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THE DEVELOPMENT OF GUIDELINES FOR CLOSING UNDERGROUND MINES: MICHIGAN CASE HISTORIES

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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. For since the start of mining in the early 1880's the district has 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-agriculatural society through the industrial revolution and into the beginnings of the computer and space age.

There are many lessons that can be learned from such a rich history. This report attempts to provide such a lesson. Through the use of case histories, deficiencies in past mining practices and mine closure procedures that have resulted in current mine related problems are documented. These problems can be grouped into three areas; 1) subsidence 2) hydrological or 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 a human life was lost because of sudden subsidence of a section of county road into a shallow stope of an old mining operation. Many mines encountered acid waters during their operation and several continued to drain acid water when they became flooded. The acid flows 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 are no known occurrences of human fatalities resulting from falls into mine shafts in Iron County. However, the presence of hundreds of shafts, some with deteriorating or inadequate protection in the form of seals or caps is also a cause for concern.

These three basic problems were investigated by the use of case histories. 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 or their effects lessened by action taken prior to mine closure, and 3) to recommend these ideas as guidelines in mine closing procedures.

RECOMMENDATIONS

Prologue

This work has addressed technical problems resulting from past mining activity. As a result, the recommendations are largely of a technical nature. However, it is recognized that technological solutions alone cannot provide answers to all of the problems facing the mining industry and resulting from mining. This is true because the problem is not simply the impact the mining has upon the land, but rather what the public perception of this impact is and their willingness or unwillingness to accept it.

The production of minerals is absolutely essential to our society. The United States must maintain a viable mining industry if it is to remain a world power. Moreover, the minerals must be produced in abundance and cheaply if Americans are to continue to enjoy the high standard of living which has been attained during the latter half of this century. Most Americans do not realize how the health and vigor of the mineral industry relates to their well being and many are critical of the impacts created by mining.

Mining, more than any other natural resource industry, creates the most severe visual impact on the land. This cannot change. This is true because the extraction of minerals disturbs the land and the impact is visible and real. Certain steps can be taken to reduce this impact, but the reduction or lessening cannot be done at an excessive cost without paying other penalties. The public must be made aware of these problems and must learn to accept some of these impacts in return for a certain standard of living.

By the same token, it is incumbent upon the mining industry to reduce the impact of mining on the environment as much as is technically and economically possible and prudent. For even if the public were willing to accept great environmental disturbance for immediate material gains, the long term effects would be costly and unacceptable.

Consequently, in addition to the technical solutions resulting from this work, other efforts are required. They include education of the public, a willingness on the part of the mining industry to attempt changes that offer promise of reduced environmental impact and a governmental attitude that recognizes the need and importance of a viable mineral industry while endeavoring to protect the environment.

Specific or Technical Recommendations

A number of steps or actions can be taken at the time of mine closure that can reduce or eliminate problems that may arise from the presence of the mine. Many problems have arisen in the past because little emphasis was placed on planning for mine closure. The actual closure process was often left for a maintainance crew and there was little incentive to place much effort into this work because it was nonproductive in the sense that it represented an expenditure and not a profit. However, with the realization that inattention to some of the details of adequate mine closure can result in a direct liability to the mine operator greater than the cost of a more effective closure, and also that the indirect and long lasting liability to the mining industry in general from a public that perceives an industry with a lack of concern for the environment.

Consequently, it is prudent to assign the closure tasks to a competent engineer —— one who understands all of the realms that make up the environment of the closed mine. This would include such disciplines as mine hydrology, overburden and soil mechanics, the geochemistry of tailings and waste rock and surface hydrology.

This engineer should gather the mine maps and data relative to subsidence potential and mine flooding and drainage. This material should be carefully reviewed. The mine maps should be compiled so that a complete up-to-date file of plan, cross-and longitudinal section maps are available in one place. A composite map should be provided that shows the workings projected to the surface (i.e., the limits of mining activity). These maps should also show all openings to the surface including shafts, raises, boreholes, and any shear zones or subsided area. Text should accompany the maps to explain the condition and physical characteristics of these openings, especially on how they were sealed, or not sealed. If the mine has connections with other mines, they should be shown on the maps and described in the text. Areas where subsidence has occurred or where rock conditions suggest that it may occur should be described along with any available supporting information.

The mine maps should be studied in detail to determine if drainage, and particularly mineralized drainage, may occur when the mine is flooded. The time required for the mine to flood should be calculated. This can be done by using the average pumping rate as an average flooding rate and using the production and grade data to calculate a volume. The spill point from the flooded mine should be determined. This will usually be a shaft or other surface opening collared at the lowest elevation and which has a natural (downhill) drainage course. If mineralized waters are present in the mine or if drainage could result in any forseen problems, alterations to the "plumbing system" of the mine should be considered as the best means to prevent or reduce the volume of drainage. This might be achieved by installing seals or bulkheads in the mine to break the hydraulic continuity. Additional drifting or drilling of holes might also be considered as a means to divert the recharging ground and surface waters so they will not become contaminated by mineralized mine water.

A careful analysis should be made to determine if any subsidence activity may occur during the period of mine flooding. If subsidence appears possible and would be undesireable, steps may be taken to avert or lessen this occurrence. One possibility is to flood the mine in a controlled manner by pumping water into the mine. On the other hand, any subsidence likely to occur during the flooding of the mine could be enhanced through ground preparation and by controlling the location of water inflow. Piping subsidence, for example, could be enhanced if the proper physical conditions are present at the mine site. This flooding induced backfilling method could be used to add stability to the mine opening.

Forced subsidence by blasting-induced pillar failure could also be considered.

Care should be used in the design and installation of permanent shaft seals and caps. Assuming that the closure is permanent, steel reinforced concrete seals should be installed in sound rock below the bedrock surface. The shaft above this should be backfilled to the surface with a suitable compacted fill material and a permanent concrete cap put in place on the surface. A vent pipe of sufficient diameter for sampling and water level measurements should be provided through both seals and the fill. If there is any liklihood of subsidence occurring after the mine is flooded, one or more large diameter vents may be useful to allow water moved by the resulting hydraulic forces to be vented.

The cap should have permanent markings to identify the shaft. Fencing is also a good idea and several permanent survey points should be placed nearby so the shaft can be accurately located should any shaft subsidence occur.

If the shaft penetrated unsound ground, backfilling instead of sealing may be the best option to employ. The design employed must guard against run out of material into drifts and crosscuts and impermeable seals may be needed to prevent the interchange of surface and mine water. The details of the mine shaft sealing procedures should be documented along with engineering drawings of the details of installation. This information should be combined with the mine maps into a single report.

Finally, it is recommended that mine closure planning not by left until just before the mine is to close. Closure plans should be an integral part of the mining operation from mine planning through mine operation.

SUMMARY AND CONCLUSIONS

Past deficiencies in underground mine closures that have resulted in current problems are illustrated by the use of selected case histories. The mining district from which the case histories were selected are in the West Menominee Range of northern Michigan. The mines in the district which operated during the period of 1882-1978 produced a direct shipping non-magnetic iron ore. The approximately 100 mines in the district are characterized mainly by underground operations that extracted ore from vertical to steeply dipping tabular ore bodies using either caving, but more often, stoping methods. Pyrite in close contact with the ore in the western end of the district created acid water problems for many of the mines when they operated. Abundant groundwater in the thick glacial overburden was also a problem in mining.

Three types of problems related to the mines are currently of concern: 1) mine subsidence 2) acid water drainage and 3) deficiencies in mine shaft protection. Several subcategories were made under each of these major topics and case histories were provided to document and illustrate each type of the subdivisions.

The subsidence heading was subdivided into short term and long term subsidence. Short term subsidence included the time span from mine shut down through mine flooding and long term subsidence had no limit on time.

Short term subsidence case histories were used to illustrate the effects that water flooding can have on an underground mine including: 1) rock mass failure due to movement on a pre-existing slip plane from gravity loading and friction reduction by inflowing water 2) broad surface subsidence accompanying the rock mass movement 3) washing of sand into the mine through pre-existing surface subsidence pits with resulting massive shear failure of sand fill in the pit 4) piping activity which forms hemispherical cavities in overburden above the bedrock as a result of groundwater transport of sands into the mine voids and 5) hydraulic forces generated in a flooded mine complex, triggered by subsidence, which may initiate secondary subsidence and disrupt shaft seals and cappings. It is concluded that occurrences of this type could be reduced by exerting some control on mine flooding. For example, if the mine was flooded from the lower levels up in effect by reversing the pumps, many of the above mechanisms would not become active and these types of short term subsidence would not occur. However, the added degree of stability that these subsidence adjustments impart to the overall mine structure may be desireable. Conversely, then it would be possible to enhance and induce these adjustments by controlling or directing the water inflow. Ground preparation involving drilling and blasting could provide this control and enhance the mechanisms by channeling the water/sediment flow into the desired area of the mine. In essence, a controlled flooding of sand and water into the mine voids is similar to hydraulic backfilling processes. Performing this backfilling conjunction with mine flooding could be an advantage.

Long term subsidence occurs as the result of progressive failure in the roof pillars of stopes that causes the opening to move towards the bedrock surface. Sloughing, the slow spalling of fractured rock by gravity and other stresses, chemical alteration and seismic energy absorption are most often responsible for this type of subsidence. Because so many variables influence its occurrence the timing of the subsidence cannot be determined without monitoring.

In the Iron River district, subsidence at property boundries was common. Unless the owners on each side of the boundry coordinated their mining plans, these pillars were probably thinner than most. In some of the earlier workings mining often went right to the property boundry (and in some cases, beyond).

Aside from backfilling mine stopes, or daylighting (caving the mine) there can be no real prevention of eventual mine subsidence. The problem is one that must be lived with and factored into long range development plans. Development should not be allowed over areas with subsidence potential where, if the surface subsided, that high cost damage would occur or that a significant risk of life is possible. These lands should be held in single ownership either by the mining company or by government that recognizes this responsibility.

Accurate mine maps and data relevant to subsidence potential should be prepared as a single document at the time of mine closure by the mining companies. This information should be made available to responsible user groups with the guarantee that it cannot be used as the basis for any future liability.

Case histories were used to illustrate acid drainage problems originating from both underground and surface sources. Acid drainage from underground mines was observed to occur when a significant difference in elevation existed between the recharge areas and the spill point (the mine opening from which the water would flow). In all cases it was observed that flow issued from a mine shaft collared at lower elevation in a river valley that was part of a larger mine complex. The mines of a complex were often developed independently and physically connected at a later date. Deep interconnections between the mine are responsible for the large volumes of acid that must drain until the upper levels are flushed of acid.

It is concluded that a preclosure evaluation of mine hydrology can determine if mineralized drainage will occur, how severe it might be and what preventive steps are possible. Changes to the "plumbing system" of the mine, including the installation of seals or bulkheads and/or providing supplementary water flow routes by drifting or drilling, are suggested as possible methods to lessen or prevent acid or other mineralized drainage.

Acid drainage from surface piles of pyritic slate exists at one mine complex in the Iron River district. Surface waters and near-surface groundwaters become acid as they pass through the slate. Treatment by neutralization and precipitation of metal compounds in holding ponds is probably the best solution to this persistent problem. This occurrence is recognized largely as a historic problem as acid generating waste rock could no longer be placed in a flood plain and the effluents allowed to drain into surface waters. However, this type of problem will continue to receive much attention because it is so common.

Deficiencies in mine shaft cappings were grouped into three separate areas; 1) inadequacies resulting from the use of unsuitable materials 2) problems resulting from poor design and 3) problems resulting from unexpected occurrences. In the first category, problems have resulted from the use of unsuitable materials to cap mine shafts. Wood planks and timber covered shafts, sometimes earth-covered, rot and collapse in a relatively short period of time because of the moist climatic conditions in Michigan. Steel plates may last longer than wood but will eventually rust away. Neither of these materials should be used for constructing permanent mine shaft caps, although they are both suitable for temporary protection.

Several case histories were presented which illustrate problems with the design of the cappings. In these cases, well constructed reinforced concrete caps had been placed over the shaft collar. Through time, the portion of the shaft liner through overburden had failed causing the unconsolidated ground to cave into the shaft and undermine the caps. This problem can be avoided by installing steel-reinforced concrete seals in the shaft below the bedrock surface, backfilling to the surface and capping the shaft area. A vent pipe should also be provided to allow pressure equilibration and to permit water level monitoring and sampling. Fencing and surveyed monuments should also be provided so the area will always be recognized as a shaft location and can be relocated easily by survey if the surface presence of the shaft becomes obscured over time.

The category of unexpected problems originated as a result of the case histories of shaft capping and sealing failures resulting from water surges in flooded mines. The water surges may be triggered by subsidence elsewhere in the mine or mine complex. The transmitted hydraulic forces cause water to surge through the "plumbing system" of the mine and to disrupt shaft caps and seals.

Disruption of this type can usually be designed against by installing sound shaft seals as previously described and by providing a vent pipe of sufficiently large diameter for pressure release. Backfilling of the shafts may also be done if it is anticipated that hydraulic surges may be a problem.

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, varing 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.

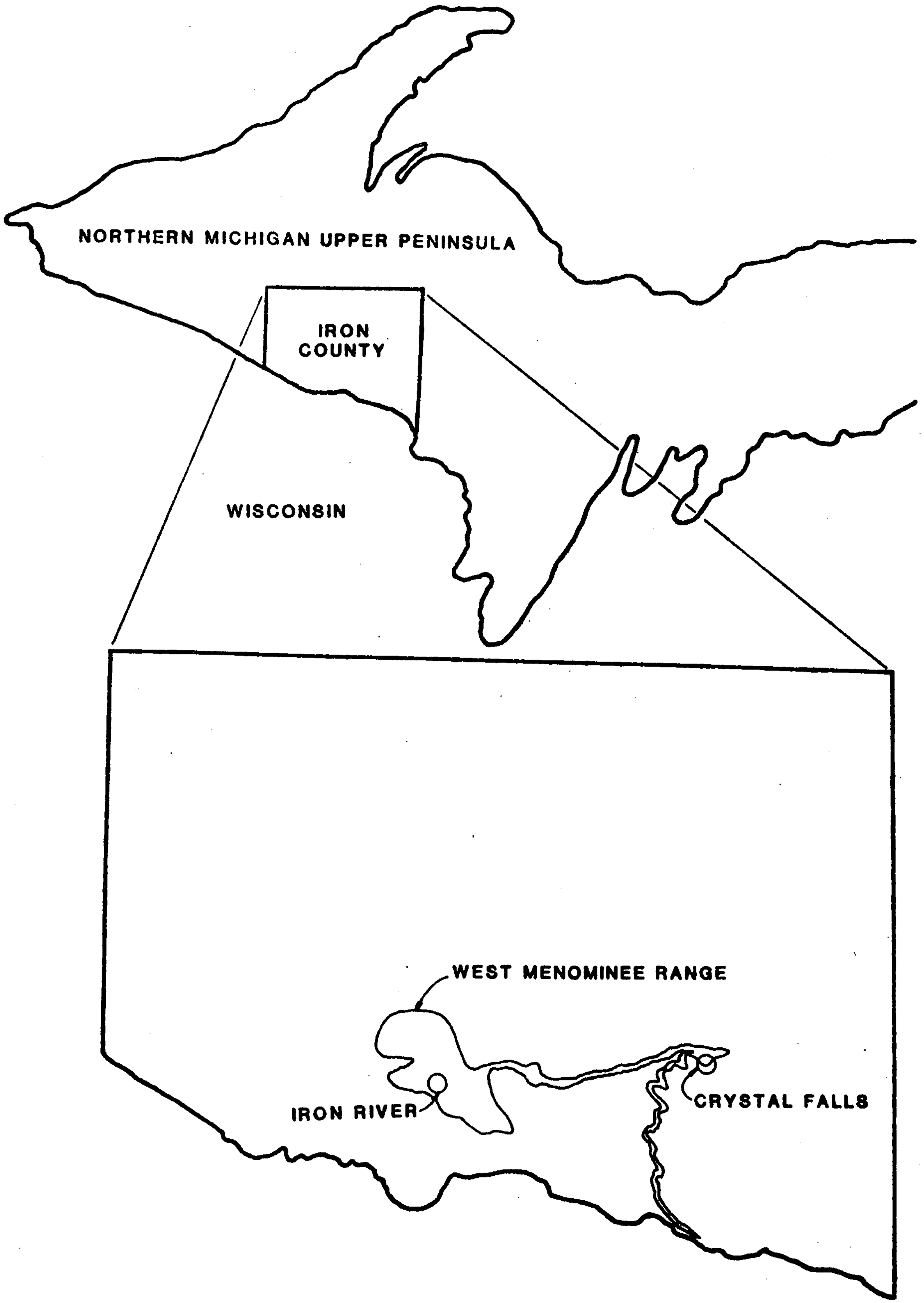


Figure 1. Location of the Cities of Crystal Falls and Iron River on the Menominee Range in Iron County, Michigan

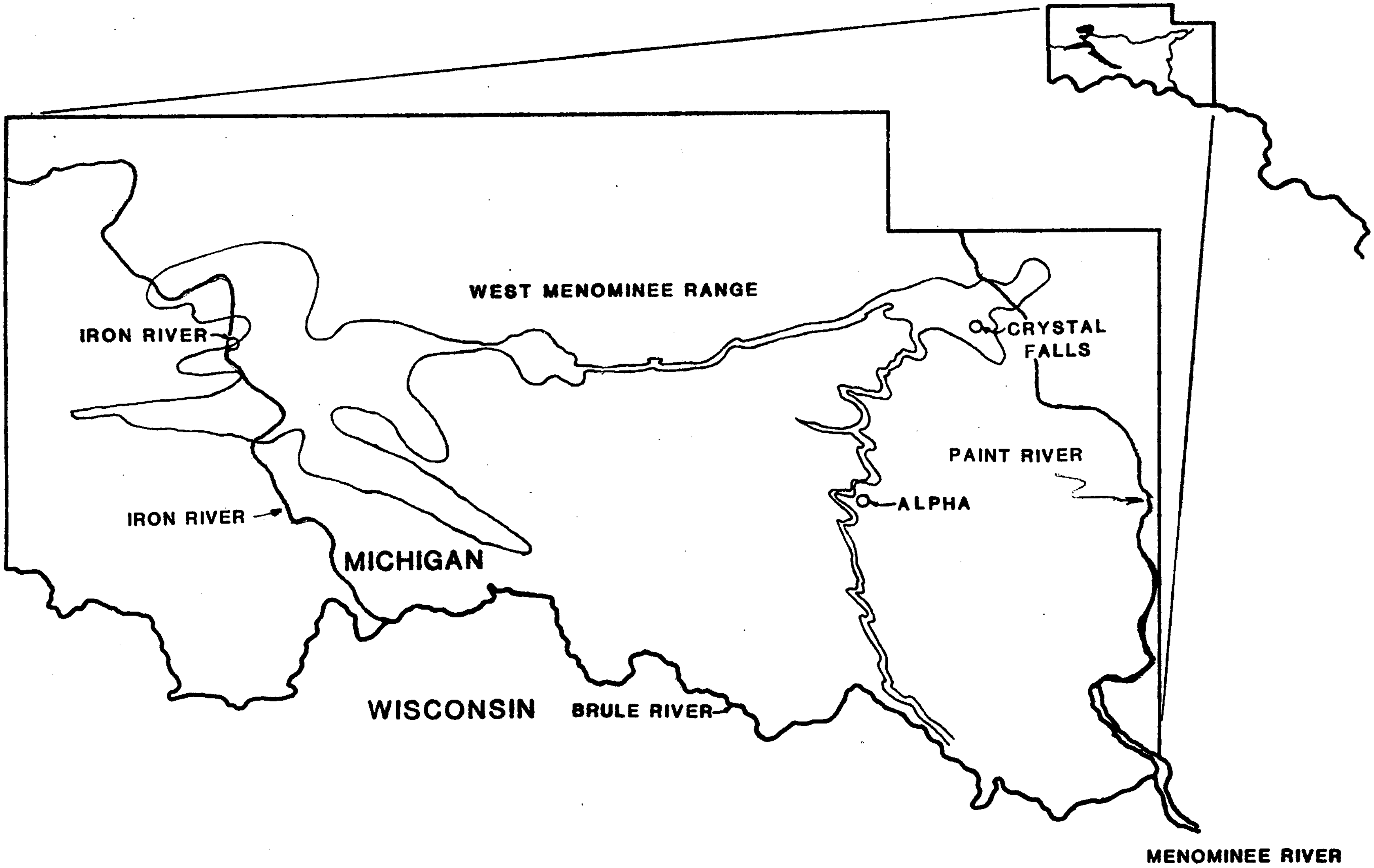


Figure 2. Drainage from the West Menominee Range

Geology

The west Menominee Range is comprised of a series of complexly folded sedimentary rocks of Middle Precambrain 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.
				Unconformity	
Ordovician			Sandstone, dolomite	0–100	Flat-lying remnants of sandstone and dolomite in the southwestern part of the area.
				Unconformity	
Upper Precambrian			Silica rock	0–200	Massive cherty rock that probably represents silicified erosion surface on dolomite.
				Unconformity	
	Keweenawan Series		Diabase		Rare dikes. Unaltered; magnetic and inversely polarized.
Middle Precambrian			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.
	Animikie Series	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.
			Hiawatha Graywacke	0–500	Massive graywacke, commonly sideritic, and gray slate. Lowermost part commonly contains abundant chert fragments.
				Minor unconformity	
			Riverton Iron-Formation	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 (Wauseca 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 more highly metamorphosed equivalents. Probably contains some ferruginous beds in uppermost part.
			Amasa 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.
		Chocolay 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, <u>et</u> <u>al</u>., p.17, 1968

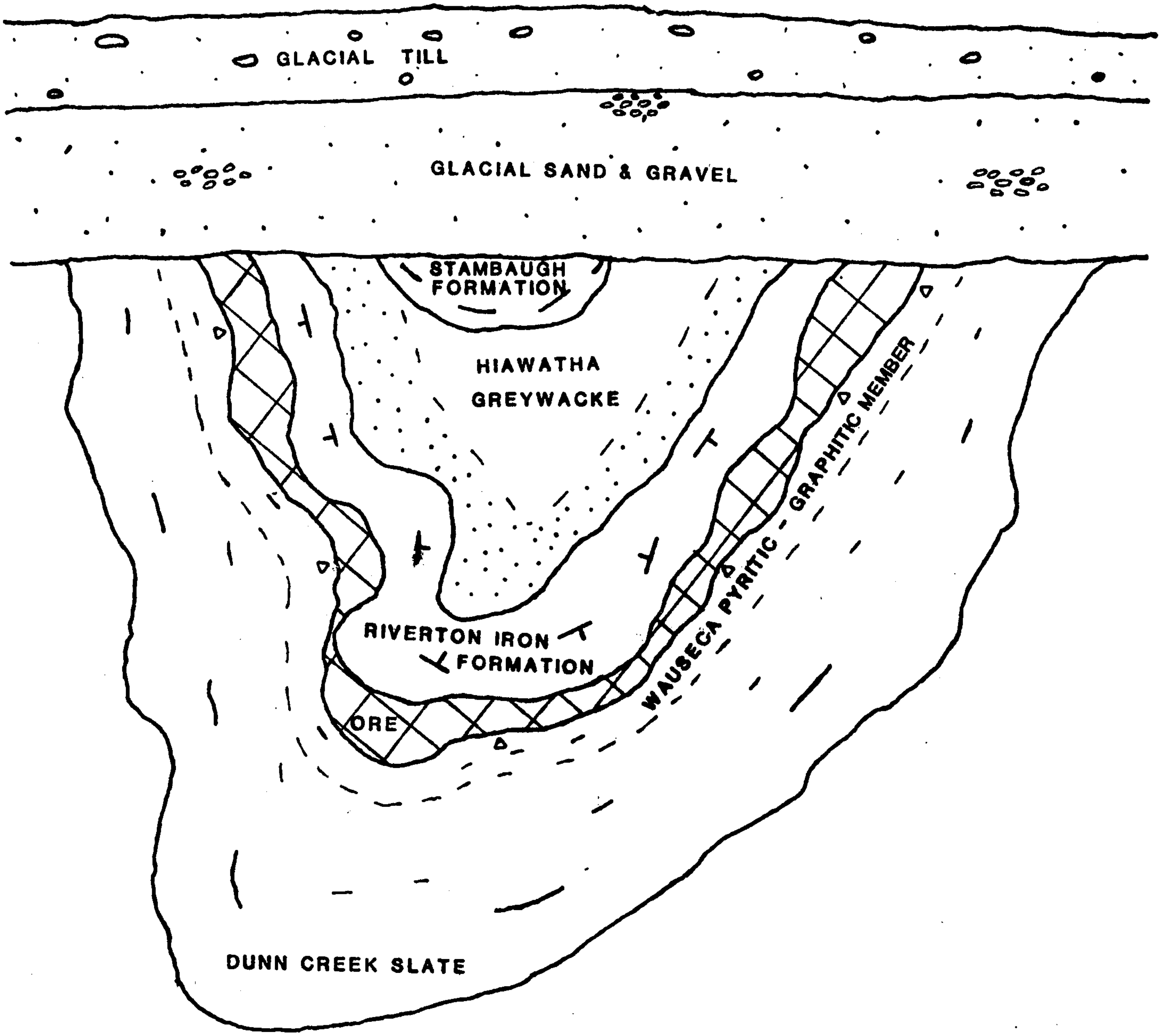


Figure 3. Generalized Geologic Relationships of the Folded Paint River Group Formations in the Iron River District

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,

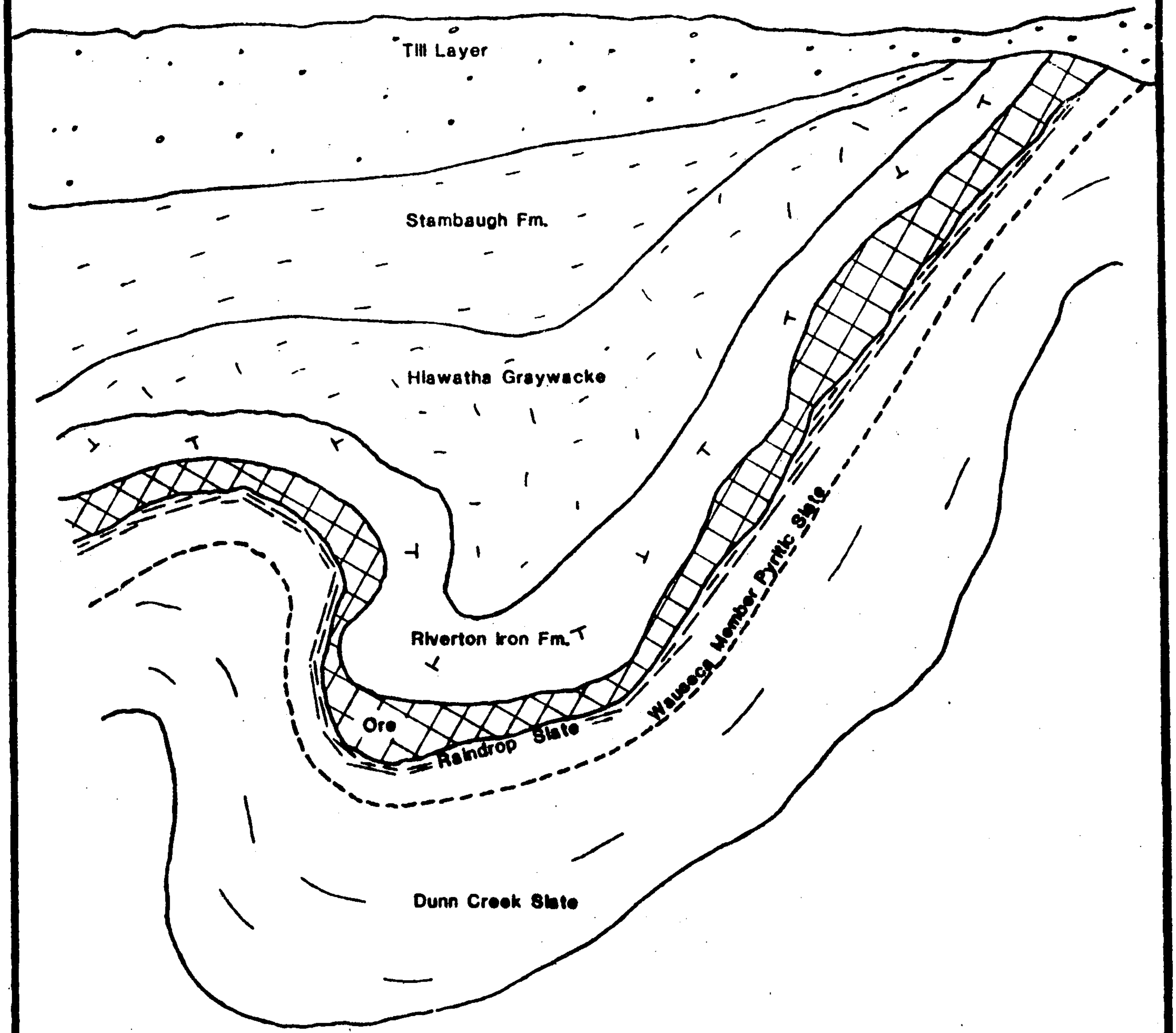


Figure 4. Stratigraphic geologic relationship in the Crystal Falls district.

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.

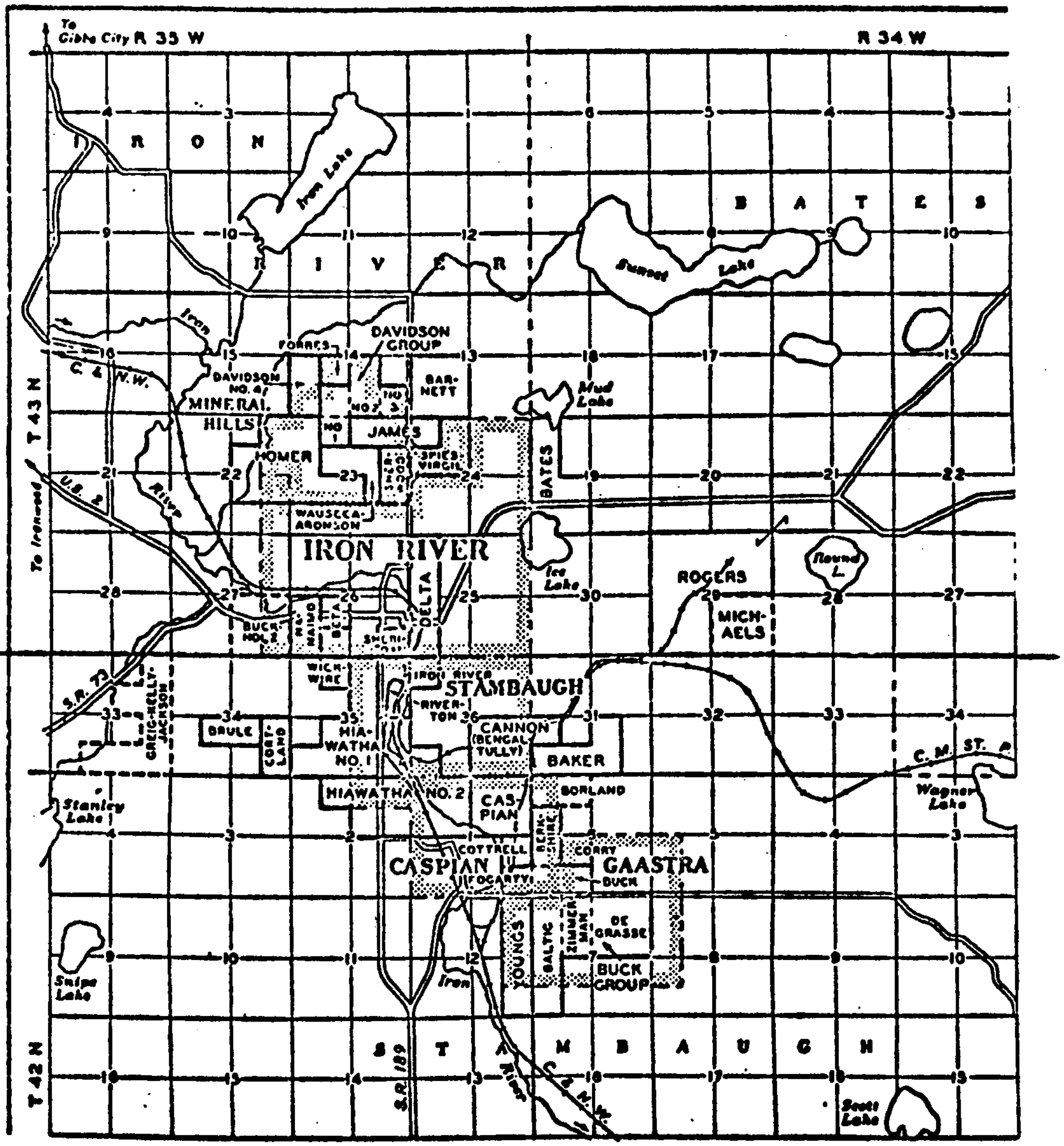
Underground mining methods. The vertical to near vertical and tabular shape of the ore bodies on the Menominee Range dictated the underground mining methods that were used in the district. The most common methods included top slicing, block caving, sublevel caving and sublevel and other stoping methods. The caving methods were used only where the ore was amenable to a caving operation. Stoping 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

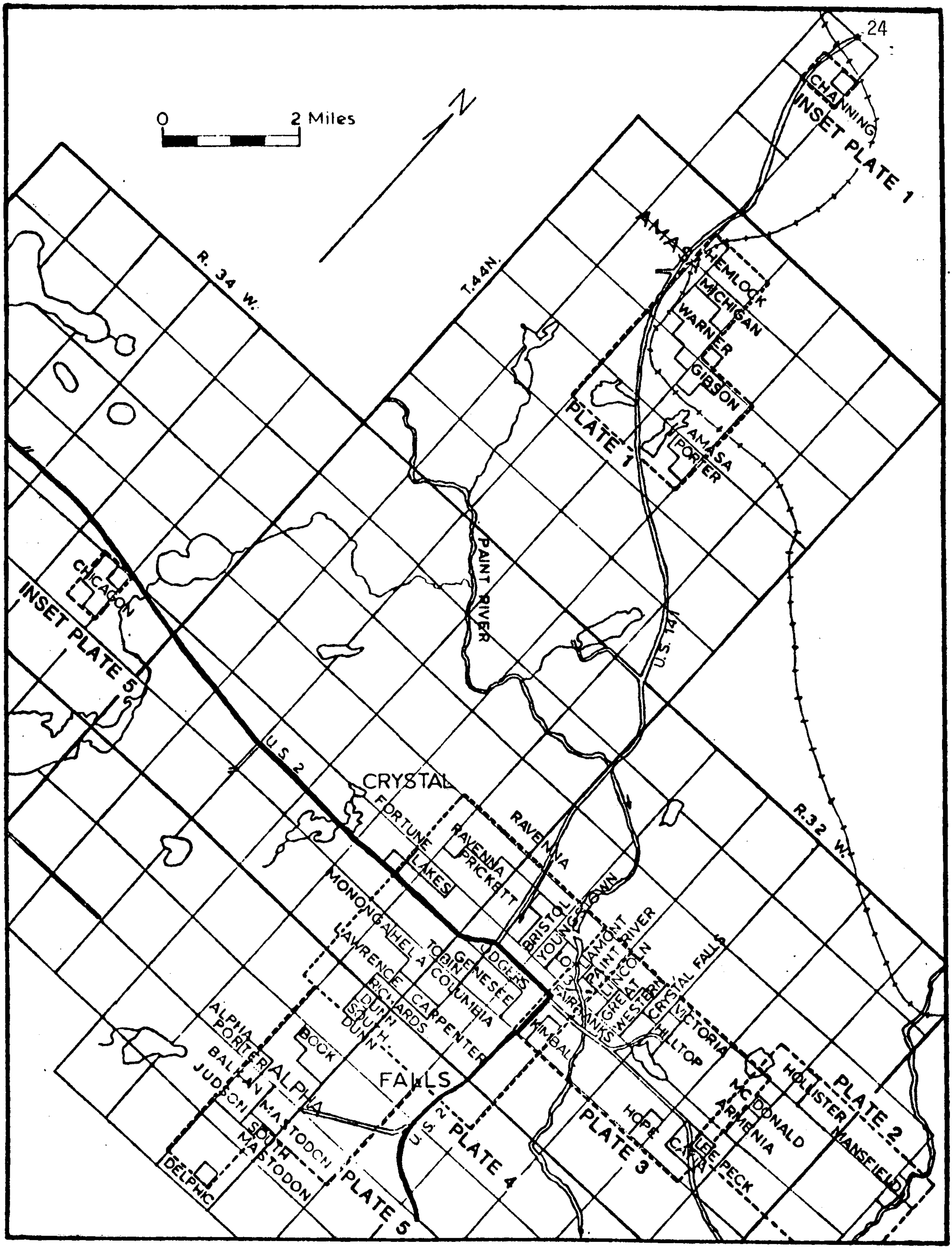


Figure 6. Mine and map plate locations in the Crystal Falls district, Menominee Iron Range.

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., studing 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
Chicagon	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	

Source: Reed (1975)

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
Cayia	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	3,417,030	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 or 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

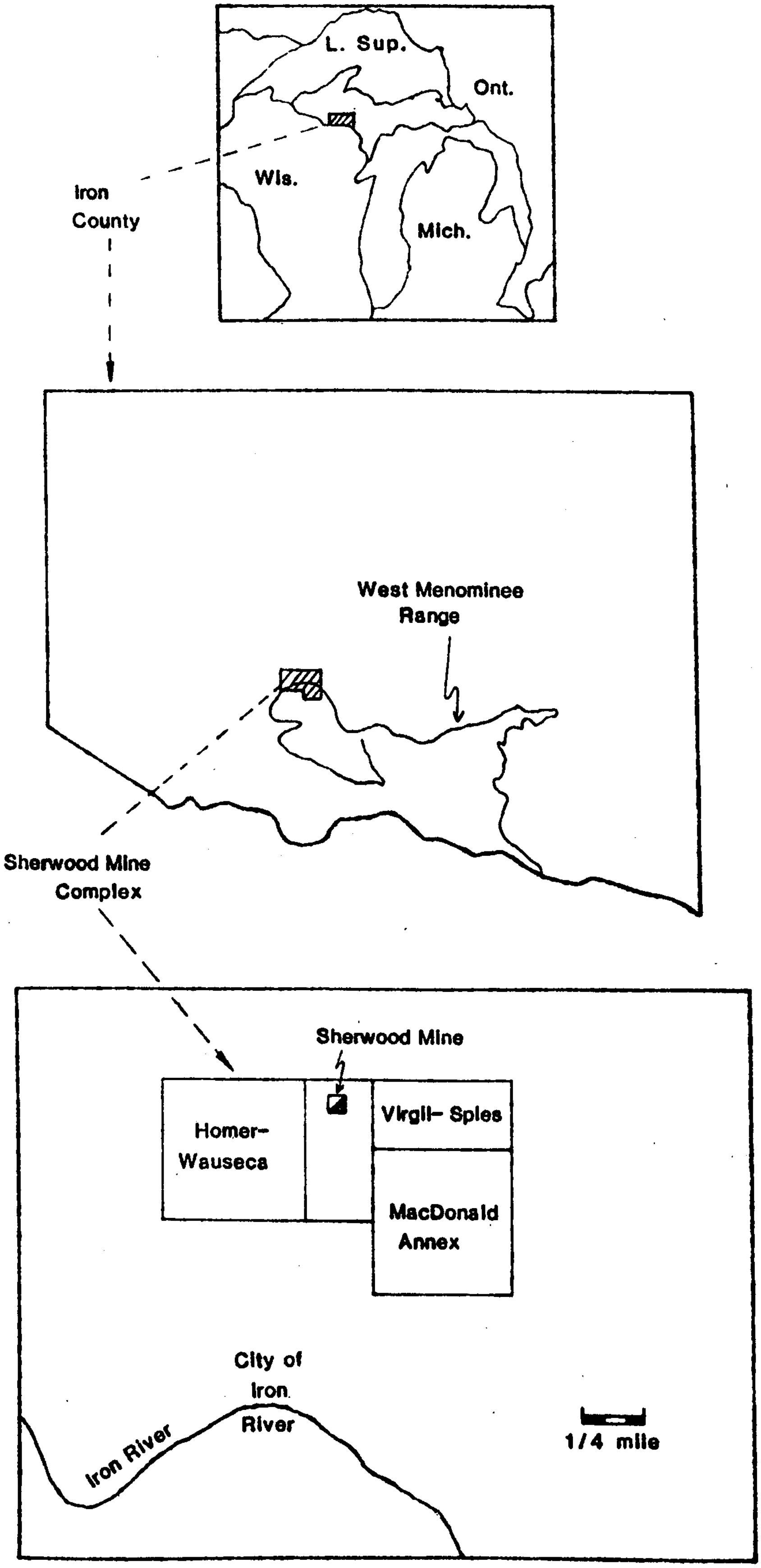
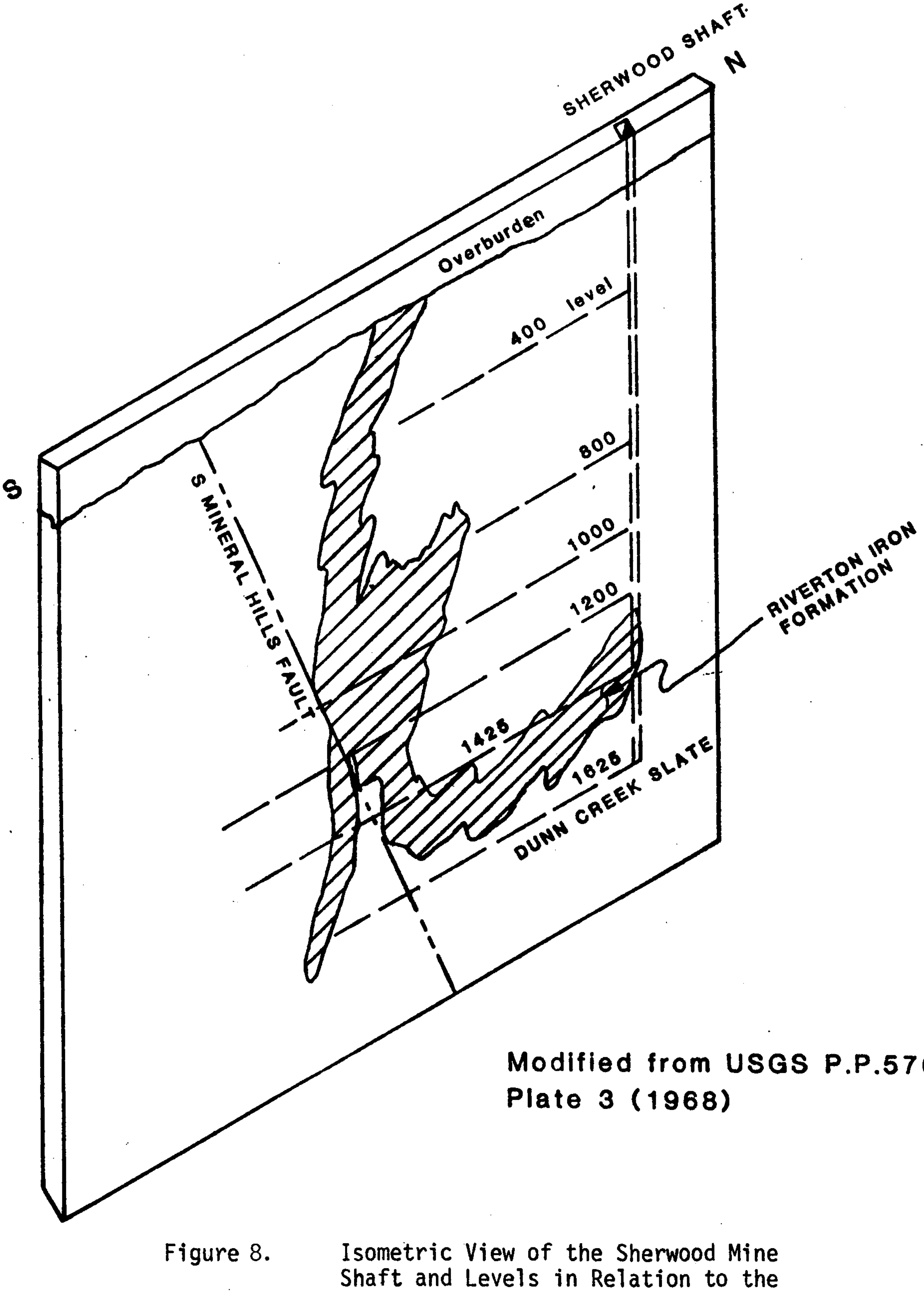


Figure 7. Location of the Sherwood Mine Complex in the Iron River District of Northern Michigan



Modified from USGS P.P.570
Plate 3 (1968)

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

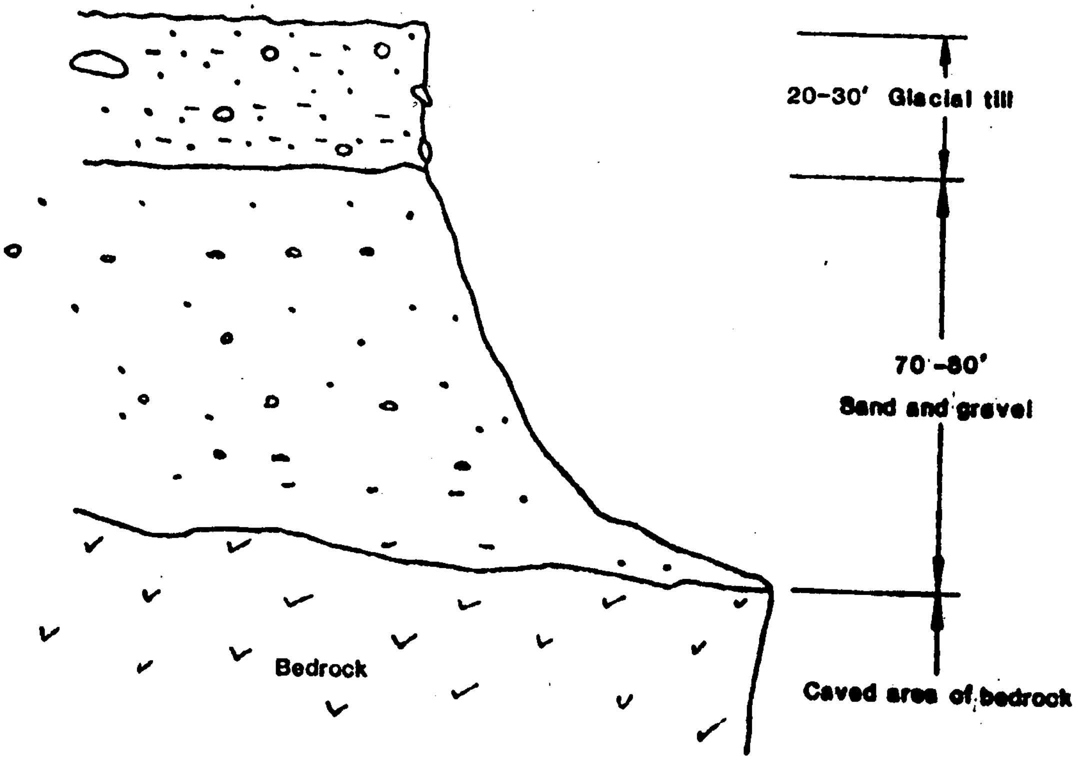


Figure 9. Generalized Profile of Glacial Overburden at the Sherwood Mine in the East Pit

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^{0} 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

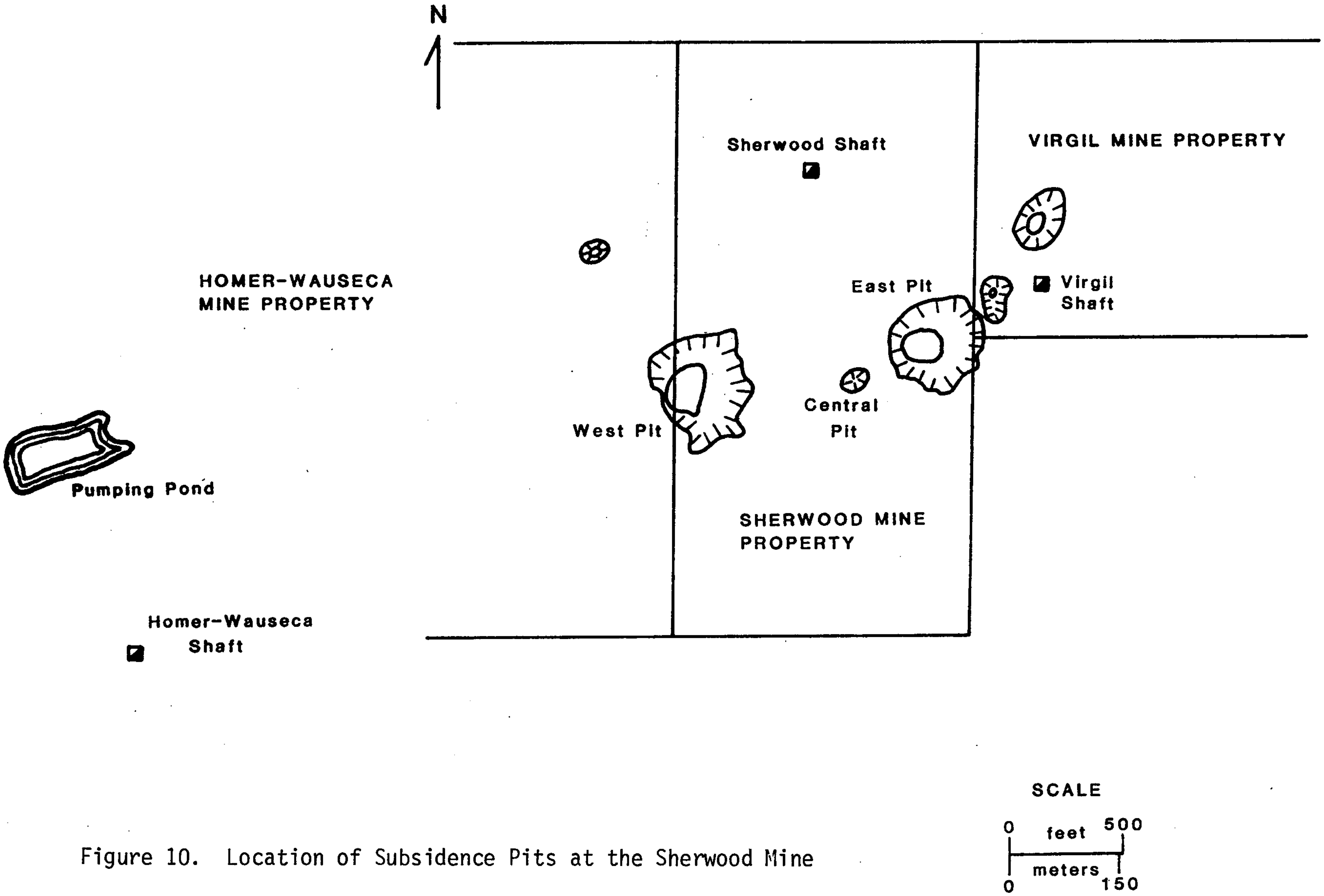


Figure 10. Location of Subsidence Pits at the Sherwood Mine

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 develope 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 thorugh 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

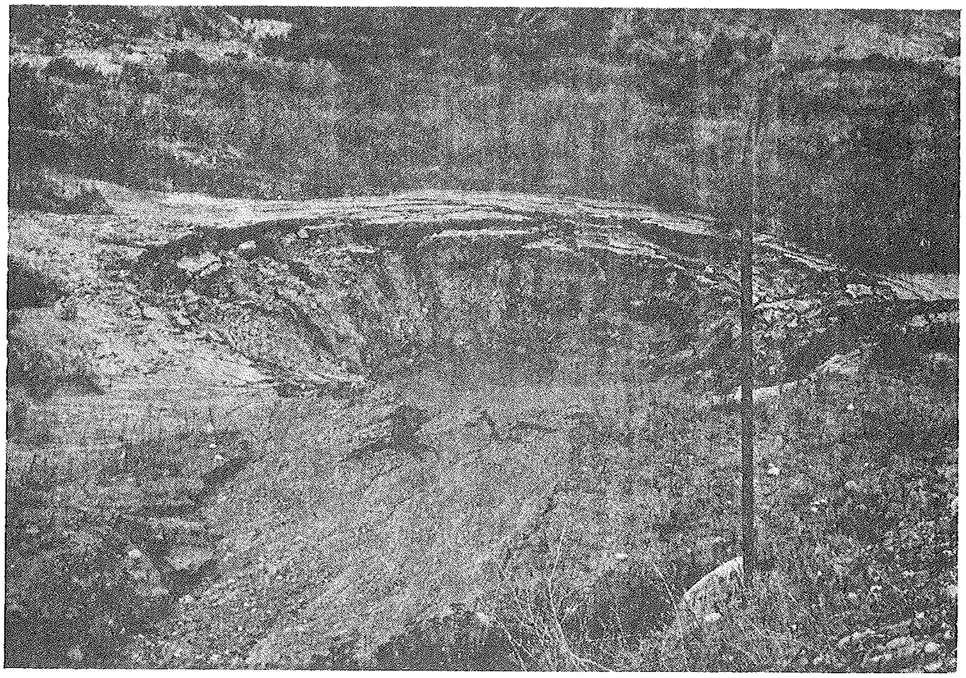


Figure 11. Photograph of initial subsidence in West Pit area taken on September 7, 1979. The subsidence pit is about 30 feet in diameter and ten feet deep. The bent pipe in the foreground is an old well casing installed in the 1940's. Photograph taken with a 50 mm lens on a 35 mm camera, looking southeast.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

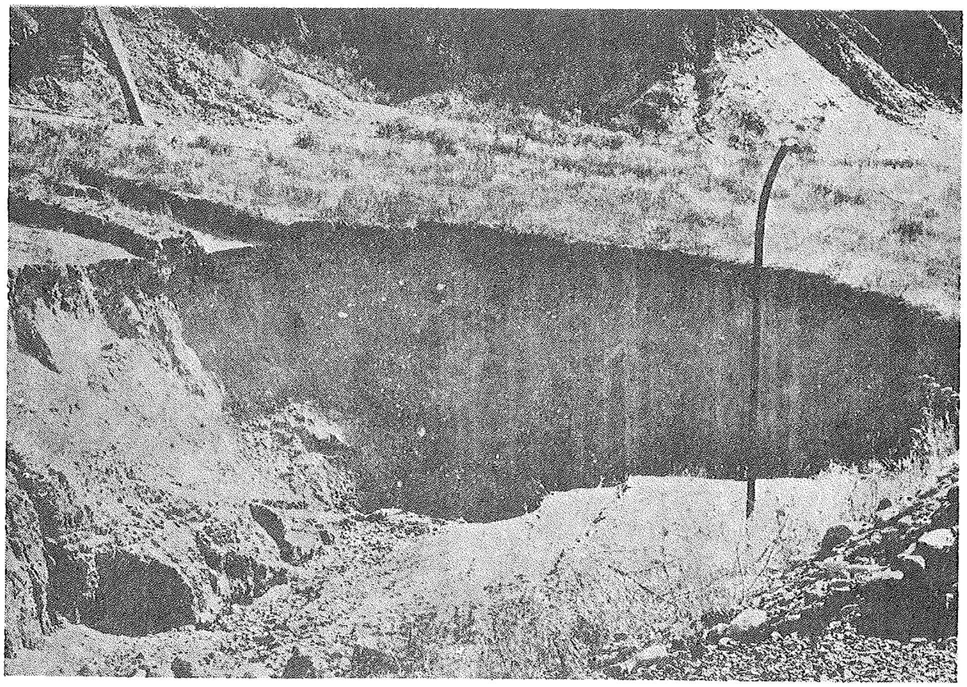
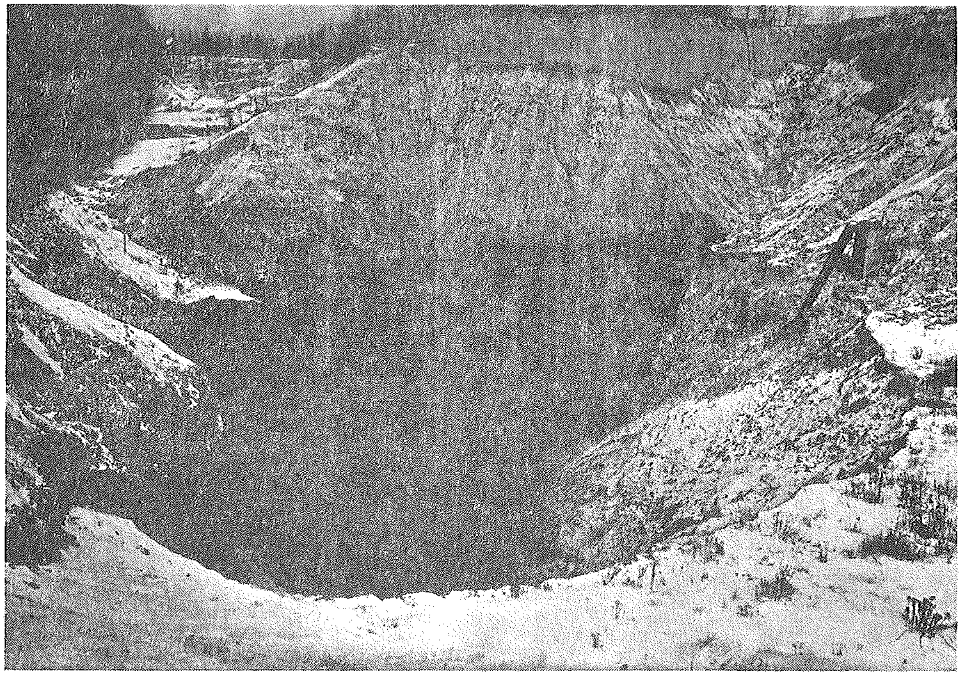
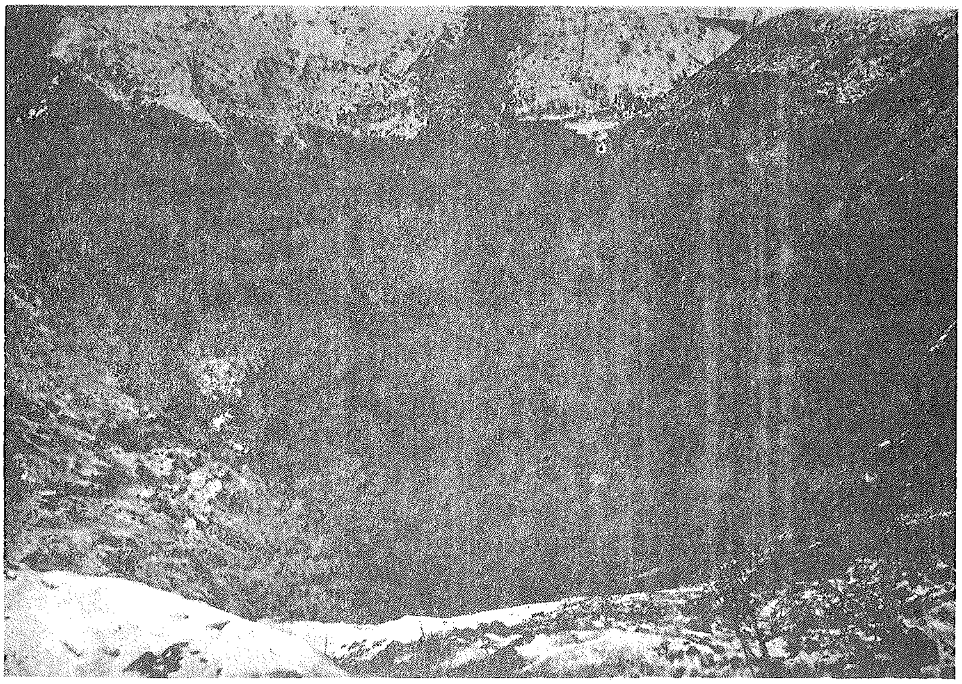


Figure 12. Photograph of enlarged subsidence pit which caved on October 14, 1979. The resulting pit is about 100 feet in diameter and 60 feet deep. Note old well casing pipe in foreground; also cribbing and bent over 30-inch pipe in background at upper left, formerly used for sand filling stopes under 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 70^0 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 meassive 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

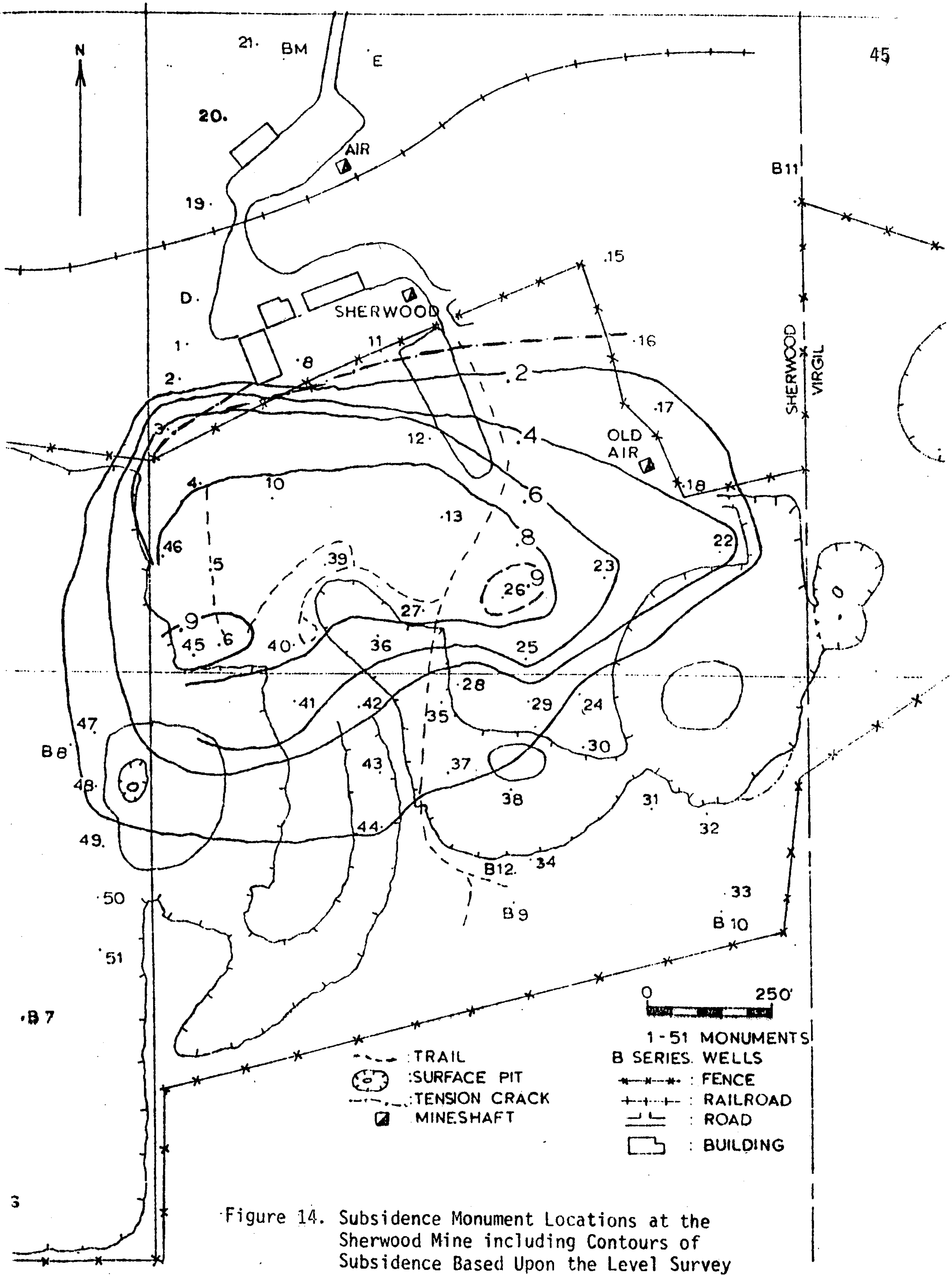


Figure 14. Subsidence Monument Locations at the Sherwood Mine including Contours of Subsidence Based Upon the Level Survey of December 9, 1980.

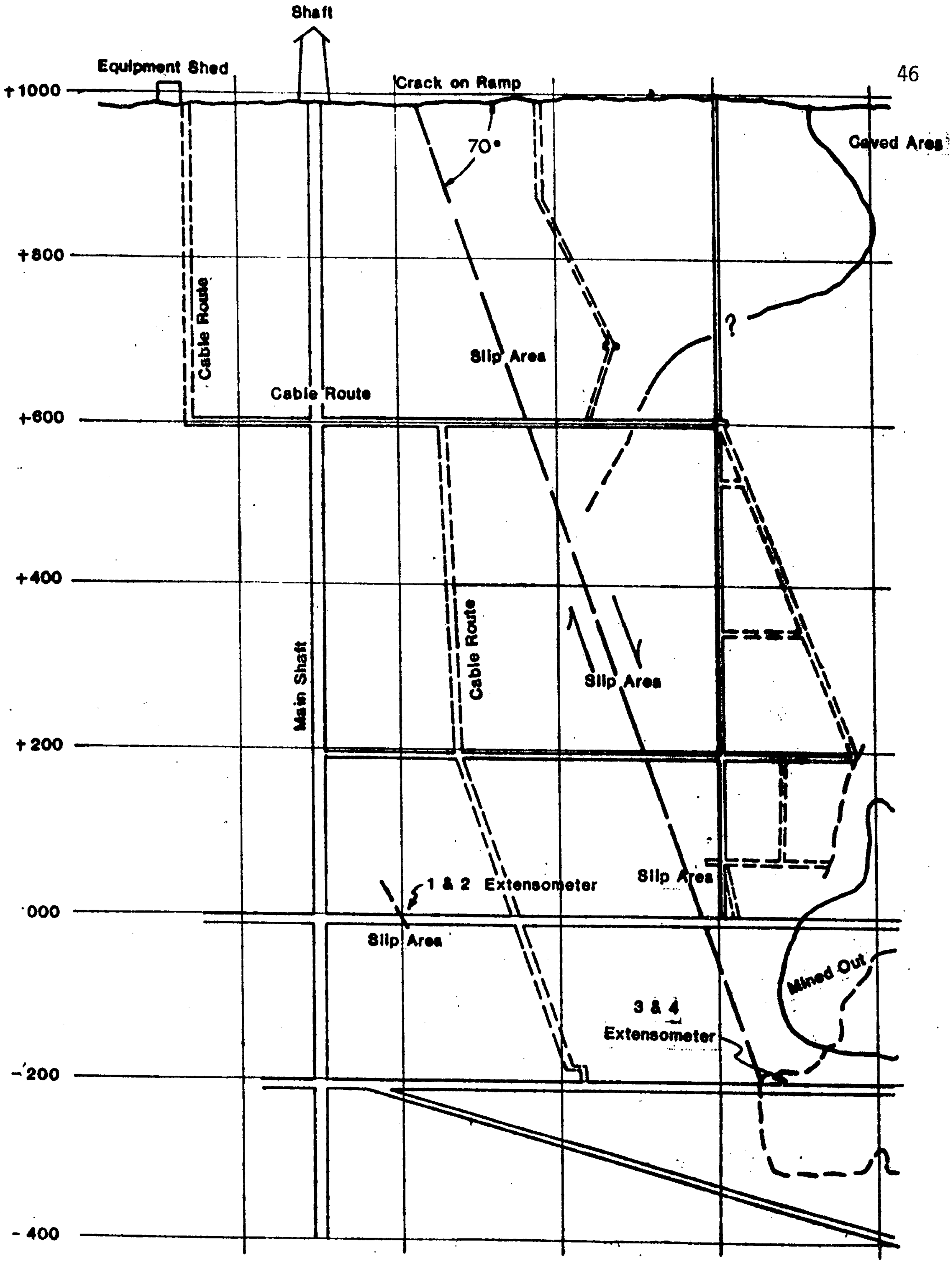


Figure 15 Location of Extensometer Installations in Shear Zones on the 1000 and 1200 Levels of the Sherwood Mine: Looking East

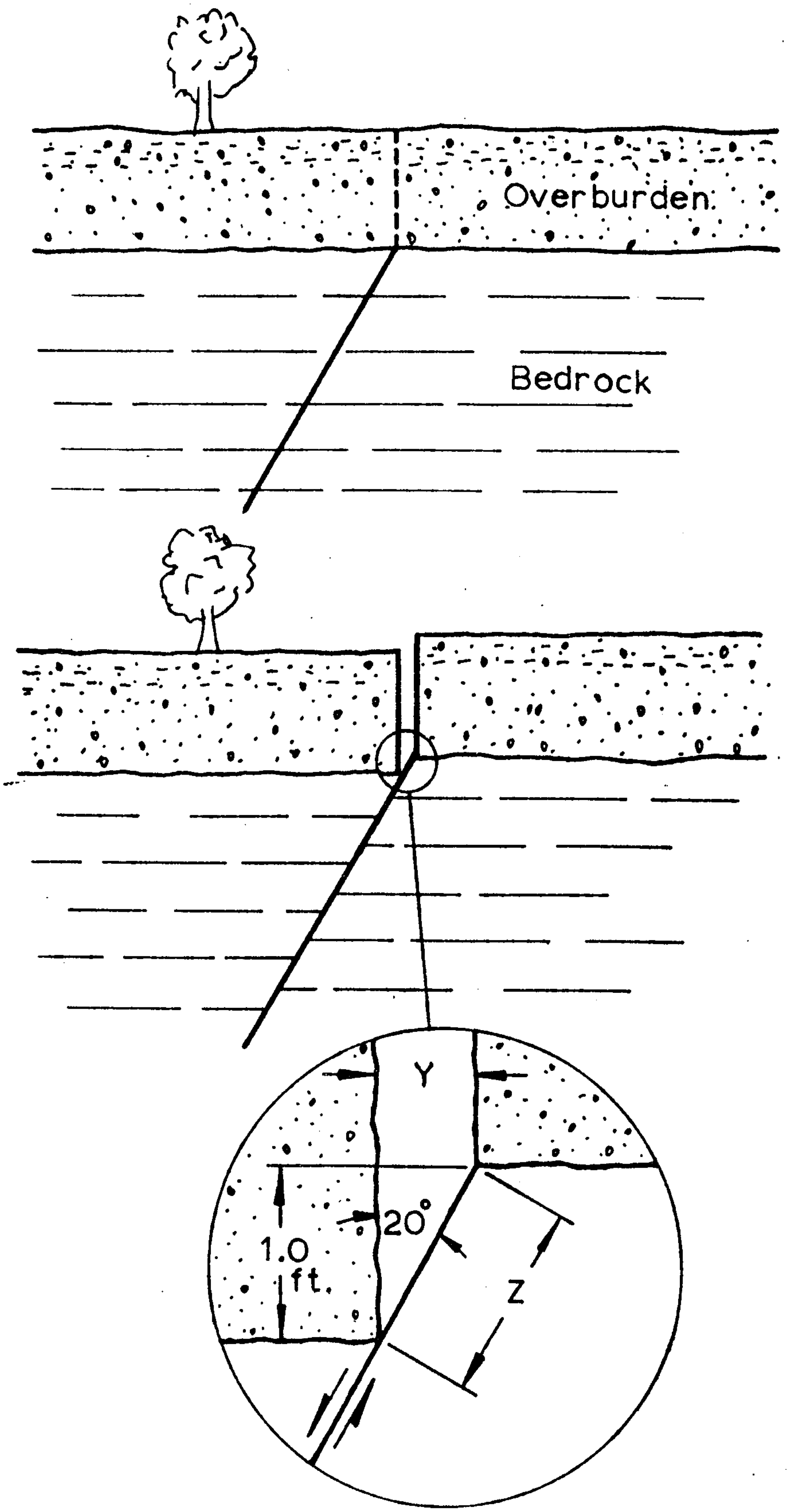


Figure 16. Suggested Mechanism to Explain Surface Pits on South Block of Surface Shear - Looking West.

the West Pit sand plug failure described in the previous section, although sand movement from groundwater inflow was undoubtely 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 fromm 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 "pluming 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 stong 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.

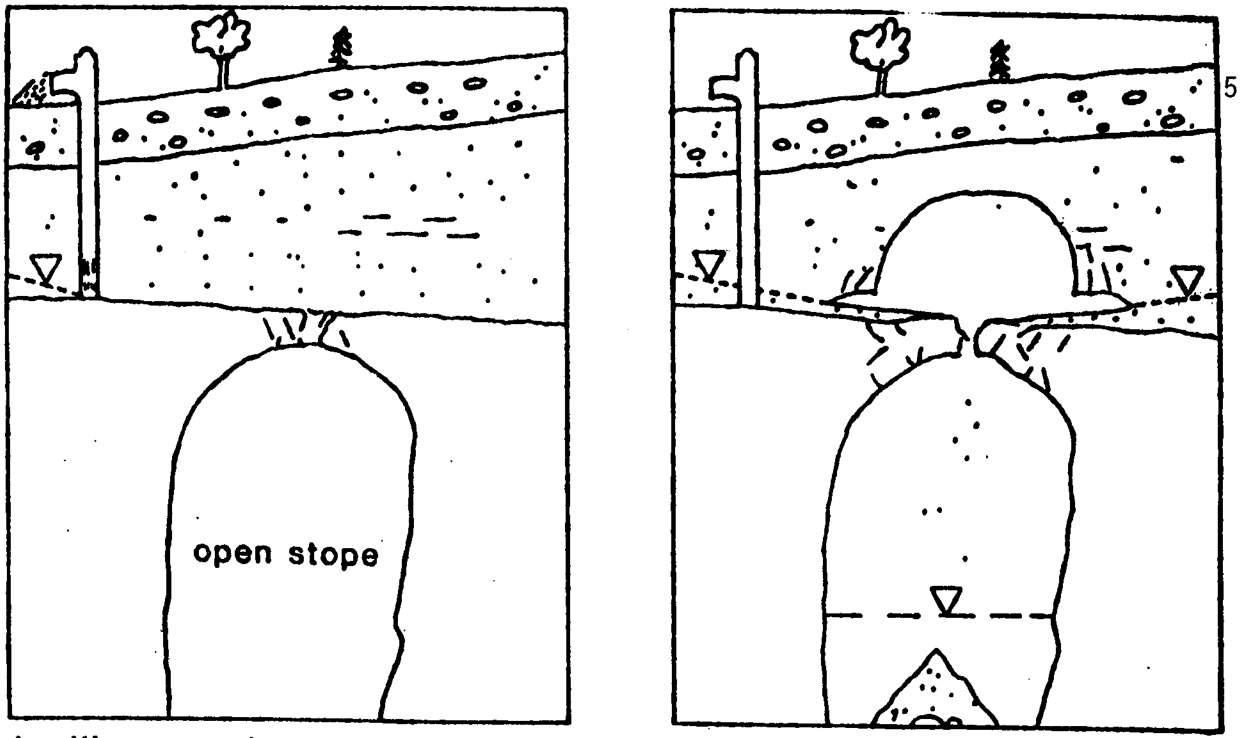
Piping-induced subsidence. One of the most interesting and significant aspects of the hydraulic subsidence event was the formation of a subsidence pit which was believed to have existed previously as a concealed cavity in the glacial overburden formed by piping activity.

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 phenomenen 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:

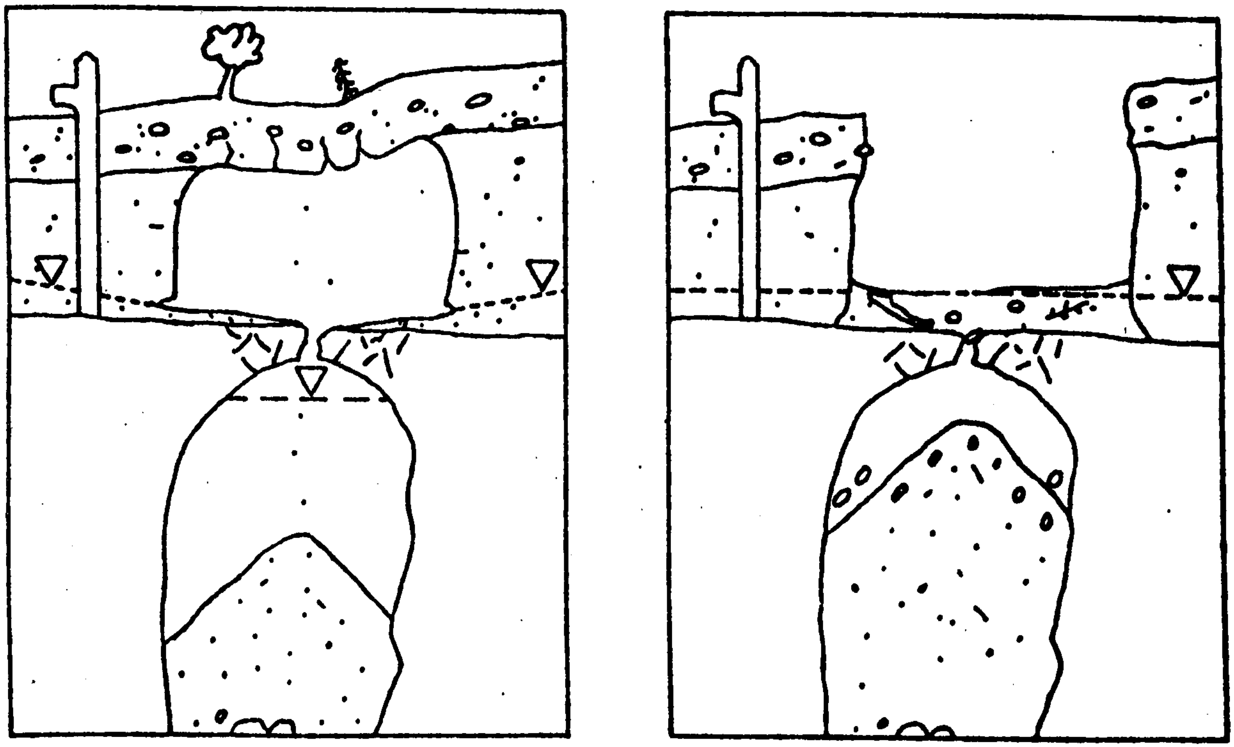
1. The mine becomes flooded and water flow is stopped.
2. The volume and velocity of groundwater flow is no longer sufficient to erode and/or transport sand into the mine void.
3. The channelway into the mine void becomes plugged or a filter pack of sand and gravel develops which "screens out" clastic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

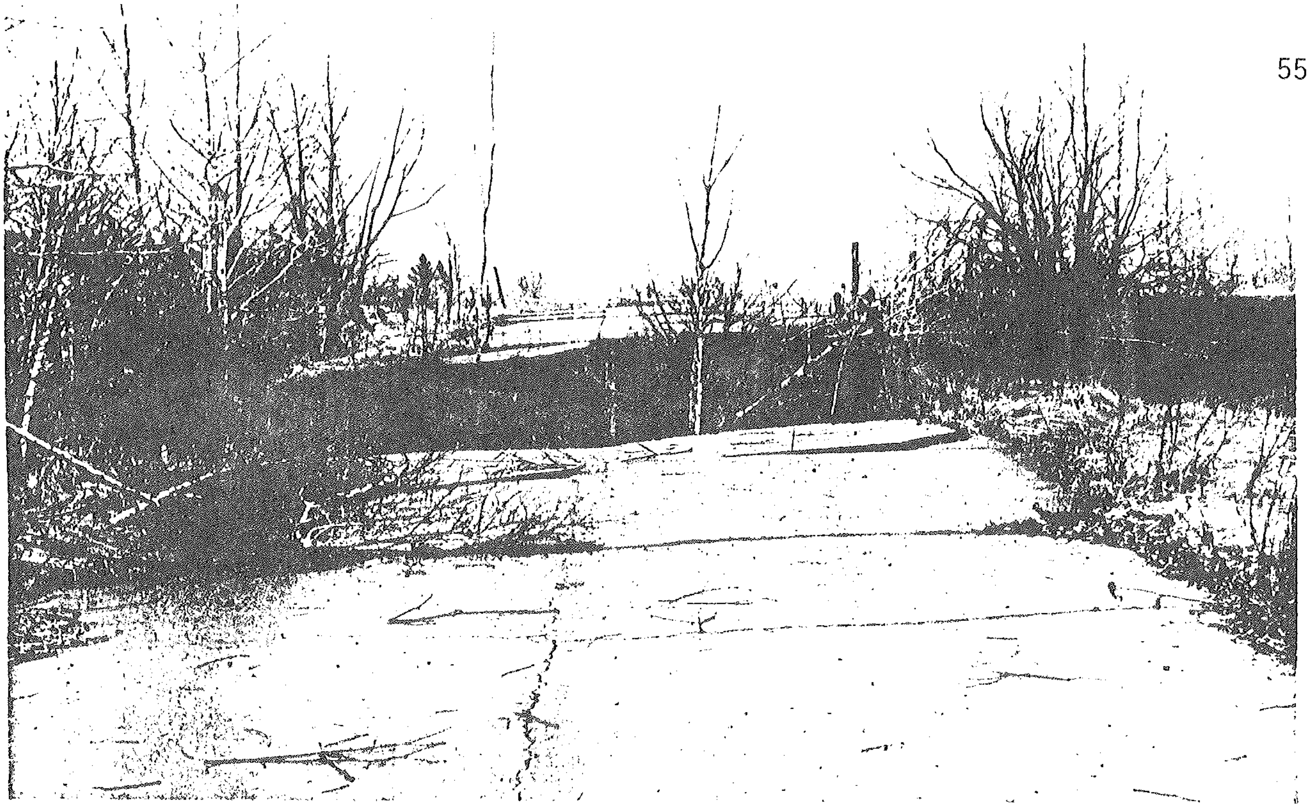


Figure 18. Smuggler Mine Cave-in on County Road 424: Looking East

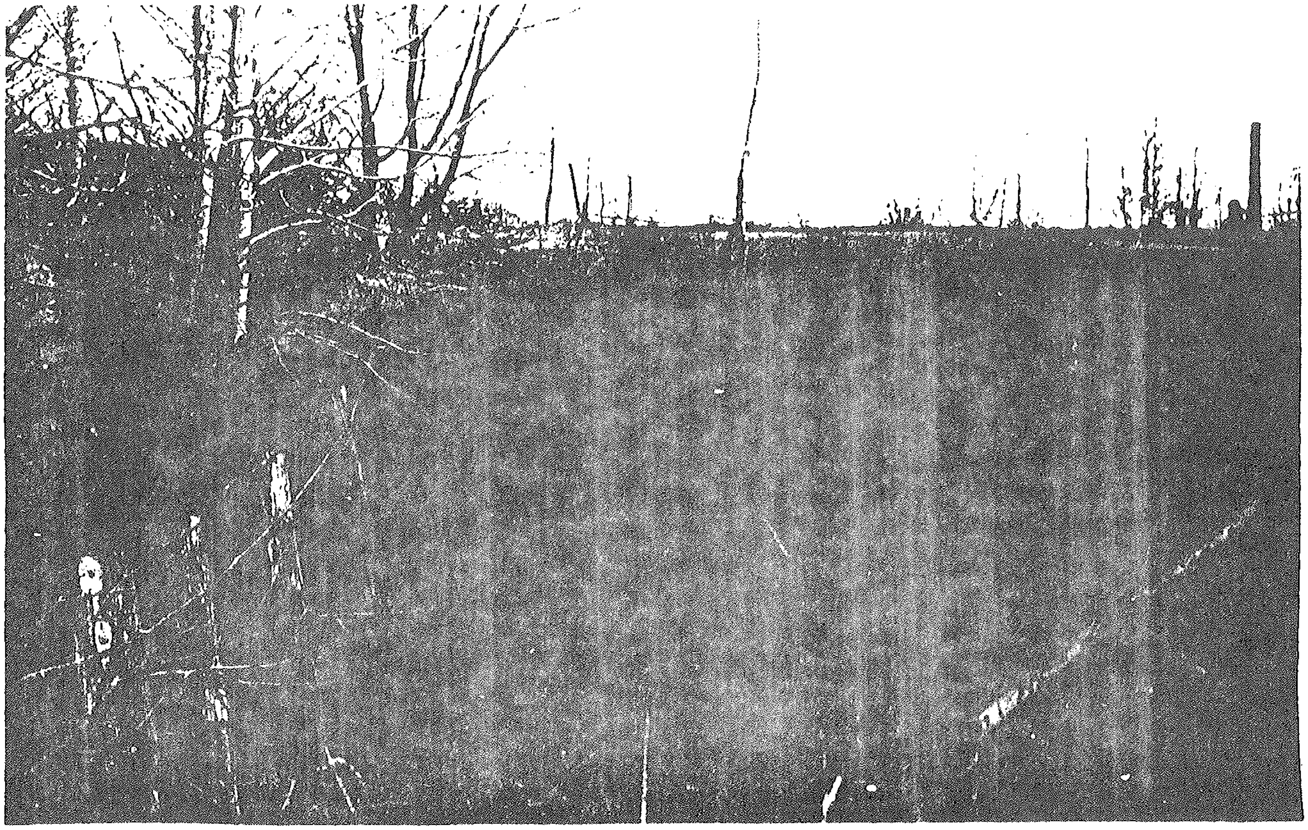


Figure 19. Close-up of Smuggler Mine Cave-in: Looking East

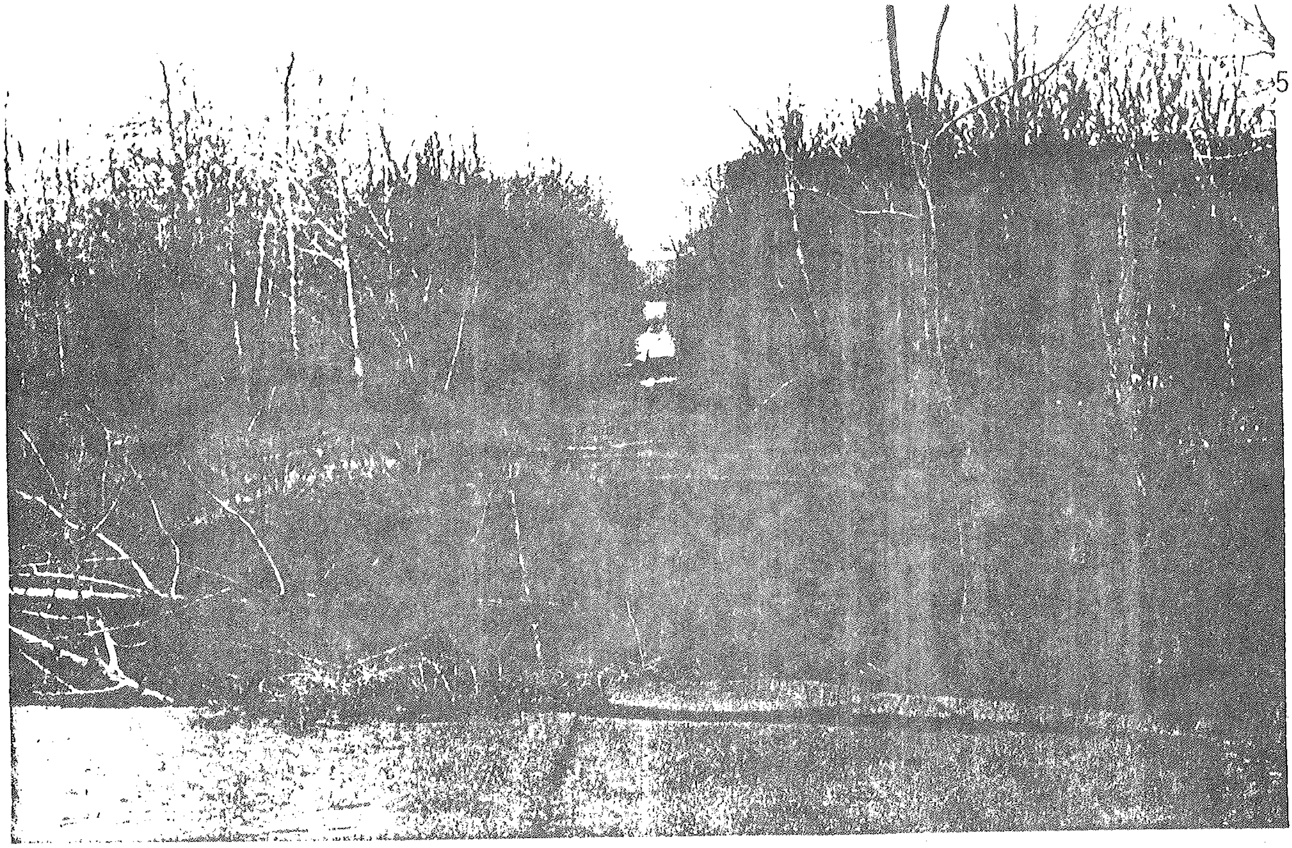


Figure 20. Smuggler Mine Cave-in on County Road 424: Looking West

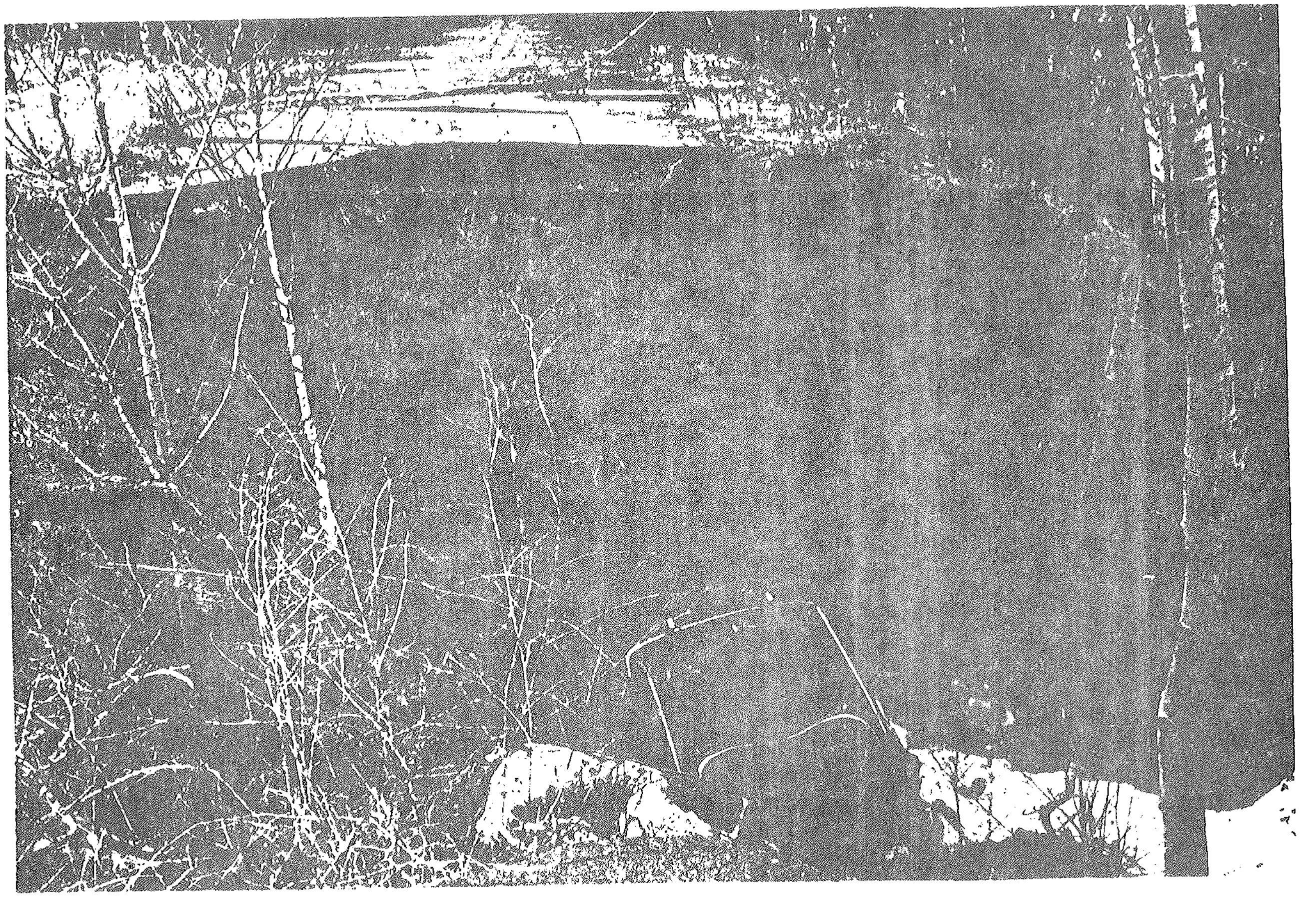


Figure 21. Close-up of Smuggler Mine Cave-in: Looking West

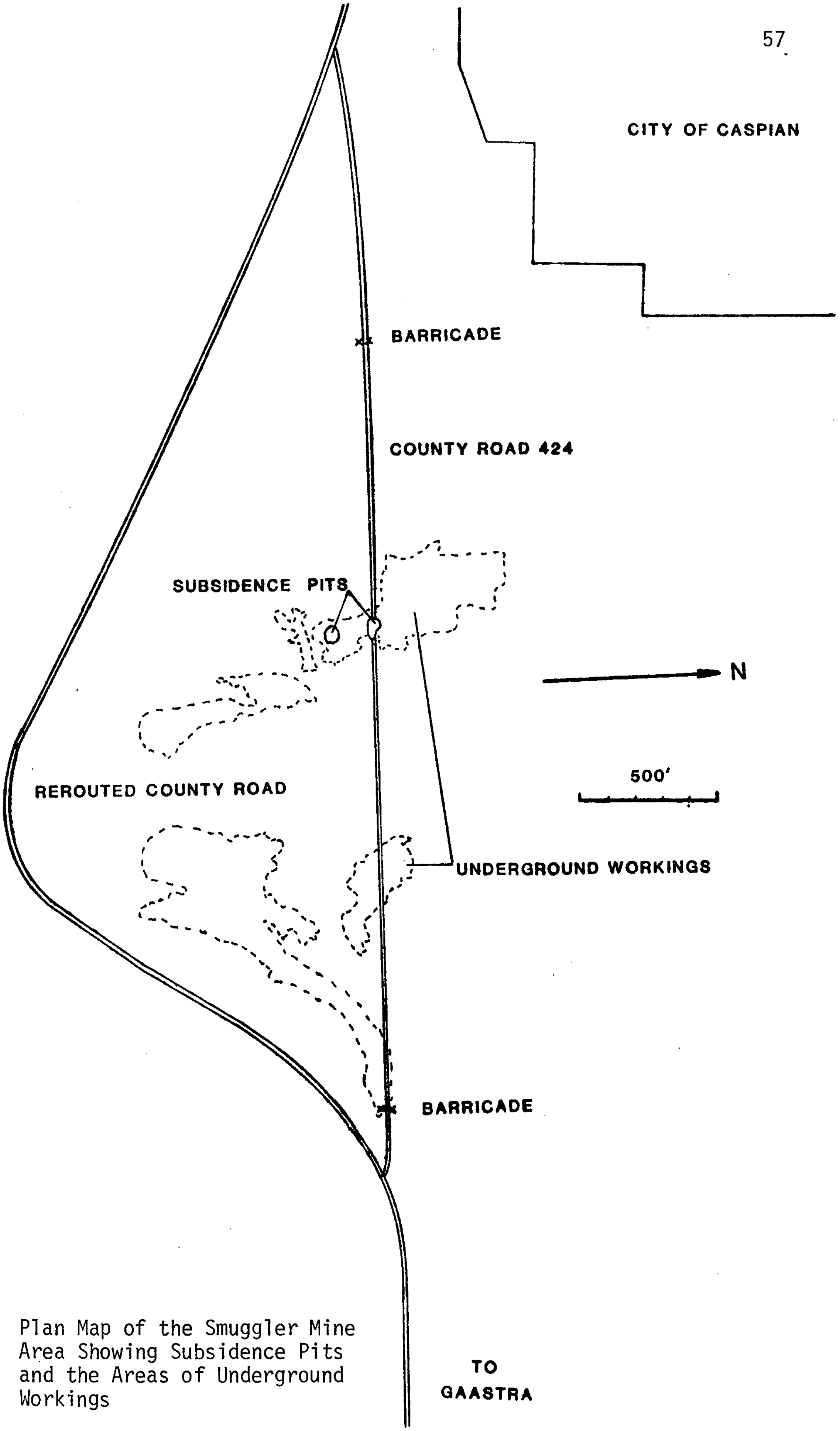


Figure 22. Plan Map of the Smuggler Mine Area Showing Subsidence Pits and the Areas of Underground Workings

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

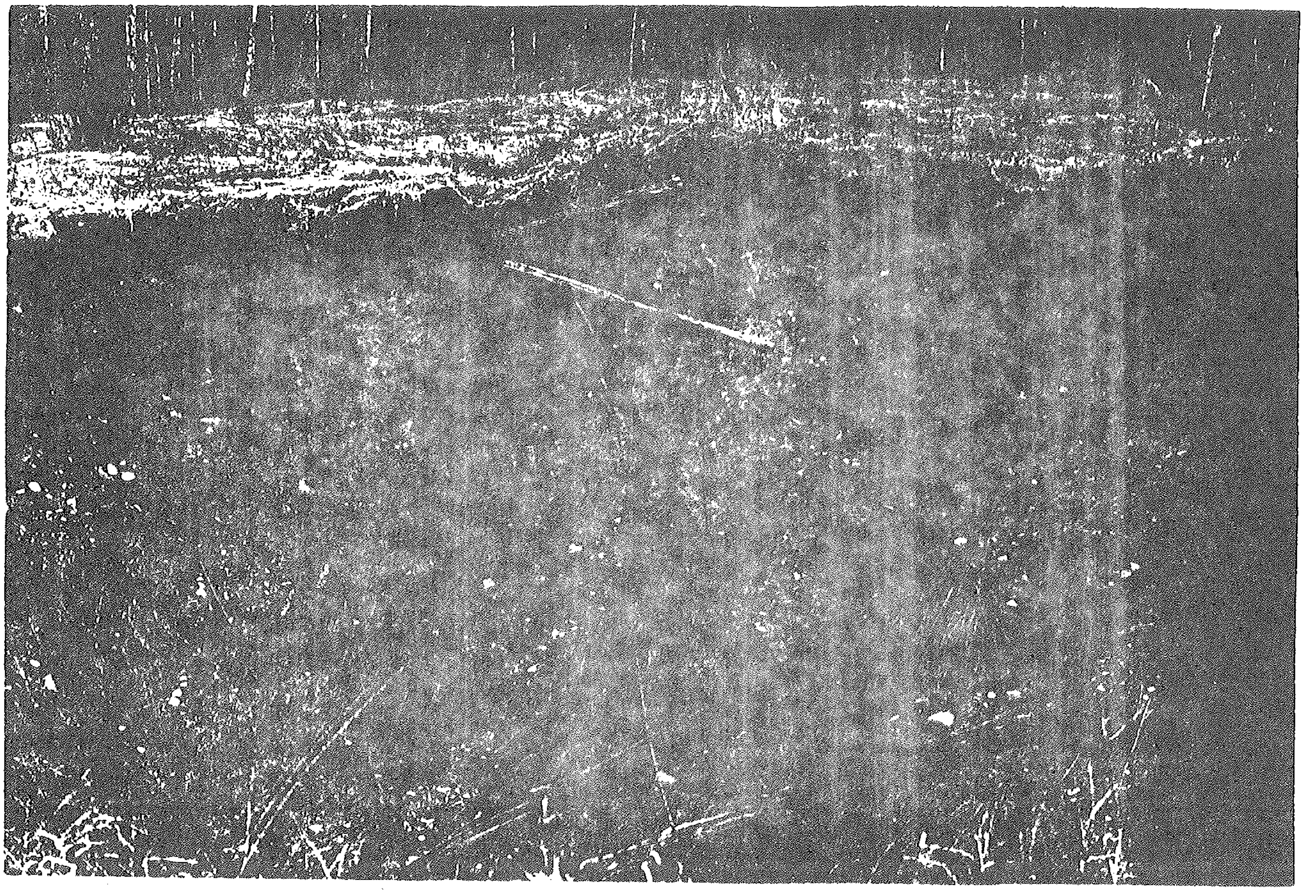
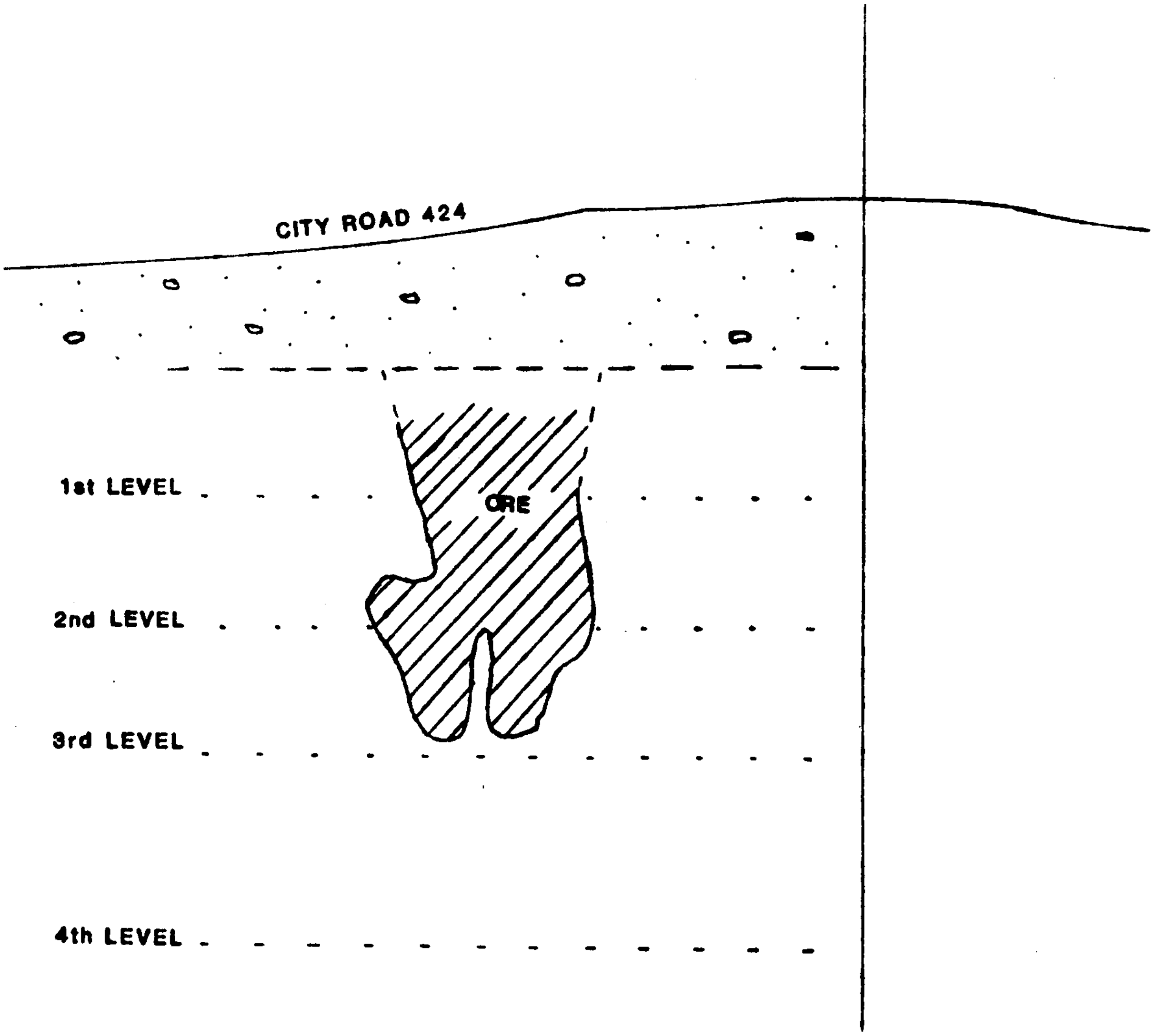


Figure 23. Small Subsidence Pit (50 ft diameter, 25 ft deep) South of County Road 424 above Smuggler Mine



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

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

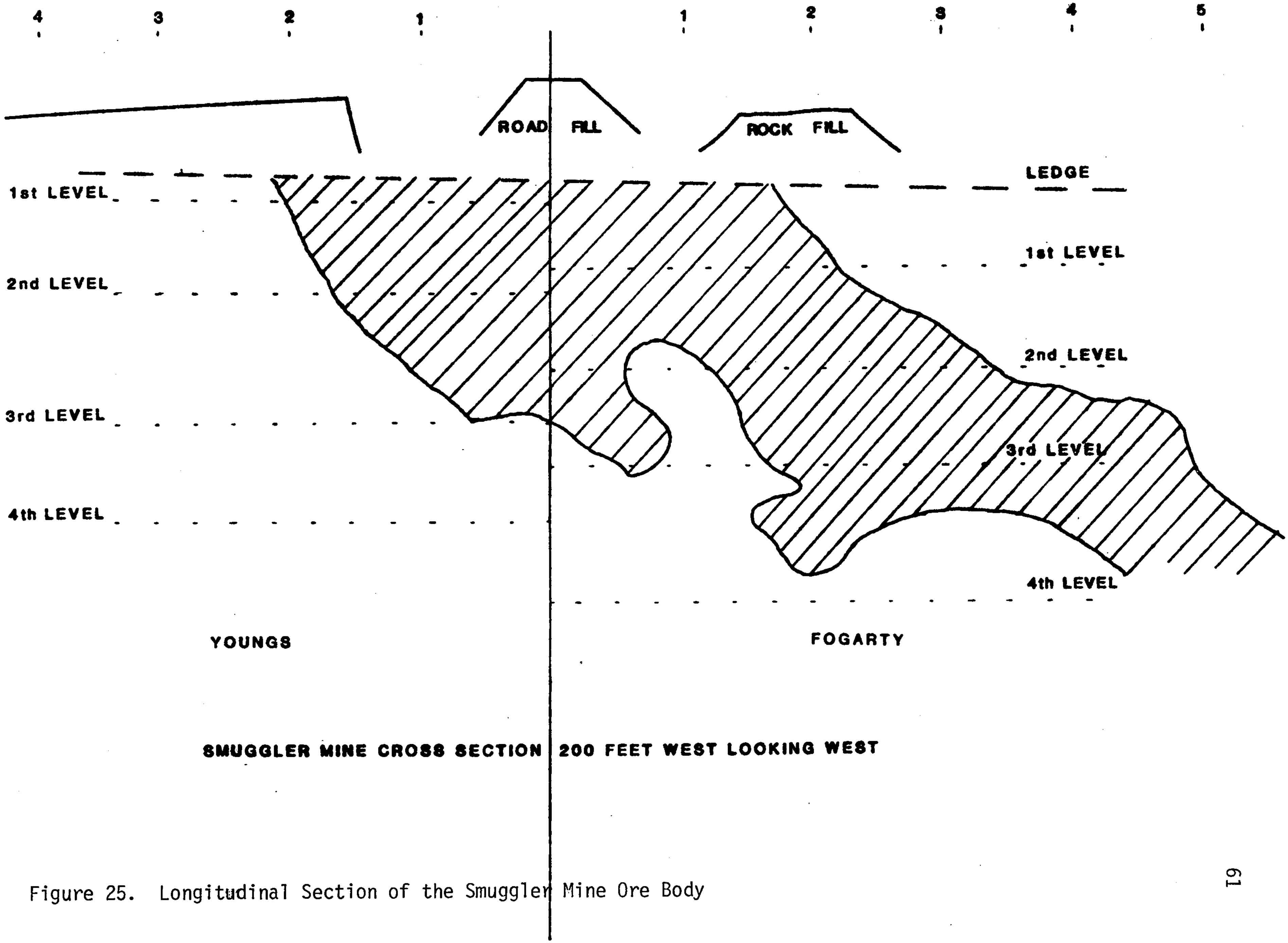


Figure 25. Longitudinal Section of the Smuggler Mine Ore Body

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.

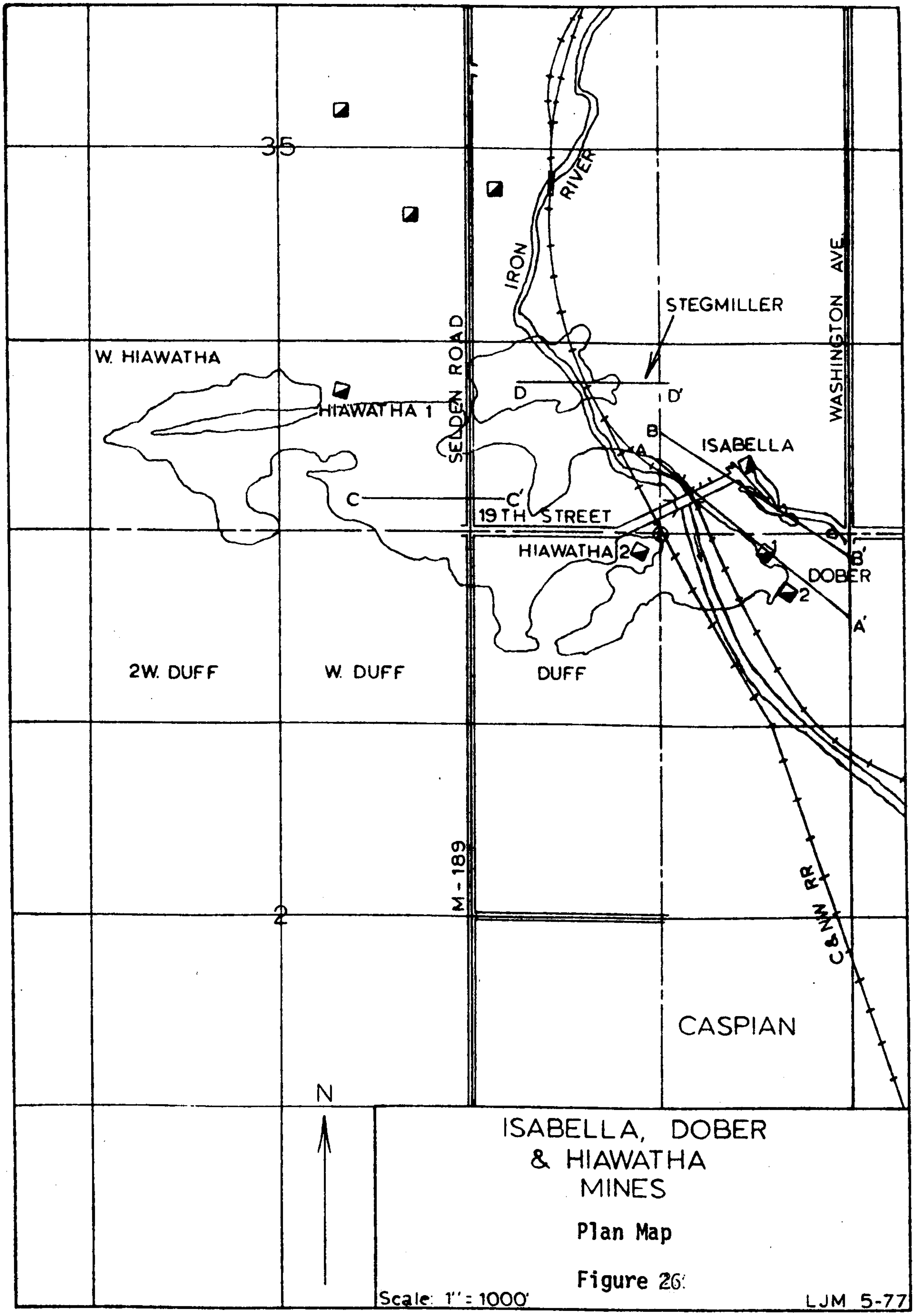
Discoloration of the Iron River by present acid drainage is not as severe as it once was, but it is still a concern. Tests by the Michigan Water Resources Commission show that trout and other fish and aquatic organisms can and do live in the clouded waters. Nevertheless, discoloration of the Iron River 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



ISABELLA, DOBER
& HIAWATHA
MINES

Plan Map

Figure 26

Scale: 1" = 1000'

LJM 5-77

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

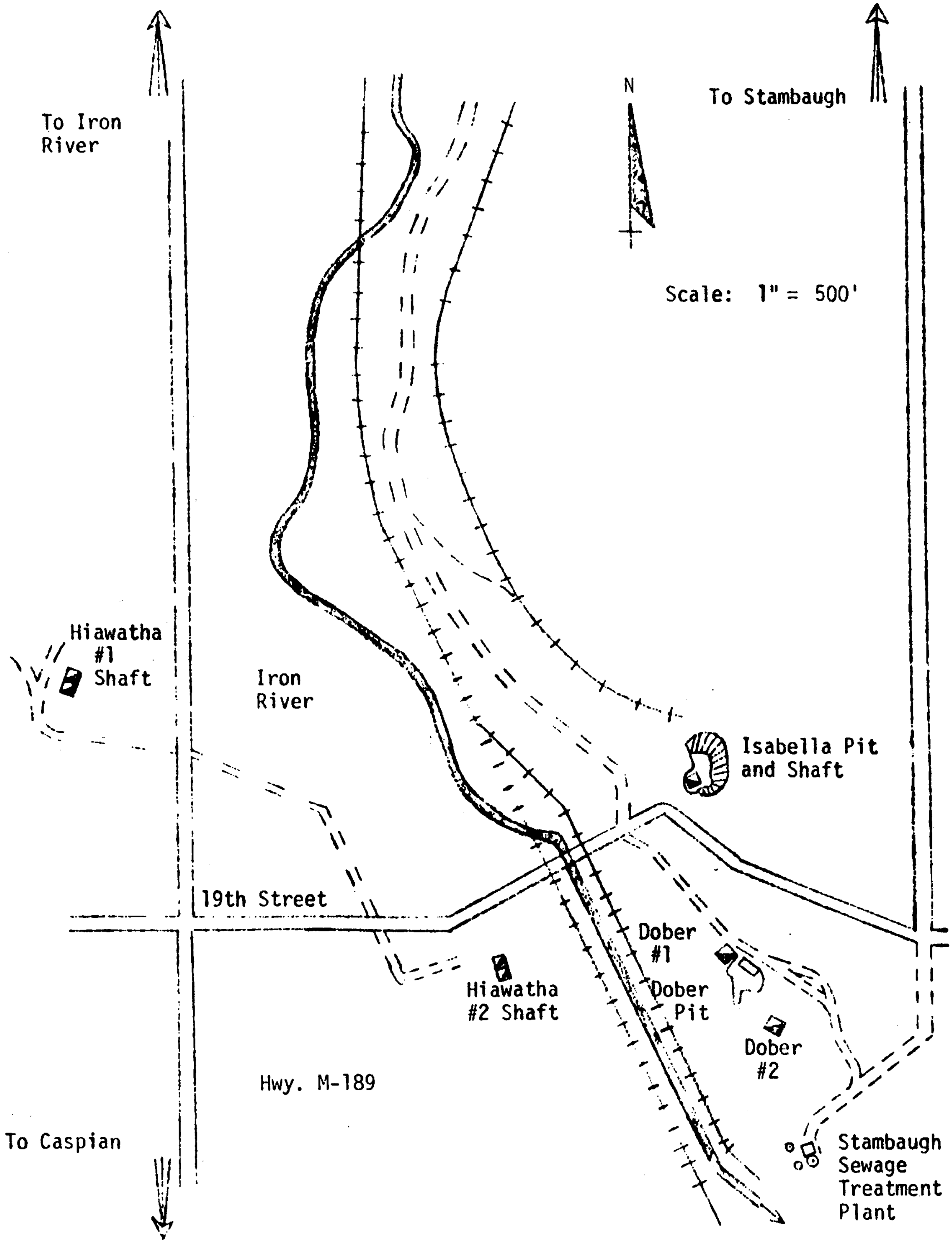


Figure 27. Surface plan map of the Dober-Hiawatha-Isabella Mine Complex

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 boundries; 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^{0}. 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

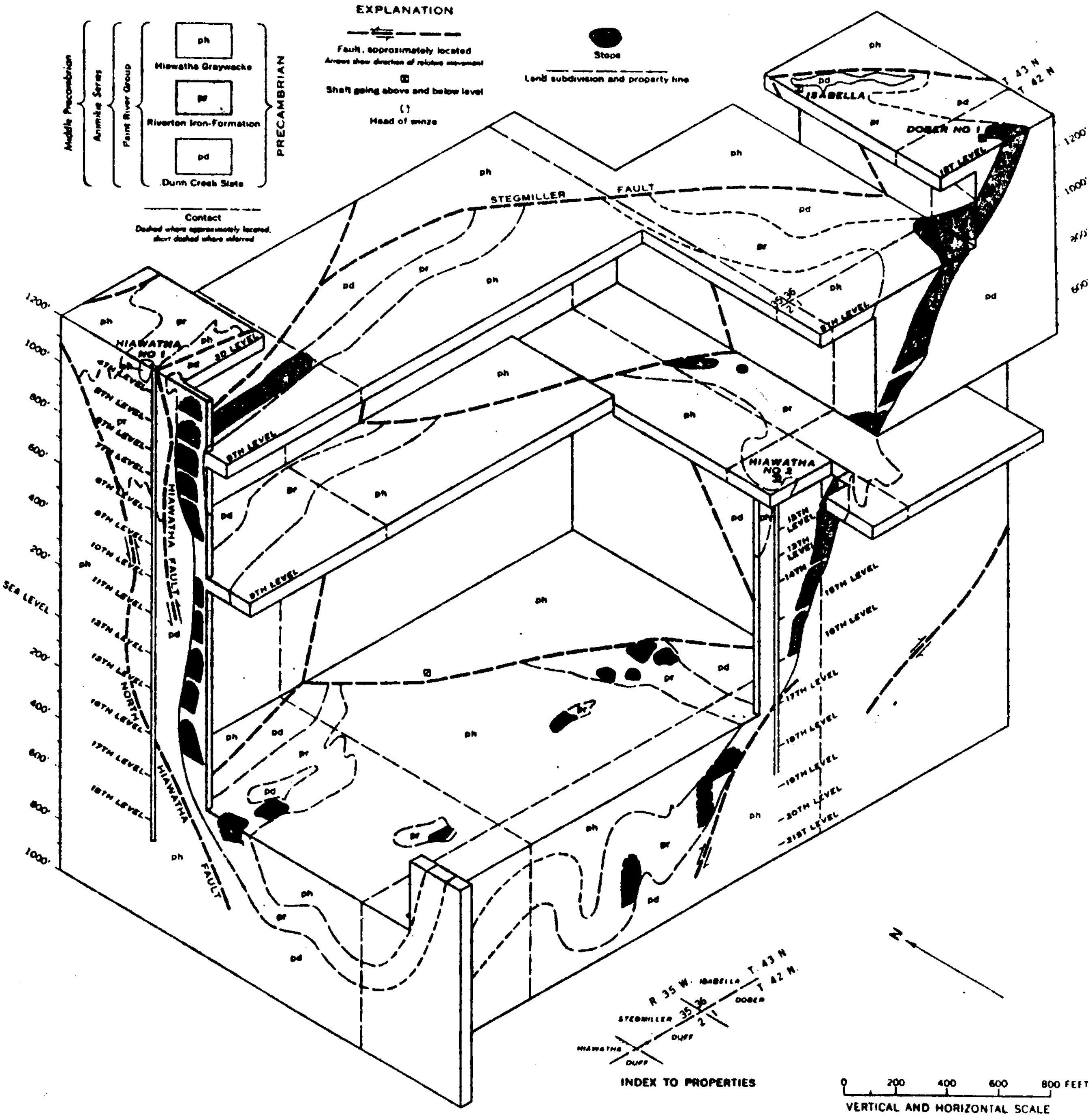


Figure 28. Isometric diagram of part of the Hiawatha and Dober Mines. (from Dutton, 1969)

the Dober Mine pit. The acid waters poured into corroded sections of the pipe and acid water entered the plant disrupting the bacteriological sewage digestor. 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:

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

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.

<u>Chemical characterization of Dober Mine acid drainage</u>. 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.

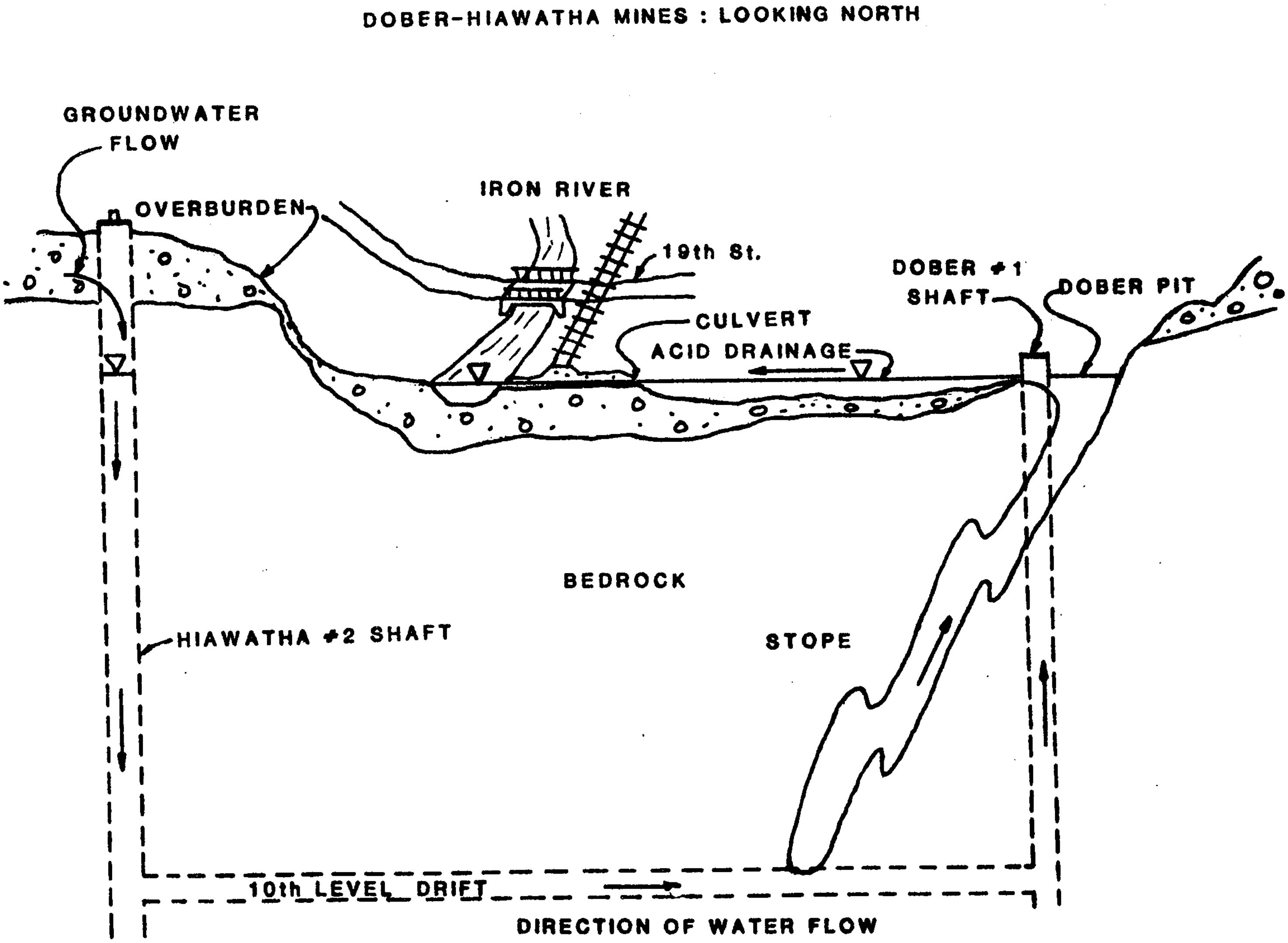


Figure 29. Schematic Diagram Showing Flow of Water in the Dober Mine Complex

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 ft^3 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 ft^3 of acid water had drained from the mine complex since it flooded in October 1972. Subtraction of this 25 million ft^3 of acid water from the total volume of 44 million ft^3 of voids calcualted for the upper 10 levels left 19 million ft^3 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

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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	198 million ft^3

...at the rate of 25 million ft^3 drained in 7 years,
198 million ft^3 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.

Acid mine drainage: surface source. The second major source of acid drainage into the Iron River is from the Buck group of mines. The Buck Mine is one mine of a complex consisting of four other mines including the Baltic Mine, Berkshire Mine, Fogarty Mine and Zimmerman Mine. The Buck Mine complex is located between the communities of Caspian and Gaastra, Michigan (see Figure 30).

The underground mines of the complex produced direct shipping iron ore by various slicing, caving and stoping methods. They operated variously from 1901 until 1962 producing a total 17.2 million long tons of ore. As the ore was direct shipping, no tailings were produced, however, waste rock generated from mine development work was dumped on the surface on the east side of the Iron River Valley where a number of the mine shafts were collared (see Figure 31). Much of the development drifting and shaft sinking took place in the upper part of the pyritic Dunn Creek slate in the Wauseca member. The area of by slate waste rock is nearly one half mile

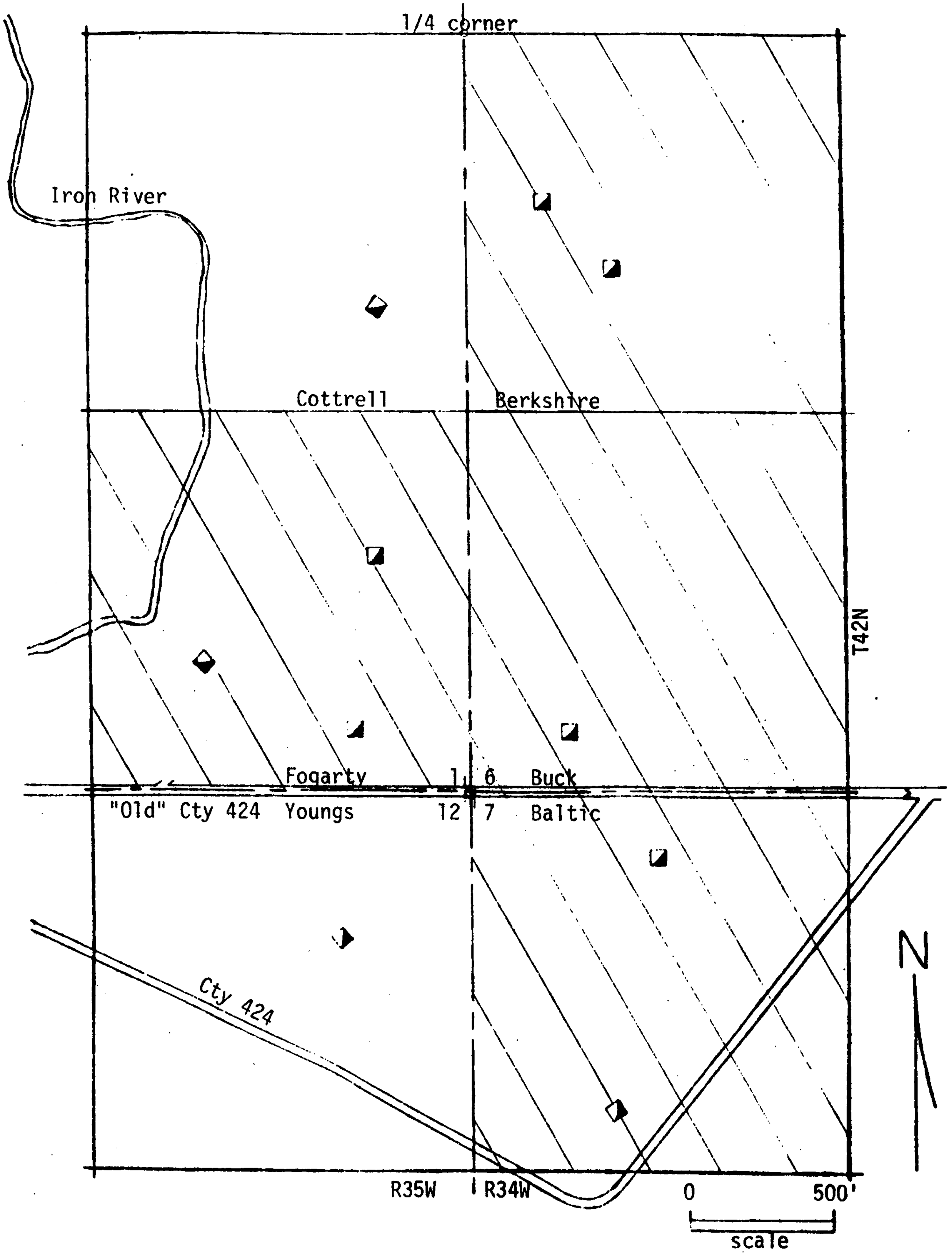


Figure 30. Relationship of Mine Properties Forming the Main Body of the Buck Group (shaded)

long and up to 600 feet wide. The black slate piles are flanked by higher ground on the east and by low marshy ground along the Iron River on the west. Numerous subsidence pits are present in the eastern area of the piles and several extend into the waste rock area. Many of the subsidence pits are flooded. Consequently both ground and surface waters flow from the elevated eastern edge of the black slate piles, through the piles and into the river flood plain along the lower western slope. These relationships are shown in Figures 31 and 32.

In addition to acid generated by the interaction of surface and near-surface groundwaters with pyrite and oxidized pyrite in the slate piles, acid water may also flow from the flooded mine reservoir. Deep sampling of water from two of the vertical shafts located within the area of the slate piles show that acid water is present in the mine. Elevated water levels in the mines of the complex relative to the elevation of water in the shafts collared within the slate pile area also suggest that acid water may be flowing from the mine complex. The flow of acid water from this mine complex may occur in a manner similar to the flow in Dober Mine complex as previously presented.

Analyses of samples augered from the slate piles from 14 locations showed that sulfur contents ranged from 0.21% to nearly 10%. This information combined with the drill hole depths and the area of the slate piles as determined by mapping was used to calculate the amount of sulfur remaining in the piles. Results showed that 10.2 million pounds of sulfur were present in the slate piles which had a volume of 129,000 cubic yards and occupied an area of 19 acres. These data are presented in Table 5. Based upon the sulfur being present in its reduced form as pyrite, it was calculated that 8.9 million pounds of iron and 31.1 million pounds of

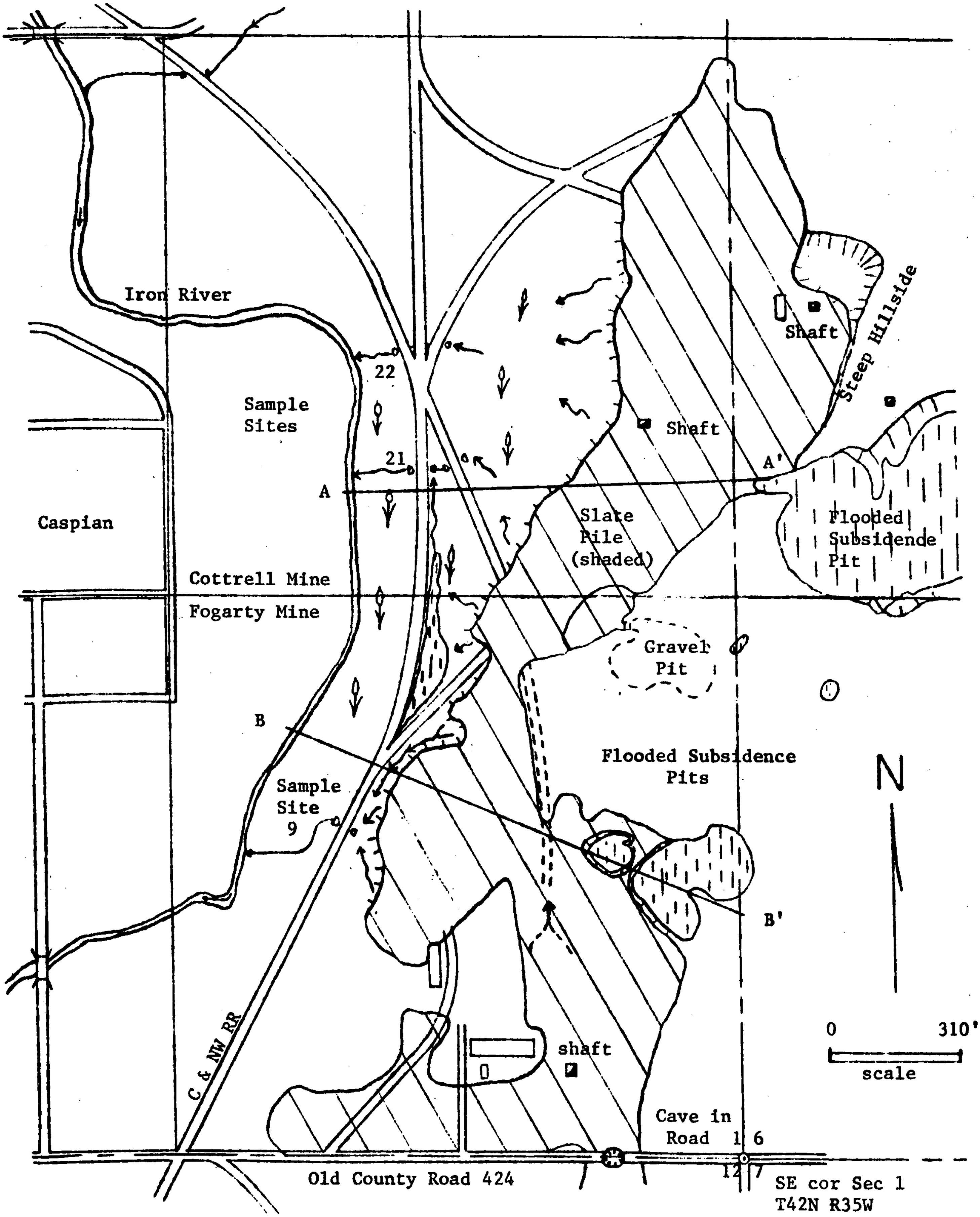
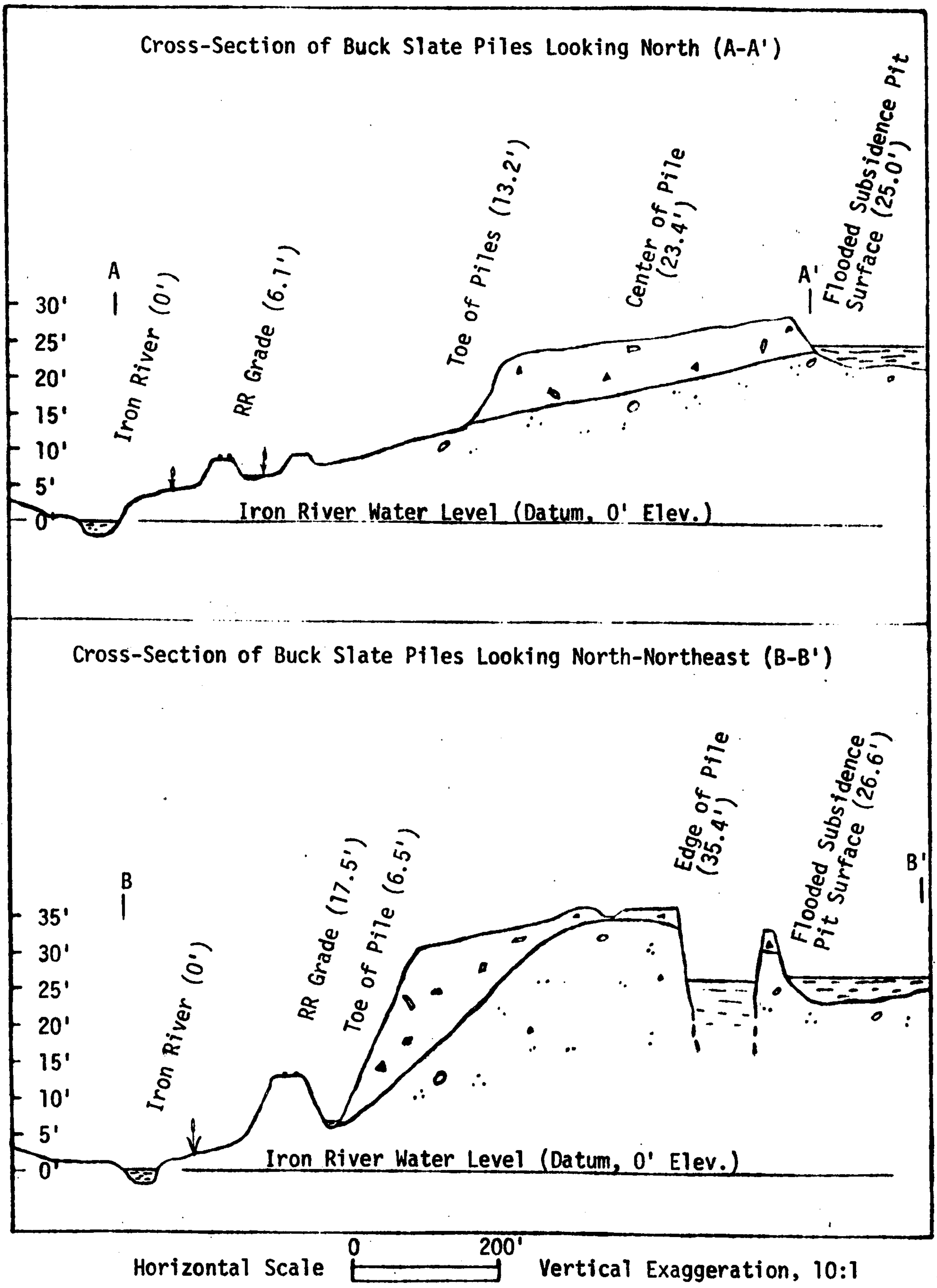


Figure 31. Map of the Buck Group Slate Piles



Cross-Section of Buck Slate Piles Looking North (A-A')

Cross-Section of Buck Slate Piles Looking North-Northeast (B-B')

Figure 32. Cross-Sectional Views of Buck Slate Piles (see Figure 31)

concentrated sulfuric acid could be produced. Thus, it is obvious that a significant amount of acid drainage can be generated by leaching from the surface slate piles.

Safety of Surface Openings

Surface openings associated with underground mines refer mainly to shafts and raises open to the surface, but also include subsidence pits. When an underground mine is closed it is normal procedure to make these surface openings as safe as possible. Fences and warning signs are placed around steep walled pits. Mine shafts and raises, in addition to being fenced, may be backfilled, sealed or capped or protected by some combination of these safeguards.

When first installed, many of these safeguards are adequate to protect the public. However, with time, many of these safeguards deteriorate or are affected in some way that makes them less reliable. Mine shaft cappings made of inferior materials or those that were poorly designed may not last long and the mine opening may actually become more dangerous. Even well designed caps may fail if the shaft lining deteriorates and subsidence causes the cap to fall into the shaft. Vandalism is another problem and sometimes unexpected forces or mechanisms may render these surface openings unsafe. Selected case histories illustrating these various problems are presented in this section.

Failures of shaft protection due to the use of unsuitable materials.

Failure of protective mine shaft cappings due to the use of inadequate materials is common in many old mining districts. The use of wood timbers or planking was common. Over the years, the wood rots and deteriorates causing a once sound shaft cap to become unsound. This slow deterioration poses a special threat, because the public may assume that the capping is safe, when in fact, a person might fall through the rotted planking or timbers into the mine below. Steel plates have also been used to permanently cap mine shafts and while steel may outlast wood, eventual rusting will cause the plates to deteriorate to the point where they are no longer safe. Several examples of shafts capped with inadequate materials are presented in the following paragraphs.

The Warner Mine is located near Amasa, Michigan about 10 miles northwest of Crystal Falls (see Figure 33). The mine operated from 1915 until 1958, producing 3.4 million long tons of ore from a series of vertical shafts that were as deep as 1700 feet. The production shafts have apparently been backfilled from the surface, however, a wood timbered air shaft was found without any cap covering. The area is fenced with several loose strands of barbed wire. It is apparent that some type of wooden planking covered the shaft at one time, but it has either rotted or been removed by vandals or by someone curious enough to pry off the wooden cap. The shaft is located in an open field near a dirt trail road. The mine is flooded and the water level is near the ground surface. Several photographs are shown in Figure 34 which illustrate the setting and the condition of the shaft collar.

The Porter Mine is also located between Crystal Falls and Amasa, Michigan. It operated from 1914 until 1927, producing 733,000 tons of ore from seven levels. The main shaft was vertical, some 850 feet deep and was capped with heavy wood planking supported by two large steel I-beams. The I-beams have remained in position, but the wooden planking has rotted and collapsed. There is some subsidence around the shaft collar. A secure fence does limit access to the shaft. A photograph of the capping is shown in Figure 35.

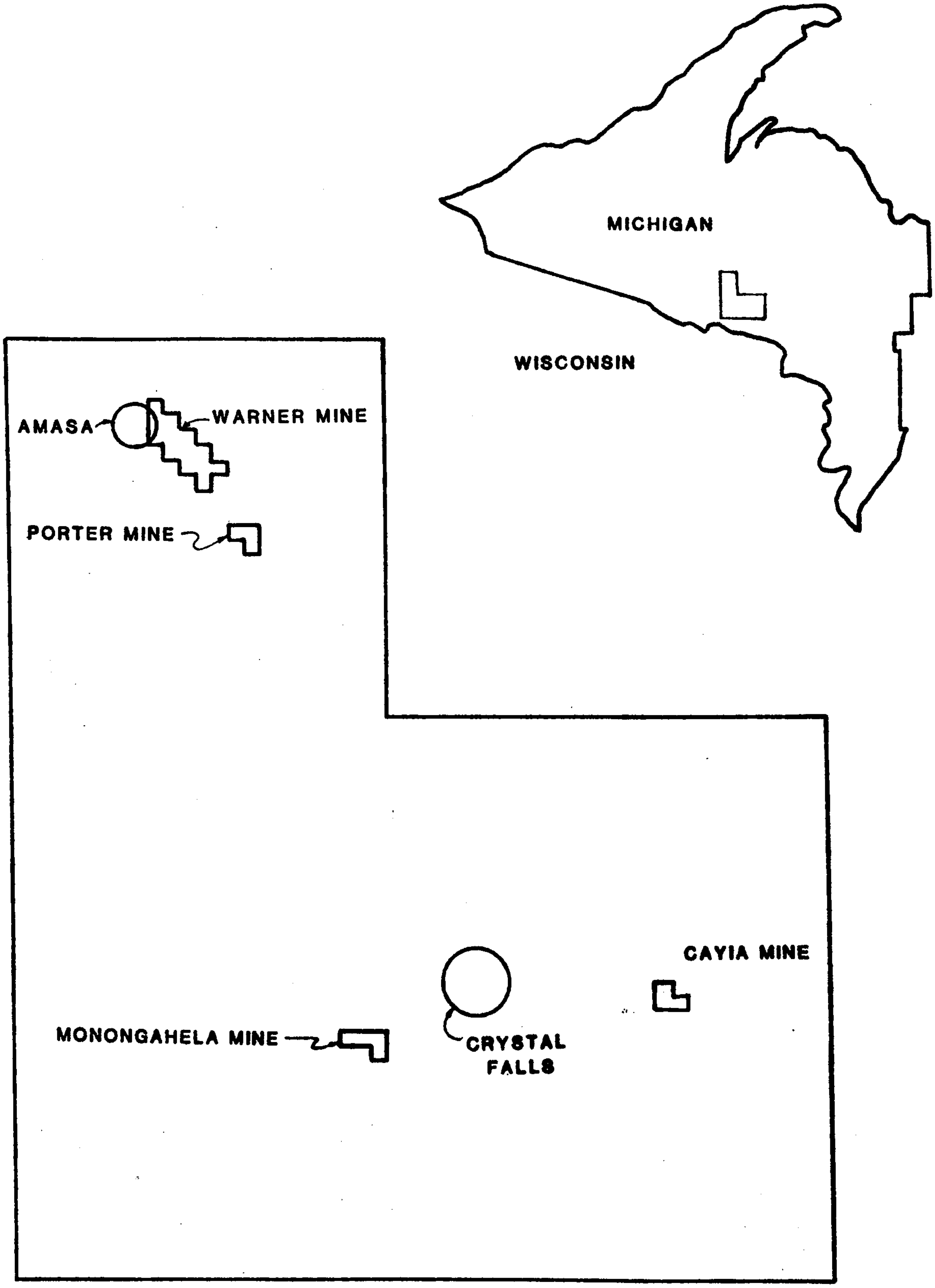


Figure 33. Mine Locations in the Crystal Falls District

a. Overview of Warner Mine Air Shaft Looking Approximately Northeast

b. Close-up of Warner Mine Air Shaft

Figure 34. Photographs of Warner Mine Air Shaft

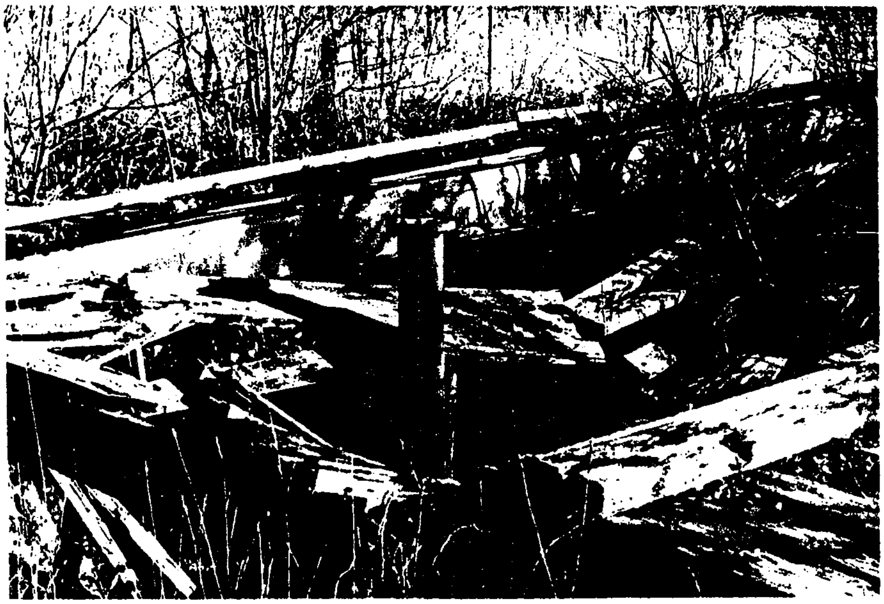


Figure 35. Collapsed Wooden Plank Capping on Porter Mine Shaft

The Davidson Number Two Mine is located about one mile north of the City of Iron River, Michigan (see Figure 36). There are three other Davidson Mine "forties" in the same area. They all began in 1911 and the last mine was closed ir 1947. The Davidson ore was mined to depths of between 500 and 1000 feet deep by stoping and caving methods. The shaft serving the No. 2 mine was lined with timber through thick glacial overburden. It is inclined about 80^0 to the south. When the mine was shut down the shaft was capped with wood planking. The planking remains in place but it is nearly rotted away. The timbered shaft lining has also rotted and a large subsidence pit, about 100 feet in diameter and 30 feet deep has formed south of the shaft. The shaft is exposed in the north side of the pit. Photographs are shown in Figure 37. A six-foot high chain link fence is around the pit and adequately protects the shaft.

Although the Pike Mine is not on the Menominee Range, the recent cave-in of this old mine shaft provides a good example of shaft cave-ins resulting from the deterioration of inadequately capped shafts. This occurrence also illustrates a common problem resulting from inadequate record keeping of mine shaft openings and previous capping procedures.

The Pike Mine is located in Wakefield, Michigan on the Gogebic Iron Range (see Figure 38). Records show that the Pike Mine operated from 1891 until 1910 producing a total of 105,000 tons of ore. The Pike Mine had two shafts, the No. 1 and the No. 2 which are shown on the section map of Figure 38.

On October 31, 1982, the Number 2 shaft of the Pike Mine caved to the surface. Subsequent investigations showed that the original timber capping over the shaft had failed. The ground surface had been brought to the contour of the west sloping hillside and had been maintained as a lawn area

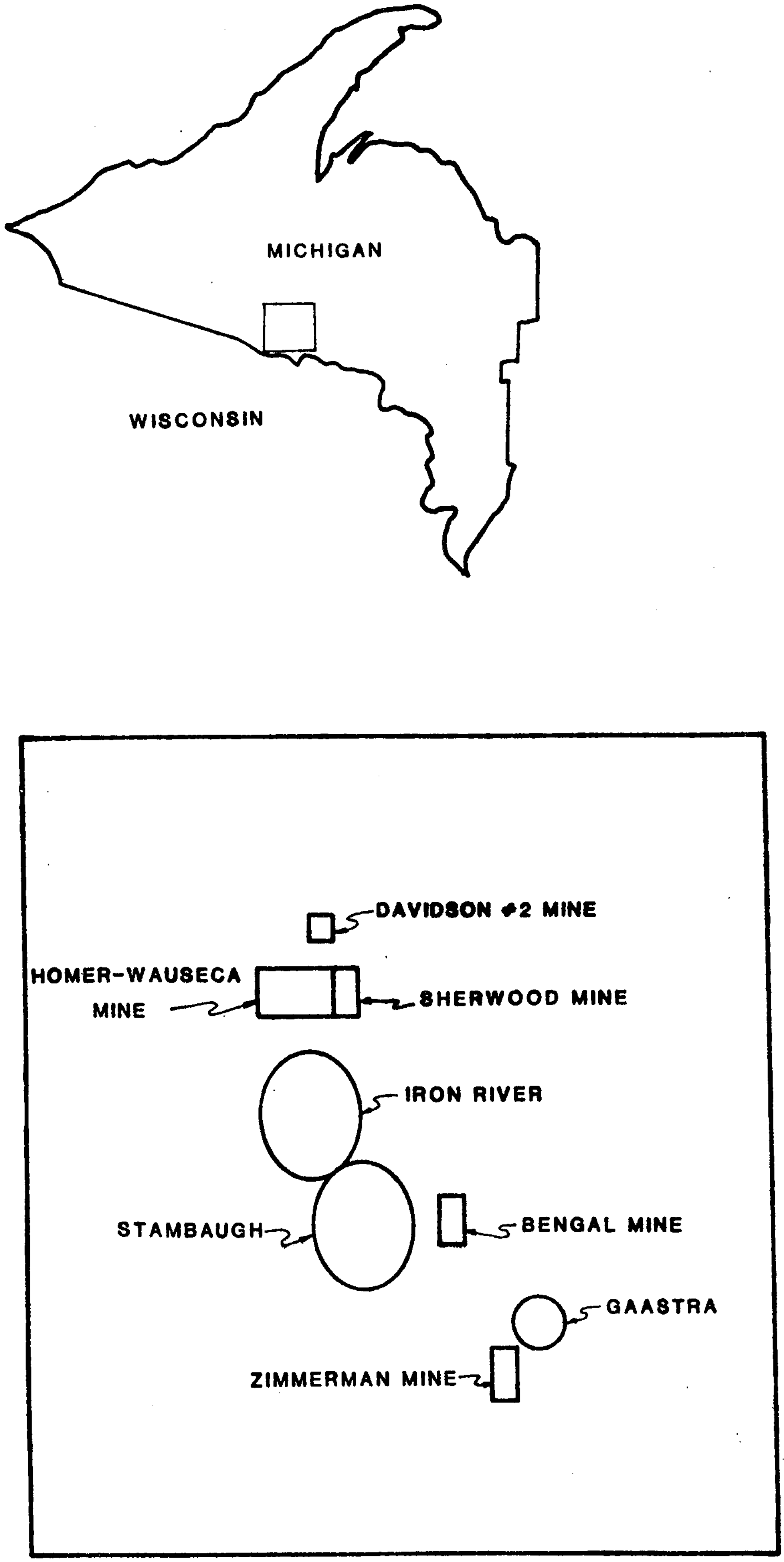
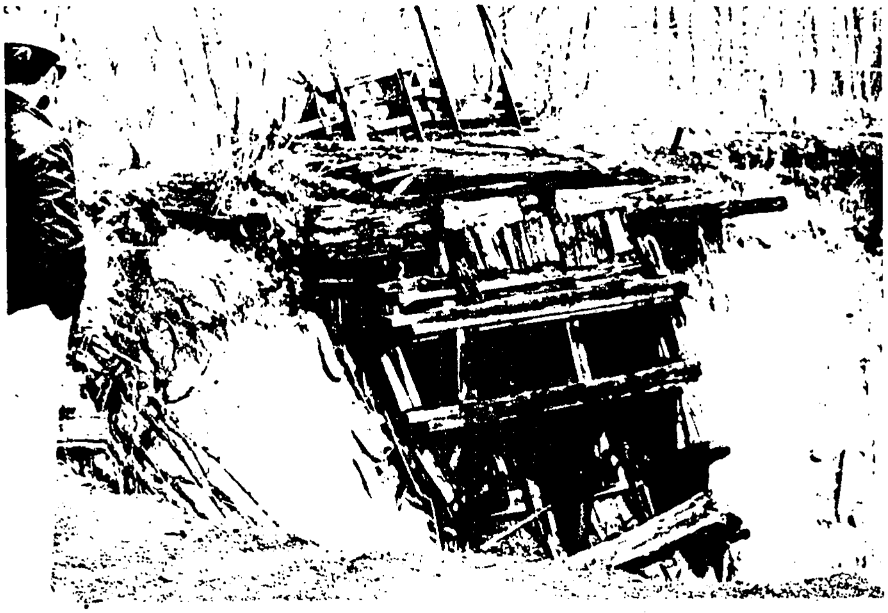
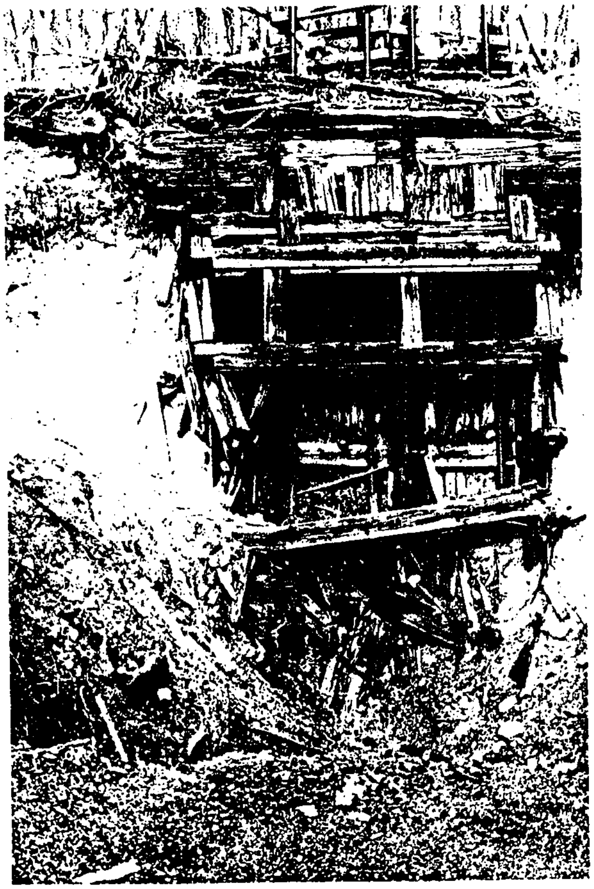


Figure 36. Mine Locations in the Iron River District



a. Davidson No. 2 Shaft: Looking Northeast



b. Davidson No. 2 Shaft: Looking North

Figure 37. Photographs of Davidson No. 2 Mine Shaft

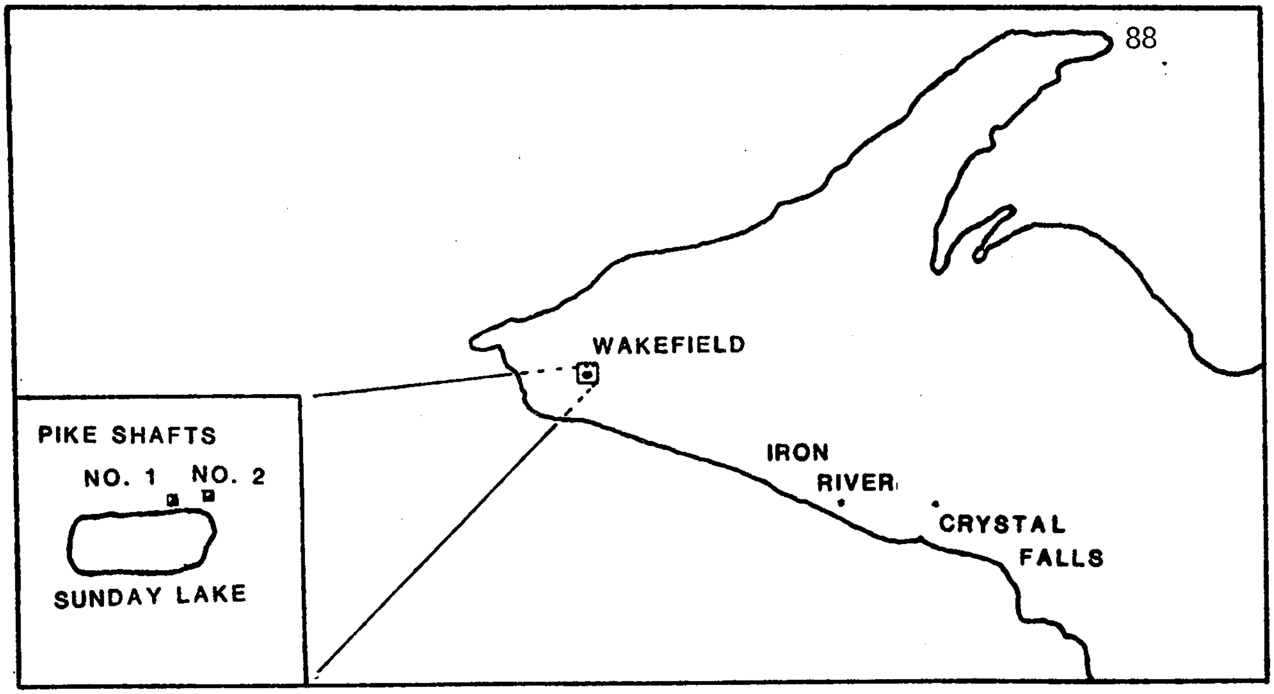


Figure 38a. Location of the Pike Mine

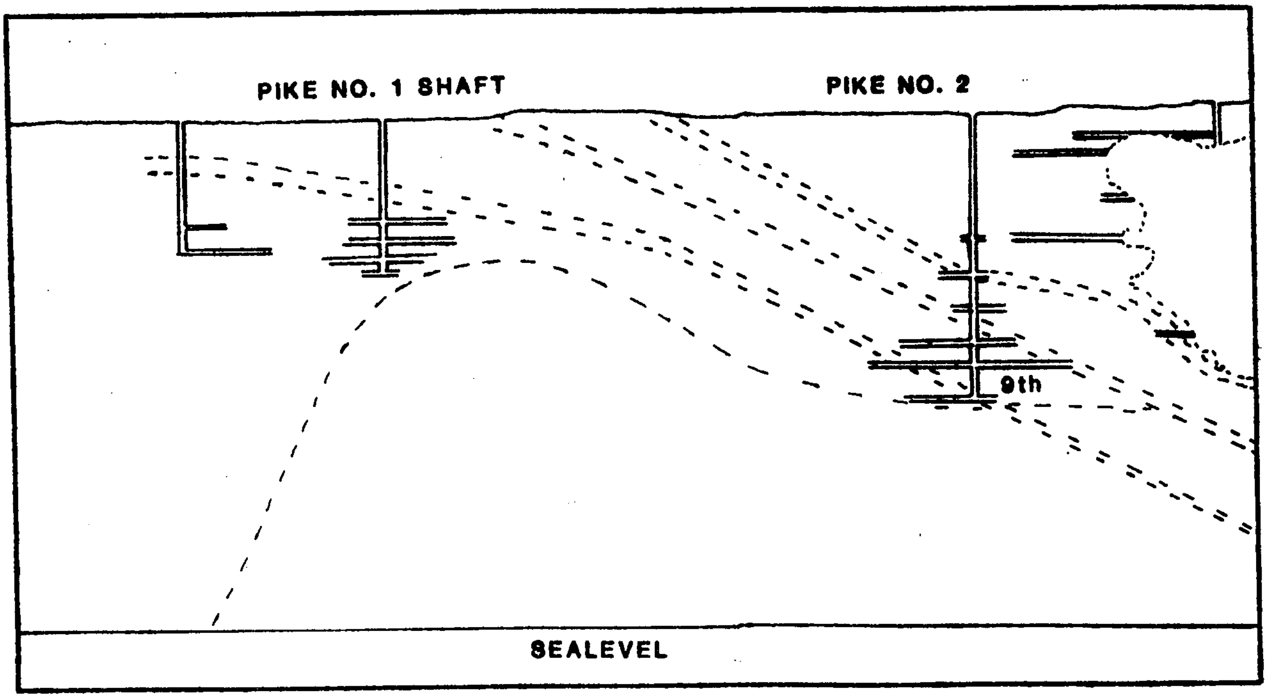
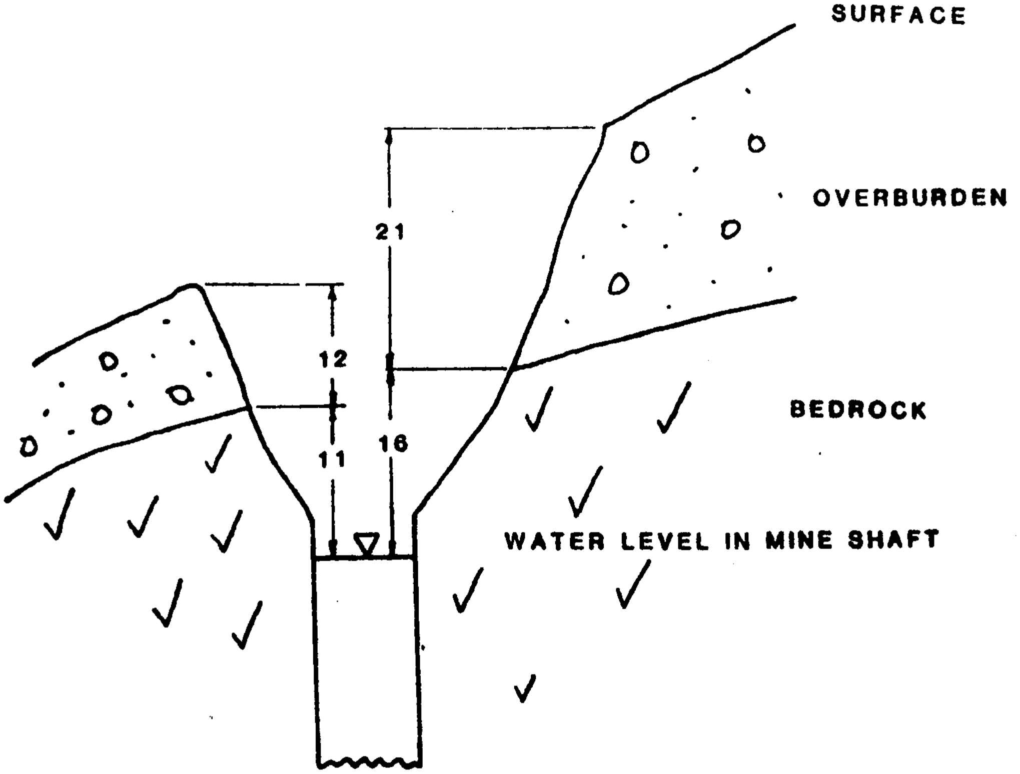


Figure 38b. Longitudinal Section of the Pike Mine

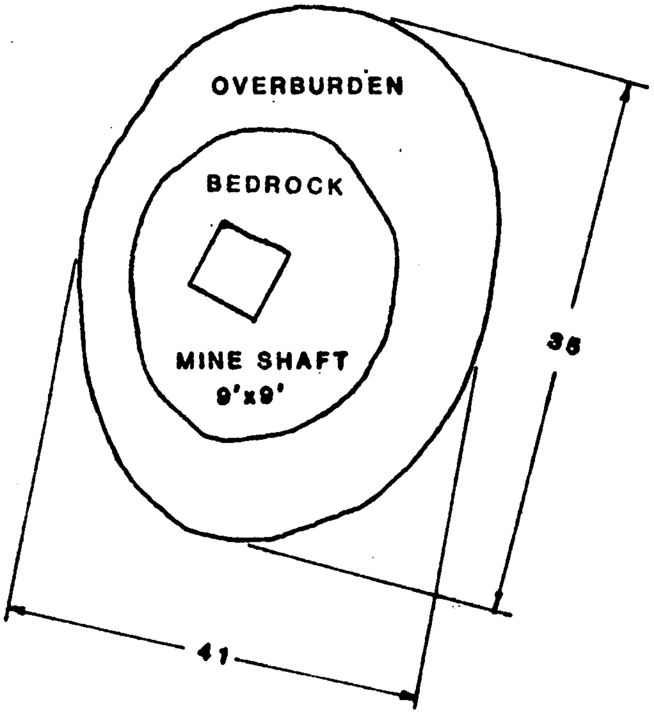
to an adjacent residence. The cave-in produced a cone-shaped pit with steep sides sloping to the 900 foot deep mine shaft. Sketch drawings of plan and cross section views of the surface opening are shown in Figure 39.

The Zimmerman No. 1 Mine shaft capping consists of steel plates of various thicknesses. Although the capping has not failed, the use of steel for a permanent capping is questionable. The mine shaft is located about 3/8 of a mile southwest of Gaastra, Michigan (see Figure 36). The mine operated from 1907 until 1950 producing 3.6 million tons of ore by caving and stoping methods. The vertical No. 1 shaft is 600 feet deep. Records indicate that the shaft has three compartments. From field investigations it was observed that the shaft is capped with three sizes of steel plates, 1/8-inch, 1/4-inch, and 1/2-inch thick. Although it was not possible to determine how the plates are supported, it is likely that steel stringers extend across the shortest dimension of the shaft. Sketches of the shaft and capping materials are shown in Figure 40. Initially, the steel plates would provide a very stong and secure capping except for perhaps the 1/8-inch thick plates on the east side of the shaft. However, with the passage of time, the plates rust and lose strength. A thin layer of soil and moss covering on the steel plates retains moisture which will hasten the rusting of the plates. It is apparent that with time the strength of the capping will deteriorate to the point that the weight of a person can no longer be supported by the thinner plates of the cap. An inadequate fence does little to restrict access to the cap and a serious accident could occur when the steel plates deteriorate sufficiently. The safety of the capping is also questionable from the standpoint of subsidence. Openings in the soil around the shaft indicate that the shaft liner may also be deteriorating.

Failure of shaft protection due to poor or inadequate design. Shaft

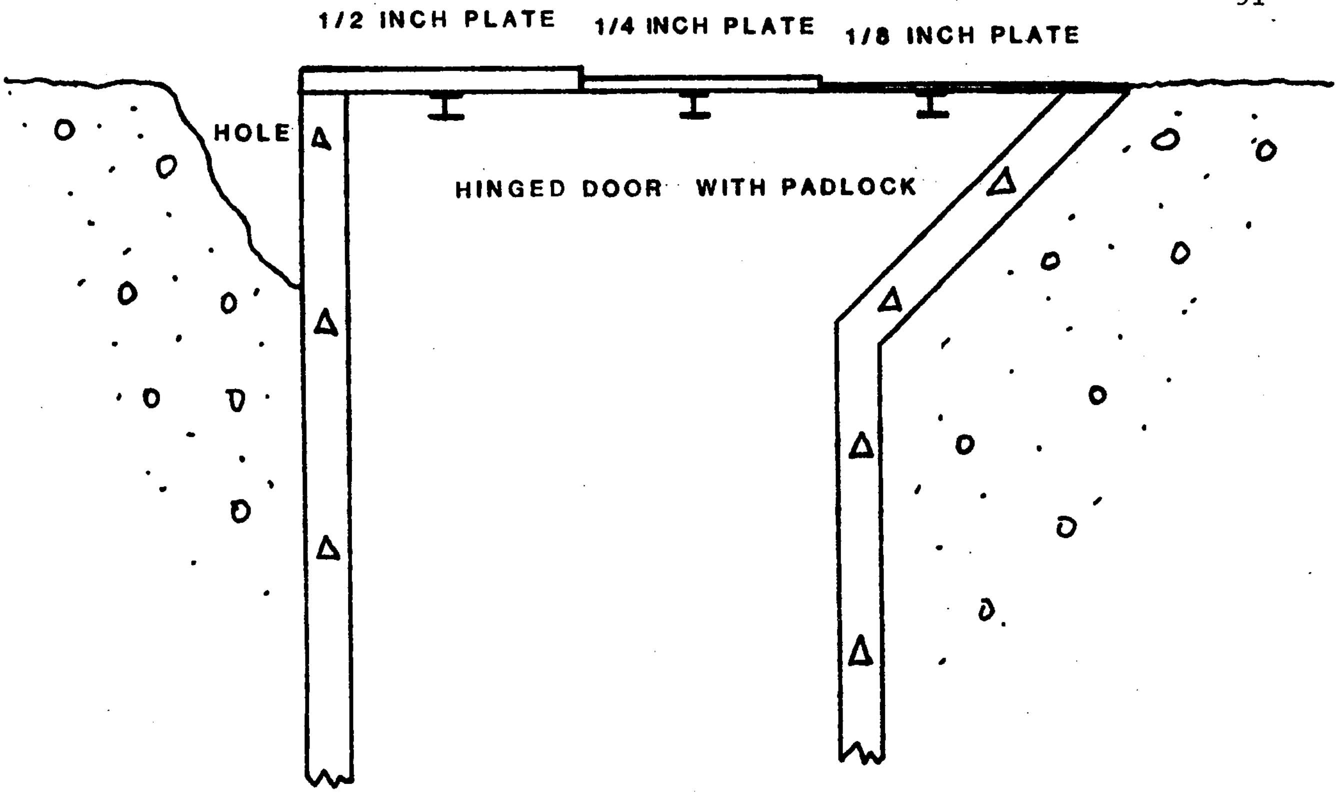


A. CROSS SECTION SKETCH OF PIKE #2 MINE SHAFT : LOOKING APPROXIMATELY NORTHWEST



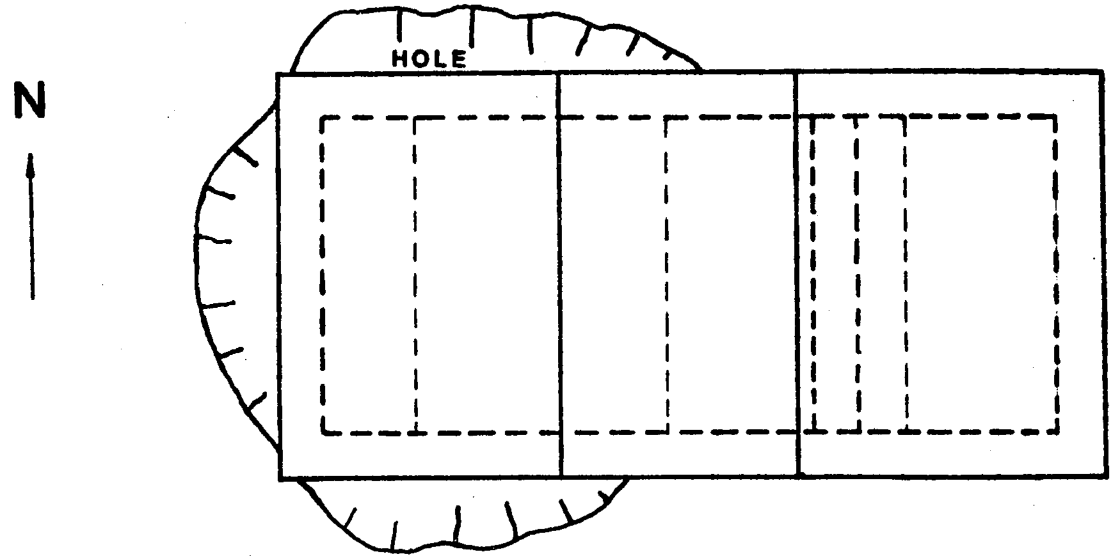
B. PLAN SKETCH OF PIKE #2 MINE SHAFT

Figure 39. Sketch Map Showing Plan and Section Views of the Pike Mine No. 2 Shaft



A. CROSS SECTION SKETCH : LOOKING NORTH

NOTE : NO SCALE, FEATURES SHOWN BELOW THE CAP ARE SURMISED



B. PLAN SKETCH OF SHAFT

Figure 40. Plan and Section Views of the Zimmerman Mine No. 1 Shaft Capping

cappings may also fail because of poor or inadequate design. The case histories presented in this section illustrate this problem.

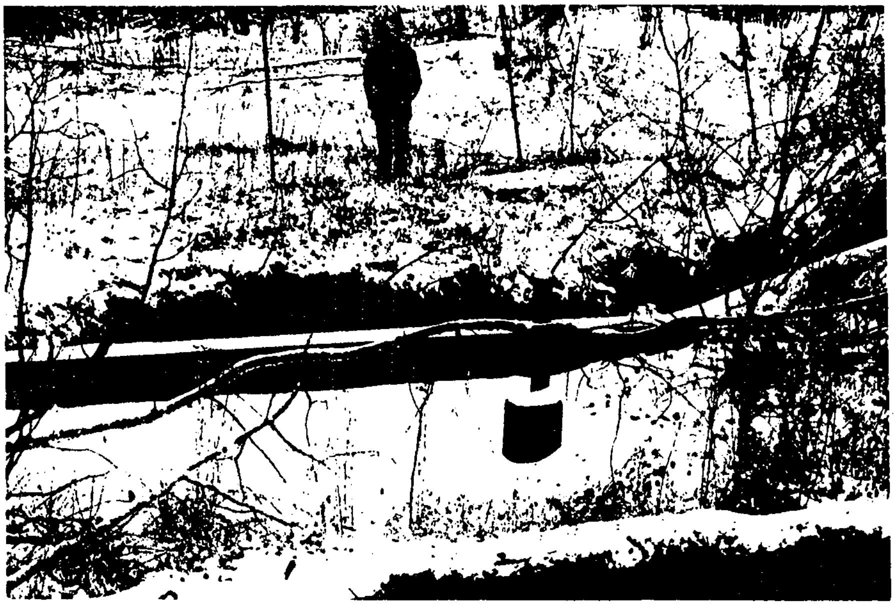
The Cayia Mine is located 2-1/2 miles east of Crystal Falls, Michigan (see Figure 33). Operating from 1951 to 1954, only 45,000 tons of direct shipping iron ore was mined from the 400 and 600 foot levels of the mine. The main shaft is vertical and 653 feet deep.

Following the closing of the mine, the main shaft was capped with a steel and concrete cap that embodies many good features in its design. Heavy steel I-beams set into massive concrete piers beyond the corners of the shaft opening provide the main support. A thick concrete cap apparently with steel reinforcing was poured in place to make the cap a solid integrel unit. A steel vent pipe with a locking cover plate was also provided.

However, the shaft was timber lined through thick glacial overburden. Subsequent deterioration of the timber lining has resulted in surface caving around the concrete cap. When first observed in 1979 the caving had progressed to the point that openings were present on all sides of the shaft allowing one to see down into the shaft. It was observed that many of the shaft timbers were loose and had fallen into the shaft opening. Erosion of overburden from around the shaft had proceeded to the point that the massive concrete piers serving as the main support for the cap were partly undermined. It was evident that the cap might eventually fall into the shaft as the overbruden erosion continued.

Photographs of the cap illustrating the condition of the shaft opening as described above are presented in Figure 41 and 42. These relationships are graphically shown in the sketches of Figure 43.

The Cayia Mine shaft capping, although strong and well designed, failed because no consideration was given to the strength or durability of the



a. Cayia Mine Shaft: Looking North

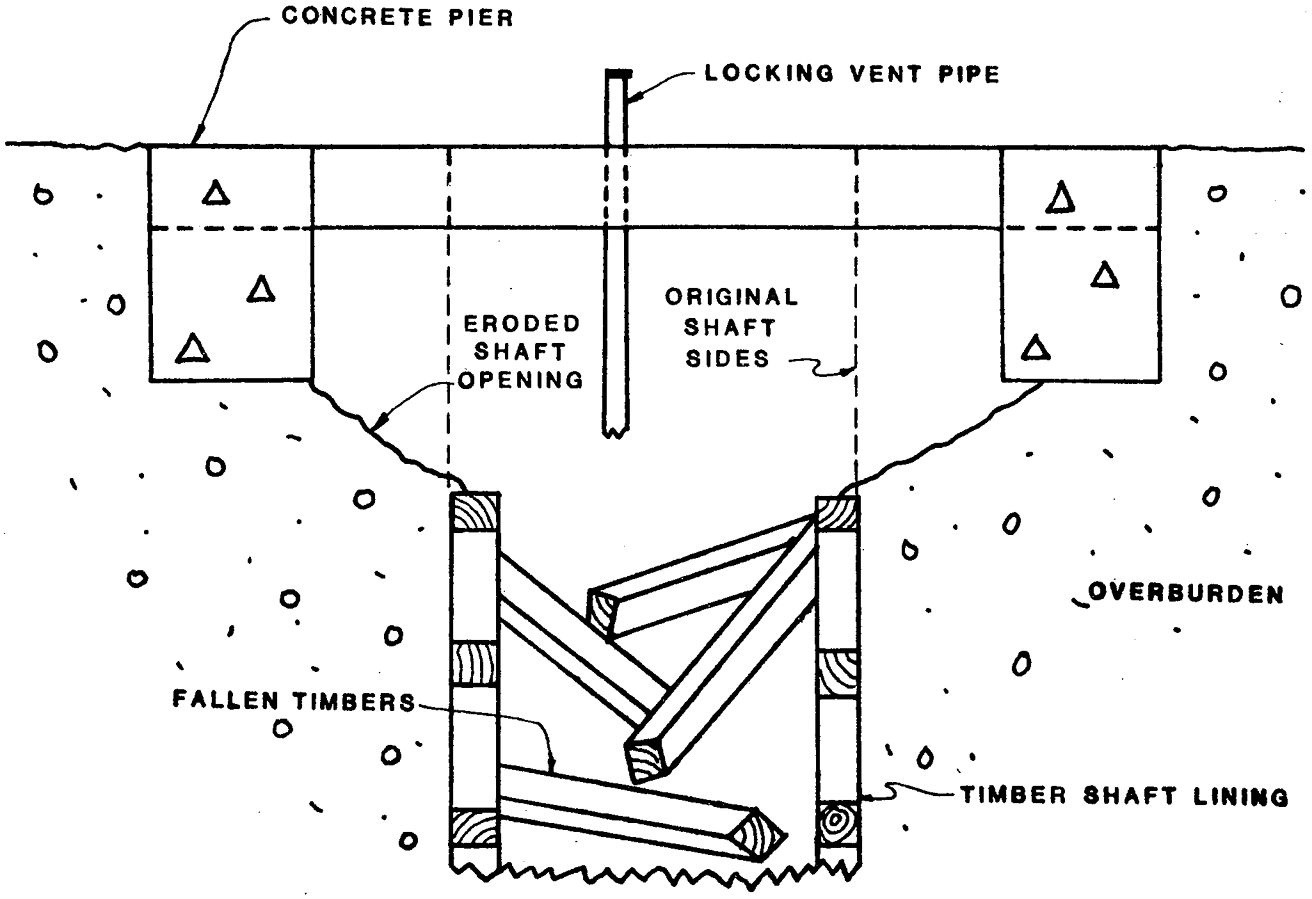
b. Cayia Mine Shaft: Looking Southeast

Figure 41. Photographs of Cayia Mine Shaft

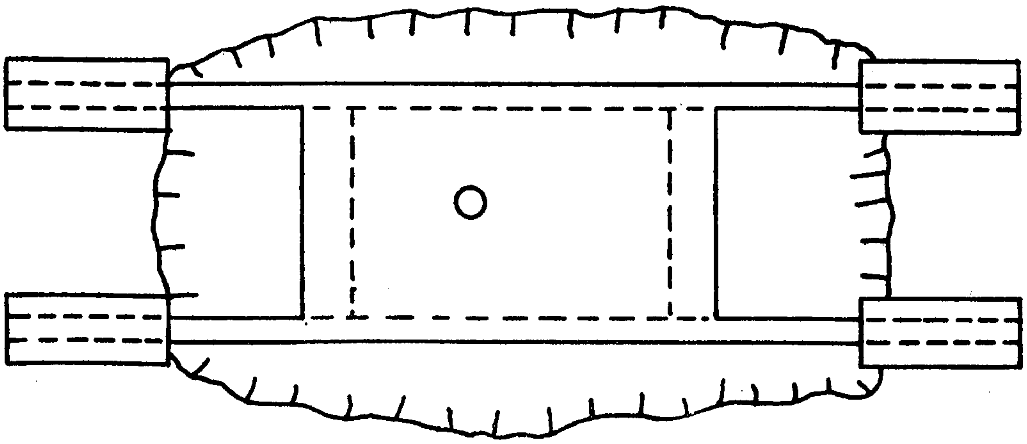
a. Undermined Concrete Pier in Southeast Corner of Shaft

b. Looking Down into the Shaft from Concrete Pier in SE Corner

Figure 42. Cayia Mine Shaft Photographs



A. SIDE SKETCH VIEW OF CAYIA MINE SHAFT NOTE : NO SCALE



B. PLAN SKETCH VIEW OF CAYIA MINE SHAFT

Figure 43. Plan and Section Sketches of the Cayia Mine Shaft Capping

shaft lining. The timbered lining gave way and the overburden around the shaft collar has caved and washed into the shaft. This deterioration will continue, and it is only a matter of time until the capping falls into the enlarged shaft opening.

The Bengal Mine is located in the Iron River district (Figure 36). Operating from 1913 to 1949, 5.7 million long tons of direct shipping iron ore was produced by top slicing and sub level stoping methods. The mine was served by two vertical shafts located east of the ore body. The location of the mine and the shafts are shown in Figure 44.

Following mining the 670-foot deep Number 1 or main shaft was capped at the surface with a massive two foot thick concrete cap. The shaft capping has since failed. Apparently, the three compartment shaft was timber lined through 150 feet of overburden. Failure of the shaft lining in the overburden has caused extensive surface subsidence around the shaft collar and has caused the concrete cap to fall into the shaft opening. Photographs of the shaft capping failure are shown in Figure 45.

Shaft capping failures due to unforseen events. This category of shaft capping failures is actually an extension of the former category of inadequately or poorly designed caps. In the former category both case histories provided examples of the loss of well-designed and strong caps into the mine shaft as a result of overburden caving through a failed shaft liner. The case histories that are presented in this section are the result of forces or mechanisms that are less known. Consequently, to design against such occurrences is difficult. Four case histories are presented which fall under this heading. Three of them document shaft capping failures or shortcomings that resulted from the hydraulic event which took place at the Sherwood Mine on April 1, 1981. This event occurred when the

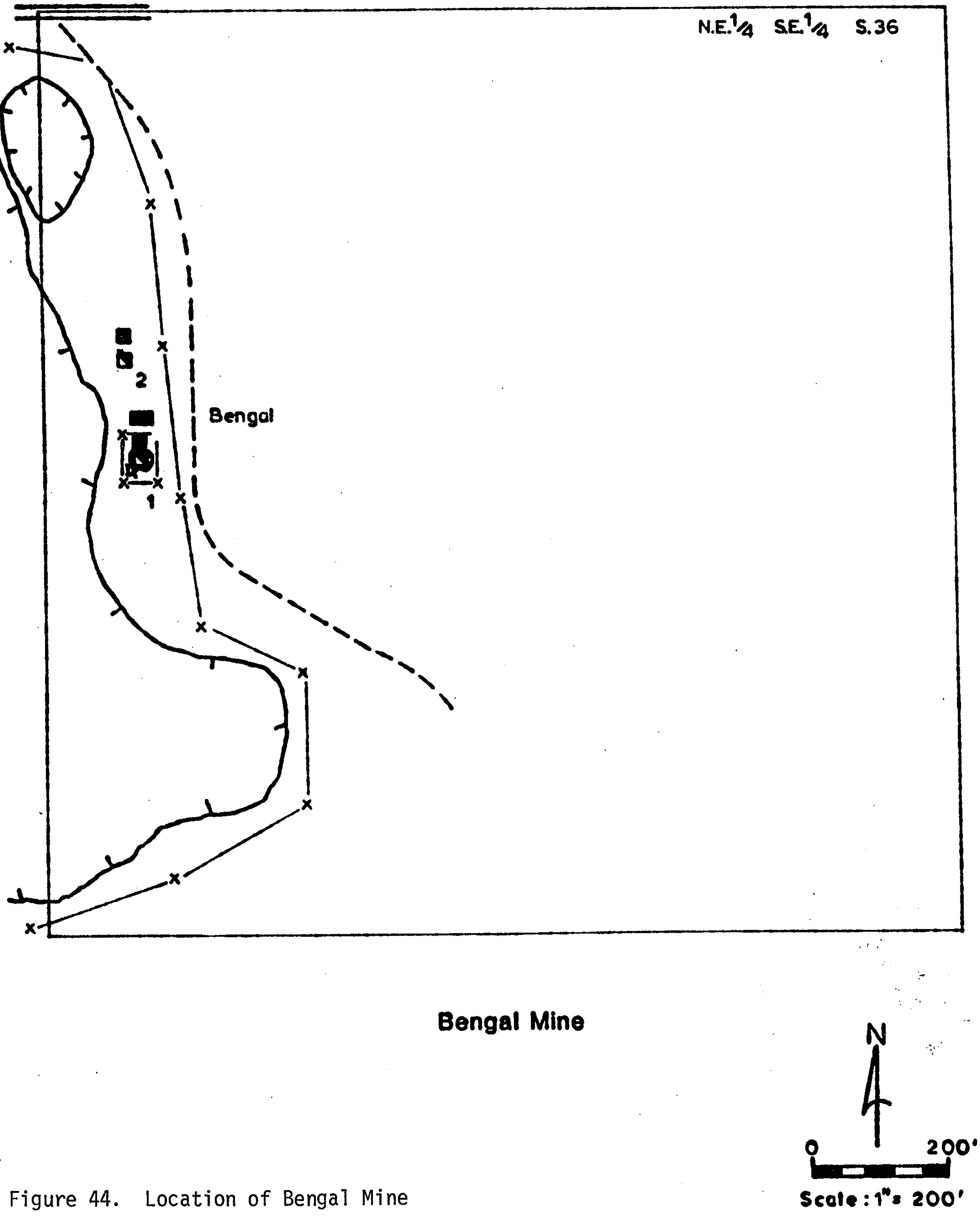
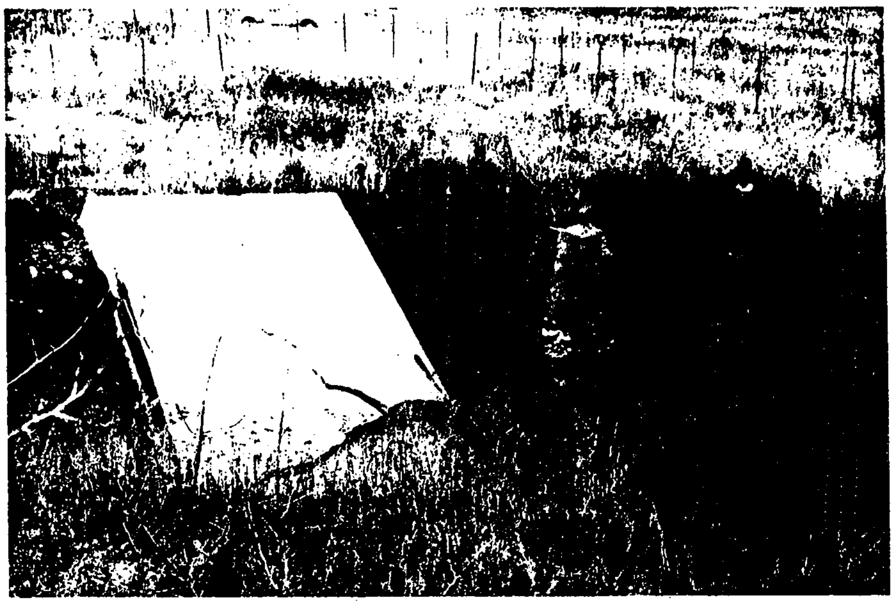
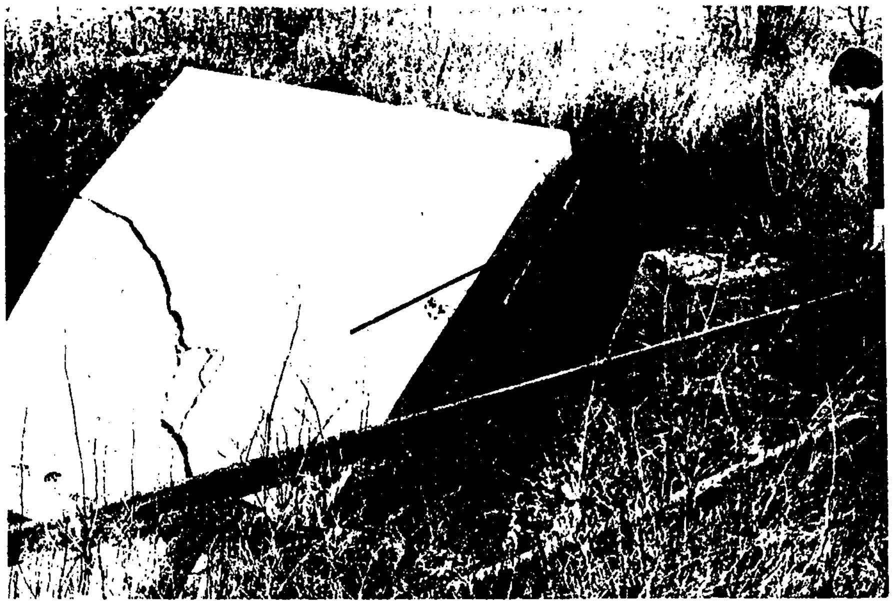


Figure 44. Location of Bengal Mine



a. Bengal Shaft: Looking Northeast



b. Bengal Shaft Capping: Looking Northwest

Figure 45. Photographs of the Bengal Mine Shaft

Sherwood Mine and associated mines of the complex were nearly flooded. An infall of surface overburden or rock is believed to have generated high pressures in the nearly flooded mine which caused surging waters and triggered other subsidence events throughout the mine. These surging waters disrupted or circumvented several shaft seals and caps. Details of the hydraulic event were presented in the earlier subsidence section of this report. More detailed documentation is available in a report prepared by Johnson and Frantti (1983b). The following case histories are extracted from that report largely as field notes made by Johnson. The affected shafts include the Homer-Wauseca, the Minkler and the Sherwood air and main shafts. Their locations are shown on the plan map of Figure 46.

Homer-Wauseca Mine shaft. The Homer-Wauseca Mine shaft and associated dry and mine buildings are presently being used by McPhearson Company as offices and shops for diesel engine repair and servicing. During the evening of April 1 or the early morning hours of April 2, large quantities of muddy water issued from the periphery of the shaft collar at the dry level and partially flooded the old dry area which had been converted into shops. It appeared that mine water had been forced up the shaft circumventing a concrete seal which was emplaced about 30 feet below the shaft collar. Based upon a description of how the seal was constructed provided by Mr. David McPhearson, I concluded that water under very high pressure had forced its way to the outside periphery of the circular shaft and through the soil overburden next to the shaft to the surface of the dry level. The route through the shaft collar was presumably provided by holes cut into the concrete liner of the shaft for steel I-beam supports. According to Mr. McPhearson a 5-foot thick concrete seal was poured in place over the I-beam supports. A cross-sectional sketch of the seal and likely path of the water is shown in Figure 47.

Minkler shaft. The Minkler shaft is located a short distance west of the Sherwood Mine property (Figure 46). No water was forced from this capped shaft, however, a small blowout of soil was observed on the north side of the concrete cap as shown in the photographs of Figure 48. Apparently, high air pressure caused the blowout. I believe the sudden rise of water in the shaft compressed the air. No other damage was observed.

Sherwood Mine air shaft. Extensive damage was done to the concrete capping over an air shaft at the Sherwood Mine. The air shaft is located about 300 feet north and slightly west of the Sherwood Shaft (Figure 46). The ground surface around the shaft had been visibly scoured and channeled by water forced from the mine. The surrounding area of about one to two acres was muddy and a large shallow pond of water covered the area north and east of the shaft.

The recently poured concrete cap, some 14 inches thick and about 20

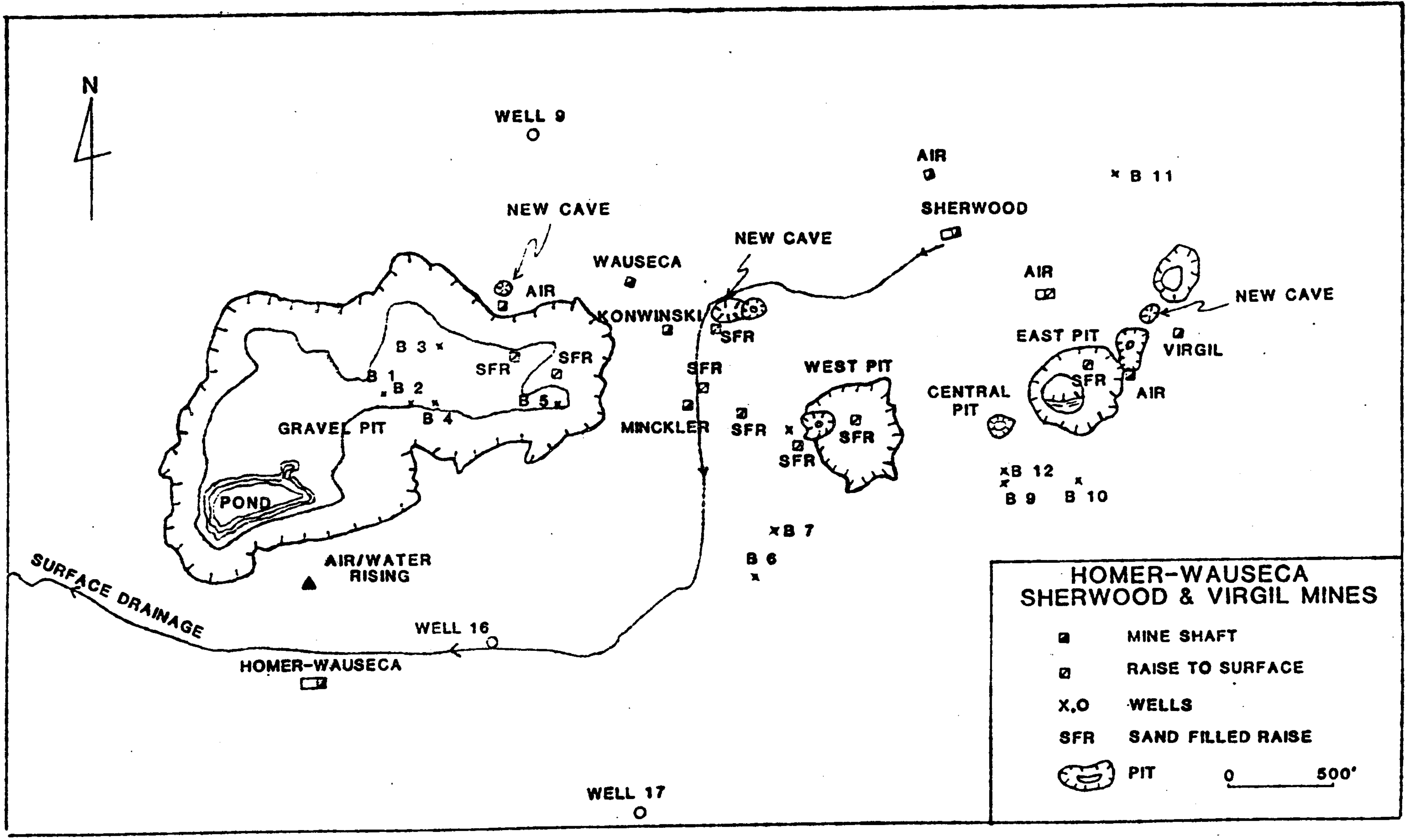
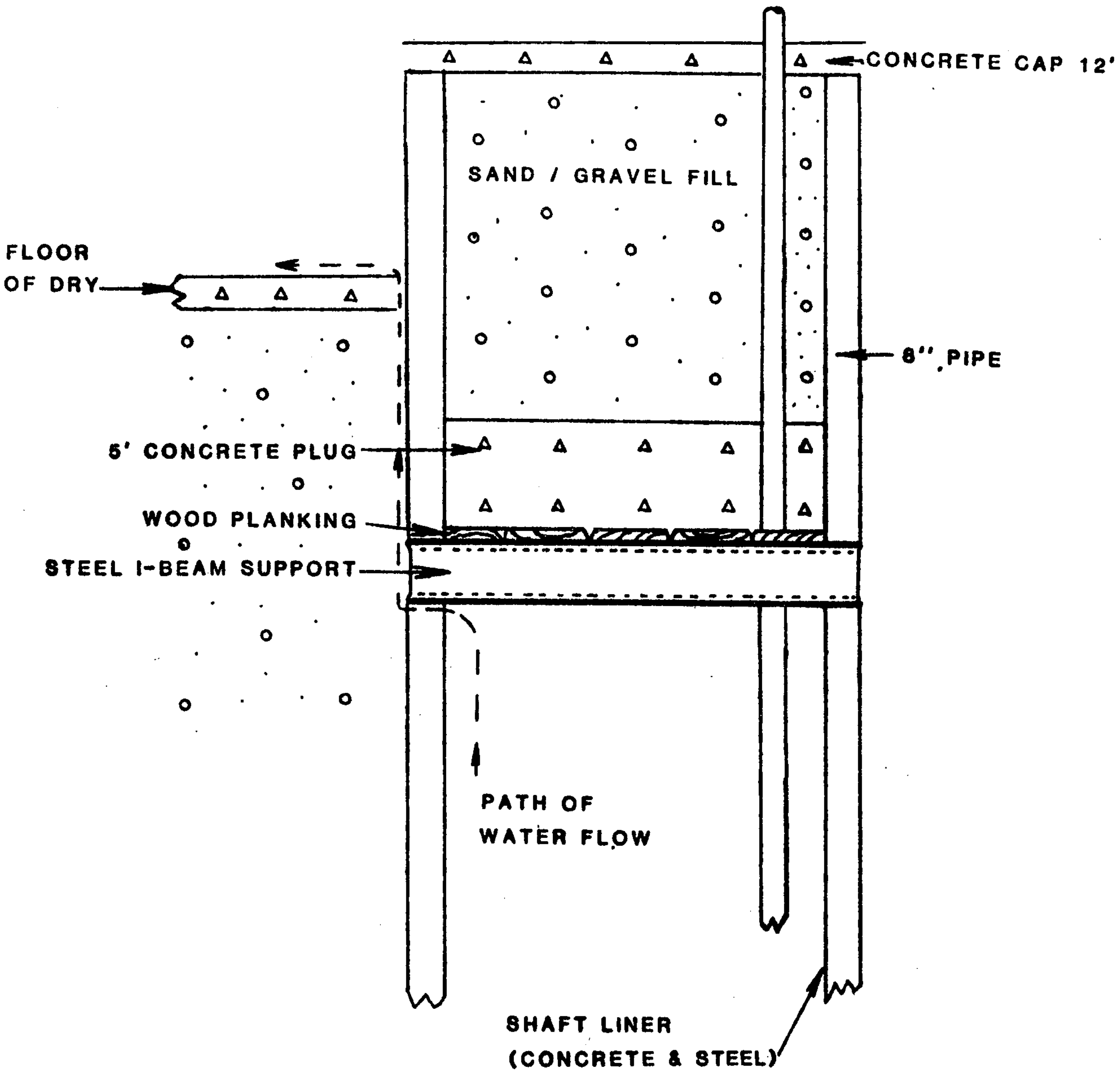


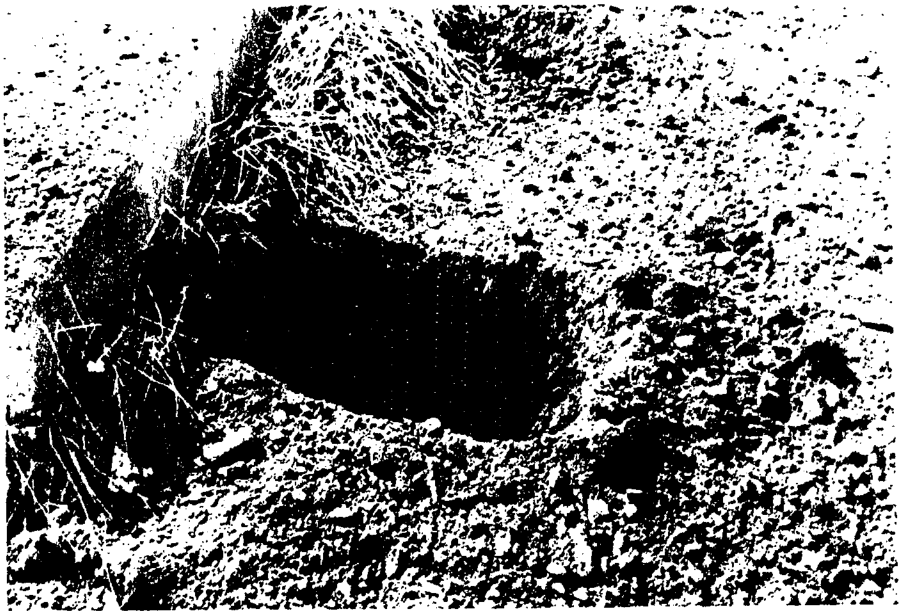
Figure 46. Locations of Surface Features at the Sherwood Mine Complex Including Subsidence Features Resulting From April 1, 1981 Event.



CIRCULAR SHAFT 16' DIAMETER

Figure 47. Cross-Section Sketch of Homer-Wauseca Shaft Seal

a. Minkler Mine Shaft, Looking Southwest: Note Soil on Near Corner of Shaft Capping



b. Blow-out near Northeast Corner of Minkler Shaft Cap. The Hole is about one foot in Longest Dimension

Figure 48. Photographs of Minkler Shaft

feet square had not only been lifted and moved a short distance, but the cap was cracked. Apparently the force of rising water in the shaft lifted the cap and caused it to break. The cap was raised several inches in the center along the fracture. A great deal of soil erosion was evident under the lifted margin of the cap. The erosion was apparently caused by a large volume of water forced out from the shaft. Photographs of the damaged cap are shown in Figure 49.

Wires and cables connecting underground extensometers and acoustic emission sensors in the mine and wired to surface recorders were destroyed. It should be noted that this capping was temporary. It had been installed as a temporary capping so that cables connecting underground sensors to the surface could remain in service. The shaft was subsequently backfilled to the surface and a new cap was poured.

Sherwood Mine shaft. No visible damage was done to the Sherwood Mine shaft excepting the water level measuring device which had been suspended in a 10-inch diameter pipe extending into the shaft. The pipe was used previously for mine water pumpage. The sensor leads were lying in a tangled pile on the concrete cap. A small wooden shed that had sheltered the water level sensor was lying on its side a short distance away. Abundant ferric hydroxide precipitate (yellow boy) scale was observed on and around the mine cap. A long plume of yellow boy stain was noticeable on the surface extending in a southeast direction from the cap. It contrasted sharply with the black slate waste rock present over much of the surface. It was apparent that a geyser of water had been forcibly ejected from the shaft through the pipe. The yellow boy scale was apparently from the pipe walls and was stripped by the high velocity flow of water. It is not known how high the water was forced, but an indication of great height was suggested by the length of the yellow boy plume. Local residents reported high northwest winds blowing during the night. Yellow boy mud was found on automobiles parked more than one eighth of a mile away downwind at the Virgil location (Figure 46).

The Monongahela Mine is located about 1-1/2 miles southwest of Crystal Falls, Michigan (Figure 33). The mine was opened as part of a larger mine complex with mines to the north and south. Records show a total production of 1.35 million tons of iron ore from the Monongahela Mine.

The shaft serving the Monongahela Mine is vertical and 633 feet deep as scaled from mine maps. The shaft is flooded to very near the collar elevation. Matted grass south of the shaft indicates that water occasionally flows from the shaft in this direction. The shaft is capped with concrete reinforced with steel rails. The concrete cap is 16 feet by 16 feet and about one foot thick. The data marked in the concrete of the cap is October 21, 1963. Since that time, some disruptive event has caused

a. Lifted Shaft Capping: Looking South

b. Looking Approximately West

c. (to right) Close-up: Looking West

Figure 49. Photographs of Sherwood Mine Air Shaft

the capping to be raised, split down the middle and separated by about three feet. A photograph of the shaft capping is shown in Figure 50. The cap separated because the reinforcing steel rails were imbedded in the concrete in only one direction. It was initially believed that freezing of water in the flooded shaft may have caused it to be lifted, resulting in the crack and separation. However, following the hydraulically triggered subsidence event at the Sherwood Mine as previously described, it was recognized that a similar event could have caused the damage to the Monongahela shaft cap.

If subsidence occurred in the Monongahela Mine or one of the interconnected mines of the complex, hydraulic forces could have been generated which could have easily lifted, ruptured and separated the cap. A hypothetical sketch showing this sequence of events is shown in Figure 51.

The striking similarity of the Monongahela shaft capping shown in Figure 50 to the Sherwood air shaft cap photos shown in Figure 49, strongly suggest that a hydraulic ram effect may have also been developed in the Mononghela shaft. The fact that the Monongahela Mine shaft is flooded to the surface and that a number of mines in which subsidence was possible form the complex, are further evidence of a circumstantial nature that support this contention.

With the recognition of this new mechanism of mine shaft capping disruption it is probable that many more similar cases can be found in other mining districts having similar physical attributes; i.e., flooded underground mines with a history of subsidence.

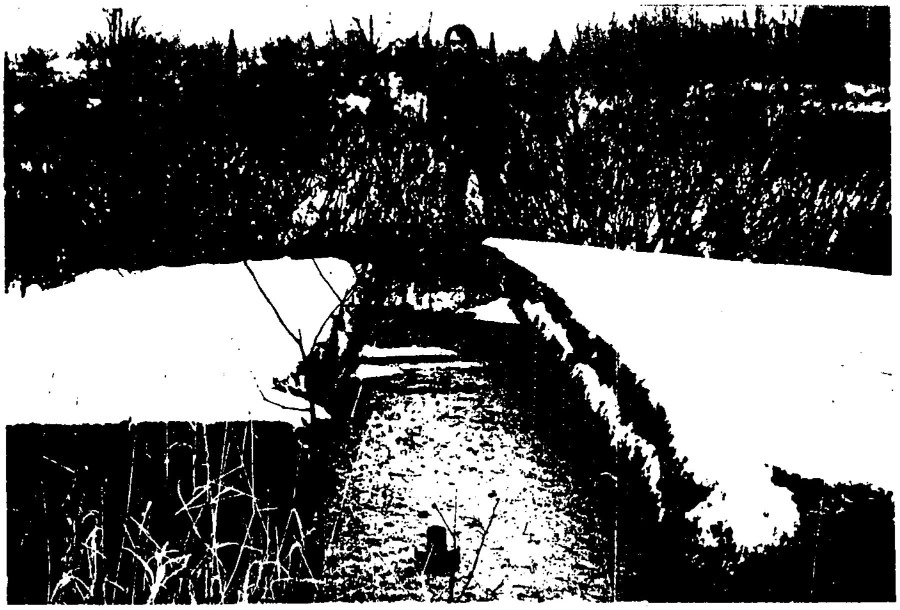
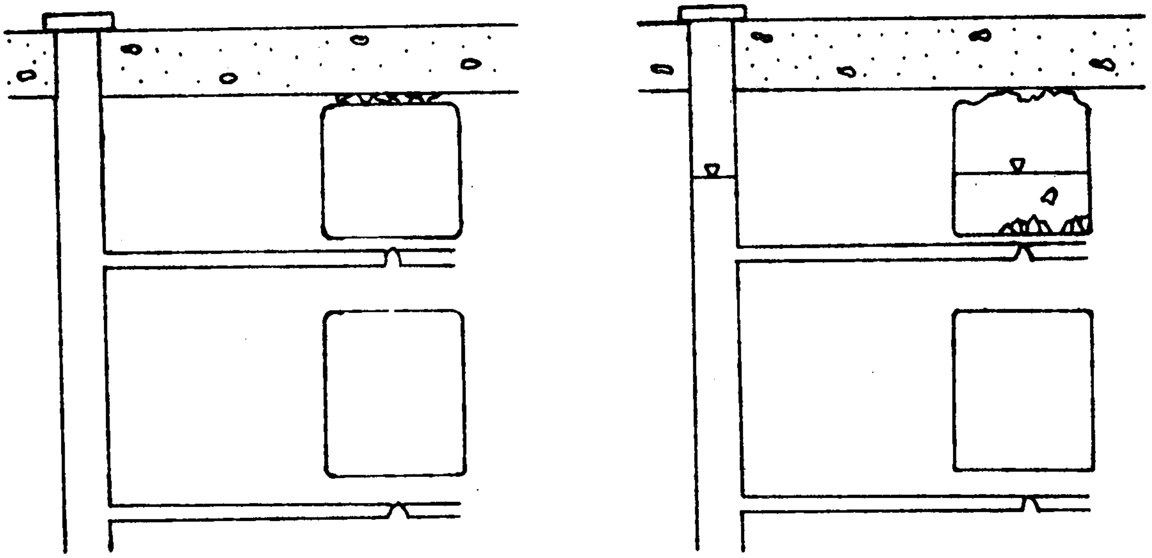
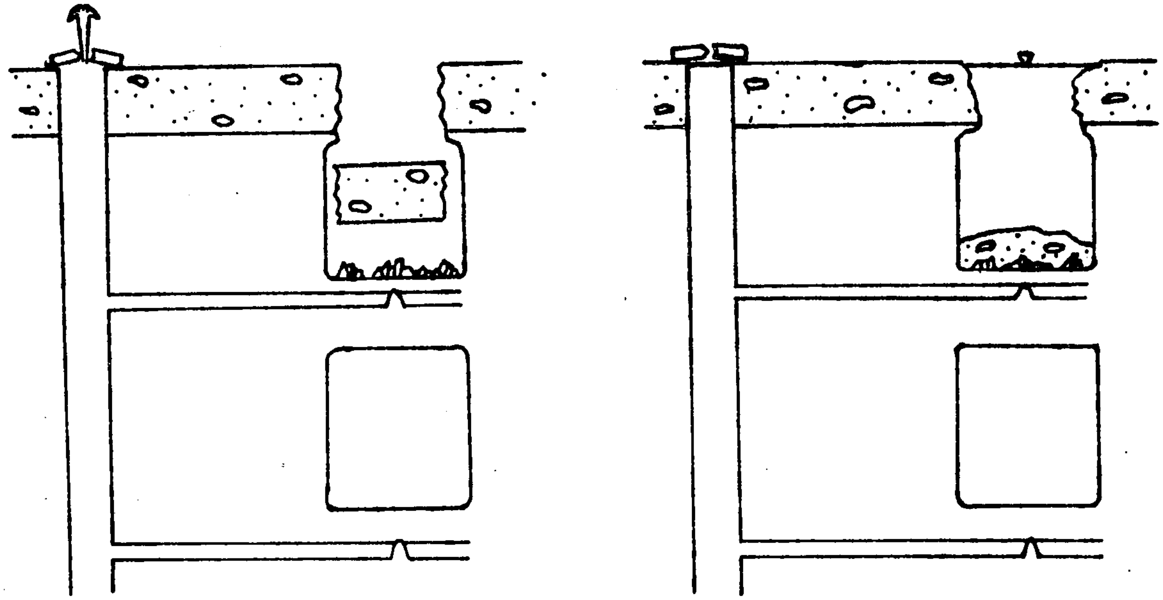


Figure 50. Photograph of Monongahela Shaft Capping



A. Mine shortly after ceasing operation; shaft capped, mine not flooded.

B. Mine nearly flooded, sloughing of back in upper stope implies imminent surface subsidence



C. Subsidence occurs. Large mass of falling overburden generates hydraulic forces in mine which disrupt cap and create temporary geyser effect.

D. Subsidence no longer active, mine flooded to equilibrium level, mine shaft capping disrupted.

Figure 51. Sketch Diagrams Illustrating a Hypothetical Sequence of Events Proposed for the Disruption of the Monongahela Shaft Capping

DISCUSSION OF FINDINGS

Three different types of problems resulting from underground mines in a Michigan iron ore district were identified and illustrated by case histories. The problems include mine subsidence, acid water drainage and problems resulting from inadequate shaft sealing or capping measures. In some respects these problems and the data that were developed from them are specific to the mines of the West Menominee Range or to mines in other districts with similar physical characteristics; i.e., steeply dipping ore bodies that were mined by caving and/or stoping methods, a thick glacial overburden with abundant water, acid drainage from the presence of pyrite and mines that become flooded when mining ceases. Although the case histories are specific to the district, they do represent a sufficiently large number of occurrences to make the observations statistically valid. Furthermore, the case history method may be considered as an experiment in which the variables are not manipulated. So, if the data are interpreted properly, the conclusions are of real use. Furthermore the mechanisms of subsidence and the chemistry resulting in acid water drainage are universal. Thus, although the lessons that can be learned from the study of case histories in a mining district may not be complete, they are significant. The subject lessons are presented in the same order that the case histories were presented in the text; i.e., 1) subsidence 2) acid water drainage and 3) deficiencies in mine shaft cappings and seals.

Subsidence

Three classes of subsidence were identified including; 1) subsidence that occurred directly as a result of mining; i.e., from the use of caving techniques 2) short term subsidence which occurs between the time that the mine ceases operation and ends when flooding is complete, and 3) long term or delayed subsidence which includes all subsidence occurring after the mine floods with no limit on the timing of subsidence. Of these three classes of subsidence, case histories were presented of only the last two, the results of which will be discussed in greater detail.

Short term subsidence. A number of mechanisms involving the role of water during mine flooding were identified from the case histories that were provided by a study of the closing of the Sherwood Mine. The mechanisms were:

1. Reduction of friction in fault or shear planes resulting from rock mass movement occurring by direct lubrication or through elevated hydraulic pressures in the fault plane.
2. Water loading which may induce movement of blocks which may have a record of previous movement.
3. Erosion of surface material (sand, clay, gravel, silt) into the mine via the force of running water. An example in the case history was repeated shear failure of a sand plug in a previous subsidence pit.
4. A special case of the inwash of glacial overburden or soil from the bedrock/soil interface by piping. Piping under these conditions produces hemispherical cavities in the soil above the bedrock. The cavity may or may not result in surface subsidence. The presence of a competent capping of glacial till at the Sherwood Mine site apparently allowed the cavity to assume a large size without collapsing until the failure was triggered by surging waters in the nearby flooded mine complex.
5. A hydraulic ram mechanism was also documented. Its major effects

were to disrupt shaft cappings and to trigger secondary subsidence activity as water under high pressure surged through the mine complex. Available evidence suggests that this mechanism may be initiated by falls of large masses of rock or overburden sands into a flooded mine complex; i.e., an initial or triggering subsidence event.

If subsidence events as those described above are anticipated upon mine closure, it may be possible to avoid them or to reduce their effect by controlling mine flooding. Instead of letting the mine flood naturally; i.e., movement from groundwater and surface water reservoirs through prexisting routes into the mine, flooding could be accomplished by pumping water into the mine from the surface. In effect, this would amount to reversing the pumps and filling the mine from the bottom up. If the mine was flooded in this manner the lubrication and hydraulic pressuring of preexisting fault planes could be lessened. This method would greatly reduce water loading of rock mass blocks before the mine voids were filled with water, thus effectively reducing the stress differential that might otherwise cause their movement. Additionally it would eliminate sand washing into the mine reducing greatly any possible piping activity or sand runs.

However, even though uncontrolled water flooding may result in surface subsidence this may provide a greater degree of stability for the mine. For example, sand washed into mine stopes reduces the volume of the mine openings and reduces the potential for futher subsidence. Similarly, any rock mass movement lessens the potential for subsequent movement. In fact, if the uncontrolled stope filling that may occur naturally by sand washing and piping during mine flooding was enhanced, a greater degree of mine stability would result. This control could be achieved by providing openings into selected areas of the mine by drilling and blasting. Water could be allowed to flow through overburden into these areas so that piping was enhanced. Further enhancement could be achieved by pumping.

Long term subsidence. In many respects this is the area of most concern for the timing of subsidence cannot be accurately predicted without monitoring. There are no easy solutions to eliminating long term subsidence potential that are affordable and practical. Under special conditions, mine backfilling or daylighting may be considered, but the costs are high and the results not always are as expected. The most practical courses of action are those that attempt to reduce the impact of any eventual subsidence. For example, in the case history of the Smuggler Mine cave—in that resulted in a traffic fatality, it is easy with the aid of hindsight to say what should have or should not have been done to avoid the accident. Open stope mining should not have taken place so near to the bedrock surface. If backfilling was attempted it should have been done more completely. The road should not have been built or improved over this obviously dangerous area. Why did this series of events take place? No one would assume that a road would be built over a mine void that was likely to result in surface subsidence. The logical answer is that the highway engineer either did not know of the mine void or thought that backfilling in the area had corrected the problem. In the former case he would have had no knowledge of the presence of the void and in the second he would have been guilty of an error in judgement. It is useless to speculate on the actual reason, but what is important is that tragic and costly accidents resulting from mine subsidence be avoided. One may argue correctly that such accidents are rare and that with current laws and regulations that they will become even less likely. The problem with this line of reasoning is that laws and regulations do not prevent naturally occurring events from happening -- they merely make their occurrence illegal and subject to penalty of law. For example, the law may state: "Roadways shall not be built over or near undermined areas where surface subsidence may occur, nor shall prexisting roads be made hazardous by any subsequent mining, under penalty of law". This would be a reasonable law, but unless it is "obeyed" it is a meaningless concept, except as a vehicle to assign responsibility, and fix penalties. To "obey" such a law the road builder would have to know with a fair degree of accuracy where the undermined areas were. We will assume that the mine operator knew where his workings were with relation to the surface. With or without the law neither of these professionals would have knowingly violated the common sense statement that is presented in the hypothetical law. Thus it is concluded that laws in themselves cannot prevent tragic subsidence events from occurring, although they do make it illegal. Rather it is the availability of accurate information on the location of mine voids that would avoid accidents like the Smuggler Mine case history in the future.

In recent work by Johnson and Frantti (1978) and by MacDonald and Johnson (1983), in-use surface structures (roads, buildings) that are underlain by mine workings in Iron County, Michigan were identified as "critical areas". It is of interest to note that 11 critical areas were identified in the Iron River district and 5 were listed for the Crystal Falls district. None of them are considered as prone to subsidence as the Smuggler Mine area, but this cannot be stated with any degree of reliability.

It is recognized that subsidence is most likely to occur when open stopes lie close to the bedrock surface so that the roof pillar is thin.

Subsidence is much more likely if the pillar is highly fractured, severely distressed or otherwise made less competent. The condition of the roof pillar above the Smuggler Mine would probably have been placed in this category. Vibrations from automobile and truck traffic probably weakened it further and may have triggered the collapse. The point is, unless evidence is present to the contrary, one cannot say with any degree of confidence what condition a hidden mine void is in or even know its position. Spalling from a fractured roof can cause the opening to chimney or migrate upwards; or overburden may be lost into a mine void if a channel exists so that the hard capping surface of a road may temporarily bridge a cavity until the road is collapsed by a vehicle too heavy to be supported by the pavement.

The best approach to dealing with existing mine openings is to have them accurately mapped. This is not possible with many early mines for which no maps are available — either never existing or lost. However, for new mine closures, accurate maps should be available. The maps should reflect the most recent mining development. Plan maps of the surface and of each level, plus longitudinal and cross-section maps should all be available. The scales should be uniform. It would be helpful to prepare a composite plan map showing the limit of the mine openings projected to a surface plan map at a scale suitable for planning purposes. It would also be useful to preserve information on zones of bad ground where subsidence may be likely to occur. The maps should also identify major slips or shears and areas of water inflow. Any bulkheads or seals installed in the mine that would restrict water flow should be marked on the maps and information concerning how the seals were constructed should be provided. If there are connections to any other mines, they should be noted. The details of all shaft capping and sealing procedures should be carefully and accurately documented complete with drafted engineering figures. The types and amounts of materials used in constructing the seals and caps should be listed. If backfilling or stope filling was practiced the method and amount of filling should be recorded. If the stopes were sealed, this should also be documented.

If subsidence occurred at any time during the mine operation, detailed reports on its occurrence, extent and periods of activity should be recorded. Photographs would be helpful.

The person or persons who gather or provide this information should be identified so that if clarification or further information is needed, they may be contacted.

The mining company should prepare this information as a single bound document (not in loose leaf form) for their permanent files. If the mining company continues to hold and control the land they should, as a courtesy, provide copies of this report to mine inspectors, and to agencies with responsibilities for land use decisions such as highway departments and local governmental offices. If copies are not provided to libraries, the existance of the document should at least be recorded. If the land will no longer be held, the company has the responsibility of providing this information to the new owner.

A certain degree of risk or liability may accompany the preparation of such a document and a greater degree with its distribution. If the regulatory agencies or their representatives wish to have a good working relationship with the mineral producers, they should formally and officially recognize their responsibility in earning this confidence. If it is not recognized it will never be earned and even if required by law, the quality of the information and cooperation will not be as great. This is one area in which improvement can be made.

Acid Water Drainage

Case histories were presented which illustrated two types of acid mine drainage; 1) drainage from an underground source and 2) drainage from a predominately surface source. Findings and conclusions from these studies are presented separately.

Underground source of acid drainage. Acid water drains from the Dober Mine pit into the Iron River because of groundwater recharge into the interconnected Hiawatha Mines across the river. Flow occurs because the Dober Mine is collared at a relatively low elevation in the Iron River valley compared to the higher elevation of recharge above the Hiawatha Mine. The flow rate is equivalent to the recharge which fluctuates with seasonal variations in precipitation, but averages about 50 gpm.

Acid water is no longer being produced in the flooded mine because no oxygen is available to react with the pyrite. However, a very large volume of acid water exists in the mine and because the shallowest open interconnection is on the tenth level, 1000 feet below the surface, all of the acid water in the upper ten levels will drain from the mine.

This case history was used previously to propose means by which a preclosure mine evalution could be used to determine if acid drainage might occur, how severe it might be and several possible methods that might be used to stop or abate the drainage. The paper by Johnson (1983) recommends that these steps be taken before the mine floods. Possible options to reduce or eliminate acid drainage involve altering the "plumbing system" formed by the mine workings; e.g., 1) installing bulkheads or seals within the mine to break the hydraulic continunity, 2) sealing off areas that could be a source of mineralized water or 3) drilling or drifting to provide new routes for water flow. It was recognized that if corrective steps are not taken prior to mine closure, that the options for correcting mine water drainage problems are greatly reduced, much more difficult to solve, and usually less effective and more expensive. It was recognized that hydrologic planning could be much more effective if it was an integral part of mine planning and operation.

Surface sources of acid drainage. Extensive piles of pyrite-bearing black slate are a source of acid water drainage at the Buck Mine complex in Caspian, Michigan. The waste slate rock covers 19 acres in an area within and adjacent to the flood plain of the Iron River. The pyrite in the piles is subject to oxidation and subsequent leaching by surface and near surface groundwaters which issue from the glacial drift bank on the elevated east side of the slate piles. The mineralized waters flow a short distance from the west edge of the slate piles into the Iron River. The problem is persistent because of the large quantitiy of sulfur present in the slate piles, an estimated 10.2 million pounds of sulfur.

The problems exhibited by this case history are common in old mining operations, particularly coal mining operations, where extensive amounts of sulfide-bearing waste rock or gob is exposed to air and water. The problem can be avoided by not permitting the sulfides to oxidize by keeping them under water away from oxygen, by not permitting leaching once they are oxidized or by treatment of the water after leaching has occurred. Recent studies by Kleinman et al (1978) report on the use of chemical inhibitors to reduce acid drainage.

Current federal and state regulations limit the metal content and pH of effluents from mining operations. Consequently, a great deal of attention is given to acid drainage problems at active mines. Often considerable effort and expense is required to stay within the effluent limits. Given the current emphasis on acid drainage control the type of problem that is found at the Buck Mine complex should not occur in the future. Probably the best method that can be used to reduce the problem at the Buck Mine would be to install a series of holding ponds in which neutralization and aeration would allow the iron and aluminum in the acid water to precipitate and settle similar to the plans being formulated for current work at the Dober Mine.

Deficiencies in Mine Shaft Cappings and Seals

Three classifications of problems were identified in the area of inadequate mine shaft protection; 1) the use of unsuitable materials, 2) poor engineering design and 3) inadequacies due to unusual or unforseen events. Case histories were presented to illustrate occurrences in each of these areas. They will be discussed separately.

Mine shafts protected with unsuitable materials.

Most of the examples used to illustrate this problem included shafts that were capped with wooden timbers or planks. Weathering and rot have caused these caps to deteriorate to a dangerous condition in approximately 25 to 50 years. The untreated wood used for these cappings cannot last long in the humid conditions of northern Michigan. Even during the Winter, snows cover the caps and continual thawing by the heat from the mine water (10 to 15^{O}C) keeps the wood in a saturated condition which enhances rot.

The case history in which a mine shaft was permanently capped with steel plates is another example of the use of unsuitable materials. In a drier climate, the steel may be more long lasting, but in a moist climate, the plates are subject to slow rusting. Moisture from melting snow is in contact with the steel during much of the winter and the accumulation of soil and growth of vegetation (moss, grass) on the plates also holds moisture which hastens oxidation.

The cave-in of the Pike Mine No. 2 shaft was used to illustrate a very common problem in all of the old mining districts in Michigan. In this case heavy wooden timbers had been placed over the mine shaft opening above bedrock and the shaft opening above bedrock had been backfilled and the surface contoured. Thus, there was no surface expression or indication of the shaft location. With time the timbers were rotted and fell into the open flooded shaft along with a large amount of the surface. The resulting steep-sloped pit appeared suddenly surprising many residents. Fortunately, no one was hurt.

Although not cited as a case history, a number of mine shafts in the Keweenaw Peninsula which have caved to the surface in recent years have been backfilled from the surface with old automobile bodies and then bulldozed over with waste mine rock from surrounding dumps. When these auto bodies rust away, the shafts, the position of which has been obscured, will cave again. This is a poor practice.

In many respects the problems arising from the use of unsuitable materials in the construction of mine shaft capping protection are a historic problem. That is, this practice is much less likely to be followed in any current mine closure practices. However, the lessons to be learned from these case histories are valuable, as they illustrate that no material can be expected to last forever; they all have some finite life. Wood, steel and concrete, in that order, are ranked according to their longevity. Depending upon conditions, wood may last from 10 to 100 or more years, steel, depending upon thickness somewhat longer and concrete may last perhaps a number of centuries. It is obvious that under most conditions wood or steel should be used to protect mine shafts only on a temporary basis, perhaps for mines that are inactive and not permanently closed.

Inadequately designed mine shaft cappings. Two case histories were used to demonstrate inadequacies in the engineering design of mine shaft caps. In both cases a thick reinforced concrete cap was placed over the mine shaft opening. A steel vent pipe with a locking cap was even provided in one of the caps, which is a good feature as it allows air pressure to adjust rapidly as the mine floods and provides access for water sampling and water level measurements. However, these caps no longer provide protection from the mine shaft. In both cases the shaft lining material (timber) has failed and allowed the thick glacial overburden to cave into the shaft opening which has caused surface subsidence around the caps. The cap on the Bengal Mine shaft has caved into the enlarged shaft opening and the cap on the Cayia Mine was very near collapse when last visited in 1982.

Thus, both of these cases illustrate the necessity of providing more than just surface protection of the mine openings. A number of the better protected mine shafts in the district such as the Hiawatha No. 1 and the Sherwood shaft have steel and concrete seals keyed into the bedrock around the shaft. The shafts were backfilled with waste rock up through the liner and capped on the surface with a concrete pad. Steel vent pipes through the cap, waste rock fill, and seal allow pressure equalization and access for sampling or measurements .

Shaft seal and capping deficiencies resulting from unusual events. Several case histories were presented in which problems with mine shaft caps and in one case a shaft seal arose because of unexpected disruptive forces. The disruption was caused by surging waters within the nearly flooded mine complex. It was concluded that an initial subsidence event has caused a large mass of overburden or rock to fall into a mine stope and displace and pressurize the water. These pressures were transmitted throughout the "plumbing system" of the mine. Water surges were forced towards surface openings which triggered secondary subsidence and intensified the hydraulic forces. Water under high pressure circumvented a seal in the Homer-Wauseca shaft and the temporary concrete cap over the Sherwood air shaft was raised and split open and a large quantity of water was forced out onto the surface. The seal in the Homer-Wauseca shaft was circumvented because the water exited the shaft through openings cut for the I-beams which supported the concrete seal when it was poured. The pressurized water forced its way to the surface through the overburden along the outside of the shaft liner where it then washed into the old dry area which was being used as a machine shop for diesel engine repair. If this seal had been placed below the bedrock surface, water would not have been able to reach the surface except through the vent pipe or by bursting the seal, which would be unlikely.

The main shaft at the Sherwood Mine had a seal that was correctly installed below the bedrock surface. This seal held, although water was forced up the vent pipes under high velocity and great pressure as evidenced by the fallout of yellow boy scale stripped from the pipe walls by the water rushing through the pipe. Yellow boy mud was found splattered on automobiles parked about one eighth mile away, southeast of the shaft. A strong southeast wind had been blowing when the event occurred.

Air pressure built up sufficiently in the Minkler shaft to cause a small blowout of rock fill below the base of the cap. Apparently waters surging up into the Minkler shaft caused the air in the upper part of the shaft to become highly pressurized which resulted in the blow out.

Thus, it is apparent that flooded mines may develop internal forces which in addition to triggering subsidence, may disrupt seals and caps protecting the mine shafts. Apparently the best insurance against this happening is to install secure reinforced concrete seals below the bedrock surface in shafts and raises. Backfilling of the shafts may also be effective in eliminating this problem. If shafts are backfilled, the material used should be sized and graded to reduce compaction shrinkage. Special care is needed so that outflow of material will not occur where crosscuts or drifts intersect the shaft.

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