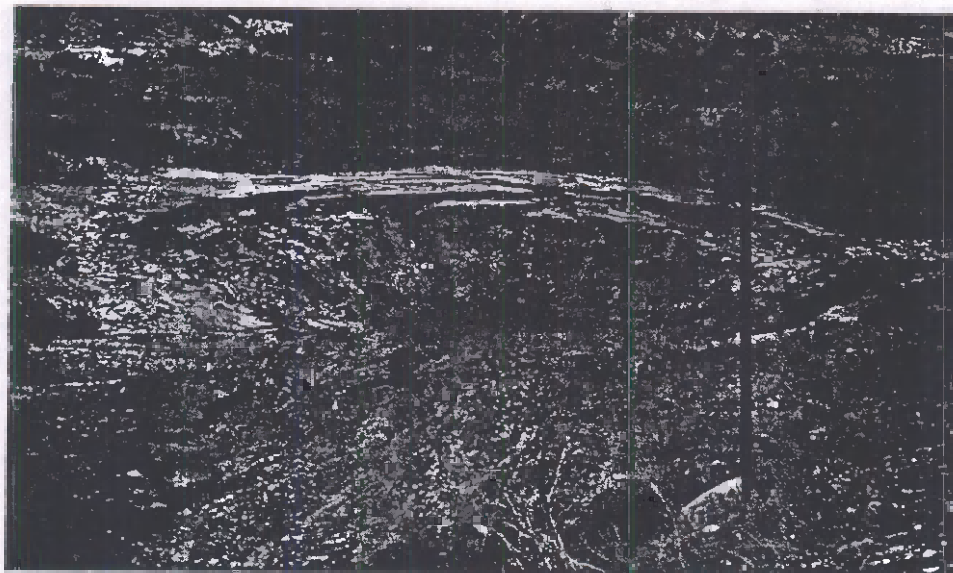


Figure 11. Photograph of initial subsidence in West Pit area taken on September 7, 1979. The subsidence pit is about 30 feet in diameter and ten feet deep. The bent pipe in the foreground is an old well casing installed in the 1940's. Photograph taken with a 50 mm lens on a 35 mm camera, looking southeast. Cave first observed August 31, 1979.

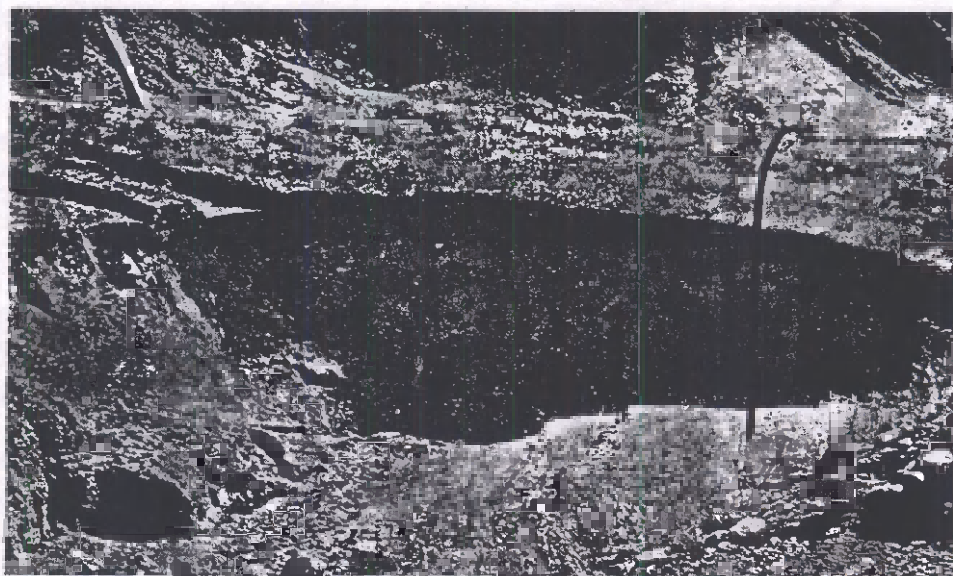
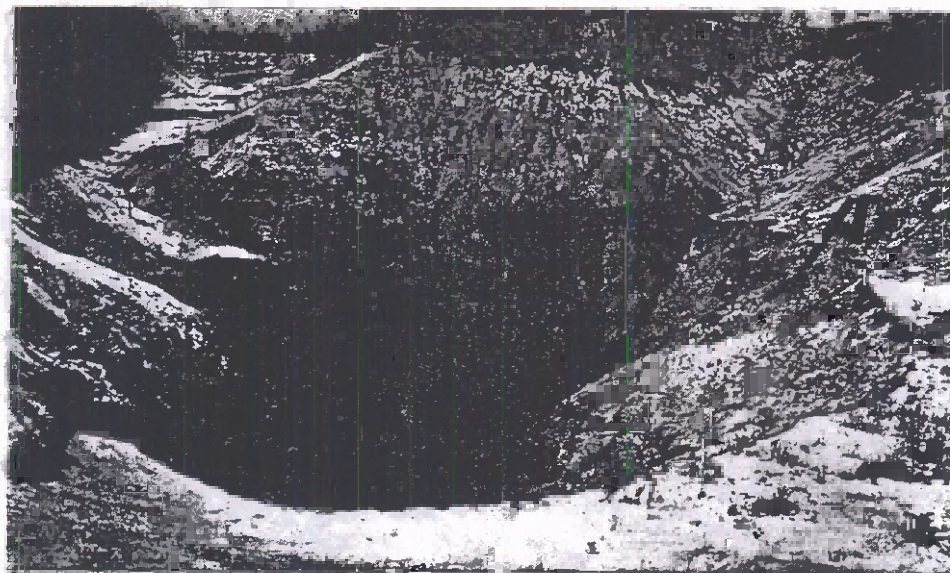
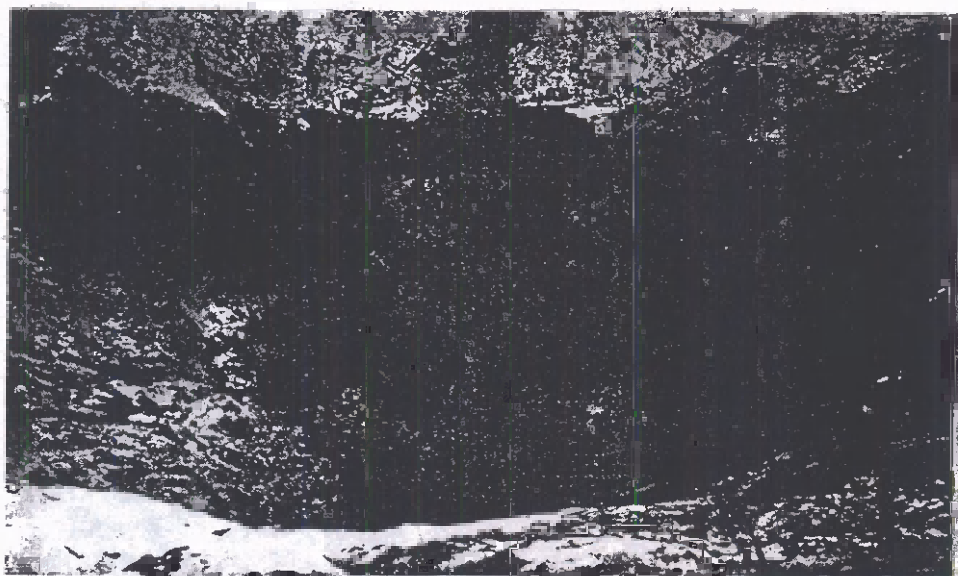


Figure 12. Photograph of enlarged subsidence pit which caved on October 14, 1979. The resulting pit is about 100 feet in diameter and 60 feet deep. Note old well casing pipe in foreground; also cribbing and bent over 30-inch pipe in background at upper left, formerly used for sand filling stopes under this area. Looking southeast, photo taken with 35 mm camera equipped with a 50 mm lens.



- a Greatly enlarged subsidence pit which caved on October 19, 1979. The pit is about 200 feet in diameter and 100 feet deep. Shear rock walls are exposed on the west and north walls of the pit. Note the old well casing on the far right and sand filling pipe and cribbing on the left. This cave occurred on October 19, 1979. View looking north. Photograph taken with a 28 mm wide angle lens on a 35 mm camera.



- b Close up of the October 19, 1979 cave. View is looking northwest. Note 30-inch diameter sand fill pipe in near foreground and old well casing in background. Photograph taken with a 28 mm wide angle lens, 35 mm camera.

Figure 13. Enlarged West Pit After October 19, 1979 Subsidence Event

the caved stope, caused the observed series of subsidence events. The circular shape of the opening, the tension fractures around the opening and the resulting cone-shaped void all suggest that shear failure from gravity loading of the unstable sand mass best explains this subsidence occurrence.

Surface subsidence resulting from rock mass movement. Leveling surveys of a 47-movement grid were performed periodically at the Sherwood Mine following its shut down. Surface subsidence over a broad area (25 acres) above the main ore body was first detected in late 1979. Surface subsidence continued throughout 1980 until the maximum downward displacement was 1.3 feet. The northern extent of the surface subsidence was marked by the surface trace of an east-west trending shear that was about 100 feet south of the main shaft. These features including the monument locations are shown on Figure 14. The contours of subsidence based upon a level survey in December 1980 are also shown.

The surface subsidence described above developed in response to rock mass movement within the mine. The initial phases of this movement were detected and monitored by extensometers installed across the 70° south dipping shear plane. A cross section map of the mine in Figure 15 shows the location of the shear zone in relation to the mine workings and the extensometer installations. The relationship between the movement on the shear plane and the broad surface subsidence is shown in Figure 16.

It is hypothesized that renewed movement of the massive south block of the mine occurred as a result of mine flooding. It is likely that groundwater inflow into the shear zone reduced the frictional forces holding the block in position and perhaps loading of the sealed stopes within the block with water may have helped this movement. It is also possible that movement on the shear plane may have been partly responsible for initiating

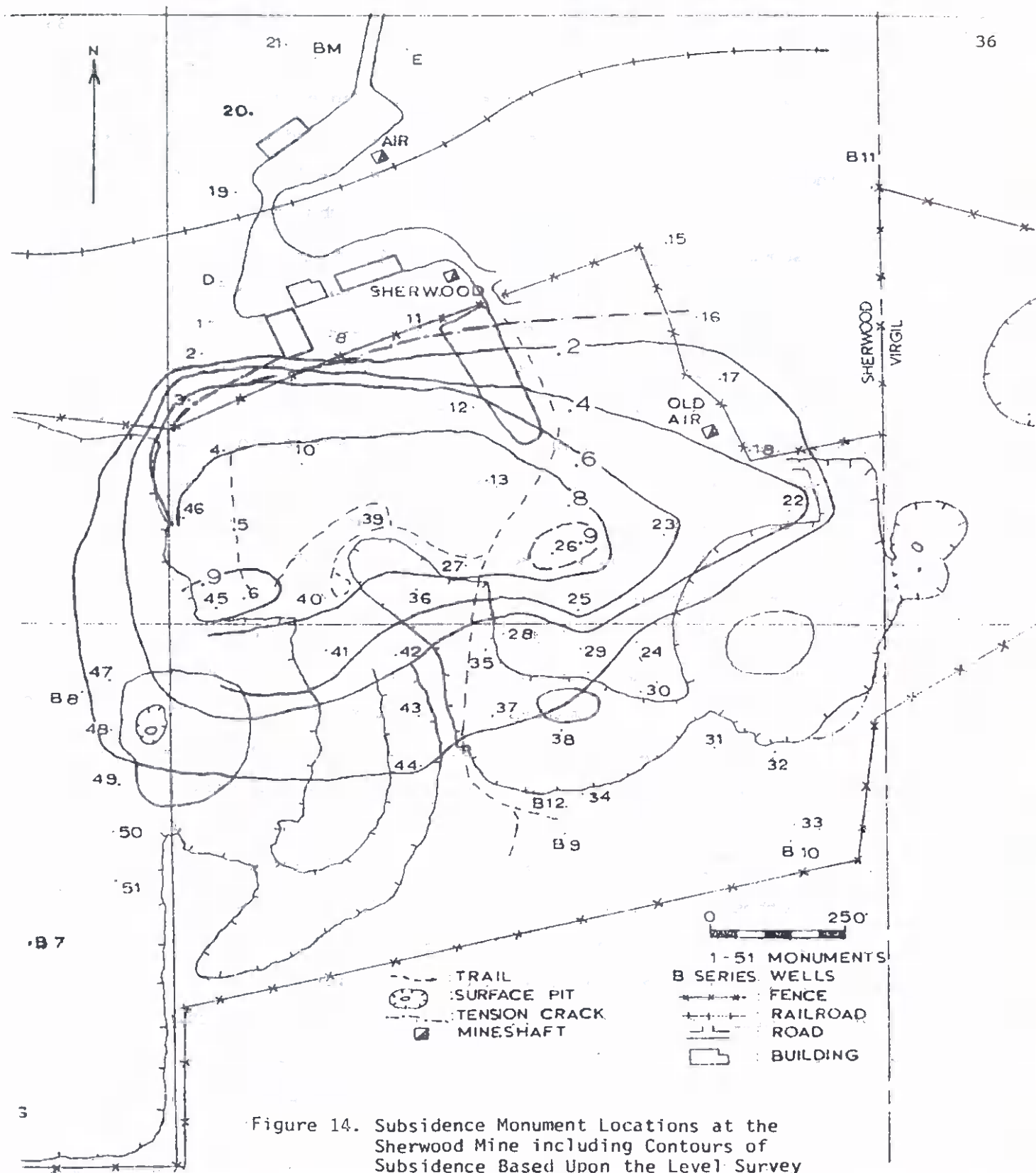


Figure 14. Subsidence Monument Locations at the Sherwood Mine including Contours of Subsidence Based Upon the Level Survey of December 9, 1980.

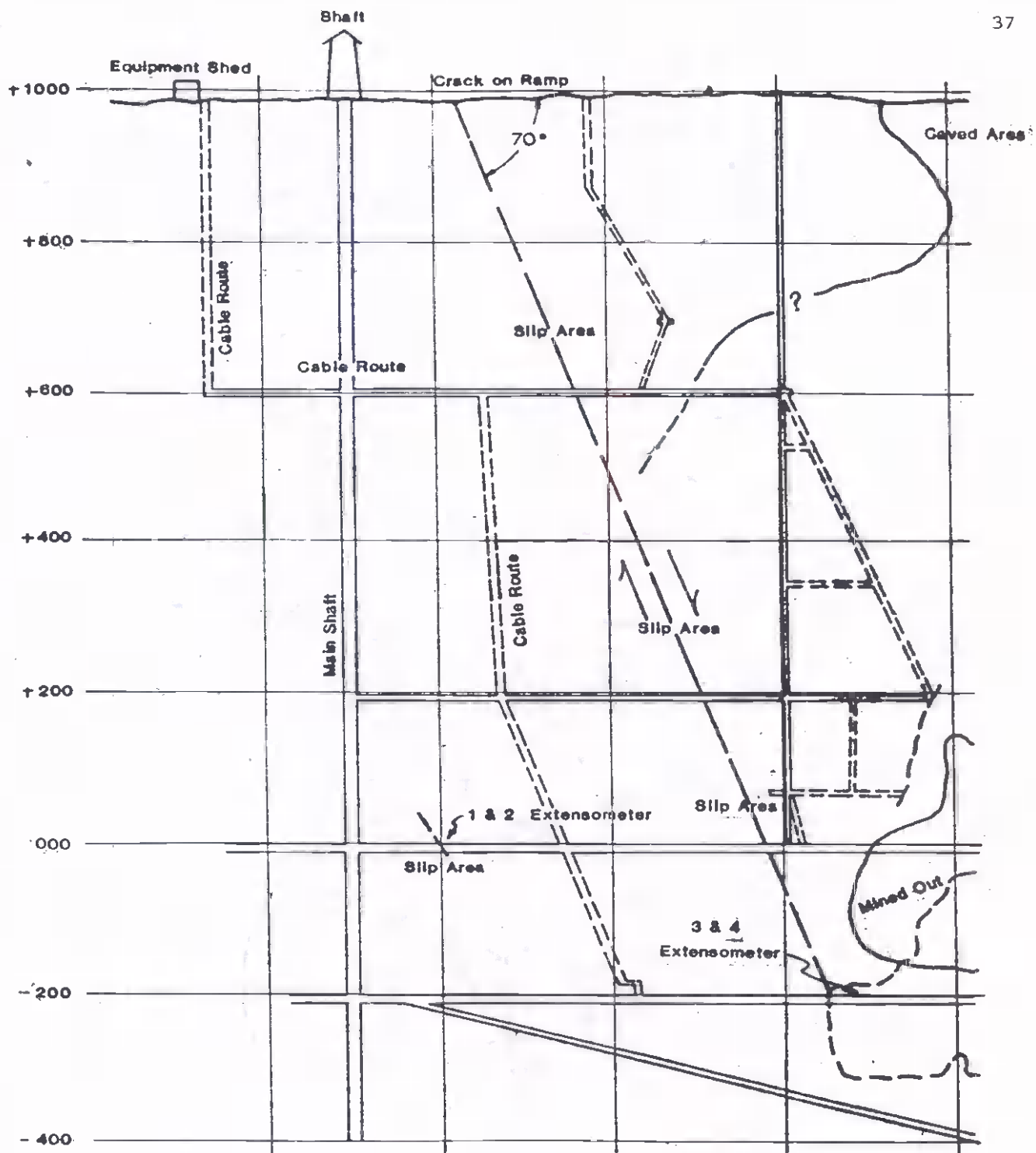


Figure 15 Location of Extensometer Installations in Shear Zones on the 1000 and 1200 Levels of the Sherwood Mine: Looking East

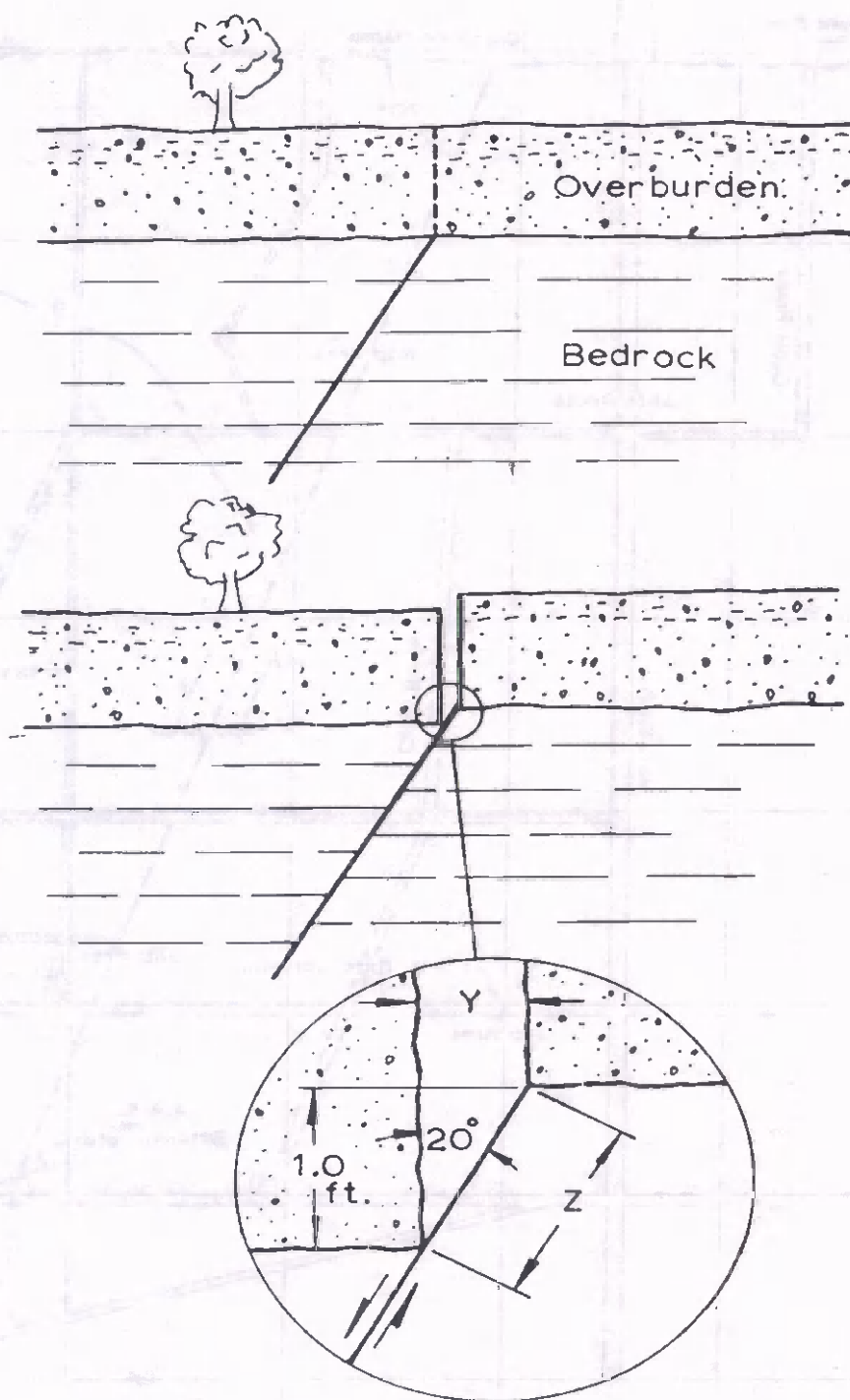


Figure 16. Suggested Mechanism to Explain Surface Pits on South Block of Surface Shear - Looking West.

the West Pit sand plug failure described in the previous section, although sand movement from groundwater inflow was undoubtedly at least a contributing factor.

Hydraulically triggered subsidence. In the late evening of April 1, 1981 when the Sherwood Mine complex was within 100 feet of being flooded a most unusual sequence of events either caused or were created by surface subsidence. Massive surface subsidence took place in the East and West Pits, and two other new pits of significant size were formed. This extensive subsidence in turn produced great hydraulic pressures in the nearly flooded mine complex. Surges of water were forced up mine shafts and sand filling raises, rupturing or destroying their seals and cappings. The sudden uprush of water forced water from the mine openings to the surface causing extensive erosion near the openings. In one area, water and mud were carried into a diesel engine repair facility located in mine buildings near the Homer-Wauseca shaft. Evidence shows that water in the Sherwood Mine shaft produced a geyser effect as a result of being forced to exit through a 10-inch diameter pipe in the securely sealed and capped shaft. The seals in two vertical raises located beneath two surface pond areas west of the Sherwood Mine were disrupted. Waters drained rapidly from these ponds into the mine complex. Measurements show that the water level in the mine complex rose 17-feet over a two-day period which spanned the subsidence events, whereas, prior to the event the flooding rate was about two and one half feet per day.

None of these occurrences were witnessed, as the short-lived event apparently occurred during the night of April 1, 1981. Mr. Robert Edwards, Mine Manager (retired), reported that a residence of a home just north of the Sherwood Mine shaft heard sounds about 11:30 p.m. on April 1st that

"sounded like the ore crusher starting up". Of course, the ore crusher was no longer operating and in fact had been removed from the property for some time. It is probable that the sounds were from the subsidence activity.

The cause of the event is not known. However, it is likely that the subsidence activity was initiated by a single subsidence event. A large mass of sand and/or rock falling into the nearly flooded mine would have displaced and pressurized the mine water causing it to surge throughout the mine complex and to initiate the other disruptive events. Increased activity from an acoustic emission sensor was recorded prior to the April 1st event which suggests that the triggering subsidence event may have initiated near the center of the Sherwood property.

If it is accepted that the event was triggered by a single surface subsidence, it follows that the hydraulic force generated by the first subsidence event caused additional subsidence. This occurrence could have been repeated several times similar to a chain reaction. It is likely that a series of subsidence events did occur, each one triggering additional activity. It is also likely that the life of intense subsidence activity was short, perhaps on the order of one-half hour or less. Unfortunately the acoustic emission sensors were much too sensitive to distinguish the period of the most intense activity.

An interesting analogy to this subsidence event would be to think of the underground openings of the mine complex as the "plumbing^b system" of a hydraulic unit with the mine water representing hydraulic fluid. However, unlike a hydraulic system which is strongly sealed and fluid-filled, the mine was incompletely filled and the seals on shafts and other surface openings were for the most part not designed to withstand great hydraulic forces. As water surged upward through these channels leading to the

surface, the air between the surface of the rising water and the shaft capping or seal would have been rapidly compressed. If the surface seal or capping was not strong enough to resist the combined forces of the compressed air and the rising water, it would have been either lifted or disrupted. These types of occurrences were documented following the April 1st subsidence event at the Sherwood Mine.

In similar fashion, the sand "seals" in the bottom of old subsidence pits were disrupted. These "seals" were formed by the gradual inwash of sandy overburden into the pits following subsidence. The strength of these sand plugs would be low. They would be uncemented and the main forces holding the sands in place would be frictional with gravity loading. Compressed air and surging water moving up through the caved area beneath these seals could have easily caused them to fail.

Piping-induced subsidence. One of the most interesting and significant aspects of the hydraulic subsidence event was the formation of a subsidence pit which was believed to have existed previously as a concealed cavity in the glacial overburden formed by piping activity.

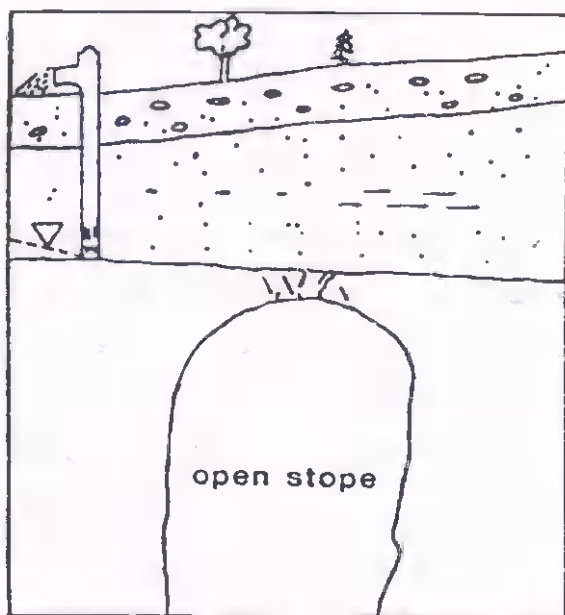
Piping, as it relates to surface subsidence, occurs when groundwater flows into underground mine openings through openings (fractures, drill holes, etc.) that are large enough to allow passage of sand grains from the overburden. This transport mechanism can result in the formation of large cavities within the soil above the bedrock surface. The conditions that favor this process are threefold: 1) an easily erodible soil above bedrock, 2) channelways that permit water transported soil to move from the overburden into the mine void and 3) a substantial groundwater flow. Given these conditions plus a thick overburden layer, large volumes of groundwater flow and a large mine void reservoir (for water and sand) the piping-induced

cavity can become very large. The presence of a competent surface layer which serves as a capping can allow the soil cavity to attain large horizontal and vertical dimensions before collapse occurs.

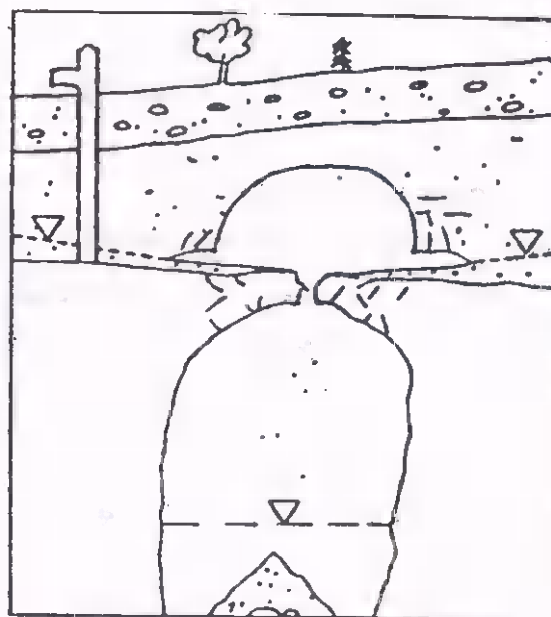
This mechanism of surface subsidence not previously described in the literature, was presented by Johnson, Hodek and Frantti (1981). A conceptual model of the piping subsidence phenomenon is illustrated in Figure 17. It can be seen in Figure 17 that the initial flow of sand and groundwater produces a cavity in the soil at the point of intersection of the bedrock channel and the overburden. Growth proceeds by gravity collapse of unstable sands from the undercut periphery of the opening — the undercutting being caused by groundwater erosion and transport of the sand. Cavity growth ceases when any of the following conditions are met:

1. The mine becomes flooded and water flow is stopped.
2. The volume and velocity of groundwater flow is no longer sufficient to erode and/or transport sand into the mine void.
3. The channelway into the mine void becomes plugged or a filter pack of sand and gravel develops which "screens out" clastic material.

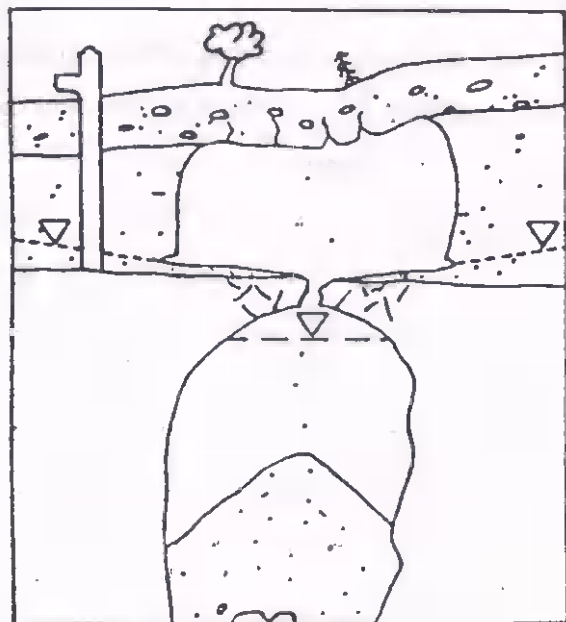
If the diameter of the hemispherical piping cavity exceeds the length that the surface capping will withstand, surface collapse will occur. The resulting pit will be straight-walled with a high depth to width ratio. This will serve to distinguish a piping-generated cavity from one formed by shear failure of running sands. These cavities may apparently exist for long periods without any surface expression to indicate their presence. Capping failures may be triggered by outside forces; i.e., explosions or hydraulic forces as occurred at the Sherwood Mine.



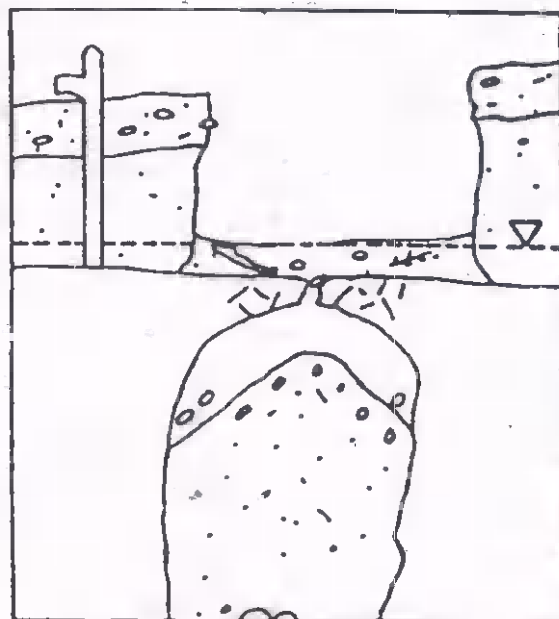
A. Mine operating, surface and underground pumping in progress. Stope underlies erodible sands and competent till capping.



B. Mine closed, pumping stopped. Groundwater rises in overburden and mine begins to flood. Cavity develops in sands above bedrock as sand/water mixture flows into the stope via open fractures.



C. Soil cavity enlarges as water inflow causes undercutting at periphery resulting in sand collapses from the roof. Soil is carried into mine by groundwater flow. Competent capping layer still intact.



D. Collapse of cap, subsidence is complete the mine is flooded and the groundwater table is at equilibrium. Resulting pit has near vertical walls and a flat bottom.

Figure 17. Improved conceptual model of piping subsidence over an underground mine.

Long Term Subsidence

Long term subsidence was defined as subsidence that occurs following mine closure and the time required for a mine to flood. It was mentioned previously that the major mechanism responsible for long term subsidence was the force of gravity and other stresses to which mine pillars and stope walls are subjected. Loss of rock strength by weathering, oxidation or other chemical/physical reactions also play a role in long term subsidence. Seismic shock — natural or resulting from man's activity may also be a causing factor in long term subsidence. Natural shocks would occur from earthquakes; man-made shocks would include explosions, operations of heavy machinery and rail, truck and automobile traffic. Hydraulic shock which was described in the previous section could also be a factor in a flooded mine, being generated by either natural or man-made shocks.

Long term subsidence, by its very name, implies a process that is slow and unpredictable in terms of timing. The factors which control the timing are many. Of these, the size and position of mine openings and the thickness and competency of the bedrock above the mine stopes are of particular importance. The structural conditions inherent in the rock, the effective stress field and the presence of moisture are additional important factors governing the stability of mine openings.

Generally speaking, the most important factor in delayed or long term mine subsidence relates to the proximity of the mine void to the surface. Other variables being equal, near-surface stopes have the greatest possibility of subsidence.

Although only one case history of long term subsidence is presented in detail, it illustrates all of the real concerns that may arise from this delayed subsidence. It is the only documented case of mine subsidence that

resulted in a human fatality in Iron County. The subsidence event occurred in June of 1960 between the City of Caspian and the Village of Gaastra in the Iron River district. The following description of the circumstances of the subsidence event is from a memorandum report prepared by R.O. Pynnonen and R.L. Bernard of the U.S. Bureau of Mines in 1968.

"A 40-foot section of County Highway 424 approximately 2 miles south of Iron River caved early in the morning on June 11, 1960. One person was killed and two others injured when two automobiles were driven into the cave during early morning darkness and a heavy fog. The cave-in was 40 feet long, 30 feet wide, and about 30 feet deep. Records show that the cave-in occurred on the property line separating the operating Buck Mine of Pickands-Mather & Company and the abandoned Smuggler Mine, Gaastra Iron Company. The Smuggler Mine produced slightly more than 800,000 tons of ore from a depth of less than 520 feet. A stope 80 to 120 feet wide beneath the road reportedly was mined to within 20 feet of ledge."

Following the accident, the caved section of the road was blockaded on the east and west. The road has not been repaired and the subsidence pit was left as it was. Except for the growth of vegetation and trees the area has changed little from 1960. Large slabs of broken pavement lie in the pit. Wooden posts connected by steel cables which once served as a guard rail on the north side of the road hang suspended on the north side of the pit. Broken water pipes which were exposed by the cave-in are exposed in the pit sides. According to a local resident the two car bodies in the pit were involved in the 1960 accident -- they are the proper vintage. Photographs of the pit taken in 1980 are shown in Figures 18 through 21. Except for the small aspen and birch trees which had grown in the 20 years following the accident, little has changed at the scene and it remains as a grim reminder of one of the most threatening aspects of long term or delayed subsidence.

The location of the subsided area is shown in the plan map of Figure 22 which was traced from an aerial photograph. Note the subsidence pit in the



Figure 18. Smuggler Mine Cave-in on County Road 424: Looking East



Figure 19. Close-up of Smuggler Mine Cave-in: Looking East



Figure 20. Smuggler Mine Cave-in on County Road 424: Looking West



Figure 21. Close-up of Smuggler Mine Cave-in: Looking West

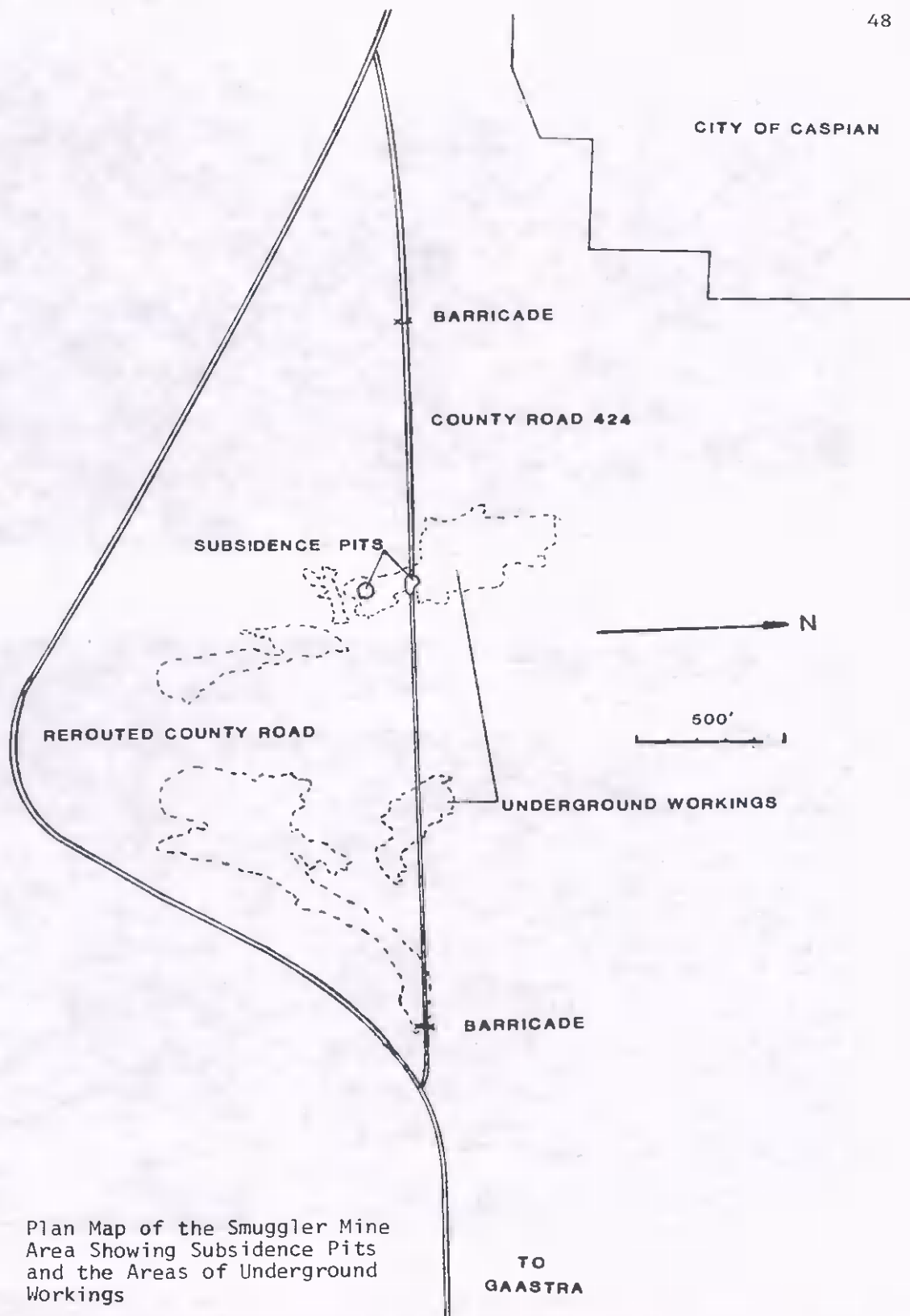


Figure 22. Plan Map of the Smuggler Mine Area Showing Subsidence Pits and the Areas of Underground Workings

road and a second one of similar size a short distance south of the road. A photograph of this second subsidence pit is shown in Figure 23. Both of these pits are underlain by the Smuggler Mine. Accurate mine maps of the Smuggler Mine are not available, however, two old maps were found which show section views of the Smuggler ore body. Figure 24 is a cross section view looking north and Figure 25 is a longitudinal section looking west. Although the mine stopes are not shown, it is apparent that any development above the first level would have brought the mine stopes very near the ledge (the bedrock surface). This obviously occurred.

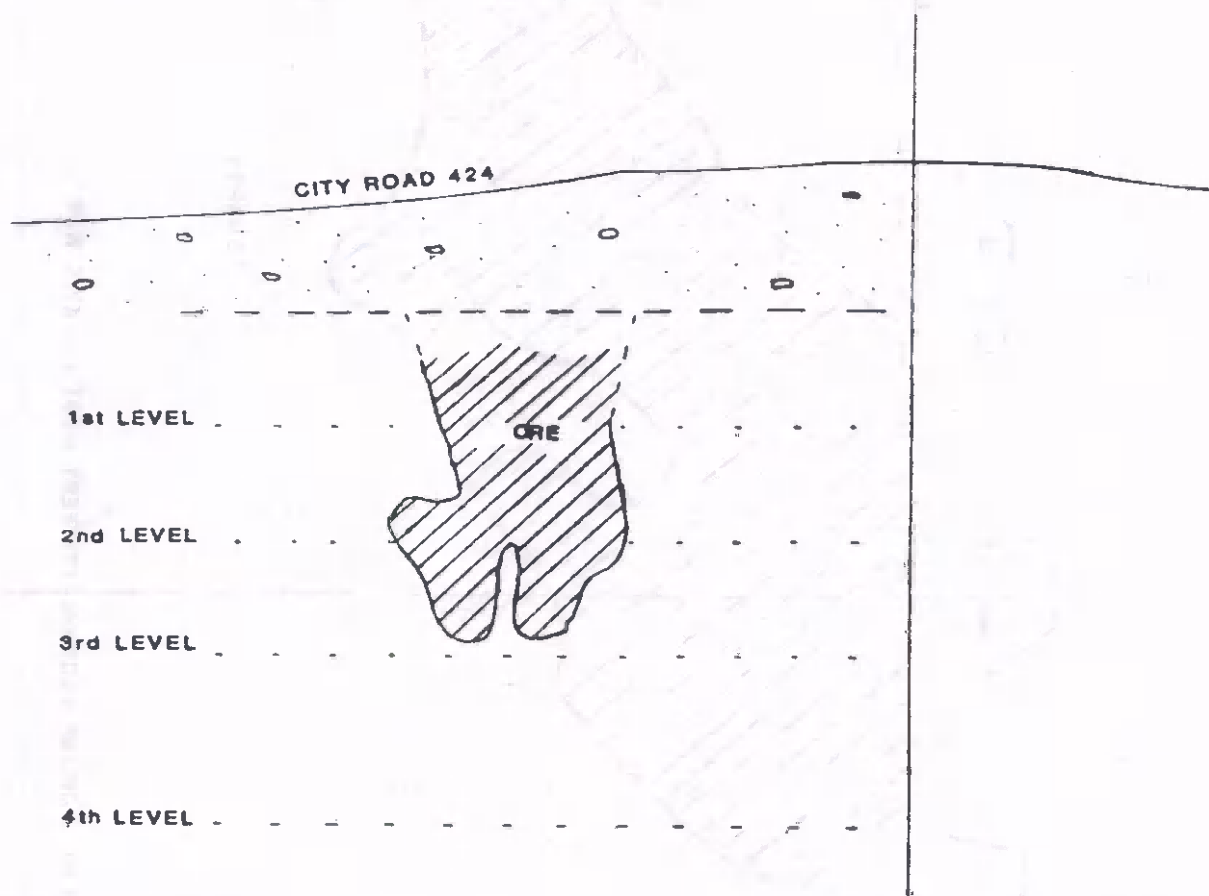
Perhaps at this time there was no road in this area, or perhaps it was only a trail. From information on the map shown in Figure 25, it is suggested that rock may have been used to fill the mine void. However, this is not known. What is clear, is that with County Road 424 over a mined-out and largely forgotten early mining operation, that the stage for eventual subsidence of the roadway was set. The unfortuitous timing of the subsidence event, on a foggy night, played a large role in causing the human fatality.

Acid Water Drainage

Acid water drainage is not a problem that is usually associated with iron mines. However, in the Iron River district, the iron ore was in direct contact with the underlying pyrite-rich Wauseca member of the Dunn Creek slate and lenses of pyritic slate were sometimes found in the iron ore. When the pyritic slate was exposed during mining, it would oxidize so rapidly that sometimes mine fires were the result. As many of the mines were wet and required pumping, the pumped water was acid. Consequently, acid water drainage has been a problem in the Iron River district since the mines were opened. When many mines were operating, acid waters pumped from



Figure 23. Small Subsidence Pit (50 ft diameter, 25 ft deep) South of County Road 424 above Smuggler Mine



SMUGGLER MINE CROSS SECTION 0 FEET SOUTH LOOKING NORTH SCALE 1" = 100 ft.

Figure 24. Cross-Section Map of the Smuggler Mine Ore Body

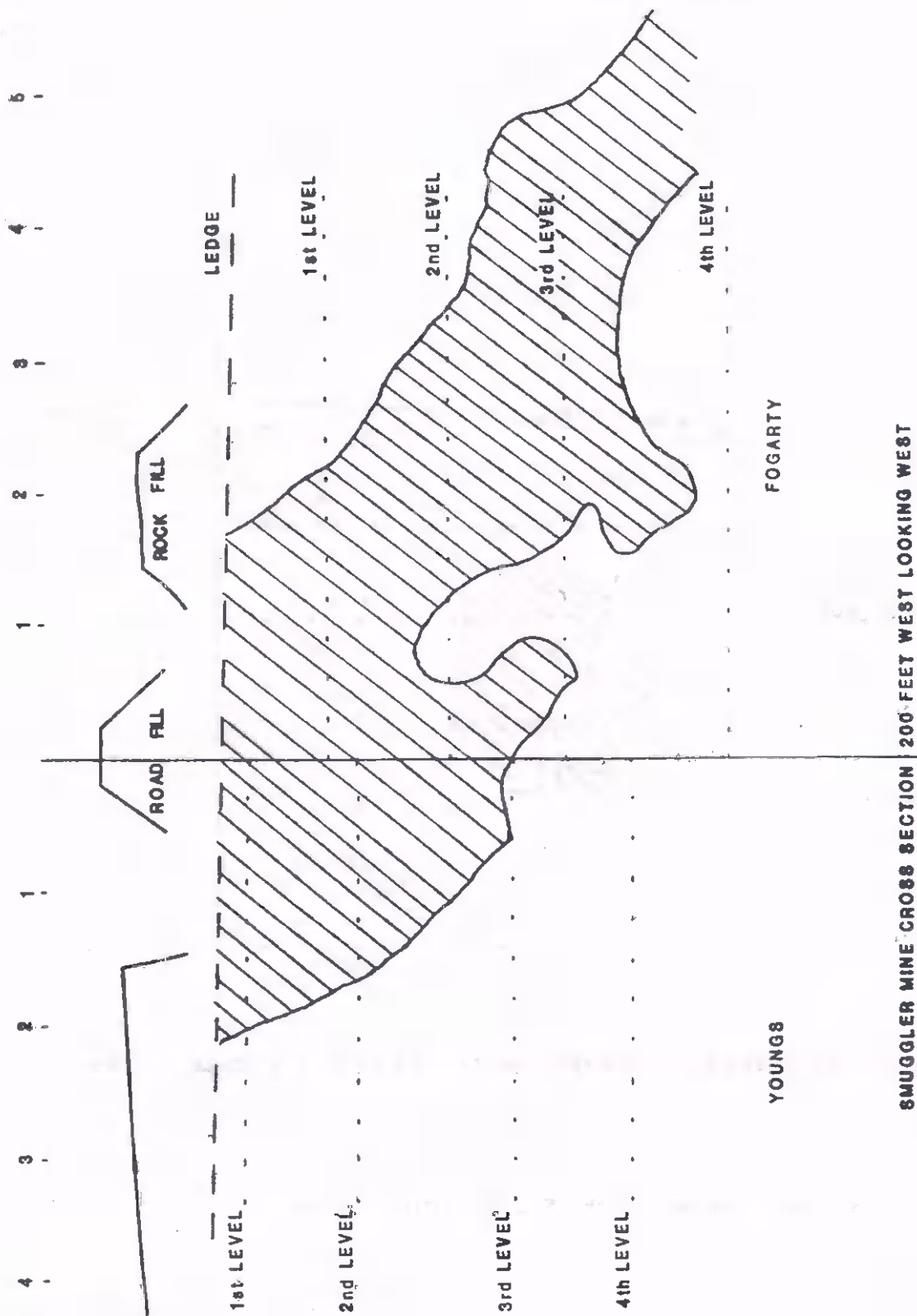


Figure 25. Longitudinal Section of the Smuggler Mine Ore Body

them caused the Iron River to run red. In more recent years as mines closed and pumping ceased, acid water drainage abated. Some mining companies which instituted corrective measures to improve the quality of mine waters before draining them into the river also caused a great improvement in the acid water situation. In fact, for a while, it seemed reasonable that acid water drainage would cease to be a problem in the district.

Such was not the case, however, for as the mines closed and pumping was halted, underground water levels began to rise. Workings kept dry for all the years the mines were in operation began to flood. In some cases it took several years for the mines to fill with water. The waters rose until they reached their natural levels --- the levels existing prior to mining activity. Mines collared at lower elevation in the Iron River valley flooded to the surface and flow from some of them carried acid into the Iron River.

Sulfur-bearing black slate often used for surface fill around mine workings came into direct contact with the elevated groundwaters and acid waters issued from this source too.

Discoloration of the Iron River by present acid drainage is not as severe as it once was, but it is still a concern. Tests by the Michigan Water Resources Commission show that trout and other fish and aquatic organisms can and do live in the clouded waters. Nevertheless, discoloration of the Iron River is highly visible and aesthetically displeasing. Precipitation of insoluble iron compounds coats all submerged objects with a yellow-brown slime and the extreme fineness of the precipitates allows them to be carried far downstream.

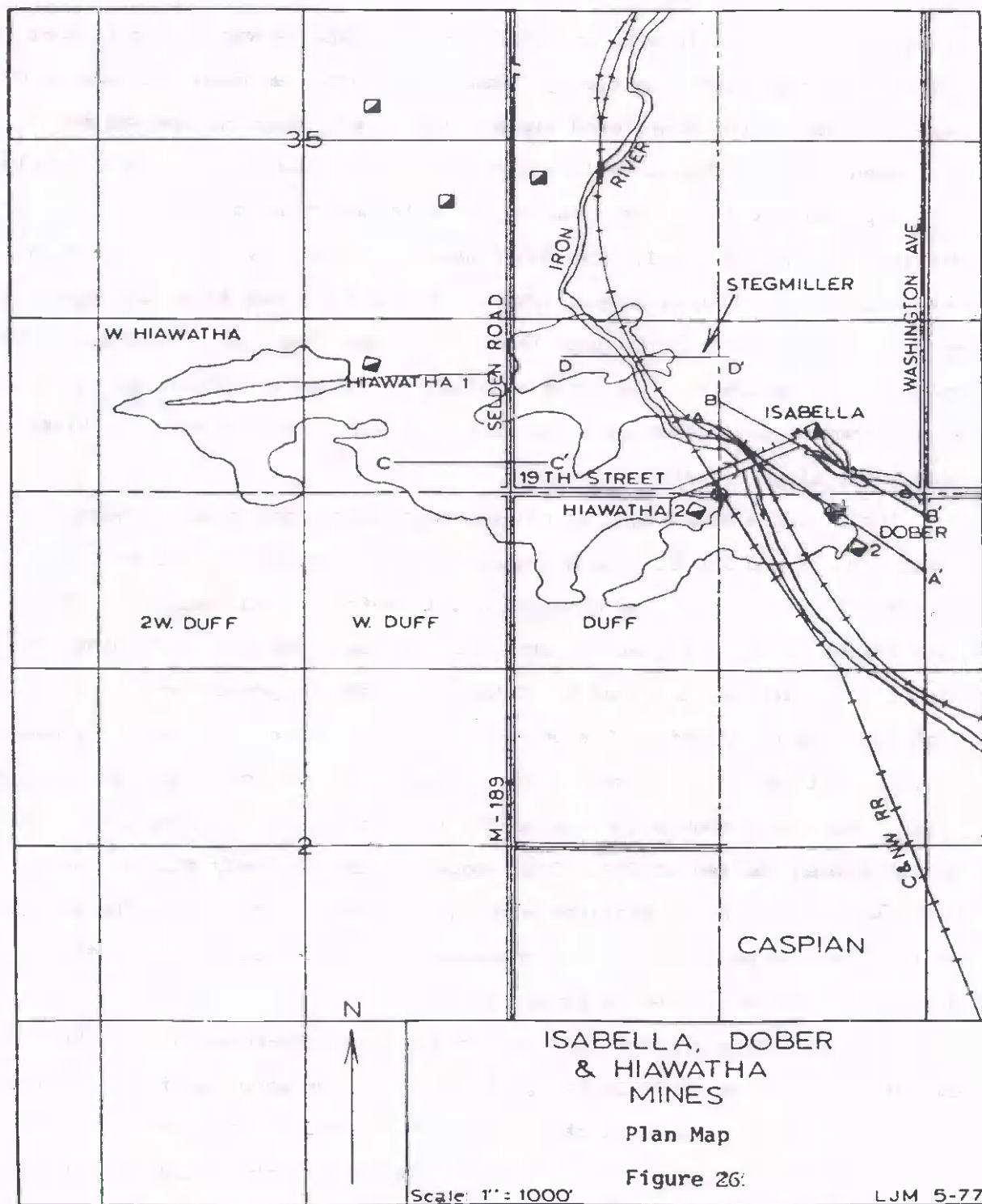
Several miles south of Caspian where the Iron empties into the Brule, their confluence is marked by a noticeable plume of turbid water entering

the Brule River. The Brule River marks the boundry between Michigan and Wisconsin. It is also the northern border of the 650,000 acre Nicolet National Forest. A report issued by Nicolet National Forest personnel documents the pollution by chemical analysis and by low level, colored aerial photography (Hunt, 1974).

Since 1974 the Institute of Mineral Research has been studying acid drainage problems in the Iron River district. Two sources of acid drainage from closed mine properties were identified. The most serious acid drainage was that flowing from the Dober Mine pit which in the late 1970's accounted for more than 75% of the acid drainage into the Iron River, on the basis of dissolved iron. The remainder of the acid drainage issues from extensive piles of pyrite-bearing black slate filling a low marshy area over the Buck group of mines about one mile to the south. These two occurrences provide the case histories for acid drainage. The information has been extracted from reports prepared by Johnson and Frantti (1976, 1978) Cregger (1979) and Johnson (1979).

Acid mine drainage: underground source. The most serious and best documented source of acid drainage in the Iron River district occurs at the Dober Mine. The Dober Mine is part of a larger mine complex consisting also of the Isabella and Hiawatha Mines. The mine complex is situated west of the City of Stambaugh and south of the City of Iron River. It consists of eight, forty-acre parcels identified as the Dober, Isabella, Stegmiller, Hiawatha #2 (formerly Duff), Hiawatha, Hiawatha #1, Hiawatha #1 West and Hiawatha #2 West properties. The Iron River flows in a southerly direction over the Stegmiller, Isabella and Dober properties. Locations of the properties are shown in Figure 26.

History. The Dober and Isabella Mines were two of the earliest iron



mines to open in the Iron River District; the Isabella was opened in 1882 and the Dober in 1888. Initially, both were started as open pits and later were developed into underground mines. The direct shipping ore was mined from open stopes. The Isabella was served by one shaft in the upper levels to a depth of 430 feet. This shallow mine is interconnected with the Dober workings on the 4th level. The Dober Mine was served by two shafts; #1 a vertical shaft, 950 feet deep, north of the open pit and #2 an inclined shaft which descends to the 10th level (1000 feet deep) and is located just south of the open pit. The Dober and Isabella Mines were operated by Oliver Mining Company until 1935 at which time they were combined with the Hiawatha Mine under single ownership.

The Hiawatha Mine began as two separate operations from two vertical shafts, No. 1 and No. 2. The Hiawatha No. 1 was opened in 1893 by the Hiawatha Iron Company. The Hiawatha No. 1 shaft is 2180 feet deep. The Hiawatha No. 2 or Duff shaft as it was first named was put in to mine ore from the western extension of the Dober and Isabella properties below the 10th level by the American Boston Mining Company. The Hiawatha No. 2 shaft is 2500 feet deep. The Hiawatha No. 2 shaft interconnects the Dober Mine at depth. Mine maps show a bulkheaded 8th level drift and an open 10th level drift between the two shafts. Open stopes in the ore body also connected Dober workings with the Hiawatha workings. Levels from the 10th to the 21st of the Hiawatha No. 2 shaft are connected to the Hiawatha No. 1 shaft. Shaft locations are shown in Figure 27.

When the Dober and Isabella operations were incorporated with the Hiawatha No. 2 Mine in 1935, the production records were combined and after 1943 the shipping records of the Hiawatha No. 1 and No. 2 mines were combined. Until closing in 1967 combined shipments totaled 22,162,905 long

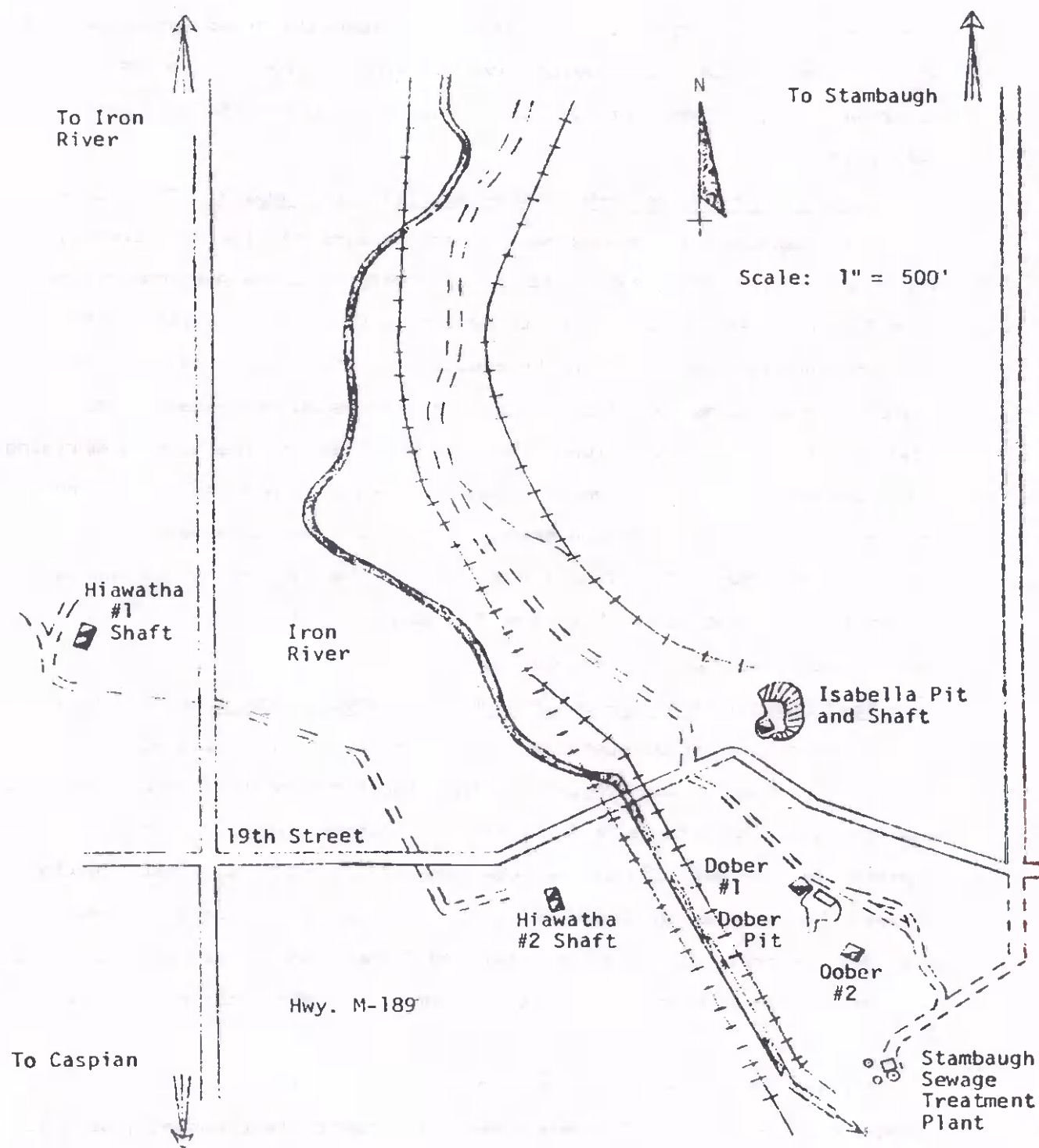


Figure 27. Surface plan map of the Dober-Hiawatha-Isabella Mine Complex

tons. Earlier production from the Dober and Isabella Mines (prior to 1935) had been combined with the nearby Riverton Mine and referred to as the Riverton Group. A total of 5,881,550 tons were reported for the period 1882-1937.

Structure of the Dober-Hiawatha-Isabella mine complex. The Dober-Hiawatha-Isabella Mine complex may perhaps be more readily described by structural than by geographic boundaries; namely as those portions of the iron formation bounded on the north by the North Hiawatha fault, on the south by the Duff fault and on the east by the Stegmiller fault. These faults form a triangular block which incorporates an east-west trending syncline of the iron formation. The iron formation on the north comprising the Hiawatha No. 1 Mine is vertical to overturned with an east-west trend. On the east the iron formation trends north south and dips westerly at an angle of about 60° . This limb was mined from the surface by the Isabella and Dober Mines and at depth by the Hiawatha No. 2 Mine. These relationships are shown in Figure 28.

Acid drainage from the Dober-Hiawatha-Isabella mine complex. In 1966 after nearly 85 years of operation the Dober Mine complex ceased operations. Pumping was stopped and the mine began to fill with water. It was not until some six years later in early October of 1972 that water first appeared in the open pits of the Dober and Isabella mines. Over a period of 45 days the water in the Dober pit rose about 100 feet. Local residents were quite surprised to see the Dober and Isabella Mines flood as they had been dry for as long as anyone could remember — since the mines were open in the 1880's.

The rising acid waters were of more than just idle curiosity. The main sewage line feeding the Stambaugh Sewage Treatment Plant passed just west of

the Dober Mine pit. The acid waters poured into corroded sections of the pipe and acid water entered the plant disrupting the bacteriological sewage digester. The sewage problem was eventually solved by the DNR and the City of Stambaugh by inserting a plastic pipe inside the sewage line. Water in the Dober Mine pit was lowered about two feet by ditching from the pit to the river. The details of this sequence of events have been documented by Van Alstine (1973).

Flooding of the mine complex took six years because neither the Hiawatha No. 1 nor the No. 2 were exceptionally wet mines. Records for 1948 indicate that 230 gallons per minute (gpm) were pumped from the Hiawatha No. 2 and 300 gpm from the Hiawatha No. 1 for a total of 530 gpm. Using these data in conjunction with mine volumes calculated from ore shipping records and stopes filling measurements the time required to flood could have been estimated. Based on measurements made by Cregger (1977) the mine complex has a volume of 281 million cubic feet from ore removed, less a stope filling sand volume of 58 million cubic feet resulting in a total of 223 million cubic feet. The calculation of the time to flood is:

$$\text{Time to Flood} = \frac{223 \times 10^6 \text{ FT}^3 \times 7.48 \text{ GAL/FT}}{530 \text{ GAL/MIN} \times 60 \text{ MIN/HR} \times 24 \text{ HR/DAY} \times 365 \text{ DAYS/YR}} = 6.0 \text{ YEARS}$$

This simple calculation could have been made to predict the time of flooding. Of course, no one had anticipated at the time that water, especially acid water, would flow from the Dober Mine into the Iron River.

Flow rates of acid drainage from the Dober Mine measured since 1975 have varied from a low of about 30 gpm to highs in excess of 100 gpm. During 1978 the flow rate ranged from 39 to 90 gpm with an average of 67 gpm.

Chemical characterization of Dober Mine acid drainage. Acid drainage from the Dober Mine pit was periodically sampled during the period 1975 to

1978. Chemical analyses for iron, manganese, aluminum and sulfate were routinely performed. In addition, temperature, pH, specific conductance and acidities were measured. Results of these analyses are shown in Table 4. Average values of water quality measurements in 1975 were: pH = 4.1, acidity = 2900 mg/l CaCO_3 , specific conductance = 5000 mhos/cm, iron = 1125 mg/l, manganese = 121 mg/l and sulfate = 5130 mg/l. In 1975 drainage from the Dober Mine accounted for nearly 90% of the total amount of iron entering the Iron River from all mine drainages in the District. For the study period, 1975 through 1977, the Dober Mine drained an average of 654 pounds of iron per day into the Iron River, of 71% of the total amount entering the river from all sources.

Model for acid drainage from the Dober Mine complex. Simply stated, the model for acid drainage from the Dober Mine pit is one of recharging surface waters entering the mine complex above the Hiawatha workings on the west side of the Iron River to force acid waters through the interconnected mine workings into the Dober "leg" of the mine via a 10th level drift connecting the workings. Sufficient head exists in the Hiawatha workings to cause a flow of acid water from the Dober Mine into the Iron River. Flow occurs because of recharge and because the Dober Mine pit lies at a lower elevation in the Iron River Valley. These relationships are shown schematically in Figure 29.

Measurements of the acid flow from the Dober Mine pit during the period 1975 to 1978 ranged from a low of about 25 gpm in the drought winter of 1976-77 to highs of about 150 gpm during spring runoff. The response of flow to precipitation is well established.

Prospects for long term acid drainage from the Dober complex. When the Dober-Hiawatha-Isabella Mine closed in 1967 the workings were

TABLE IV
AVERAGE OF YEARLY ANALYSES OF DOBER MINE ACID DRAINAGE
1975-1978

YEAR	Fe mg/l	Mn mg/l	Al mg/l	SO ₄ mg/l	pH	Spec. Cond. μmhos/cm	Acidity ppm CaCO ₃ /l
1975	1125	121	114	5130	4.1	4990	2900
1976	1290	90	279	5450	3.7	4910	3500
1977*	707	59	157	3320	2.4	2180	1370
1978	1280	80	123	5930	---	---	3680

* NOTE: Low 1977 values are due to dilution of surface waters in the Dober pit by runoff and flooding by the Iron River.

DOBER-HIAWATHA MINES : LOOKING NORTH

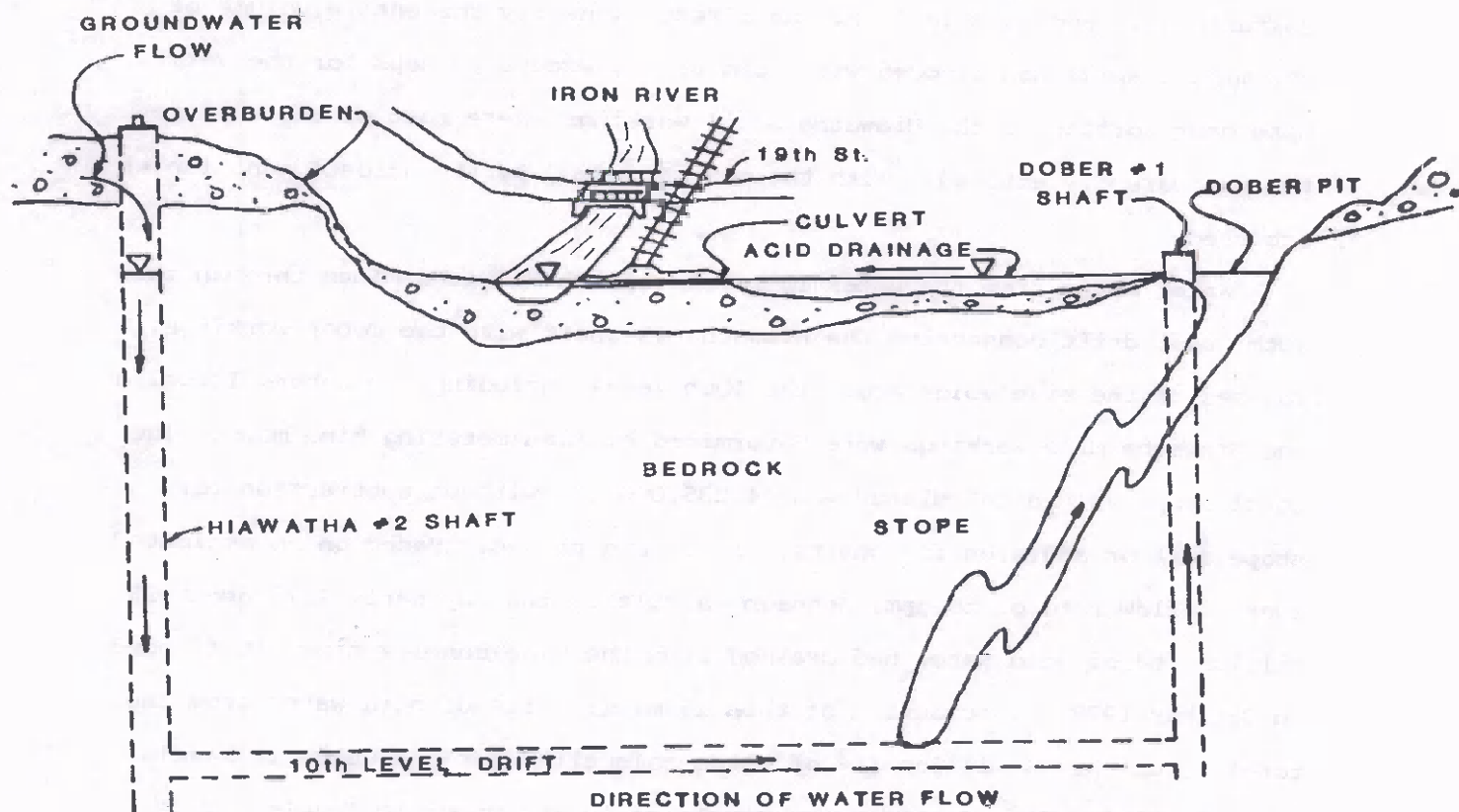


Figure 29. Schematic Diagram Showing Flow of Water in the Dober Mine Complex

dry. Following closure the mine complex was allowed to flood. Prior to flooding, oxygen and water reacted with pyrite-bearing slates wherever they were exposed in the hanging and footwall and in caved stopes, forming soluble ferrous sulfate compounds. These compounds dissolve readily to form sulfuric acid and soluble iron. As a result, nearly the entire volume of the mine complex was flooded with acid water, except perhaps for the very uppermost portion of the Hiawatha No. 1 workings where most of the surface water apparently entered. With the mine flooded, pyrite oxidation no longer occurred.

Water moves from the upper 10 levels of the Hiawatha Mines through the 10th level drift connecting the Hiawatha #2 shaft with the Dober workings. Volumes of the mine voids above the 10th level including the Dober, Isabella and Hiawatha Mine workings were determined by planimetering mine maps. The total stope volume calculated was 44,235,000 ft³ without subtraction for stope fill or addition for shafts, drifts and raises. Based on an estimated average flow rate of 50 gpm, Johnson calculated that by early 1979 about 25 million ft³ of acid water had drained from the mine complex since it flooded in October 1972. Subtraction of this 25 million ft³ of acid water from the total volume of 44 million ft³ of voids calculated for the upper 10 levels left 19 million ft³ of acid water remaining in the upper 10 levels. This simplified calculation indicated that 57 percent of the acid water in the upper 10 levels had been replaced with surface water. If drainage continued at this average rate (50 gpm), about 5 1/2 years would have been required to flush the acid from the upper ten levels of the mine. However, this was not possible as mixing of fresh waters with the denser acid waters would occur and greatly lengthen the time required to expel the remaining acid from the mine complex.

Field evidence also suggested that acid waters were gradually being expelled from the mine complex. It was logical to assume that as the recharging groundwater mixed with acid water that the head differential between the free water surface in the various mines of the complex would equilibrate. Except for slight differences due to recharge and frictional losses, the fresh water surface would eventually lie at the same elevation throughout the mine complex. Comparison of water level measurements taken in the mine complex since 1976 indicates that this equalization process is well underway.

These observations and calculations indicate, as acid water in the upper 10 levels is replaced with fresh water, that acid water drainage from the Dober-Hiawatha-Isabella Mine complex will eventually cease to be a problem. However, a very large amount of acid water remains in the mine complex below the 10th level. If blockage occurs on the 10th level interconnection between the Hiawatha and Dober workings or on interconnections between the Hiawatha #1 workings and the Hiawatha #2 shaft very serious acid drainage could continue for many years. These blockages could result from rock caving in the drifts or possibly from the formation of "yellow boy" dams in drifts connecting the mines. This latter phenomena was observed in the Sherwood Mine during its operation ¹. Acid waters flowing in a drift gradually built up a series of "yellow boy" deltas in a terrace or step-like fashion until the drift was completely blocked. Although this damming effect occurred below an air-water interface it may be possible that the damming could occur at the interface between oxygen-bearing "surface" waters and lower acid waters on the 10th level interconnections at the time that the upper levels of the mine complex

¹ Personal communication with Robert Edwards, former Superintendent of the Sherwood Mine, Iron River, Michigan.

are flushed of acid water. This would cause the water to flow through the next lower interconnection, expelling more acid water. The process could conceivably continue until the entire mine was purged of acid. Based on mine volume calculations and the present flow rate, severe acid drainage could last for 55 years; e.g.,

Total volume of mine complex	= 223 million ft ³
Volume of acid drained in 7 years	= 25 million ft ³
Volume of acid remaining	<u>198 million ft³</u>

...at the rate of 25 million ft³ drained in 7 years, 198 million ft³ would require 55 years to drain.

Actually, if the above conditions were met, acid drainage would persist for a period greater than 55 years, as the acid waters would continually mix with fresher waters resulting in some dilution and a greatly extended period of acid flow.

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