STUDY OF MINE SUBSIDENCE AND ACID WATER DRAINAGE IN THE IRON RIVER VALLEY, IRON COUNTY, MICHIGAN

STATUS OF INITIAL WORK

INSTITUTE of MINERAL RESEARCH
MICHIGAN TECHNOLOGICAL UNIVERSITY
HOUGHTON, MICHIGAN

STUDY OF MINE SUBSIDENCE AND ACID

WATER DRAINAGE IN THE IRON RIVER

VALLEY, IRON COUNTY, MICHIGAN

Prepared for:

Michigan Geological Survey Division
Department of Natural Resources
Stevens T. Mason Building
Lansing, Michigan

and

West Side Planning Commission, Iron County
Iron County, Michigan

IMR Projects R-250 and R-277

April 1978

Report Prepared by:

Dr. Allan M. Johnson
Senior Research Geologist
Institute of Mineral Research

Prof. Gordon Frantti
Associate Professor
Department of Geology and
Geological Engineering

Michigan Technological University
Houghton, Michigan 49931

ACKNOWLEDGEMENTS

Completion of this project would not have been possible without the help, guidance and support of a great many people. Among those to whom we are indebted include members of the West Side Planning Commission and West Iron County Sewage Authority who recognized the problems and sought assistance; officials in Iron County and the Iron River District including Reino Anderson, Leo Pisoni, Francis Wills, George Hammer, Klint Safford, Frank and Jim Shepich - and others are thanked for their suggestions, support and the use of facilities under their jurisdiction; Michigan Department of Natural Resources personnel of the Geological Survey Division and Water Quality Division familiar in detail with various phases of the work were most cooperative; Jack Van Alstine, Joseph Bal, David Williams, and Bob Reed who deserves special mention because of his continued assistance in providing the thousands of mine maps on file at the Survey offices in Lansing; mining company personnel: Bob Edwards and Bert Caverson of Inland Steel, Burton Boyum and Mel Viant of Cleveland-Cliffs Iron Co., Peter Kuchan (retired, Dober Mine Captain), Jack Quayle (retired, Hiawatha Mine Captain), George Koehler (retired, Hiawatha Mine Superintendent) and Jim Rullcoski (retired, Hanna Mining Co. Chief Clerk), Stan Zuchowski, Joe Konaki and Reginald Raymond of Zuchowski Iron and Metal Co. and Jack Snowden of ZIMCO.

In addition the following Michigan Technological University students in the Department of Geology and Geological Engineering are acknowledged for their contributions: Don Johnson, Dave Cregger, Donald Olson, Jim DeGraff, Tony Pardini and Mike Bingham. The first three students completed Masters of Science theses on various aspects of the study. Tony Pardini did work nearly equivalent to a thesis as a senior project.

Larry MacDonald, IMR Research Associate, deserves special mention for his continual efforts throughout the project. He prepared the composite maps and compiled all of the data for the "critical area" section of this report, assisted with all field measurements and the gathering of data throughout the project, plus drafting of the figures.

Carla Straw, IMR secretary, very efficiently typed and handled the preparation of this report.

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

LIST OF TABLES

LIST OF TABLES (continued)

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

INTRODUCTION

Statement of the Problem

The Iron River District has been in the past the center of a major underground iron mining industry. Two major problems affecting future development and improvement in the Iron River valley have resulted from those past mining activities. These problems are: 1) surface subsidence (caving) into underground workings with resulting damage and hazard to surface structures and human life, and 2) flowage of acid waters from flooded mines and surface mine dumps, causing highly visible pollution of the Iron River and Brule River (Wisconsin) systems. Acid waters also caused severe problems to the operation of the Stambaugh Sewage Treatment Plant.

These problems are of concern to the West Side Planning Commission of Iron County. Commission members are making plans for the development of the five communities of the Iron River District. Obviously, the continued possibility of subsidence and acid water drainage is a major detriment to such planning.

Goals of Project

Project goals are to develop factual information on the problems of mine subsidence and acid drainage and, based on these facts, offer recommended courses of action for use by the West Side Planning Commission. A primary concern in the early phase of the project was to develop information pertaining to selection of a suitable location for a regional sewage treatment plant. Information on the location and extent of underground workings was also needed so safe routes for sewage lines could be planned.

Study Area

The area encompassed by the study is in west Iron County comprising the southeast part of Iron River Township, the southeast part of Bates Township and a northern portion of the eastern extension of Stambaugh Township. The five communities within this area are the cities of Iron River, Stambaugh, Caspian and Gaastra and Mineral Hills Village.

Project History

In July of 1974 the Institute of Mineral Research (IMR) undertook this project. The project was initially supported by an appropriation of $62,500 through the Geological Survey Division of the Department of Natural Resources. The original 18 month study, July, 1974 to December 31, 1975, was extended four months until April 30, 1976. At this time a comprehensive report on the accomplishments and status of the project was prepared. An additional $60,000 was appropriated to continue the work on these problems in greater detail. This report summarizes all work done to date and describes in detail all work subsequent to the initial status report.

Project Personnel

The principal investigator on this project was Dr. Allan M. Johnson, Senior Research Geologist at IMR. The co-principal investigator was Professor Gordon E. Frantti, Department of Geology and Geological Engineering also of Michigan Technological University.

Dr. Johnson was responsible for the overall management of the project and for basic work and studies on the problems of subsidence and acid water drainage. He authored these sections of the report. Professor Frantti was responsible for implementation and supervision of all geophysical studies related to the subsidence problem. He authored the geophysical section of the report. Conclusions and recommendations related to subsidence were prepared jointly by the two authors.

Structure of Report

This report beyond this brief introductory section consists of four major divisions.

The first division is the Executive Summary which consists of a summary of previous and current work, conclusions based on the work performed and recommendations for either corrective action or further work.

The second division entitled Subsidence consists of the history of subsidence in the Iron River District, the results of comparisons of subsidence parameters, a model for subsidence in overburden, a description of the methods used to prepare maps of mine openings and surface subsidence pits, and a list of critical areas where mine workings underlie in-use surface structures.

The third division entitled Geophysical Studies covers the application of selected geophysical techniques towards the subsidence problem. The geophysical techniques were evaluated as to their effectiveness to locate the position of underground voids and to monitor for active subsidence.

The fourth division is entitled Acid Waters. It describes work done to determine the effects of acid drainage on the Iron River and to locate the acid drainage sources. Hydrologic models for acid drainage resulting from the work are presented.

Supplementary background information is in the Appendix section of the report. Included are sections on geography, geology, mining history and detailed chemical analyses of waters.

EXECUTIVE SUMMARY

Summary of Work and Conclusions

Previous work on the problems of subsidence and acid water drainage in the Iron River was reported by Johnson and Frantti in a 1976 report entitled "Study of Mine Subsidence and Acid Water Drainage in the Iron River Valley, Iron County, Michigan - Status of Initial Work". This 113 page report covered the results of work on the project for the period July 1974 through April 1976. The results and conclusions of this and subsequent work through December 31, 1977 are summarized in this section under the major categories of Subsidence and Acid Water Drainage as follows:

Subsidence:

1. The locations of underground workings in the Iron River District as determined from available mine maps have been documented on two composite map plates at a scale of 1 inch = 500 feet. The map plates show the limits of underground workings, the location of the uppermost stopes and the deepest areas of the mine. Shaft locations are also shown.
2. Similarly the locations of surface subsidence pits were produced on two plates at the same scale. These pits were scaled from aerial photographs taken by governmental surveys in 1939, 1964 and 1975. The pits were field checked.
3. Comparisons between underground mine openings and surface subsidence pits yielded the following observations:
   a. More than 95% of visible subsidence affecting the surface in the Iron River District has occurred in sands and gravel above

bedrock. Other things being equal, subsidence is greatest where the overburden is thickest.

b. A very close relationship exists between the location of underground voids and associated surface subsidence pits. A partial offset on the Spies-Johnson property is attributed to the presence of faults. Four subsidence pits on the James property are offset to the south of the workings. These offset pits may also be due to a fault as they lie on an approximate east-west line and geophysical evidence suggests a fault zone at depth.

c. Subsidence is more prevalent over near-surface stopes than over deep stopes.

d. In several areas subsidence is still active; a small pit some 25 feet in diameter and 15 feet deep recently opened up a short distance south of the cave that affected the now abandoned County Road 424 between Gaastra and Caspian. A smaller pit just 20 feet or so north of the north rim of this pit occurred in slate rock fill. This is on the east margin of the Young Mine property. The larger pit is evident on the 1975 series of aerial photographs, but not on the 1964 series. Obviously it has caved between these two dates. Concern for active subsidence still exists near Mineral Avenue where an approximately east-west trending surface fracture is present near the south margin of the Davidson #1 property. The fracture which is approximately 100 feet long lies south of Mineral Avenue. The ground surface on the north side of the fracture is the down-dropped block with displacement approaching one foot maximum. Three small subsidence pits on the south end of the James property have formed since 1964. They lie on an east-west line offset to the south of the workings.

e. A conceptual model explaining a mechanism for the development of surface subsidence pits was developed during the study. Basically it involves the running of overburden sands into mine workings under a hydraulic gradient. Conditions for this type of subsidence are ideal when the mines are closed and pumping ceases. In areas where unconsolidated sands are capped with an individual glacial till, arching may occur. Drawing of the sands under the cap may continue until the cap can no longer support its own weight and surface collapse occurs. An understanding of the piping concept could allow formulation of a plan which might eliminate or reduce subsidence potential in selected areas.

f. The average depth of subsidence pits is 65% of the overburden thickness, based on the study of 34 subsidence pits.

g. Volumes of the surface pits are less than that of the underlying stopes. The average degree of stope filling by subsidence on a volume-to-volume basis is 39%.

h. The above two conclusions suggest that in most instances subsidence is not complete, otherwise the pits would be deeper and the stoped areas more completely filled. However, it was also observed that through time, the pits stabilize by raveling of the steep sides - the net effect is to make the pits wider and shallower. It was observed from aerial photographic measurements on 34 pits that in 10 years the pits increased in diameter by 5% with a corresponding 25% decrease in depth. The low percent of stope filling may also be due in part to inaccessability of the stopes to the running sands. However, if the piping mechanism plays an important role in the sand filling of stopes, as is proposed, incomplete filling can be explained. Piping would be active as long as water flows into the mine from the surface. When the mine is flooded, water flow and sand filling by piping would cease. Thus, the degree of sand filling might very well be incomplete.

Of the 34 subsidence pits studied, only one on the James property extended to bedrock. Here the stope had caved to ledge and overburden sands had run into the stope filling it nearly to the bedrock surface. Because only a single case of this type of subsidence was observed, it is suggested that this mechanism has not been an important one in the District.

i. Pit depths show a general correlation with the vertical dimension of the stope; stopes with greater vertical pit dimension (stope height) are deeper.

j. Correlations of subsidence with geologic parameters, the time of subsidence and the hydrologic regime, which are believed to be the critical factors affecting much of the subsidence in the Iron River District, could not be established largely because of incomplete data and to a lesser extent, the influence of the many other variables.

k. Several general types or causes of surface subsidence have been recognized in the District. Important among them are:

1) the type of mining method employed. In top slicing and block caving methods, surface subsidence is an integral part of the mining process.
2) gradual failure through the sloughing of rock from the tops of stopes whereby the opening eventually reaches the ledge - common in shallow workings.
3) rock mass movement along planes of weakness intersecting mine workings. This failure may originate even from deep workings. Mine flooding may increase the potential for this type of failure as increased pore pressures and reduced friction in the plane of weakness may trigger the movement.
4) piping, the transport of overburden sands into mine voids by running water which is described more fully under item e in this section.

4. Eleven "critical areas" are recognized in the Iron River District. Critical areas are defined as those where stopes underlie or nearly underlie in-use surface structures including roads, railroads and buildings. Should subsidence occur at these areas, the surface structures could be affected. It should be noted that the inclusion of an area does not imply that subsidence will occur, rather that should it occur there is potential for loss of property or a life hazard.

The locations of the critical areas are as follows:

1) Davidson #1 Mine: surface subsidence cracks in Mineral Avenue.
2) Cardiff-Homer Mines: deep stopes under 16th Street (9th level).
3) Homer-Wauseca Mine: stopes 35 to 150' distance from 16th Street at depth (10th and 12th levels).

4) Beta-Nanaimo Mine: a 53' vertical opening 18' wide at a depth of 310 to 350' beneath U.S. 2 west of Iron River.

5) Delta Mine: a stope 40' in maximum vertical dimension lies 224' below U.S. 2 west of the Iron River and just east of the intersection with River Avenue and Genesee Street. Also the west margin of a stope at a depth of 325' lies 40' east of the railway south of U.S. 2.

6) Chatham Mine: stopes underlie the Selden Road at least 270' upward from the 1050' level. Also, the railway passes over a 60' wide by 500' long stope at a depth of about 325'.

7) Riverton Mine: stopes from the 4th to 6th level of this early mine underlie the railway west of Stambaugh in the Iron River valley.

8) Bengal Mine: the north edge of the subsidence pit from this top slicing mine very nearly extends to Ninth Street. At depth some of the stopes lie within 15' of the center line of Ninth Street.

9) Baker Mine: the uppermost workings are within 170' of the surface and 80' of the bedrock. A county road overlies these workings.

10) Hiawatha Mine (Stegmiller Lease): a stope underlies Selden Road at a depth of about 300'. The stope has a vertical height of approximately 150'. Workings also underlie the railway.

11) Dober-Isabella Mines: workings from both mines underlie 19th Street. The Isabella workings are shallower with stope tops at 195' and 600' of the surface.

5. Subsidence of the Dober Mine, if it occurs, should not affect present structures on Stambaugh Sewage Treatment Plant property. This

assessment was made using a 70° slope projection from the stope at each mine level to project an ultimate estimated limit of subsidence to the surface. In fact, this method predicted a 300' margin of safety for the final settling tank, the structure closest to the mine.

Should the Dober Mine eventually subside, gravity collapse of the hanging wall would directly affect the undermined area. The sewage line passing over the workings would be affected. Rock failure from vertical walls to a 65 or 70° slope would influence the surface to the south, west and north of the workings. Little eastward effect of subsidence would be expected because of the westerly dip of the ore body. However, sand filling has partially stabilized the Dober Mine and the competent nature of the mine rock, plus the fact that no indications of subsidence have been detected during the study period, suggest relatively stable conditions.

6. Geophysical field investigations were conducted to test available techniques and instrumentation to both locate the presence of underground voids and to determine if subsidence was active. Five methods based on principles of seismology and gravity were outlined for investigation including (1) Seismic Refraction, (2) Gravity Modeling, (3) Wave Perturbation, (4) Microseismic and (5) Seismic Reflection.

   a. The seismic reflection technique provided the most success in monitoring the location of abandoned underground cavities. A modern Signal Enhancement Seismograph with 12-channel capability was found to be superior to a single channel system which was first used and which required an individual peak-and-trough plotting procedure for analysis. A moving source-stationary receiver field procedure employing 12 subarrays of 6 geophones worked effectively with traverse lines parallel to the general strike of the formation containing the openings.

b. Reflections from underground stopes were observed as follows:

Young-Buck Area: Reflections were probably recognized from two old stopes at depths of 170' and 199' or within ±10% of their estimated position from mine maps. These stopes are in an area that has been closed to public use.

Dober-Isabella Area: Reflections were quite likely received from three old stopes south of the Isabella shaft along 19th Street. Calculated depths are 168', 358' and 556' and are shallower than the estimated depths based on mine maps.

Hiawatha Area: Along the west side of highway M-189 just north of the 19th Street junction, reflections are indicated from two dipping stopes at depths of 239' and 347', whereas the mine maps show a single stope at 330'.

Delta Area: In a critical area south of Genesee Street near the old Memorial, reflections appear to originate from three stopes at 192', 244' and 275' or within ±15% of the estimated depths from mine maps.

Cardiff Area: Measurements carried out on the west side of 16th Street just north of Mineral Avenue indicate stopes at 445' and 532' or approximately 10% less than map predictions.

Homer-Wauseca Area: Along the east side of 16th Street south of Mineral Avenue, two possible reflections were received from stoped depths greater than 600'.

<u>Baker Area</u>: Measurements were made near the northeast corner of section 1 just southeast of the corner of the main road. Two probable reflections from old stopes indicate depths about 50' shallower than the mapped depth of 281'.

c. A strong case cannot be made for the seismic refraction technique as a general, independent method for subsidence monitoring. However, in areas where some subsurface soil or rock movement has occurred, refraction measurements are useful in locating the source of such activity. For example, in the Mineral Hills area refraction profiles suggest a possible depression in bedrock topography 500 feet north of Mineral Avenue at a site where a 6-foot scarp appears in the surface expression. This structure could be the sink for transported overburden and responsible for the pot holes and fractures in the surface near Mineral Avenue. As a second example, in the same general vicinity, a noticeable decrease in alluvium velocity coincides with the position of a surface crack 100 feet south of Mineral Avenue. Along the same seismic traverse an even more pronounced velocity decrease occurs 70 feet south of the avenue suggesting a similar crack at depth in the alluvium where no surface evidence shows. A third example is contained in a seismic refraction line over the Young Mine of the Buck Group where data indicate a bowl-shaped depression in a hardpan layer. Since this consolidated alluvium layer is usually flat-lying in this vicinity, subsurface settlement over the Young Mine is suspected beneath the depression.

d. Gravity modeling of the Dober Mine demonstrated that changes in gravity brought on by shifting the mine model 100 feet closer to the surface to simulate subsidence can be detected certainly by microgravimeters and possibly by conventional prospecting gravimeters. However, anomalies of equal size can be associated with the complex folding and layering within the geologic structures of the Iron River District. Therefore, in order to monitor pre-subsidence activity, repeated gravity surveys would have to be conducted at close station intervals ($\leq$ 25 feet) and fine measurement precision ($\leq$ 0.1 mg) over an area to seek for changes in Bouguer values with time.

e. Certain parameters describing the perturbation or distortion of waves by mine cavities were found statistically significant. The ratio of the width of the Lg spectrum and the maximum amplitude ratio SV/Lg systematically change across the mine. Computer modeling of body wave (P,S) amplitude ratios show very pronounced effects between 3 and 4 hz when water-filled cavities simulating old stopes are introduced in the earth model. It is concluded, however, that additional developmental work must be carried out before a definitive procedure can be outlined.

f. With just a few exceptions, the absence of appropriate signals on the microseismic records suggests that there were very few instances of adjustments or disturbances occurring in nearby mines during the monitoring periods (750 hours). Two events were detected which have a likely origin in the mine complex just north of Caspian and four events are suspected of originating within the Hiawatha-Dober west block. Thus it is concluded that the frequency of major rock disturbances in the local inactive mines is very low.

Acid water drainage. Acid waters in the Iron River District have their origin from the sulfur-bearing black slate that underlies the Riverton Iron Formation. The sulfur is present as fine grained pyrite which oxidizes rapidly in the presence of oxygenated waters to form sulfuric acid. Acid waters contain large quantities of sulfate, iron, calcium, magnesium, manganese and aluminum. Of these, iron is the worst pollutant because of its high concentration and insolubility. When acid waters enter the Iron River, they neutralize rapidly and precipitate iron hydroxide compounds. The yellow-brown finely divided iron hydroxides known commonly as "yellow-boy" cloud the waters and coat submerged objects. These effects are evident in the Iron River below the Iron River District and in the Brule River downstream from the confluence with the Iron River.

Periodic sampling and analysis of waters from the Iron River, its tributaries and acid drainage sources was done for the period 1975 through 1977. Due to unusual drought conditions in 1976 and 1977, the most representative data on water quality and the effects of acid drainage was obtained in 1975. Two sources of acid drainage from abandoned mines have been identified; the Dober Mine and the Buck Mine Complex. More detailed work has allowed quantification of the results and a better understanding of the factors affecting acid drainage from these sources. Each is described separately:

1. Dober Mine drainage: Highly acid underground waters well up from the Dober Mine pit and drain into the Iron River. Flow rates between 50 and 100 gallons per minute carry large amounts of dissolved solids into the Iron River. Average values of water quality measurements in

1975 were: pH = 4.1, acidity = 2900 mg/l $CaCO_3$, specific conductance = 5000 μmhos/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 total study period, 1975 through 1977, the Dober Mine drained an average of 654 pounds of iron per day into the Iron River, or 71% of the total amount entering the river from all sources.

The toxic elements, lead and cadmium, are present in low quantities in Dober Mine acid waters (0.05 and 0.02 mg/l respectively). Mercury was not detected.

A model of acid drainage was developed during the study. The model invokes recharge of surface waters into the Dober-Hiawatha Mine complex on the west over the Hiawatha workings which forces acid waters through the interconnected mine workings at depth and to the surface at the Dober Mine pit. The acid waters drain from the Dober Mine pit into the nearby Iron River.

Water level measurements show head differences between water levels in the Dober and Hiawatha Mines. Acid water in the Dober Mine lies at the lowest elevation; in the Hiawatha #2 Mine shaft the water level is about four feet higher and in the more distance Hiawatha #1 shaft, about 7 feet above the Dober pit level. Deep sampling of the Hiawatha #2 shaft disclosed the presence of a fresh water "blanket", 540 feet thick, overlying denser acid waters. Calculations suggest the head differentials are due largely to density variations between fresh and mineralized waters. Acid drainage occurs as a result of an imbalance in the heads caused by water recharge into the Hiawatha workings.

It is concluded that pumping from the mine complex in the vicinity of the Hiawatha workings would lower the driving head which in turn would either eliminate or greatly reduce acid drainage from the Dober Mine pit. The pumping, of course, must not draw the acid waters to the surface; it must draw only from the fresher surface waters. A project including a pumping test to test this hypothesis has been funded by the State of Michigan. The field work is scheduled to be done during 1978 and the report done in early 1979.

2. Buck Mine Group Acid Drainage: Black, pyrite-bearing waste rock piles fill low areas along the east bank of the Iron River east of Caspian, Michigan. The piles are about 3/8 of a mile long by 1/8 of a mile wide and cover about 19 acres. Three channels drain acid waters from the piles. The most southern drainage flows at the lowest rate but contains the most dissolved iron. The central and northern drainages flow at considerably higher rates but have lower iron contents. During 1976 and 1977 the combined average flow from these three channels was 441 gallons per minute. These drainages contributed, on the average, 117 pounds of iron, 56 pounds of manganese and 9750 pounds of sulfate per day.

The slate piles were augered in 1976 and sulfur analyses were run on the augered samples. Calculations indicate that the piles contain 10.2 million pounds of sulfur which could produce as much as 31.1 million pounds of concentrated sulfuric acid. Thus, considerable potential for acid drainage remains in the slate piles.

Results of initial work suggested the acid drainage originated from the surface piles. The model was one of surface and near surface ground waters flowing from higher elevation on the east through the piles and reacting with pyrite to produce the acid drainage. Results of leveling surveys in 1976 showed as much as a 26 foot difference in elevation from the surface of flooded subsidence pits on the east margin of the piles to the Iron River on the west, thus confirming that the above mechanism was probable. However, the large amount of flow from the piles and the rather consistent results obtained from periodic water analyses over the term of the project suggests that some portion of the acid drainage probably originates from within the mine complex beneath the surface piles.

The installation of culverts to drain waters from the elevated eastern margin of the piles may reduce acid drainage from the Buck surface piles, however, because of the possibility of acid drainage originating from within the mine complex, more detailed work is needed. The hydrologic system acting in the Buck Mine Complex should be determined so the proper steps can be taken to correct the acid drainage problem.

Recommendations

1. Retain and use the composite maps of underground workings in future planning. Do not build over or develop areas that are undermined -- where possible, keep them in governmental ownership to discourage development. However, it may be possible to use some areas for low intensity uses.
2. Exercise caution at the "critical areas" described in this report. (Critical areas are those where in-use surface structures are under or nearly underlain by mine workings). More detailed evaluation should be done at U.S. 2 near Iron River (Delta Mine) and on M-189 (Stegmiller property) where high

traffic volume increases risk. The Michigan Department of State Highways and Transportation has already done extensive testing of the Beta-Nanaimo area, but subsidence there remains a possibility.

3. Periodic inspection of fenced areas around shafts and surface openings should be done to insure that safe conditions will exist. A maintenance program should be instituted to provide for proper upkeep of the fences.

4. Mine maps on file in the Iron County Courthouse at Crystal Falls should be cataloged and properly stored for future use. Because the role of the County Mine Inspector diminishes as mining activity decreases, one of the full-time County offices, such as the engineer, road commission, a library, etc., should become the depository for these maps, maintaining them for reference use.

5. Black pyrite-bearing slate should not be used for surface or near-surface fill material. It will disintegrate and produce sulfuric acid when in contact with moisture and air. The acid will corrode metal and attack concrete. It is not suitable for use as concrete aggregate.

6. A pumping test should be run on the Dober-Hiawatha Mine Complex to determine the feasibility of controlling acid drainage from this source by hydrologic control. The waters should be pumped from an access point to the mine over the recharge area on the Hiawatha #1 property. If feasible, the corrective steps should be taken. (NOTE: $30,000 has been appropriated by the State of Michigan to do the test work in 1978.)

7. Further tests should be run on the Buck Mine Complex to determine which portion, if any, of the acid drainage originates from the mines under the slate piles. From this work a plan for corrective action should be developed. Drainage culverts from the elevated eastern margin of area may greatly

reduce acid drainage from this source.

8. Water levels in the Mineral Hills and north Iron River areas should be monitored when pumping is stopped at the Sherwood Mine. Pumping from the many mines in this area since the late 1800's has artificially lowered the water table. When the pumps at the Sherwood Mine are shut off in mid-July, ground water levels will begin to assume their original pre-mining elevations. As no known historic information on the natural water table elevation is available, it is not possible to predict what these levels will be.

   No surface flows of acid drainage are anticipated from the Sherwood or adjoining mines. The large quantities of high quality ground waters presently being pumped will quite likely form a thick "blanket" of fresh water over the deeper mineralized waters as the mine floods. Also, no serious problems with elevated water levels on and around the Sherwood property are expected because of the very thick overburden and low level of development. However, the direction of ground water flow from the area should be monitored as some low lying areas in the drainage route may be affected.

9. In order that the Iron River valley communities will have some positive means to determine if subsidence is occurring in any of the critical areas, it is recommended that a level survey grid be developed over each of the critical areas. The surveys should be run periodically, say two to four times a year. Leveling monuments (buried concrete posts with steel pins) will be needed at most sites, but many existing points such as road surfaces, steel posts, railway tracks, bridge abutments, etc. can be used. Monuments should be anchored below the level of frost penetration. The grid should thoroughly cover the surface of the critical area and have several stable survey points on either side of where any expected subsidence may

occur. These points would serve as reference to assess subsidence effects. Any noticeable changes in elevation would indicate a greater potential for subsidence, particularly if a progressive trend is observed.

In addition to level measurements at the Ninth Street location north of the Bengal Mine workings, horizontal measurements between the monuments should also be made. A significant horizontal component of failure is quite likely should this area subside because of the large open pit to the south. Should the leveling survey indicate active subsidence, precautions should be taken, and more detailed investigations made to check the results before corrective or other action is taken.

10. In areas where major movement above abandoned mines is indicated by changes in the vertical leveling data, the following steps are recommended. These should be implemented as soon as possible after movement is identified.

    a. The time interval between repeat leveling surveys should be shortened and both horizontal as well as vertical leveling should be conducted to establish both components of strain.

    b. Seismic refraction measurements should be made along traverses at right angles over the settlement zone. Measurements should be taken at 10-foot station spacing for overburden profiles and 25-foot spacing for bedrock profiles. Surveys should be repeated at least bi-monthly to examine the velocity changes with time and the development of bedrock offsets for purposes of identifying the source of surface movements.

    c. An array of at least 3 surface seismographs should be established in a triangular grid over the settlement area and operated continuously to seek for low-frequency signals indicative of large movement of rock at depth. An array of at least 6 subsurface seismic sensors should be established above the mine and operated at periodic, 15-minute intervals to identify the pattern of high-frequency signal radiation from flow zones in the overburden.

11. A shallow seismic reflection technique using several stationary sub-arrays of high frequency geophones and a varying energy source is recommended as the best single geophysical method for locating mine voids in the district. The method should be carried out with a modern signal enhancement seismograph having at least 12-channel capability. A manual, mechanical energy source is generally adequate to 275-foot depths. Beyond that, well-tamped explosive charges (or equivalent mechanical source) are required. Improved results are obtained by summing the signals from many shots of small charges rather than a few shots of large charges. Preliminary refraction measurements sufficient to well-document the velocity profile are needed to interpret the reflection signals. Reflection measurements should be carried out at least annually in the critical areas where stopes are within 200 feet of the bedrock surface.

SUBSIDENCE

Subsidence from underground mining is common to the Iron River District. More than 100 pits ranging in size from a few tens of feet to several hundreds of feet in diameter dot the mining district. In some areas smaller ones coalesce to form larger, composite pits. The larger pits are commonly 100 to 200 feet deep, circular to elliptical in shape and steep sided.

Contrary to popular opinion, not all of the subsidence pits are due to unexpected collapse of underground workings. Much of the early mining employed methods whereby it was planned that caving would occur and follow the workings down. Then too, not all of the pits are caused by subsidence. The earliest mines in the Iron River District were developed as open pits from discoveries of ore exposed in the Iron River valley where glacial cover was absent or quite thin.

Many of the subsidence pits and areas of caving ground have been fenced in. However, in a number of instances, subsidence has occurred unexpectedly over areas mined many years previously. These unexpected caves over abandoned workings have caused damage to property and in one instance, loss of life.

It is the unexpected caves from abandoned and largely forgotten workings that have caused the most serious problems. Therefore, as the district is inactive now, with the exception of the Sherwood property, it is important that information on the location and size of stopes in the more recently abandoned mines be documented and preserved. With the recent closing of a number of mines in the Iron River District, general knowledge of the underground workings is held by many local residents. However, as time passes, so will this knowledge. Younger generations, only vaguely aware of past mining activity, will be making planning and development decisions. Without preservation of information on the location of underground workings, potentially hazardous consequences could result.

Because of these considerations, a great deal of effort has gone into the preparation of accurate maps to document information on the size, shape and location of underground mine openings. Special attention has been given areas where surface structures are underlain by mine workings.

History of Subsidence in the Iron River District

This section documents cases of subsidence in the Iron River District that have resulted in loss of property (in one case life) or have necessitated added expense for local communities. This section is taken without alteration from a memorandum report prepared by R. O. Pynnonen and R. L. Bernard of the U.S. Bureau of Mines in 1968.

> "The proximity to each other of operating and abandoned mines in the district has complicated the prediction and control of subsidence. Large areas of caved ground have been fenced in areas where subsidence was expected, but in a number of cases, subsidence has occurred unexpectedly in areas where mining operations had been discontinued many years ago.
>
> "In July, 1955, a cave-in to surface resulted in a 300-foot diameter hole with near vertical walls, 80 feet deep in the southeast corner of the Spies-Virgil mine property. This cave-in occurred only 300 feet north of U.S. Highway 2. Reportedly, the cave-in was approximately 300 feet from the vertical projection of the nearest underground workings, which were 800-1,000 feet below surface. A 1951 map prepared by the U.S. Geological Survey shows two closely spaced, almost-parallel faults in this area. The cave-in occurred between the faults.
>
> "Concurrently with the subsidence, an effluence of water resulted in the flooding of the two lowest levels of the adjacent Sherwood Mine. This water entered the mine from the abandoned Spies-Virgil Mine.
>
> "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.

"In June, 1961, a cave-in at the Wauseca Mine, the Hanna Mining Company, Agents, caused the loss of some stockpiled ore and almost resulted in the loss of a diesel locomotive. The resulting cave was approximately 100 feet long, 80 feet wide, and 50 feet deep. The engineer in the locomotive noticed the start of the cave and ran from the engine. After the subsidence abated, he returned and moved the locomotive to safety moments before additional subsidence occurred, leaving the section of the track the engine had been on suspended in midair. A stope 35 feet wide and 280 feet long had been mined to within 130 feet of the surface many years ago by a former owner of the property.

"A surface cave approximately 200 feet in diameter occurred on the Virgil property in April, 1962. A smaller cave about 150 feet southwest occurred near the Sherwood Mine boundary in 1963. A third cave in August, 1964, was approximately 600 feet long and 400 feet wide. This cave was on Sherwood Mine property near the 1963 cave on Virgil property. Shortly after the last cave, cracks developed in a 400-foot section of road leading to the Spies-Virgil and Sherwood Mines. Subsidence cracks also appeared in a 100-foot section of a street in Allen's Addition, a small plat of homes near the subsidence area. This subsidence caused a break in a buried water line, necessitated the abandonment of two houses, and required the construction of a detour.

"A small cave-in in the road on the east property line of the James No. 1 Mine about 1/4 mile north of the Virgil Mine property occurred in 1963. The road was barricaded, and an old railroad grade to the east was improved as a detour. The following year, additional subsidence to the north necessitated further use of the railroad grade to completely bypass the subsidence area. Reportedly, the cost of constructing the detours was $25,000.

"A short subsidence crack (discernable for only 110 feet), with vertical and horizontal displacement at the midpoint of 6 inches, was discovered near the Wauseca-Davidson No. 1 Mine boundary in May, 1965. The location of the crack near the south access road (locally known as the Homer road) was of concern because Sherwood Mine employees and a school bus used this route. Displacement occurred on the north or side toward the abandoned Davidson Mine workings. An excavation made near the midpoint indicated a near-vertical dip. The crack ran approximately N 75° E.

"Records show that the Davidson Mine produced slightly more than 4.5 million tons of ore from the 40-acre property. Most of the ore was produced above the 650 level or within 660 feet of the surface. The south limit of the mining area was approximately 550 feet north of the subsidence crack. It is known that 150-foot high and 100-foot wide stopes were developed in the mine. No other recent subsidence cracks could be found for a distance of 750 feet north of the crack. A search of the area for approximately 300 feet south of the crack on Wauseca Mine property also failed to show any subsidence cracks. The crack was approximately over and parallel to the trough of the syncline, and no mining had been done in the trough."

Methods of Investigation

A number of methods of investigation were used to attack the subsidence problem. They included: 1) review of mine maps, production records and other documents providing data on the size, shape, volume and location of underground voids; 2) study of aerial photographs of the Iron River District to assess the visible effects of subsidence supported by field checks; 3) investigation of promising geophysical techniques to locate underground openings and also to detect any indications of active subsidence; 4) review of literature on subsidence so that useful results could be applied to the study area; 5) a quantitative study undertaken in an attempt to find correlations between subsidence and measureable mine and subsidence pit parameters; and 6) documenting areas where in-use surface structures are underlain or nearly underlain by mine workings. Eleven of these critical areas are described in detail. A separate section discusses the relationship between mining and subsidence potential.

Composite Maps of Mine Voids

Because surface subsidence is directly related to the presence of voids created by mining, a great deal of effort was invested in preparing a composite map of the underground workings for the Iron River District. The map produced as two plates was included in the 1976 status report (Johnson and Frantti, 1976) at a scale of inch = 500 feet (10.56 inches to the mile). The map was produced from tracings of thousands of mine maps available from the Geological Survey offices in Lansing and from the Iron County courthouse in Crystal Falls. The maps show in plan view: 1) the outermost limits of mining of each of the mines (solid line), 2) the lowermost limits (dotted lines), and 3) the uppermost limits (dashed lines). The map is presented again in this report as two plates, Plate I the northern part of the district and Plate II the southern portion. The area of coverage of each plate is shown in Figure A-5 (in Appendix).

These two composite map plates have been updated and are included in the back of this report. During 1976 and 1977 effort was made to verify and to improve the accuracy and completeness of the composite maps showing the limits of underground mining. Contact was made with officials of M. A. Hanna, Pickands-Mather, and Cleveland-Cliffs Mining Companies towards this end. Copies of the composite maps were sent to each with a request to review the maps for accuracy. If any errors or omissions were evident, notification was requested. No negative response was received. Officials of Cleveland-Cliffs Iron Company stated that the map was in agreement with their records.

Mine maps at the Sherwood Mine were reviewed with company permission in January of 1977. This review resulted in improvement to the composite map on some of the older, shallower workings and on new development work in the MacDonald Annex southeast of the Sherwood Mine property.

Mine maps stored in a core shed on the Caspian Mine property were examined in early March of 1977. Many mine maps for properties owned and operated by the Pickands-Mather Mining Company were stored there. Maps of the James, Buck Group and Caspian Mines with more complete information on the workings of these mines were found. They were used to improve the composite map.

Mining and Subsidence

An assessment of how the mining methods employed in the Iron River District have affected subsidence was prepared by Walfrid Been, Professor Emeritus and past Head of the Mining Department, Michigan Technological University. His assessment is as follows:

"The type of subsidence over a mine working can be predicted to a certain extent by the mining method that was employed. With top slicing and caving methods, the overburden is deliberately made to subside as mining is in progress. With any stoping method, the excavation is stabilized either by artificial supports or by pillars of ore until the maximum size of opening that can be so stabilized is reached. At this time the opening is either abandoned to collapse or backfilled to permanently stabilize it.

In the Iron River vicinity both caving and stoping methods of mining were practiced, sometimes exclusively one or the other but often in combination, with the upper levels mined by a caving method and the lower levels mined by stoping. In the directory of mines that is listed in the 1938 edition of the volume on Lake Superior Iron Ores, published by the Lake Superior Iron Ore Association, the type of mining used in each mine is usually mentioned. From this list, only three mines are listed as using a slicing or caving method exclusively; these are, the Zimmerman, the Rogers and the Nanaimo. If the directory has been correctly interpreted the subsidence over these workings was probably 90% complete when the mine was closed. The remaining subsidence would take the form of slow settlement over a period of say 5 to 10 years.

In the remaining mines where some sort of stoping method was used the time required for the openings to reach a state of complete stability cannot be predicted. Some backfilling was done for both stabilization and for fire control. Although this backfilling will lessen the size of the eventual surface opening it may actually delay the time that it will take for the opening to reach the surface. For this reason is must not be assumed that because a mine has been closed for a number of years without showing surface subsidence that the point of final stability has been reached."

Subsidence Prediction - State-of-the-Art

The term subsidence prediction can be taken to mean two things: 1) prediction of the ground area to be influenced by caving regardless of when it occurs, or 2) prediction of the time subsidence will occur. Neither prediction can be made without adequate information and each has different requirements.

To predict the area to be influenced by eventual subsidence requires precise information on the size, shape and location of underground voids, plus reliable information on possible modifying factors. Included in the latter are faults, fractures, rock contacts, shear zones, overburden thickness, water saturated zones, and water flow rates. However, even with this information, prediction of the area to be affected by subsidence in a single instance is difficult. It is most desirable to have a model based on several past occurrences of subsidence so some level of statistical accuracy can be projected.

To predict when subsidence is likely to occur adds the element of time. This requires periodic or continual measurements of prefailure ground movement which can be converted to strain rates. Strain rates are determined by calculating the rate of subsidence from field measurements. Surveyed measurements of vertical and horizontal displacements from a grid of established monuments over the area of suspected subsidence is one method to obtain these rates. Another is to take periodic readings with very sensitive tilt meters on specially constructed monuments. Any minor rotational movement of the block of ground is reflected by the monument and detected by tilt meter measurements. From this information the potential of imminent subsidence may be estimated.

A third method involves the continuous recording of microseismic signals from an area where subsidence is expected. Stressed and failing rock produces signals that can be detected by sensitive microseismic devices. Microseismic activity from a subsiding zone can be used to predict when failure is likely to occur.

Generally speaking, subsidence will take place after the strain rate increases to a certain level. A brief relaxation in the rate usually occurs just prior to massive rock failure and the resulting subsidence.

Volumes of Subsidence Pits

As an aid in the subsidence studies, volume calculations were made on each of the subsidence pits in the district. The area of each pit was planimetered from a large scale aerial photograph and the depths were determined using a parallax technique on the smaller scale overlapping prints. These volume measurements were used in making comparisons between pit and stope volumes and other measureable parameters. The volume calculations will be kept on file at IMR and will be available there should the need for this information arise.

Recent Subsidence

In several areas subsidence is still active: a small pit some 25 feet in diameter and 15 feet deep recently opened up a short distance south of the cave that affected the now abandoned County Road 464 between Gaastra and Caspian. A smaller pit just 20 feet or so north of the north rim of this pit occurred in slate rock fill. This is on the east margin of the Young Mine property. The larger pit is evident on the 1975 series of aerial photographs, but not on the 1964 series. Obviously it has caved between these two dates. Concern for active subsidence still exists near Mineral Avenue where an approximately east-west trending surface fracture is present near the south margin of the Davidson #1 property. The fracture which is approximately 100 feet long lies south of Mineral Avenue. The ground surface on the north side of the fracture is the down-dropped block with displacement approaching one foot maximum. The above information was reported in the 1976 status report.

Since the 1976 report more previously undiscovered subsidence has become evident. Aerial photographic study indicated that between 1964 and 1975 three small subsidence pits had developed. They are near the south boundary of the James workings and lie on an approximate east-west trend offset to the south from the workings. These pits have been included on Plate IA showing surface pits in the northern part of the Iron River District.

During the fall of 1977, subsidence occurred at the Virgil-Spies Mine shaft. Work was underway to back fill and recap the shaft following the cave-in.

Correlation of Subsidence Parameters

A study was made to model subsidence of glacial overburden into abandoned underground mine workings. The study involved comparison of numerous subsidence pit and mine parameters in an effort to find common relationships between them. Parameters measured included: 1) pit and stope locations and dimensions and volumes, 2) geologic and hydrologic data, and 3) time of pit formation. The techniques of measurement included abstracting measurements from scaled tracings of mine maps, photogrammetric measurements of pit shape, diameter, depth and location from three series of aerial photographs and collection of field data.

Part of the work was done by Donald Olson, a graduate student in the Department of Geology and Geological Engineering at Michigan Technological University (Olson, 1977). He undertook a study of subsidence in the Iron River District to fulfill his thesis requirements for a Masters of Science degree in Geological Engineering.

The conclusions and observations made on subsidence in the 1976 status report (Johnson and Frantti, 1976) remain valid. Consequently, they are included in this final report. The previous conclusions were:

1. Not all pits are true subsidence pits.
    a. Some pits are from open pit mines (Nanaimo, Riverton, Dober).
    b. Some pits are surface excavations used for stope filling (Homer-Wauseca, Sherwood).
    c. Some pits are planned from the mining method employed (Rogers, Caspian, Cannon).
2. More than 95% of visible subsidence affecting the surface in the Iron

River District has occurred in sands and gravel above bedrock. Other things being equal, subsidence is greatest where the overburden is thickest.

3. A very close relationship exists between the location of underground voids and associated surface subsidence pits. Minor offsets do occur, however. A subsidence pit on the Spies-Johnson property is partially offset south of the workings, apparently due to the influence of adjacent faults (see Plates I, IA). On the south margin of the James property four small subsidence pits are south of the southernmost limits of the mine workings. They are aligned in an east-west direction suggesting a bedrock fault or subsidence fracture trending east-west and perhaps with a northerly dip to intersect the James Mine workings (see Plates I, IA).
4. Subsidence is more prevalent over shallow, near-surface stopes than over deep stopes.

Conclusions drawn from the study of subsidence since the 1976 status report are:

1. The depths of the subsidence pits are greatest where the overburden is thickest, but for 34 subsidence pits studied the average depth is 65% of the overburden thickness.
2. Volumes of the surface pits are less than that of the underlying stopes. The average degree of stope filling by subsidence on a volume-to-volume basis is 39%.
3. The above two conclusions suggest that in most instances subsidence was not complete, otherwise the pits would be deeper and the stoped areas more completely filled. However, it was also observed that

through time, the pits stabilize by raveling of the steep sides - the net effect is to make the pits wider and shallower. It was observed from aerial photographic measurements on 34 pits that in 10 years the pits increased in diameter by 5% with a corresponding 25% decrease in depth. The low percent of stope filling may also be due in part to inaccessability of the stopes to the running sands. However, if the piping mechanism plays an important role in the sand filling of stopes, as is proposed, incomplete filling can be explained (piping is the transport of overburden sands by running water). Piping would be active as long as water flows into the mine from the surface. When the mine is flooded, water flow and sand filling by piping would cease. Thus, the degree of sand filling might very well be incomplete.

Of the 34 subsidence pits studied, only one on the James property extended to bedrock. Here the stope had caved to ledge and overburden sands had run into the stope filling it nearly to the bedrock surface. Because only a single case of this type of subsidence was observed, it is suggested that this mechanism has not been an important one in the District.

4. Pit depths show a general correlation with the vertical dimension of the stope; stopes with greater vertical pit dimension (stope height) are deeper.

5. Correlations of subsidence with geologic parameters, the time of subsidence and the hydrologic regime could not be established largely because of incomplete data and to a lesser extent, the influence of the many other variables. This is unfortunate because these variables are believed to be the critical ones affecting much of the subsidence in the Iron River District.

Proposed Models of Subsidence

Mines in the Iron River District have subsided or caved to the surface in a number of ways. Among them are:

1) the type of mining method used. In top slicing and block caving methods, surface subsidence is an integral part of the mining process;
2) the failure of rock either by gradual processes such as sloughing from the back (top of a stope) or by rock mass movement along planes of weakness. The gradual process is more common in older shallow workings where mining was done close to the ledge. Rock mass movement which is dependent upon failure along slip planes may produce surface subsidence from even deep workings. Loss of support with the removal of rock may cause failure along the planes of weakness. Flooding of the mines may often increase the likelihood of failure along these planes due to increased pore pressures and reduced friction between the rock masses.
3) transport of glacial overburden sands into the empty mine workings by running water. This mechanism, termed piping, was presented as a model for subsidence in the 1976 status report (Johnson and Frantti, 1976). The piping mechanism is considered to have played an important role in subsidence in the Iron River District as the conditions required for piping are matched by physical conditions. The piping model for subsidence is described in detail in the following section.

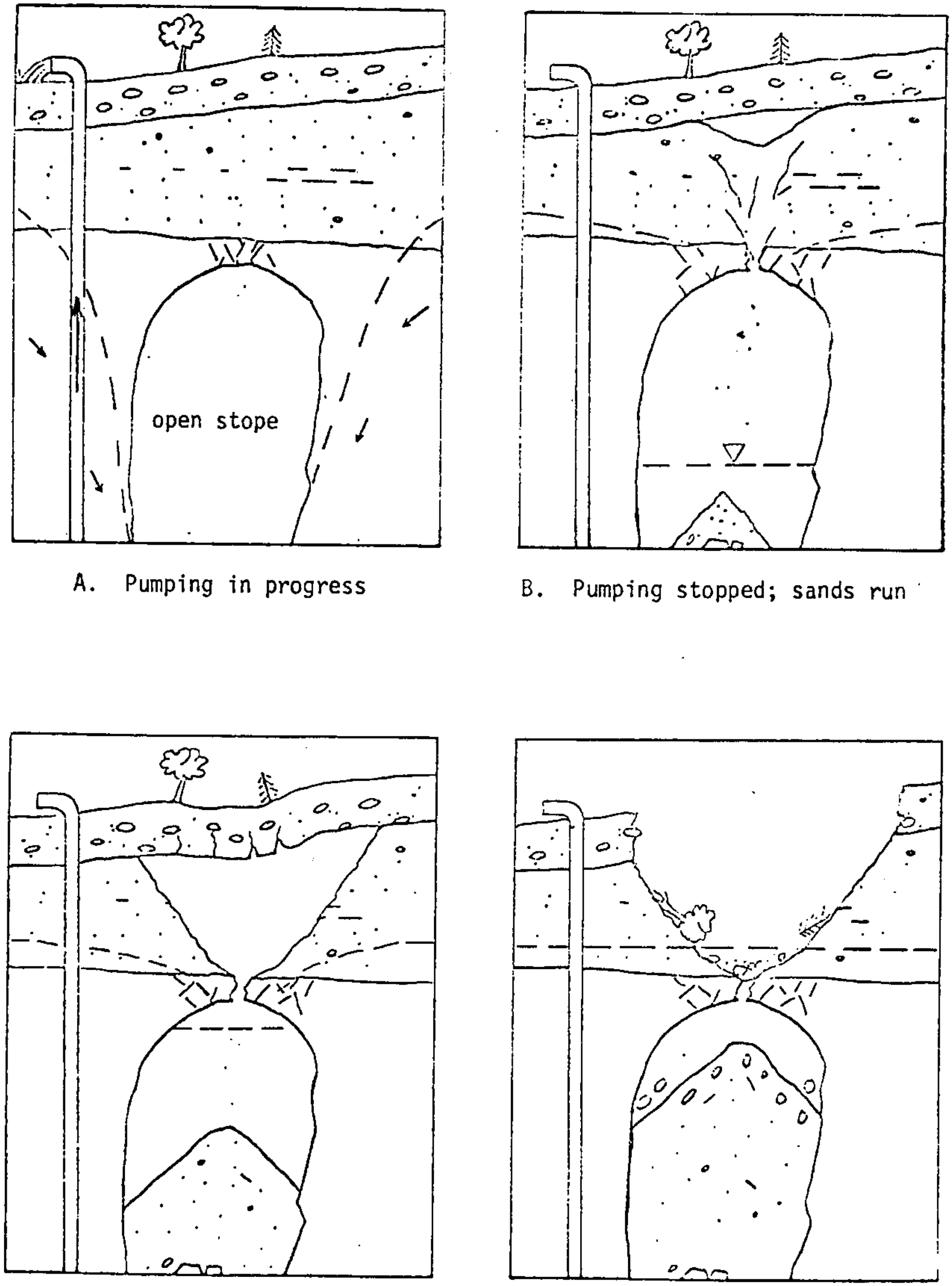
The Piping Mechanism of Subsidence Pit Formation

Great thicknesses of water-saturated glacial overburden above many of the mines in the district required pumping of large volumes of water to keep the mines dry. Besides pumping water from the mines, it was the practice to pump water from shallow surface wells to prevent these flowing into the workings. In this way only the smaller portion of water entering the mine would have to be pumped up a greater distance, at greater cost. The effect of the combined pumping was to artificially lower water levels in the vicinity of the mine workings so mining could proceed without water problems.

During the life of the mine conditions would remain rather stable. When the mine closed, however, the situation would change. Cessation of pumping would allow water in the overburden to rise to its normal level. Any openings into the recently vacated mine would provide channelways for the water. The waters would carry sand, silt and clay into the mine void. Drainage of water into the opening would create an inverted cone in the ground water table causing more or less uniform peripheral flow into this zone. Removal and transportation of unconsolidated material would likewise occur in a similar manner.

The sands would continue to run into the mine voids under the hydraulic gradient until either the gradient was too low to transport clastic material or until the void was water filled and a gradient no longer existed. However, before this equilibrium was reached, collapse of the overlying till would often occur. Unconsolidated sands beneath the more competent boulder till would be drawn away until the capping layer could no longer support its own weight, at which point collapse would occur. Of course, if the mine workings were not completely flooded the drawing process would continue. The sequence of events envisioned to take place are shown graphically in Figure 1.

Several lines of evidence support this hypothesis. All the physical conditions described above are met in the district, i.e., thick unconsolidated



A. Pumping in progress

B. Pumping stopped; sands run

C. Running sands form void under cap

D. Collapse of cap, subsidence complete, ground water at equilibrium

Figure 1. Model Showing Development of Surface Subsidence

overburden capped by a relatively competent till, water-saturated drift requiring pumping, subsidence occurring after cessation of mining and the pits forming above stopes from which ore was extracted near the surface. The circular shape of many of the pits is also suggestive of the proposed mechanism. Visual examination of many of the pits shows the capping boulder till to stand in near vertical walls, whereas the underlying sands are stable only at lesser slopes -- this is most evident from some of the more recent subsidence on the Sherwood Mine property.

Mr. Robert Edwards, Superintendent of the Sherwood Mine, related an instance of subsidence of this type during a visit to the property in October of 1974. He explained that surface material was being excavated to fill some of the worked-out stopes. They had found it more economical to drill and blast the 30 foot thick surface till layer than to dig it away directly because it was so indurated. One time immediately following a blast a circular pit 50 feet or so in diameter suddenly opened next to the area they were quarrying. Mr. Edwards surmised that the shock triggered the collapse of the till cap into a void produced by sands running into stopes below. This explanation seems reasonable and correct.

In an article entitled "Geologic Settings of Subsidence" by Allen (1969), a mechanism for subsurface mechanical erosion termed "piping" is postulated. Allen states:

> "Three conditions appear to be required for the process of underground transportation of sediments. (1) An easily erodible, pervious bed must be overlain by material sufficiently competent to maintain a roof, at least temporarily, over a cavity. The common easily erodible materials are loess, water-laid silt, and sand or sandstone that is uncemented, incompletely cemented, or decemented. (2) A source of water with sufficient head to transport grains of silt and sand must have access to the erodible bed. Access of water rarely occurs under natural conditions and then usually in areas of dry climate; it is more commonly induced by man's engineering activities. (3) An outlet must serve both as a discharge point for the flowing water and as a disposal area for the transported silt and sand grains. Gully

> walls and the rims of plateaus naturally provide outlets. Excavation and drilling of boreholes provide additional outlets that increase the probability of initiating a process whose natural occurrence is restricted."

Reflection on the three conditions described above shows that each is met in the model proposed for surface subsidence in the Iron River District: 1) a competent till caps unconsolidated sands, 2) water flow initiates after pumping in the drift ceases, and 3) the mine voids serve as a disposal area.

Applications. Some subsidence of surface material in the Iron River District might have been avoided if, when the mine closed, pumping in the overburden would be continued with the waters pumped directly into the mine until it was filled. Under this situation there would be no water transport of sands into the stope and no large unsupported cavern would form under the till capping. Consequently, subsidence would not occur immediately. When and if it did occur less surface area might be affected. However, early caving provides some insurance against unpredictable future subsidence. Then too, with early subsidence, stopes become at least partially filled and the zones most likely to subside (over the stopes) have already done so.

With proper planning this phenomenon could be used to stabilize a closing mine by drilling channelways in locations to most completely fill the stopes. Application of a modification of this method might be used to further stabilize abandoned, water-filled mines. The idea would be to induce caving over open stopes by drilling into the stopes from the surface. The second step would be to blast the bedrock above the stope causing it to fall into the stope and to create openings to the overlying drift. Pumping large volumes of water from the stope would cause ground water in the drift to flow into the stope. The flow would carry the uncemented glacial sands lying above bedrock into the stope accomplishing the filling to the degree desired or practical.

Waters pumped from the stope might be acid. They could be returned into the drift by disposal wells peripheral to but within the drawdown cone of the pumping.

Critical Areas

Critical areas are defined as those where stopes underlie or nearly underlie in-use surface structures including roads, railroads and buildings. Eleven areas in the Iron River District fall into this category. It should be noted that the inclusion of an area does not imply that subsidence will occur; however, if it does occur there is potential for loss of property or a life hazard. Considerations relative to the probability of subsidence are discussed at the end of this section of the report.

The location of the critical areas in the Iron River District are shown on the maps of Figures 2 and 3. They are as follows:

1. Davidson #1 Mine: surface subsidence cracks in Mineral Avenue.
2. Cardiff-Homer Mines: deep stopes under 16th Street (9th level).
3. Homer-Wauseca Mine: stopes 35 to 150' distance from 16th Street at depth (10th and 12th levels)
4. Beta-Nanaimo Mine: a 53' vertical opening 18' wide at a depth of 310 to 350' beneath U.S. 2 west of Iron River.
5. Delta Mine: a stope 40' in maximum vertical dimension lies 224' below U.S. 2 west of the Iron River and just east of the intersection with River Avenue and Genesee Street. Also the west margin of a stope at a depth of 325' lies 40' east of the railway south of U.S. 2.
6. Chatham Mine: stopes underlie the Selden Road at least 270' upward from the 1050' level. Also, the railway passes over a 60' wide by

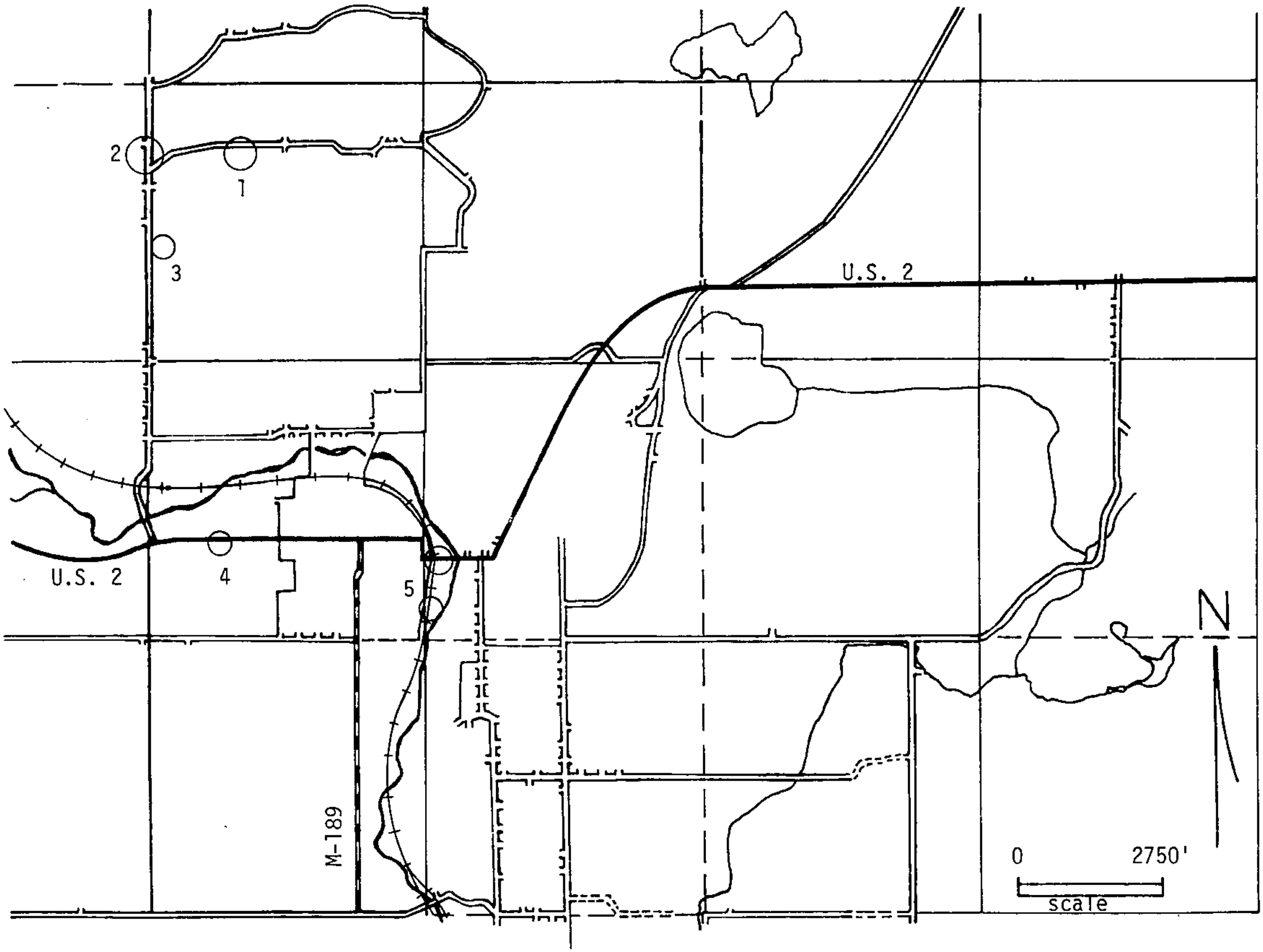


Figure 2. Locations of Critical Areas in the Northern Part of the Iron River District

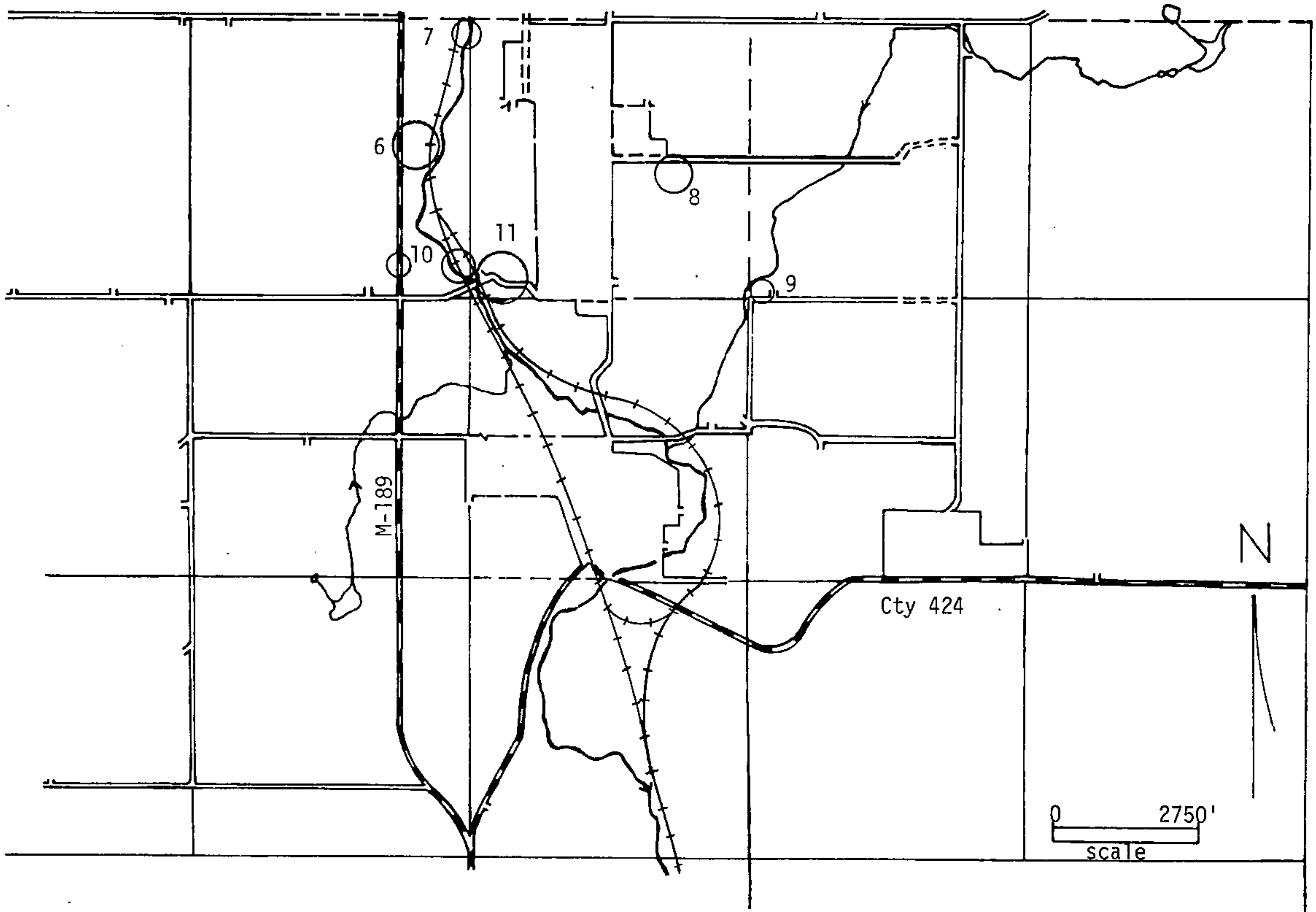


Figure 3 . Locations of Critical Areas in the Southern Part of the Iron River District

500' long stope at a depth of about 325'.

7. Riverton Mine: stopes from the 4th to 6th level of this early mine underlie the railway west of Stambaugh in the Iron River valley.
8. Bengal Mine: the north edge of the subsidence pit from this top slicing mine very nearly extends to Ninth Street. At depth some of the stopes lie within 15' of the center line of Ninth Street.
9. Baker Mine: The uppermost workings are within 170' of the surface and 80' of the bedrock. A county road overlies these workings.
10. Hiawatha Mine (Stegmiller Lease): a stope underlies Selden Road at a depth of about 300'. The stope has a vertical height of approximately 150'. Workings also underlie the railway.
11. Dober-Isabella Mines: workings from both mines underlie 19th Street. The Isabella workings are shallower with stope tops at 195' and 600' of the surface.

Each critical area is described separately in greater detail in the following section. Plan and cross-section maps are included to better document and illustrate each situation. Mine maps available from the DNR and County Mine Inspector's Office and old reports were used to construct the figures and obtain information on the locations of the stopes. Unfortunately, the information is never as complete as desired. For example, stope filling has been done in some mines, but the maps often do not indicate which stopes are filled. For the older mines, the information is more sketchy and in some cases questionable. Furthermore, it is possible that subsidence has partly filled some of the voids. It is also possible that this subsidence has caused the void to move closer to the surface than is indicated by the mine maps.

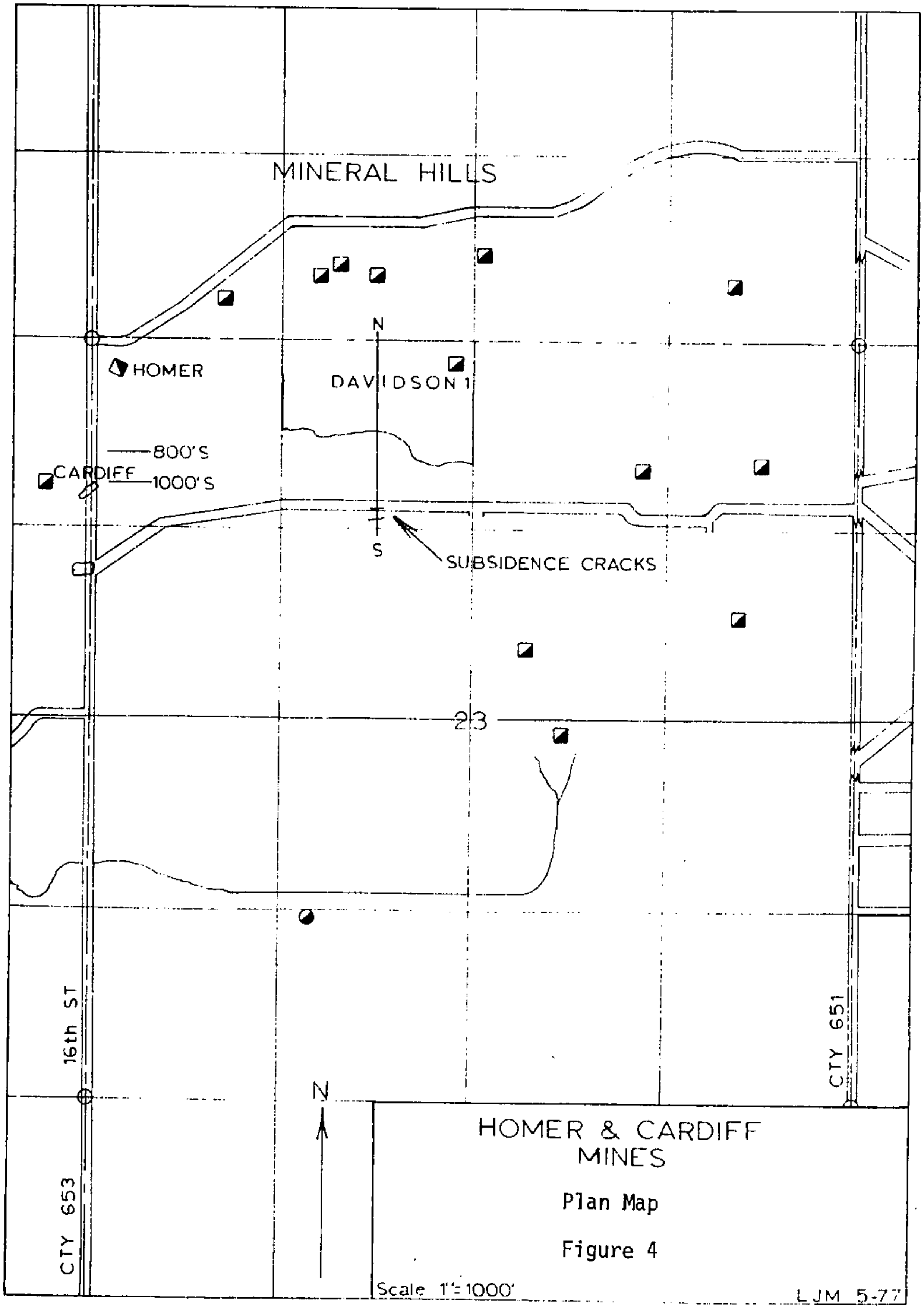
Davidson #1 Mine. The Davidson #1 Mine is the forty east of the Homer Mine property in the NE1/4, NW1/4, Sec. 23, T43N, R35W. Producing from 1911 to 1953, it was the longest operating and largest producer of the four Davidson mines. It had only one shaft on the property but was accessed also by a shaft on the Forbes forty to the north.

Stopes in the Davidson #1 Mine extend from 135 feet deep (elevation 1455 feet) to the 950 foot level (elevation 635 feet). They extend from east to west the full length of the property and due to the south dip of the ore extend from the north boundary to within 465 feet of the southern boundary at depth. The location of the property is on the plan map of Figure 4 and a cross-sectional view is shown in Figure 5.

Overburden thickness on the Davidson #1 property is about 100 feet and in some places greater. A subsidence crack on the surface 60 feet south of and parallel to Mineral Avenue is 110 feet long. It has about six inches maximum vertical displacement with the north block down dropped. In 1974 several east-west fractures were present in the surface pavement of Mineral Avenue. They were filled and have not reappeared to date. The surface subsidence crack is offset to the south from the Davidson workings. A surface projection of the mine workings places them at about 520 feet north of the surface fracture.

Cardiff and Homer Mines. The Cardiff and Homer Mines are on adjacent 40's on either side of County Road 653 west of the village of Mineral Hills. The Cardiff Mine on the west is located in the E1/2, NE1/4, Sec. 22 and the Homer on the east in the W1/2, NW1/4, Sec. 23, both in T43N, R35W.

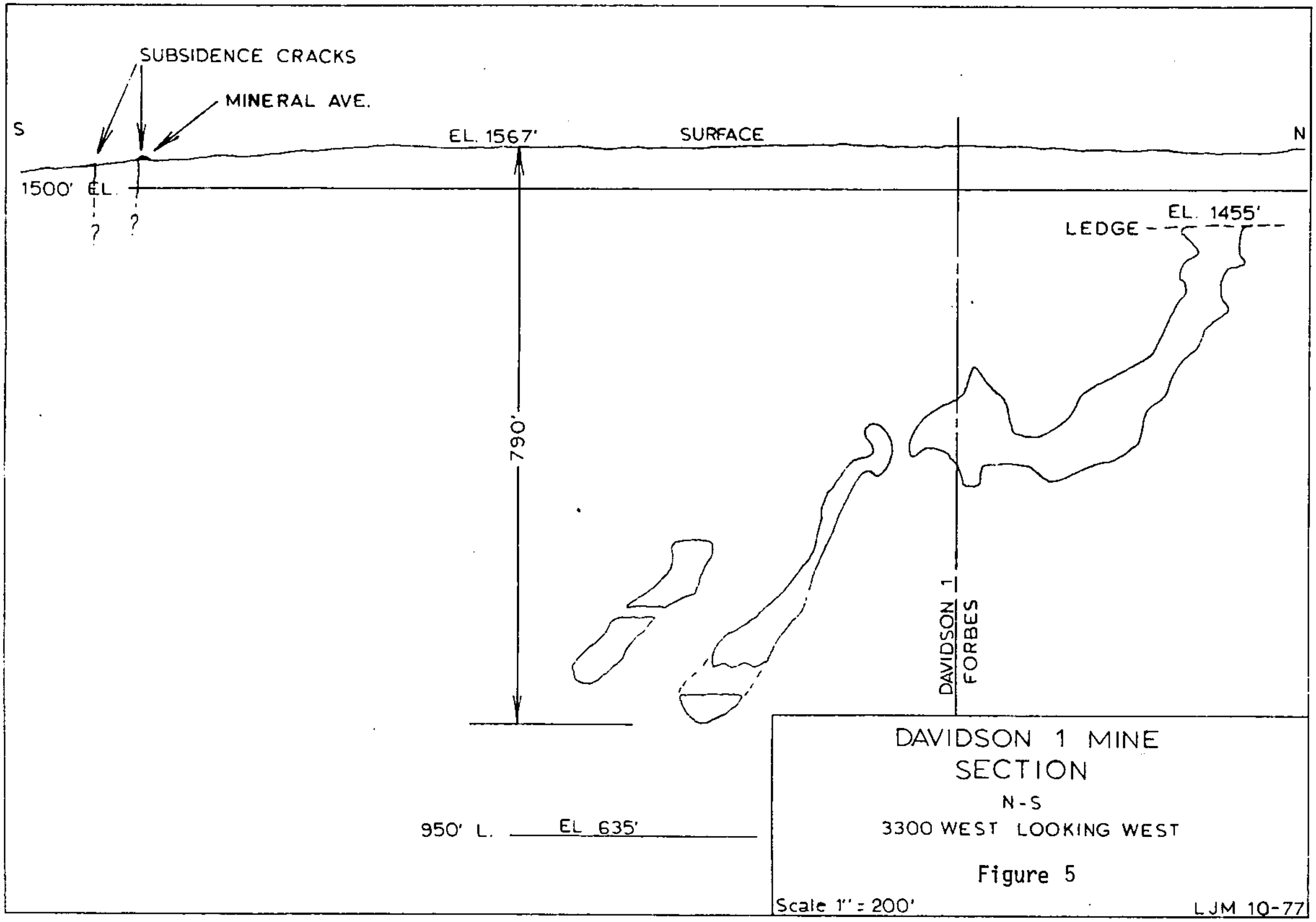
They were operated from 1914 to 1959. The dates and production records are inclusive for the Cardiff, Homer and Homer-Wauseca and total 17,493,490 tons. The early operation (Cardiff) had one shaft 593 feet deep and one level at 523



HOMER & CARDIFF MINES

Plan Map

Figure 4



DAVIDSON 1 MINE
SECTION
N-S
3300 WEST LOOKING WEST

Figure 5

Scale 1" = 200'
LJM 10-77

feet deep; collar elevation was 1500 feet. Development below the original Cardiff Mine was done through the Homer shaft and extended to the 9th level of the Homer at 430 feet elevation.

Drift thickness at the Cardiff shaft is 132 feet and the uppermost stope is about 260 feet below ledge.

Two stopes underlie County Road 653 at depth. The northermost is at the 115 foot sub-level above the 6th level (elevation 978 feet) or about 522 feet below the road and 395 feet below ledge. The mine maps indicate this stope has caved, so it would be at least partly filled. Below this level mining was extensive to the east, less extensive to the west. The southernmost stope underlying County Road 653 is at the 74 foot sub (elevation 504 feet) above the 9th level. There was extensive mining above to the west. The location of the stopes are shown in plan view in Figure 4 and in a west-looking cross-section in Figure 6.

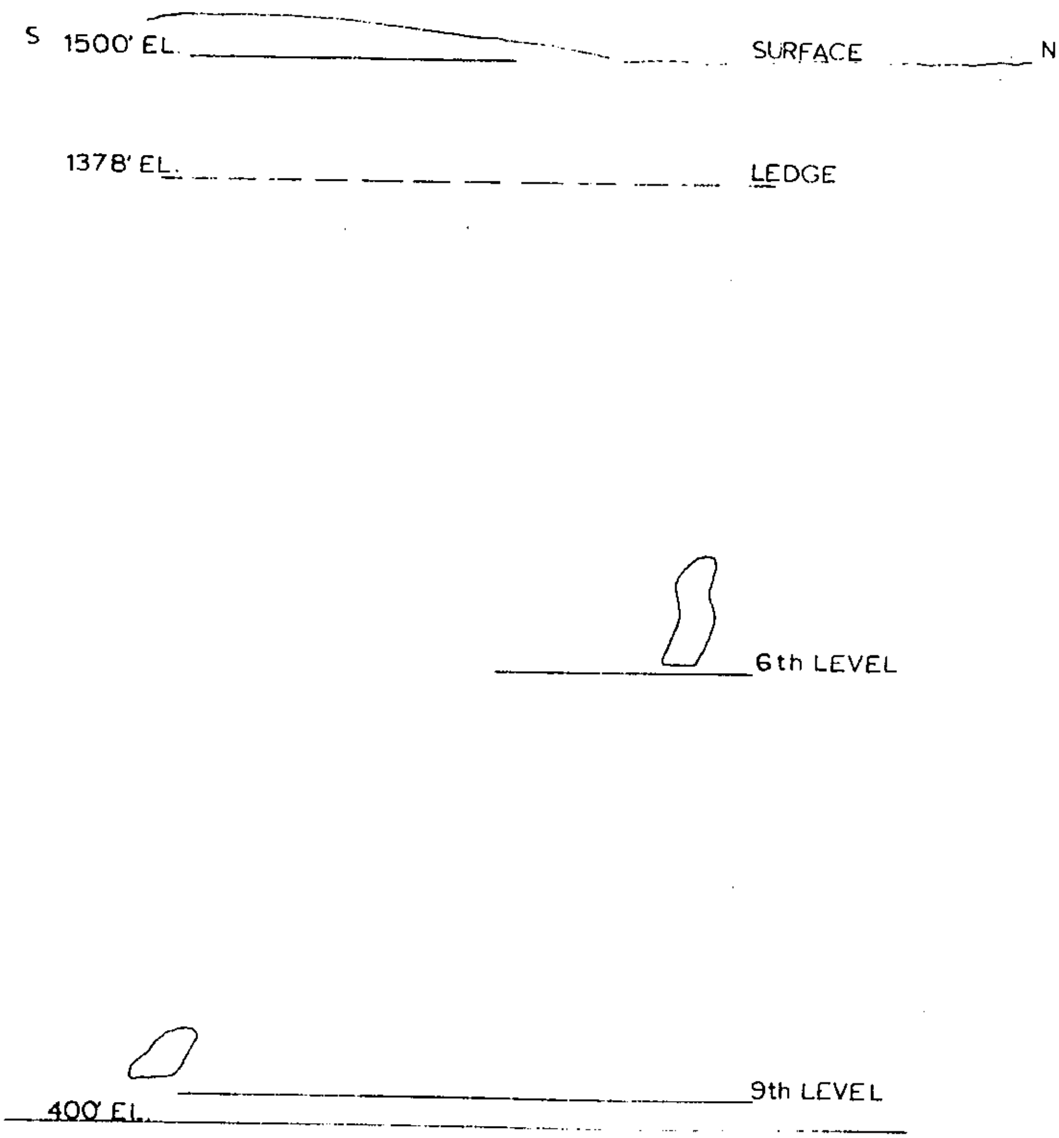
Some stopes in the Homer-Cardiff Mines are marked as filled on the mine maps, but it is not noted whether the filling is due to caving or backfill.

Homer-Wauseca Mine. This mine complex operated from 1915 to 1971. It is comprised of 7 forties in Sec. 23 of T43N, R35W. This mine complex includes the Wauseca Mine workings. It was served by six shafts, N. Homer, 1 and 2 Wauseca, Minkler, Aronson and the Homer-Wauseca. The Homer-Wauseca shaft is circular with four compartments 2740 feet deep and has 16 levels.

The strike of the ore body is generally east-west but varies considerably on the west margin.

Overburden thickness is generally in excess of 100 feet over most of the area.

Mining was quite extensive and considerable backfilling was done with both



HOMER & CARDIFF
SECTION
N-S BOUNDARY LOOKING WEST

Figure 6

Scale. 1" = 200'

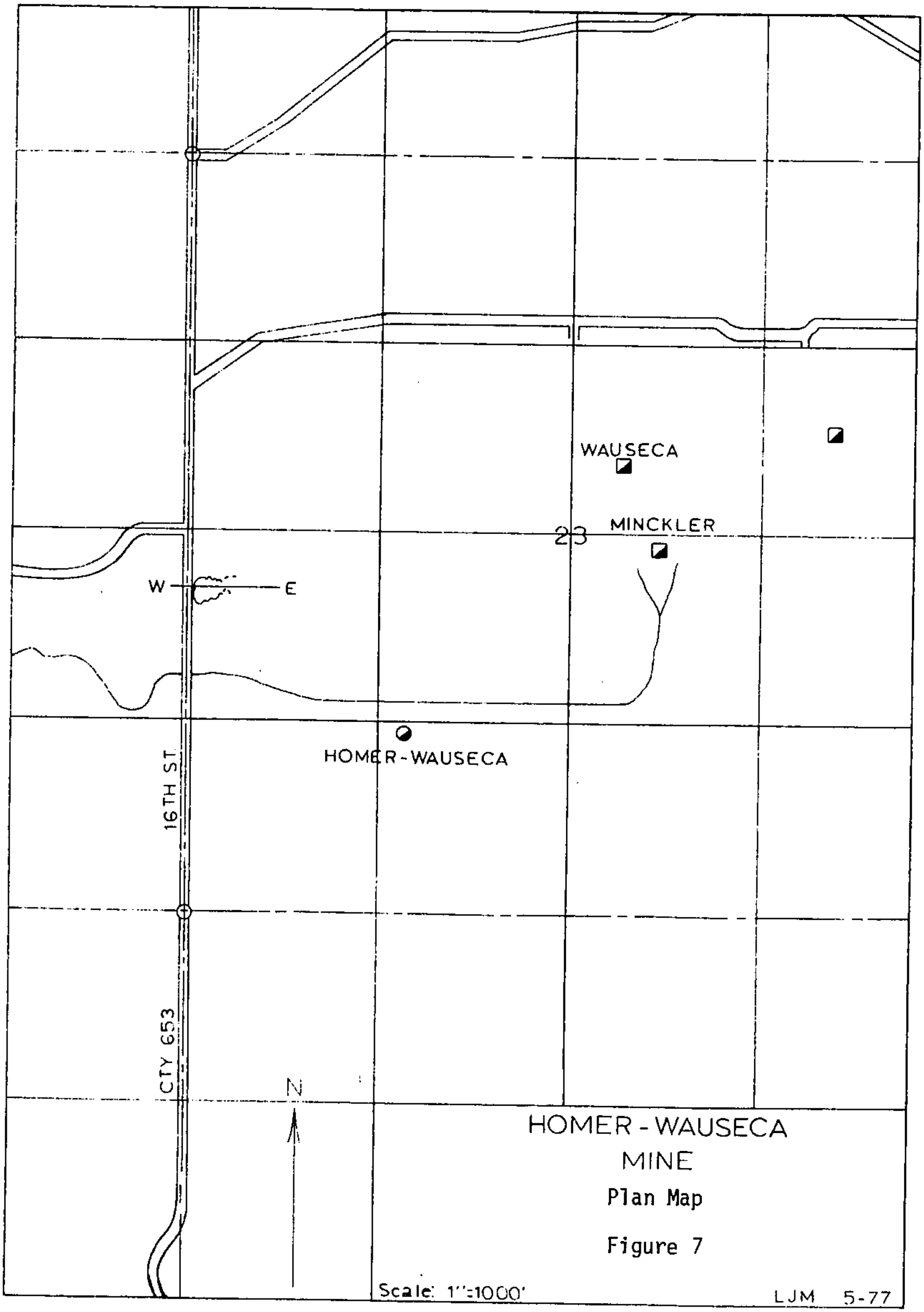
LJM 5-77

black slate gob and glacial drift material. Stoped areas within 200 feet of County Road 653 are at depth between the 9th and 13th levels. There is approximately 1100 feet of rock between the upper stope limits and the bedrock surface. The location of the stopes is shown in Figure 7 and a cross-sectional view in Figure 8. Stopes between the 9th and 12th levels shown on the longitudinal section were backfilled with black slate and gravel; those between the 12th and 13th levels are not marked as filled. (NOTE: The N-S location of the longitudinal section (W-E) in Figure 7 is tentative; it could be a projection.)

Beta-Nanaimo Mine. This very old mine comprised of the Beta and Nanaimo Mines was one of the first in the district. It operated from 1886 until 1891. It is located west of the city of Iron River, underlying U.S. Highway 2 in the NE1/4, SW1/4 and W1/2, SW1/4 of Sec. 26, T43N, R35W (see Figure 9). Both mines started as open pits but when combined were developed as an underground mine. Development proceeded to at least the fourth level, but mine maps show stopes only to the third level. Production records indicate 27,156 tons of ore produced.

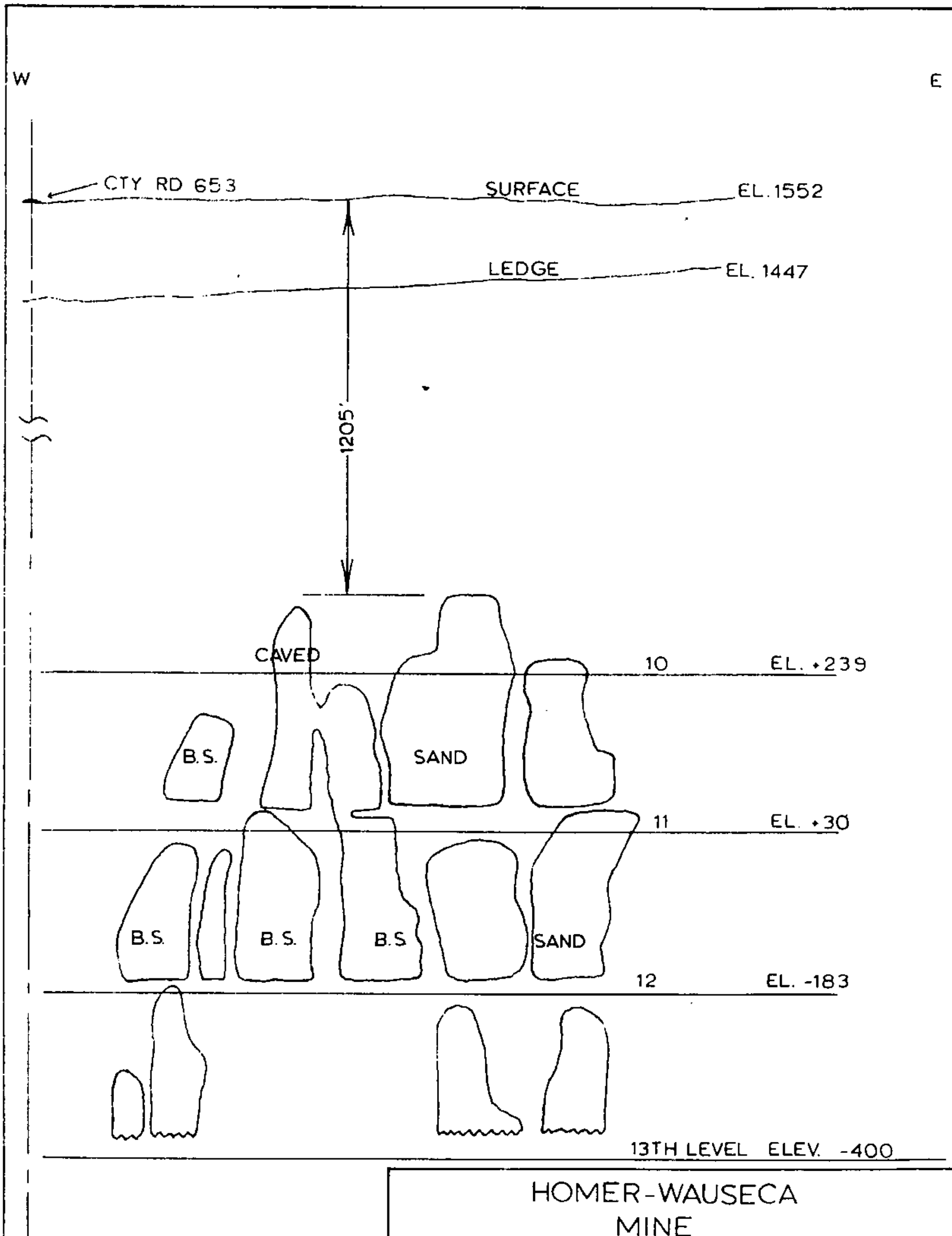
The largest stope is about 150 feet high with the top 215 feet below the surface with as much as 25 feet of overburden; however, this part of the stope is not directly under U.S. 2. Beneath the right-of-way for U.S. 2 the opening has a maximum vertical dimension of about 42 feet and is 18 feet wide. The stope has a bearing of 60° east of north and diminishes in size to the northeast. Beneath U.S. 2 the drift thickness varies from 13 to 18 feet. The top of the stope is within 308 to 332 feet of the surface under the highway. These relationships are shown in plan view (Figure 9) and in two cross-sectional views (Figures 10 and 11).

Delta Mine. The Delta Mine lies within the city of Iron River. It is located in the Iron River valley near where U.S. 2 crosses the Iron River (W1/2,



HOMER-WAUSECA
MINE
Plan Map

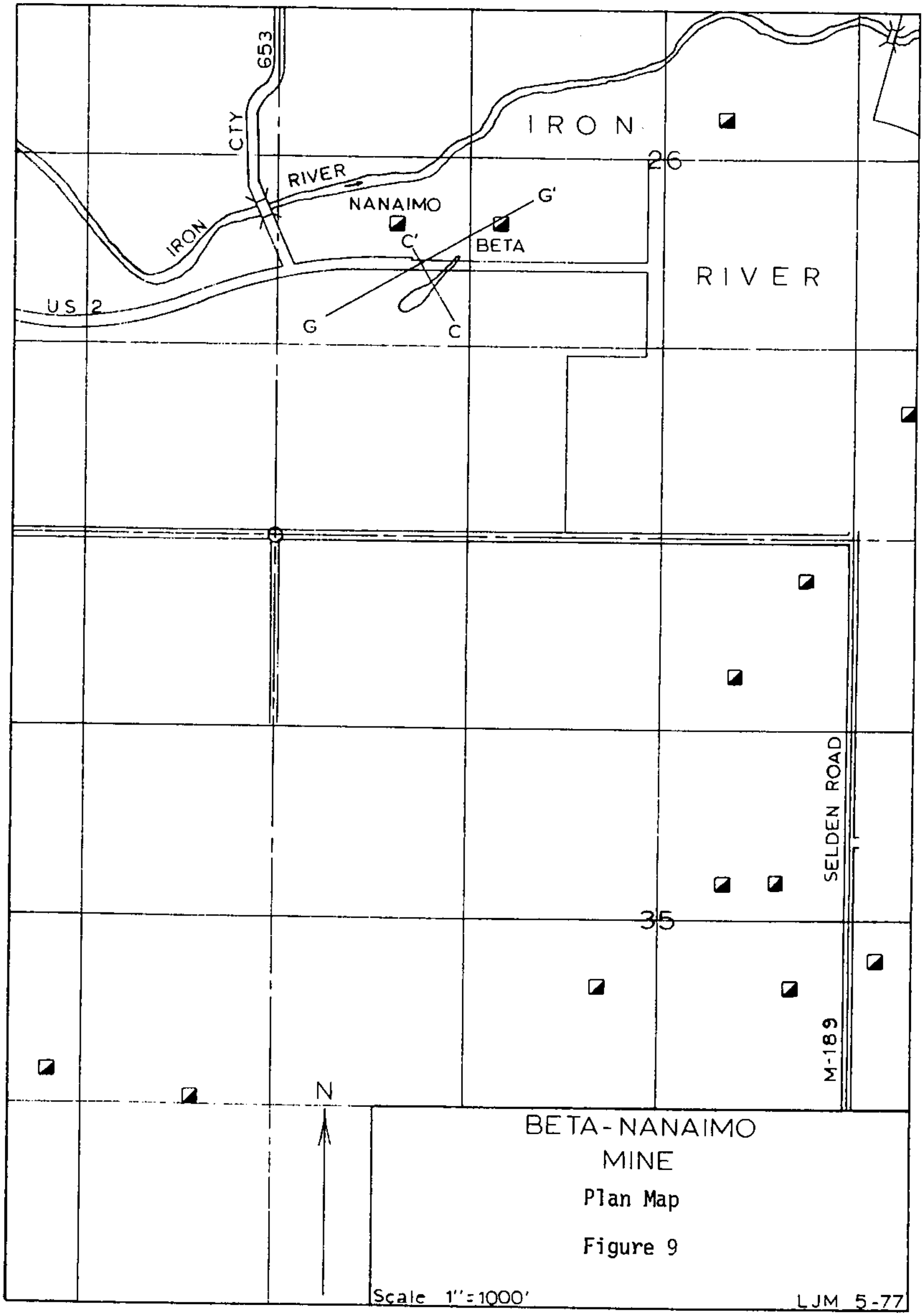
Figure 7



HOMER-WAUSECA
MINE
SECTION
LOOKING NORTH

Figure 8

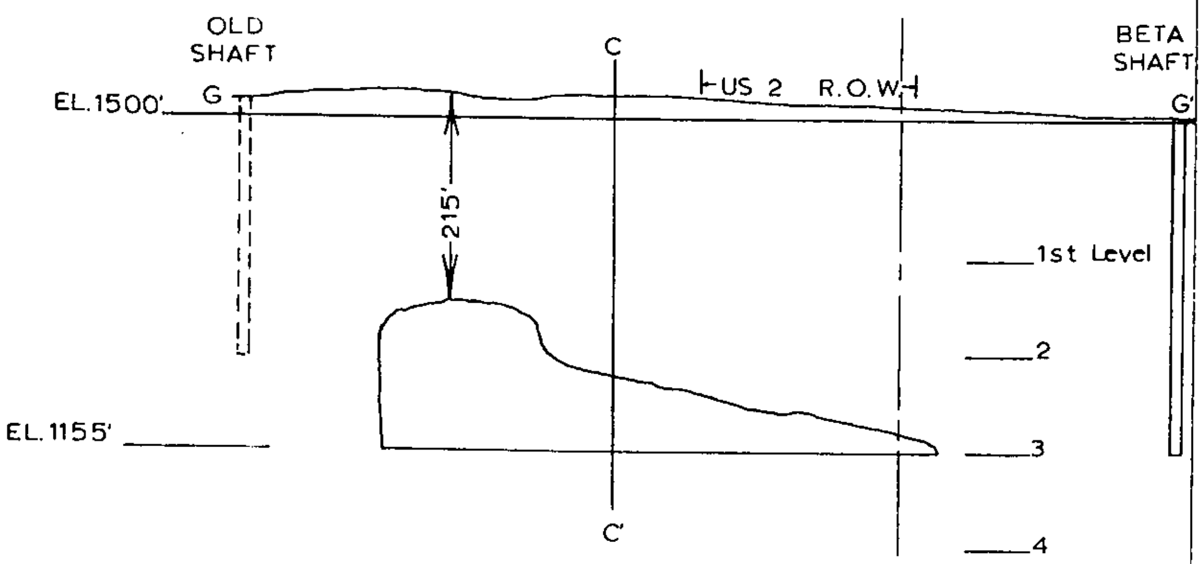
Scale: 1" = 200'   LJM 10-77



BETA-NANAIMO MINE

Plan Map

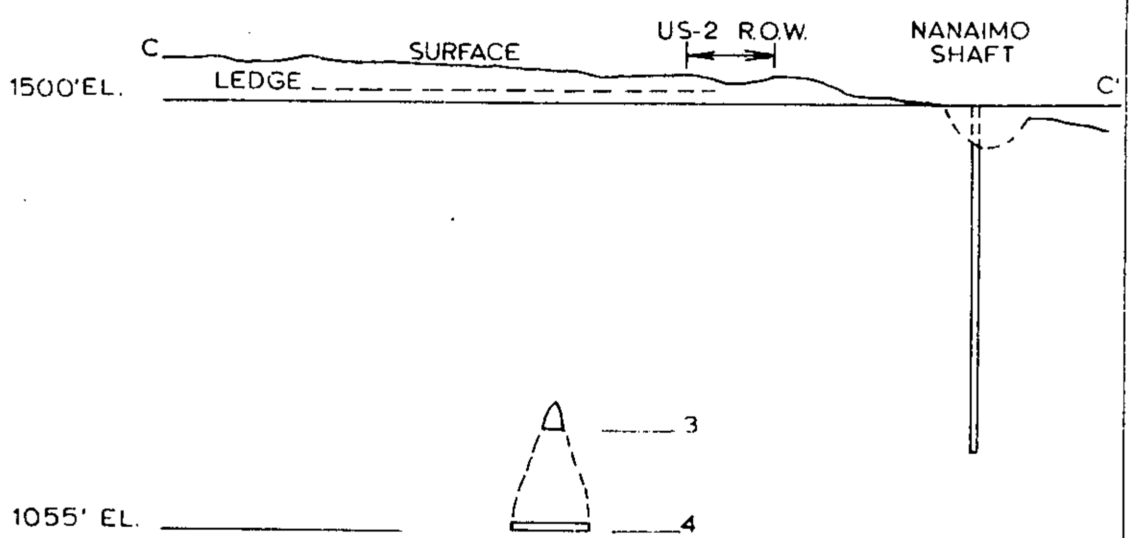
Figure 9



BETA-NANAIMO
SECTION
G-G'
LOOKING NORTHWEST

Figure 10

Scale 1" = 200' LJM 5-77



BETA-NANAIMO
SECTION
C-C'
LOOKING SOUTHWEST

Figure 11

Scale: 1" = 200'   LJM 10-77

SW1/4, Sec. 25, T43N, R35W). It was operated from 1920 to 1925 producing a total of 95,759 tons of ore.

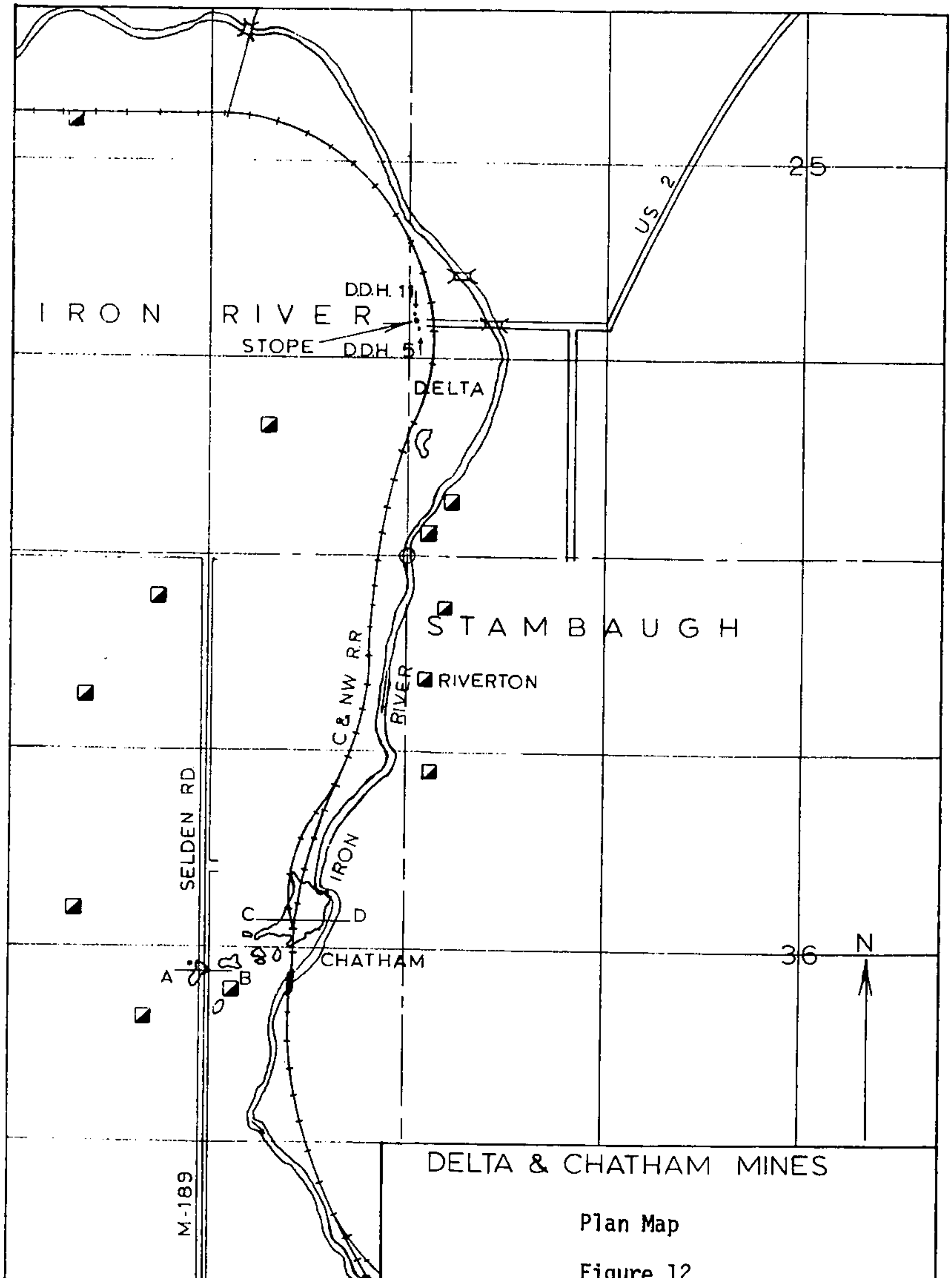
Although the mine had three shafts, only the #1 shaft hauled ore. Three levels were mined to a depth of 334 feet below the 1500 foot collar elevation of the #1 shaft.

Subsidence above the largest stope just east of the Chicago and Northwestern Railway tracks was indicated on a 1944 map by Fayette E. Brown updated to 1955 by W. E. Dewald. The northernmost stope directly underlies Highway U.S. 2 west of the railway tracks. Here the top of the 40 foot high stope is 224 feet beneath the highway. Overburden thickness is about 30 feet. These relationships are shown in Figures 12 and 13.

Chatham Mine. The Chatham Mine is located in the Iron River valley in west Stambaugh along Highway M-189 or Selden Road. The forty comprising the Chatham property is the NE1/4, SE1/4, Sec. 35, T43N, R35W (Figure 12). The mine was operated from 1907 to 1920 by the Brule Mining Company. The mine was served by three shafts, ore being hauled from the #1 shaft which was collared at an elevation of 1510 feet.

A total of 1,381,175 tons of soft, brown high phosphorus ore was produced from the ore body. The main ore body strikes generally northeast, is about 60 feet thick and stands nearly vertical, although the structure is very complex.

The main stope of the Chatham Mine underlies the Chicago and Northwestern Railway at depth and a smaller stope underlies Selden Road (M-189) also at depth. The top of the fairly extensive main stope is 710 feet below the surface of the railroad grade (Figure 14). Although drift thickness is not shown on the maps, it is probably in the neighborhood of 30 to 50 feet as the mine is located in the Iron River valley.



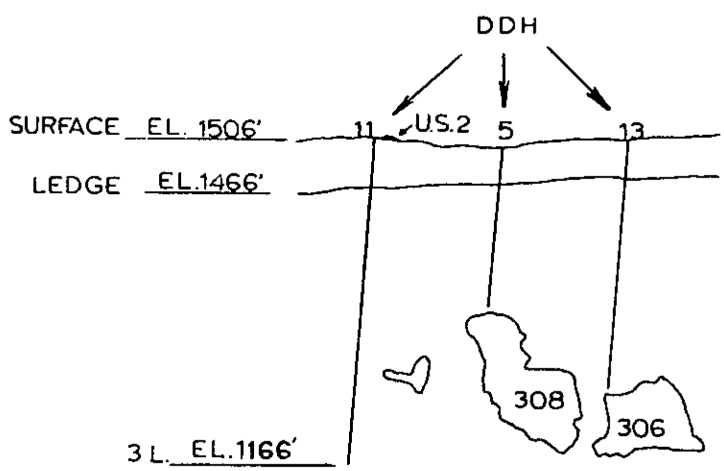
DELTA & CHATHAM MINES

Plan Map

Figure 12

Scale 1" = 1000'

LJM 5-77



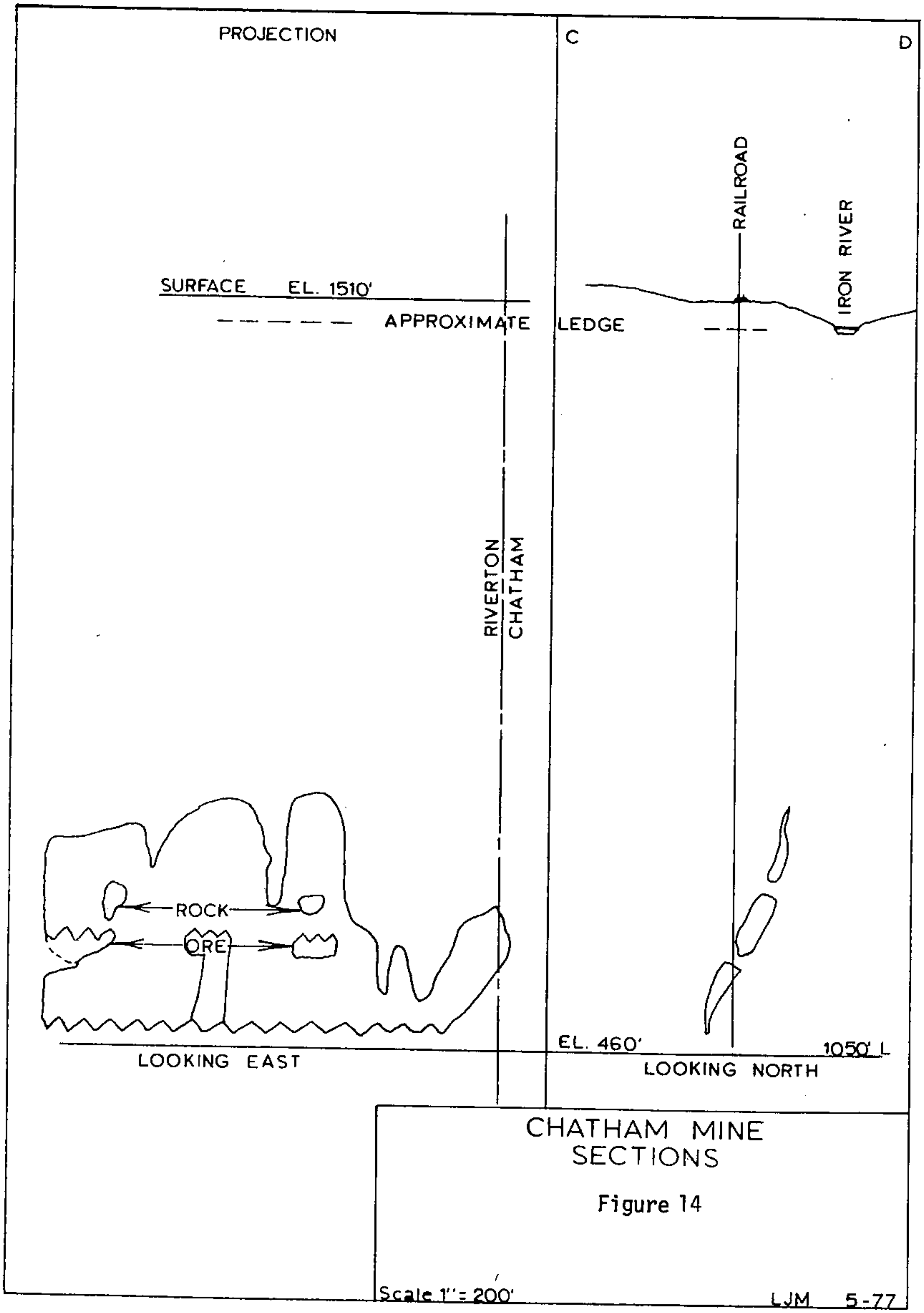
DELTA MINE
SECTION

NORTH STOPE
LOOKING EAST

Figure 13

Scale. 1"=200'

LJM 10-77



CHATHAM MINE SECTIONS

Figure 14

Mine map records are incomplete concerning the extent of stoping under Selden Road (M-189); however, they show stopes at least 270 feet high within 775 feet of the surface (see Figure 15).

Riverton Mine. The Riverton was the first mine in the Iron River District. It began as an open pit in 1882 and later moved underground, closing in 1931. The mine is located in the Iron River valley west of the city of Stambaugh in the W1/2, NW1/4, Sec. 36, T43N, R35W. Production totaled 4,881,550 tons from six levels served by six shafts. Maps for this mine came from a 1910 publication by R. C. Allen, and since the mine did not close until 1931, they are incomplete.

The ore body strikes essentially north-south and dips steeply to the west. In plan view the workings form an arcuate shape open to the west (Figure 16). Stopes on the lowest levels underlie the Chicago and Northwestern Railway on the extreme northwest end of the mine.

Cross-sections of the mine are shown in Figure 17.

Bengal Mine. The Bengal Mine was operated from 1913 to 1949 by the Verona Mining Company, producing 5,671,823 tons of soft ore. Later it became part of the Cannon Mine operation until closing in 1963. The Bengal Mine workings occupy the N1/2, SE1/4 of Sec. 36, T43N, R35W and are located in the city of Stambaugh. Ore in the upper levels was extracted by top slicing which moves the overburden down with the mining. Thus the pit outline coincides closely to the mined areas (Figure 18). However, some of the deeper ore was extracted using sub-level caving and stoping methods.

Stopes from the 6th to 8th levels lie very close to the Ninth Street right-of-way. The position of these stopes is shown in sectional view in Figure 19.

Baker Mine. The Baker Mine was established in 1909 and operated until 1915 by the Corrigan-McKinney Company. A total of 267,107 tons of soft ore were

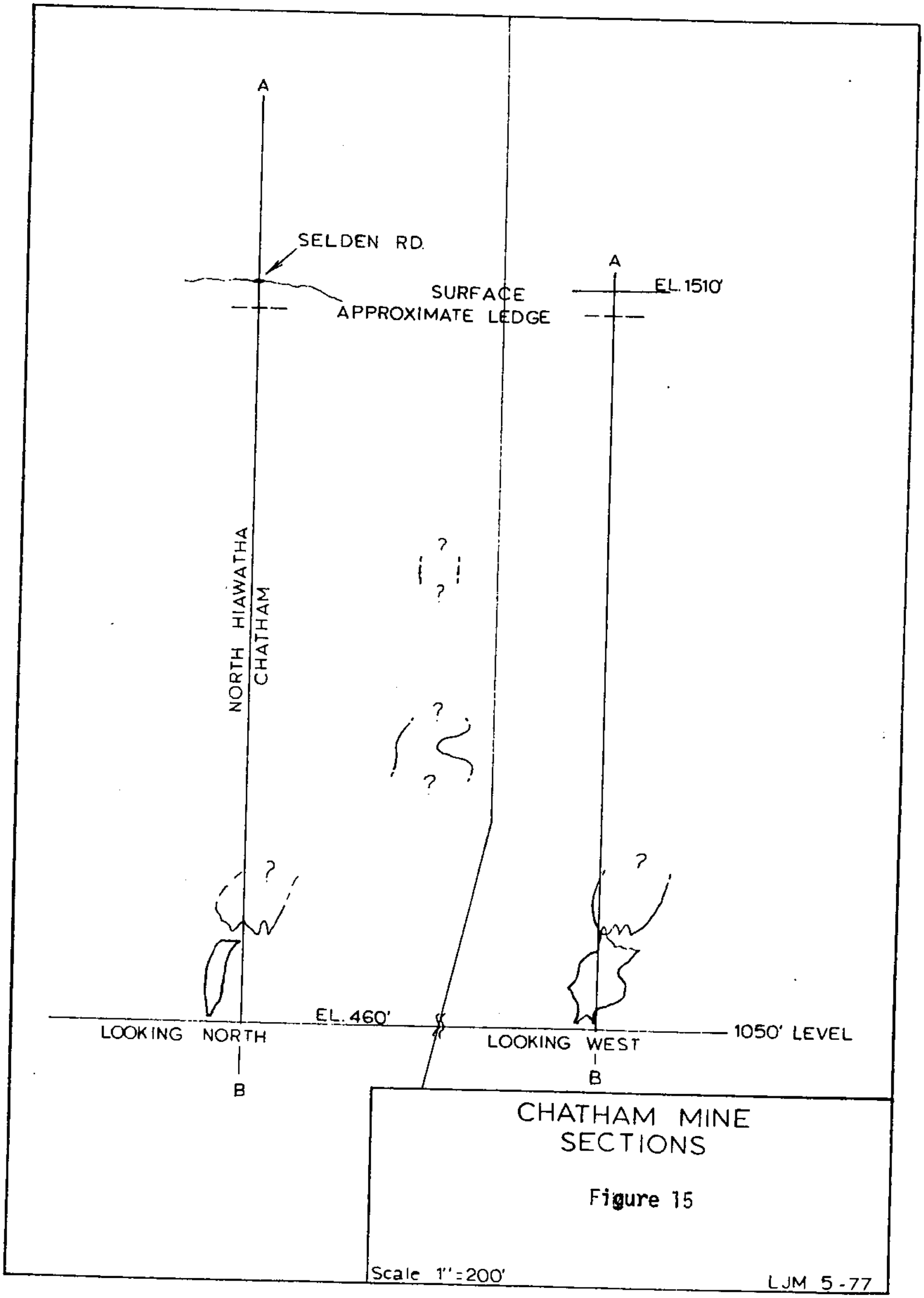
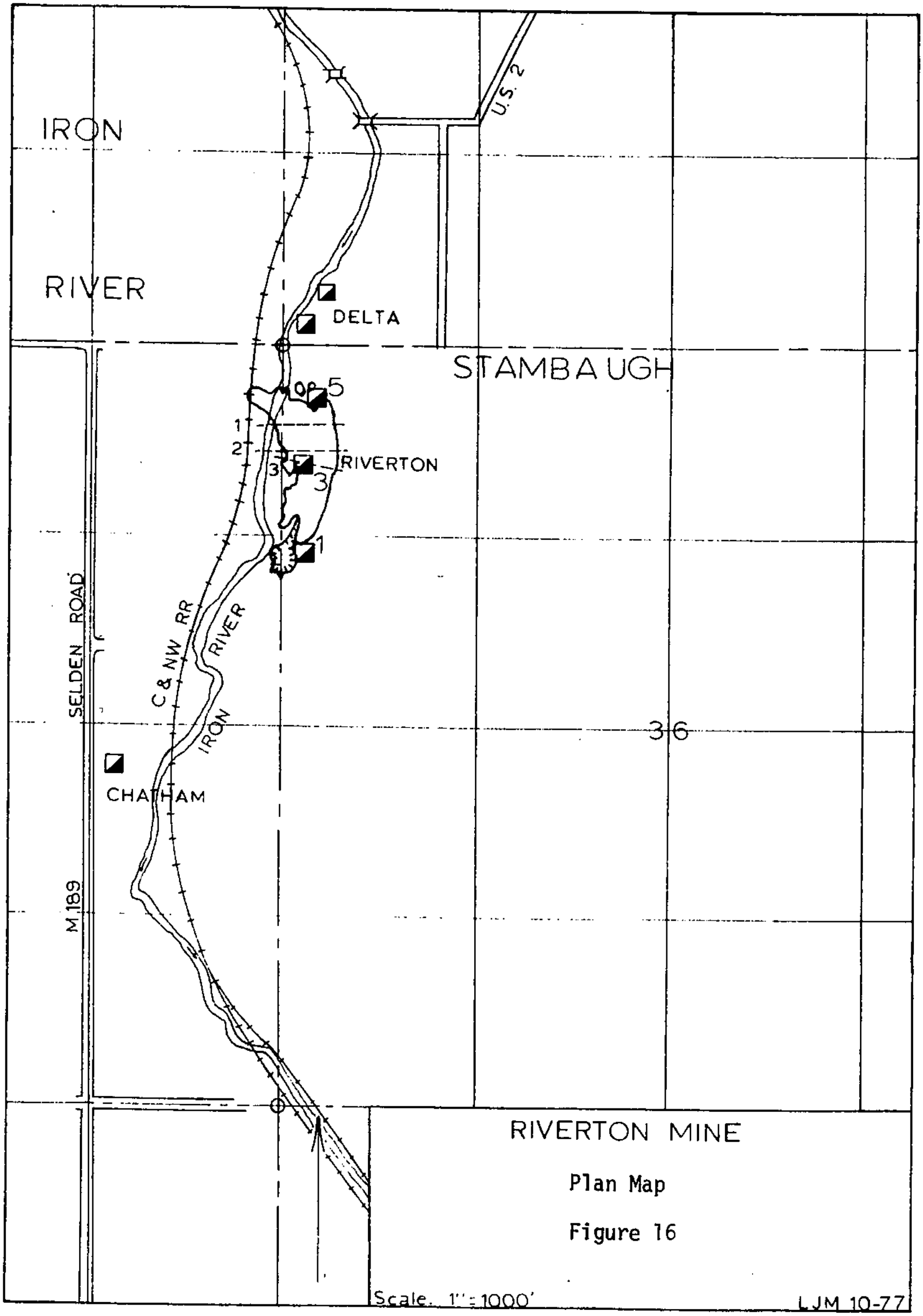

A
SELDEN RD.
A
SURFACE
EL. 1510'
APPROXIMATE LEDGE
NORTH HIAWATHA
CHATHAM
?
?
?
?
?
?
EL. 460'
LOOKING NORTH
LOOKING WEST
1050' LEVEL
B
B
CHATHAM MINE
SECTIONS
Scale 1'' = 200'
LJM 5-77

Figure 15



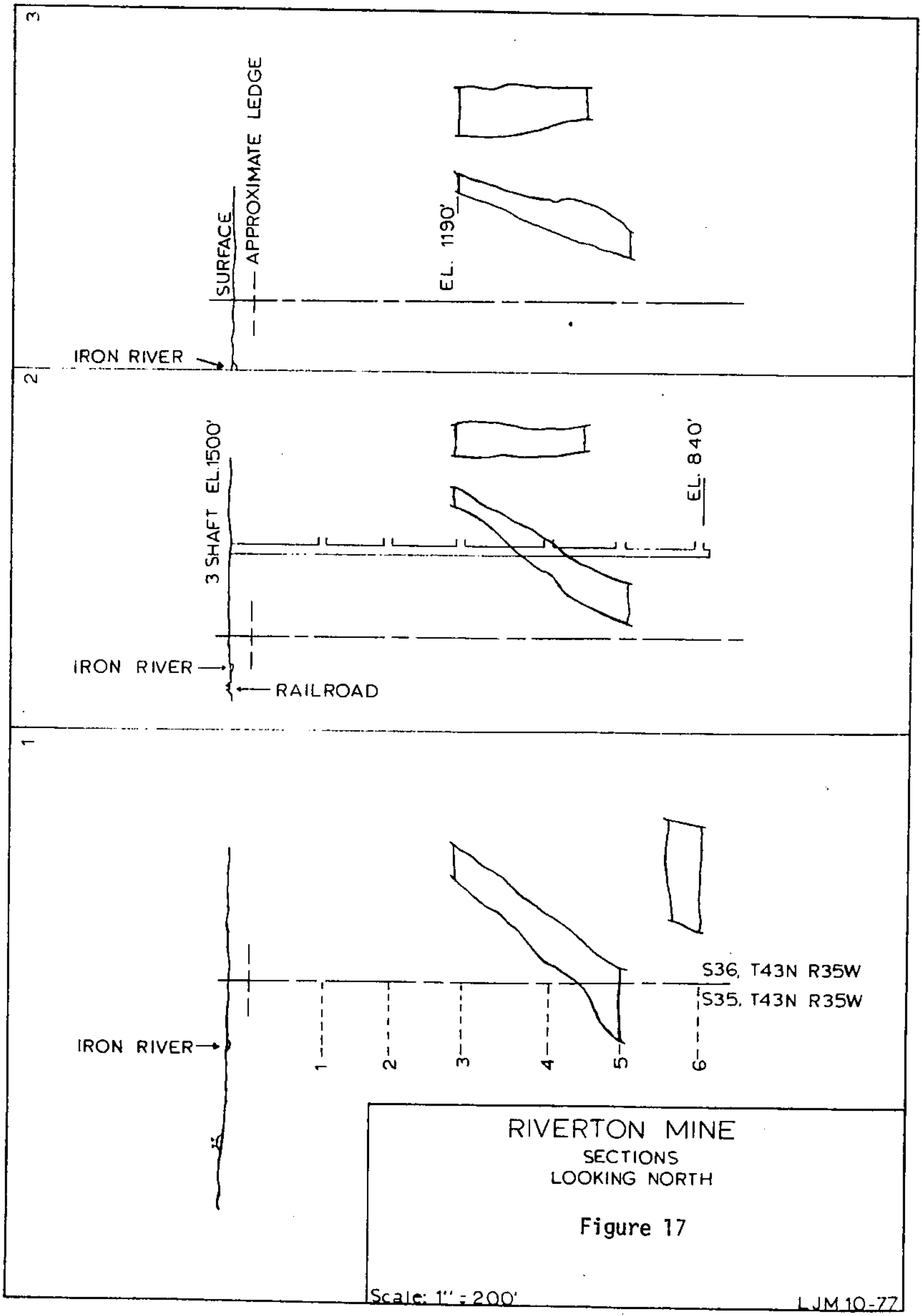
RIVERTON MINE

Plan Map

Figure 16

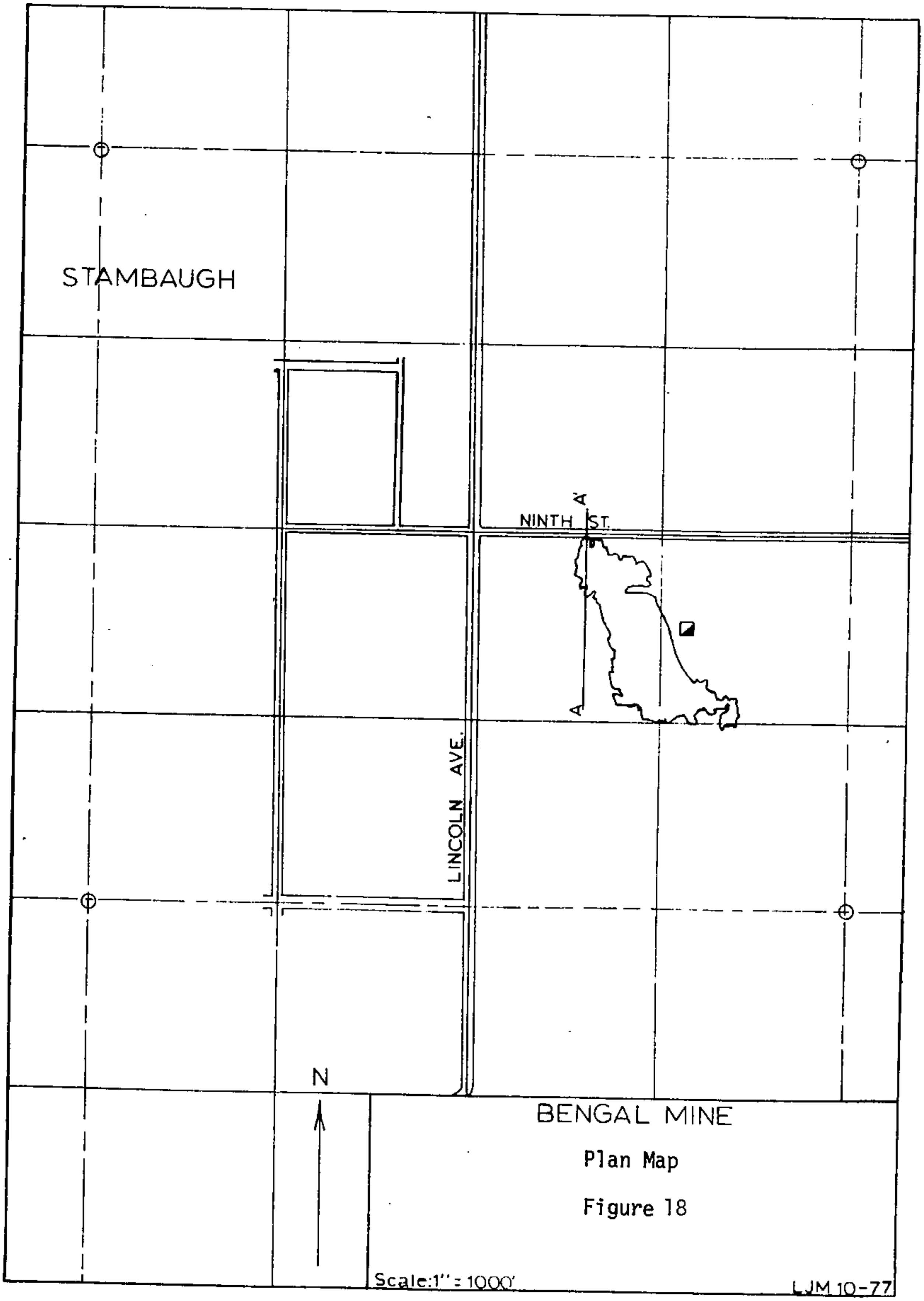
Scale. 1" = 1000'

LJM 10-77



RIVERTON MINE
SECTIONS
LOOKING NORTH

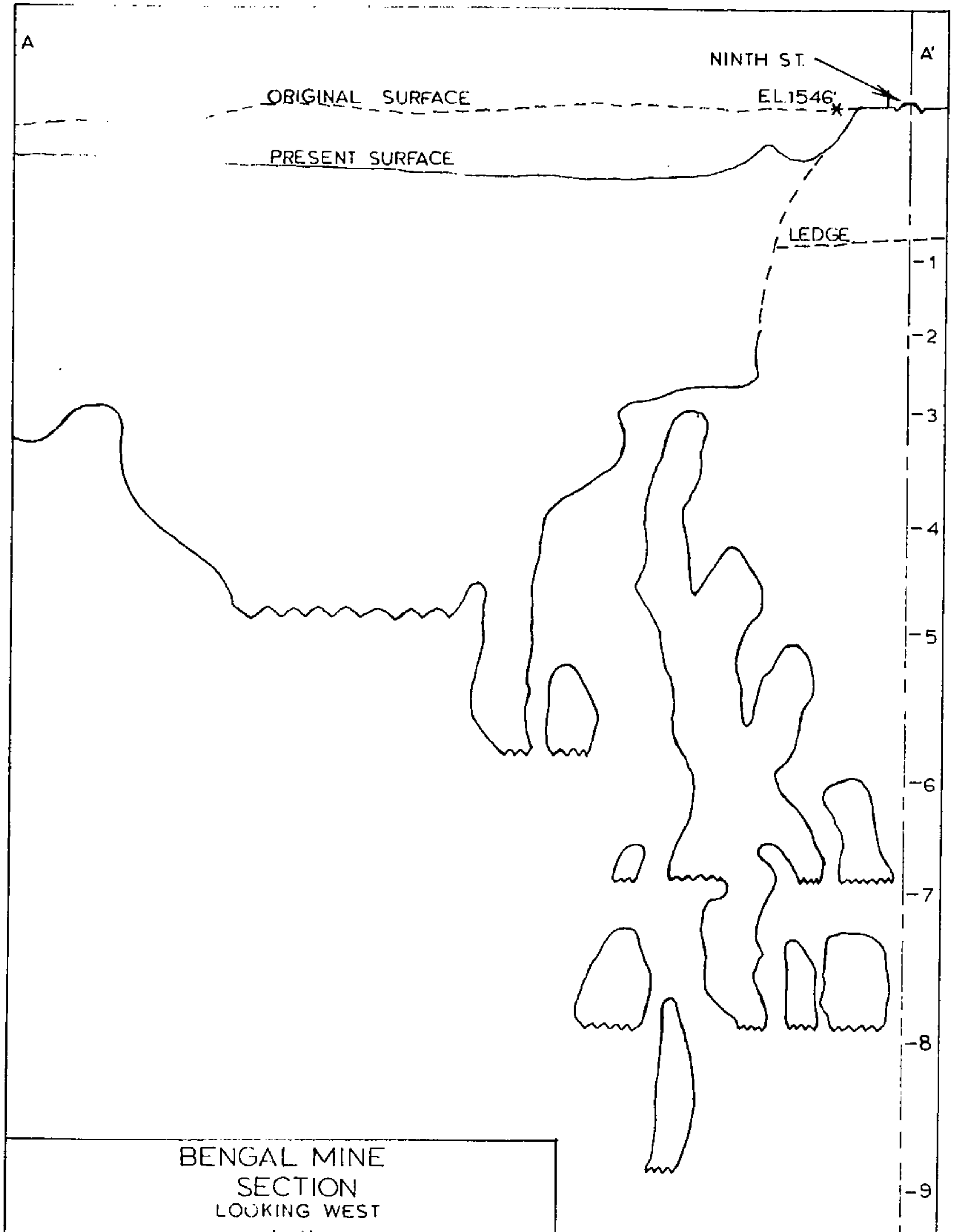
Figure 17



BENGAL MINE

Plan Map

Figure 18



BENGAL MINE
SECTION
LOOKING WEST
A - A'

Figure 19

Scale: 1" = 200'

LJM 10-77

removed from above the third level as indicated by mine maps. The Baker Mine is located east of the Cannon Mine southeast of Stambaugh in the SW1/4, SW1/4, Sec. 31, T43N, R34W.

In addition to this early production from the 457 foot deep shaft, the Baker Mine was later entered from the Tully Mine and developed to a depth of 550 feet.

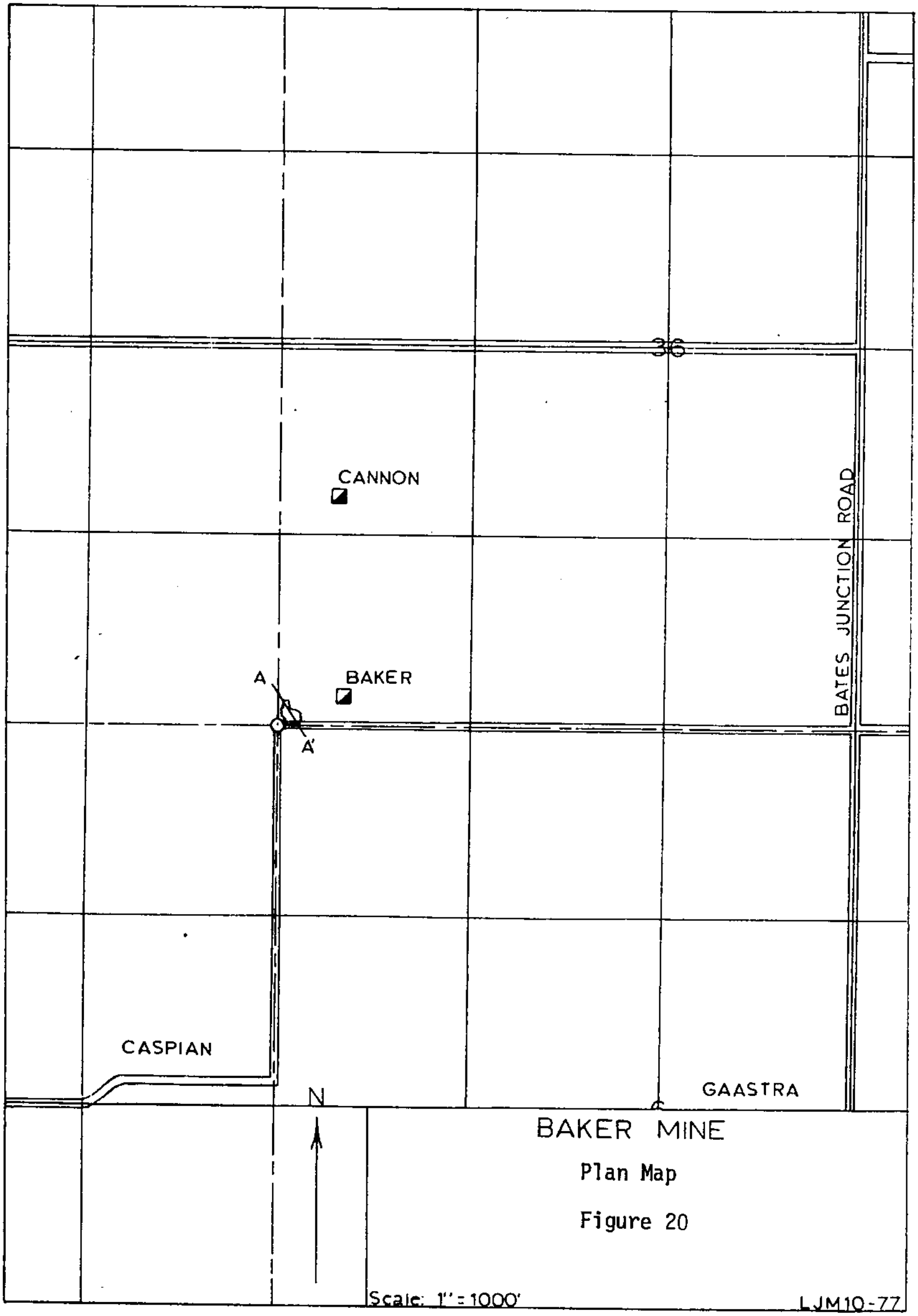
A plan view of the limits of underground workings is shown in Figure 20 and a cross-section of the stopes is presented in Figure 21. Note that top of the stope which apparently underlies the east-west road is within 79 feet of the ledge. Overburden is about 90 feet thick.

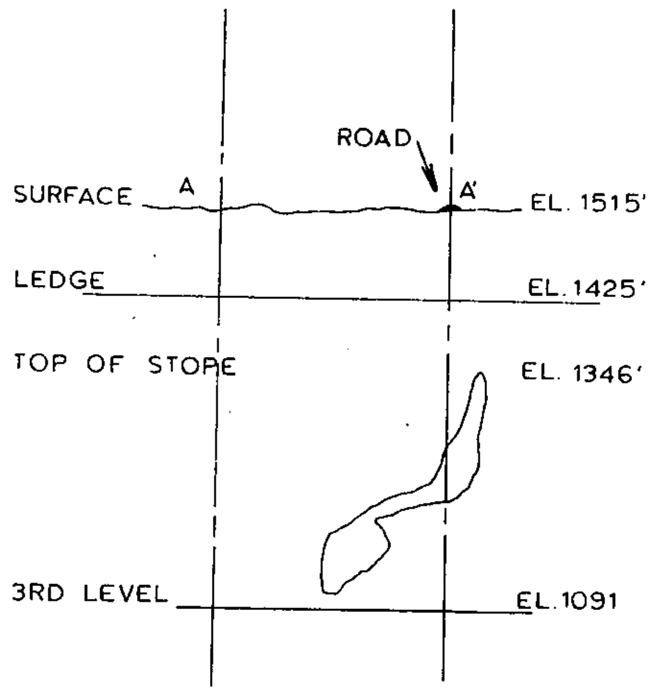
As reported by R. C. Allen (1910) the black slate in the area is granular and friable. The only visible subsidence on surface associated with the Baker Mine is that at the backfilled shaft where a conical pit 30 feet wide and 8 feet deep is present.

Hiawatha #1 Mine. The Hiawatha #1 Mine operated from 1893 to 1967 producing 8,502,729 tons of hard ore from a combined operation which later included the Dober, Isabella and Hiawatha #2 Mines. The property is located west of M-189, 1-1/4 miles south of the city of Iron River in the SW1/4, SE1/4, Sec. 35, T43N, R35W (see Figure 22).

The Hiawatha #1 shaft, collared at 1545 feet elevation, extends past the 18th level (2100 feet) and has a total depth of 2181 feet. There are altogether eight shafts involved in the development of the Hiawatha Mine complex including two stope filling shafts and some large diameter drill holes used to backfill stopes.

Stopes underlie Selden Road (M-189) which is the common boundary between the Hiawatha #1 property on the west and the Stegmiller forty on the east.


36
CANNON
BAKER
A
A'
BATES JUNCTION ROAD
CASPIAN
GAASTRA
N
BAKER MINE
Plan Map
Figure 20
Scale: 1" = 1000'
LJM10-77



BAKER MINE

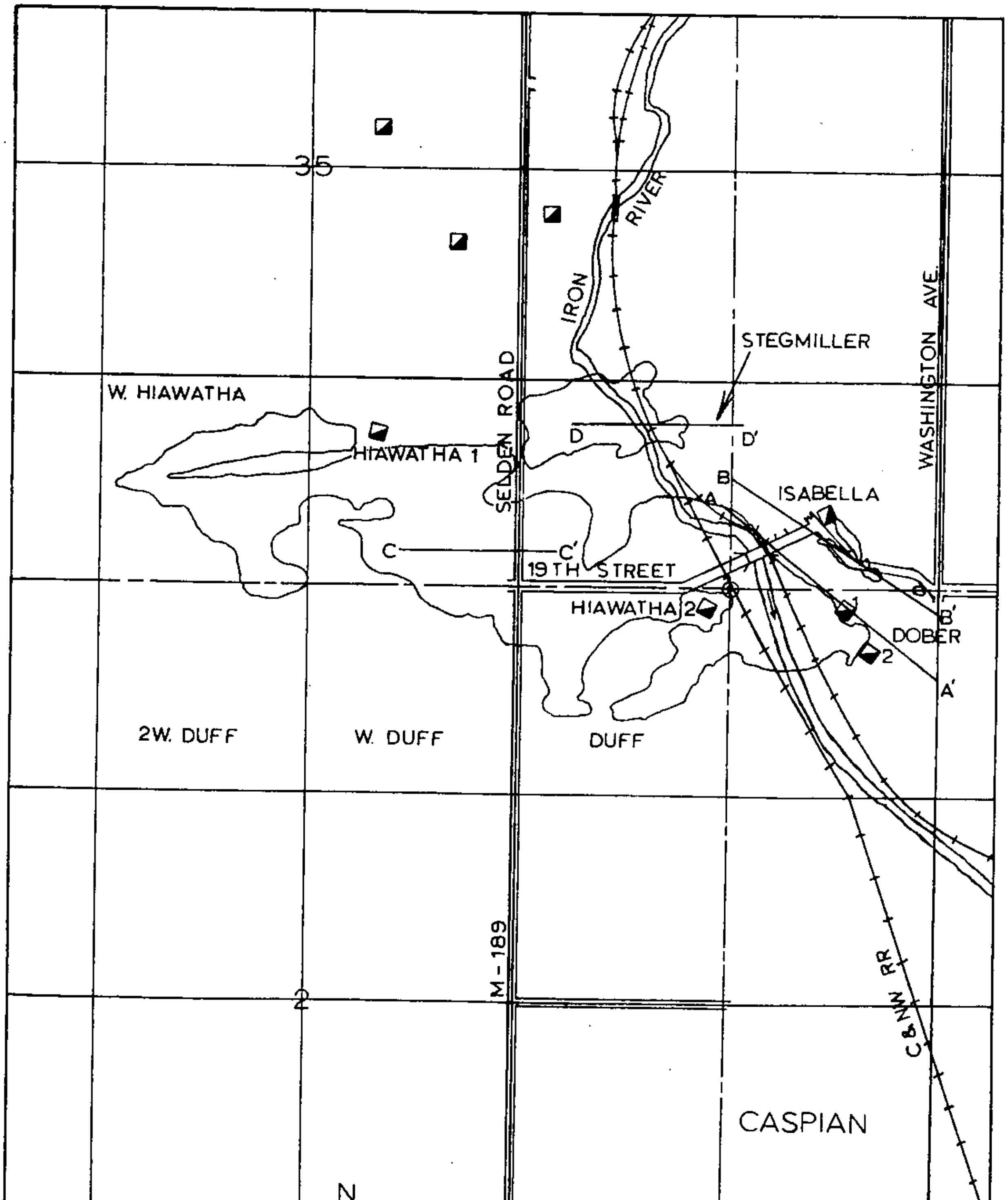
SECTION LOOKING NORTH 75° EAST

A - A'

Figure 21

Source: Constructed
Scale 1" = 200'

LJM 10-77



ISABELLA, DOBER & HIAWATHA MINES

Plan Map

Figure 22

Scale: 1" = 1000'

LJM 5-77

They also underlie the Chicago and Northwestern Railway on the Stegmiller property. The stopes below Selden Road are more extensive than those under the railroad. An east-west cross-section with projections at a point 230 feet north of the intersection of Selden Road and 19th Street shows a stope about 300 feet within the surface (see Figure 23).

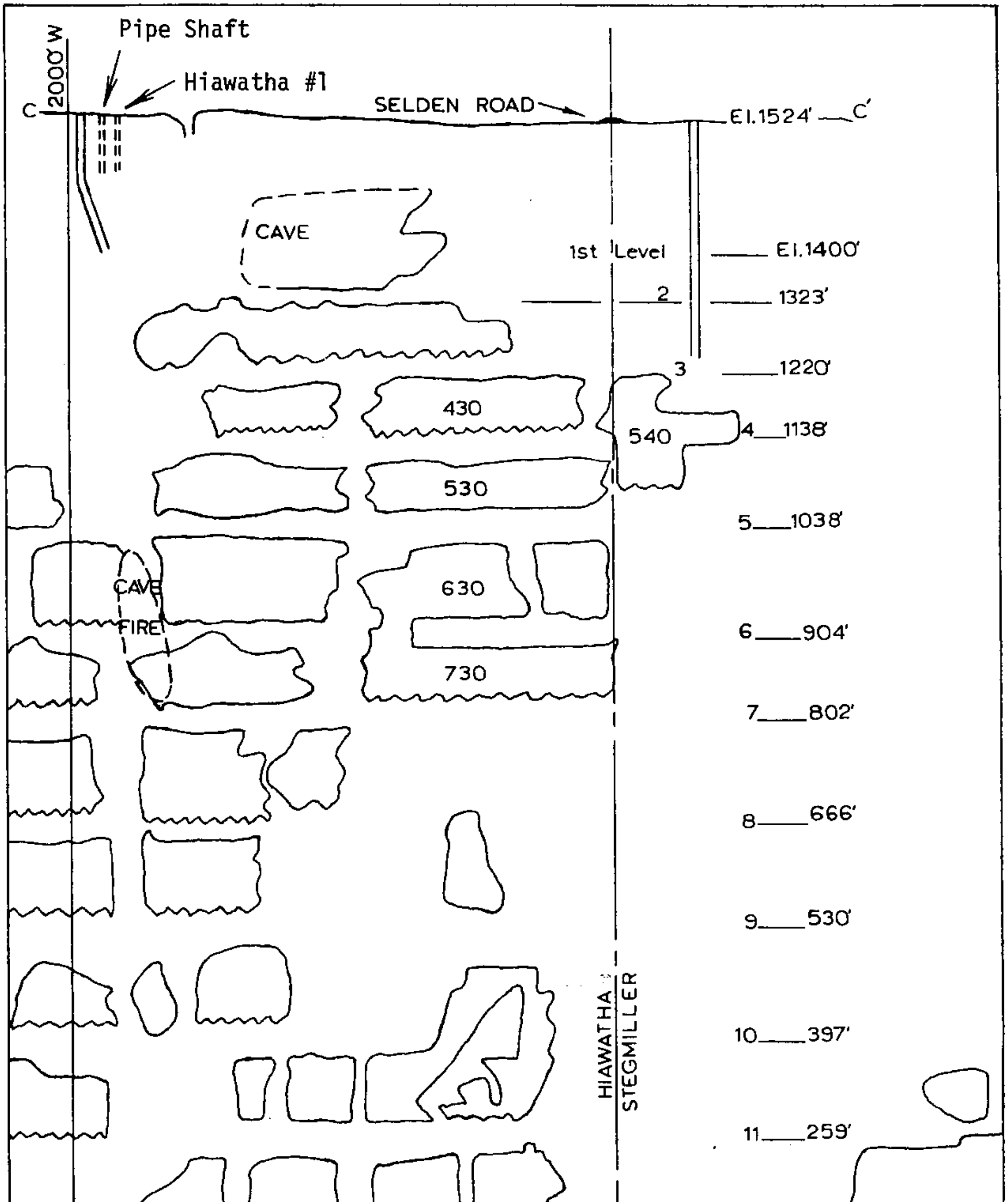
Stopes under the railroad on the east side of the Stegmiller forty are within 300 feet of the surface and extend downward some 700 feet to a depth of about 1000 feet. The stope is nearly vertical and about 80 feet wide.

Dober-Isabella Mines (19th Street). Both the Dober and Isabella were early mines in the district operated initially as open pits and later as underground operations. They later became part of the Hiawatha Complex. The mine shafts of both properties are located southwest of Stambaugh on adjacent forties on the east bank of the Iron River; the Isabella Mine in the SW1/4, SW1/4, Sec. 1, T43N, R35W and the Dober Mine in the NW1/4, NW1/4 of Sec. 1, T42N, R35W (see Figure 22).

Stopes of the Isabella workings in relation to 19th Street are shown in cross-section B-B' (Figure 24), the stope within 195 to 640 feet of the surface. On the map of Figure 24 the cross-section direction (B-B') closely approximates the strike of the formation and the dip is very steep, 80^{o} to the west. The stope varies in width from 40 to 100 feet. Stopes beneath the fourth level are part of the Dober, Hiawatha #1 and Stegmiller workings.

Section A-A' intersects 19th Street near the junction of the railroad tracks and the Iron River (Figure 22). The cross-section view shows Dober stopes under 19th Street from depths of 550 to 1200 feet beneath the surface (Figure 25).

Overburden is 20 to 25 feet thick in the area, although it varies greatly in thickness.

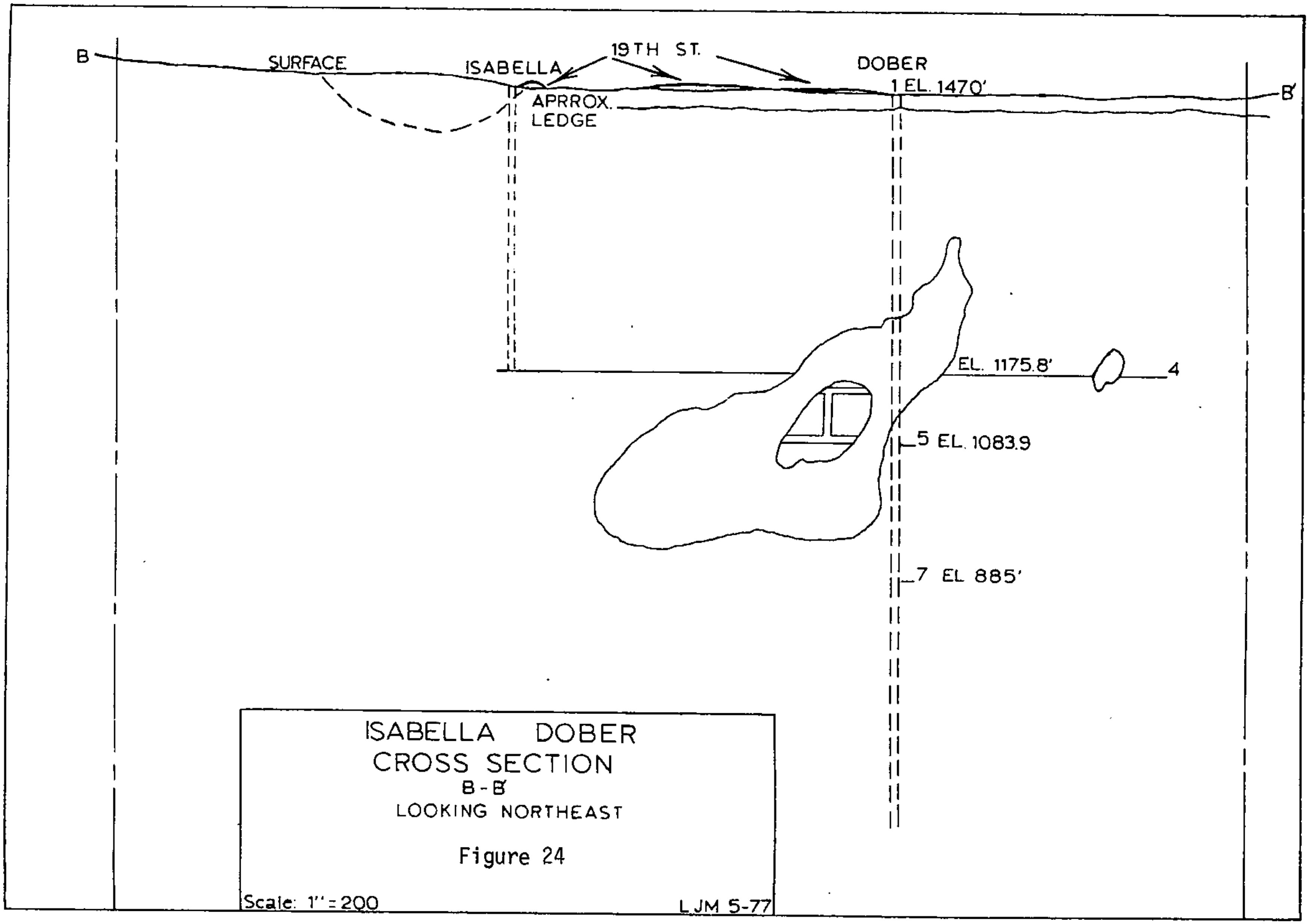


HIAWATHA MINE
SECTION
C-C' LOOKING NORTH

Figure 23

Scale: 1"=200'

LJM 10-77



ISABELLA DOBER
CROSS SECTION
B - B'
LOOKING NORTHEAST

Figure 24

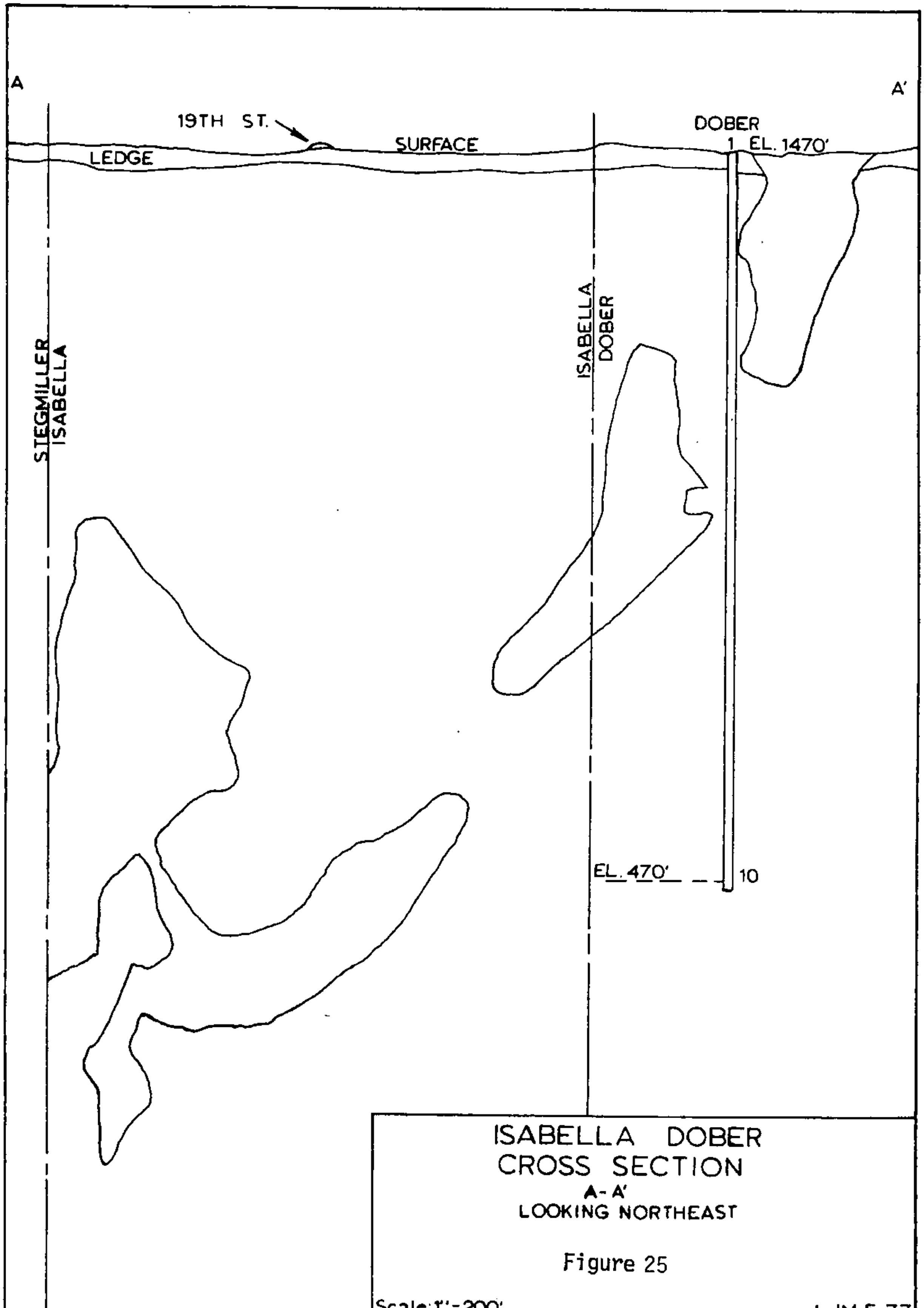

A
A'
19TH ST.
SURFACE
LEDGE
DOBER
1 EL. 1470'
STEGMILLER
ISABELLA
ISABELLA
DOBER
EL. 470'
10
ISABELLA DOBER
CROSS SECTION
A- A'
LOOKING NORTHEAST
Scale: 1" = 200'
LJM 5-77

Figure 25

A stope filling shaft is located on the Isabella property, but indications are that stope filling was done in the Hiawatha #1 and #2 workings and not in the Isabella Mine.

Considerations. The intent of pointing out these critical areas is not to alarm people. The fact that an area is assigned as a critical area does not mean subsidence is imminent or even that it will ever occur. The intent is to document those undermined areas where the surface is in use. Some of these areas are potentially more dangerous than others. For example, heavily traveled roads underlain by mine openings have more potential for problems because of the high use frequency.

In terms of the likelihood of subsidence occurring it is not possible to predict if and when caving would occur. Our study has shown generally that subsidence is more likely to occur over shallow, high volume stopes than over deep stopes. Obviously this is only common sense, for a thin layer of rock has less strength than does a thick layer. However, the presence of planes of weakness in the rock can negate this general observation. Deep stopes can and have failed to the surface through rock mass movement along slip zones. Another observation is that stopes with a greater vertical dimension are more likely to cave to the surface than are those of small vertical dimension. The logic here is if subsidence occurs by raveling (sloughing) of the stope back (roof), the opening may reach the surface before the stope is filled with the caved rubble.

The concept that caving by this raveling process in deep stopes will stop when the stopes are filled with rubble and before the caving stope penetrates to ledge is valid only if this mechanism (raveling) is operative. If the failure takes place along a weakness plane extending from ledge to the stope, the cave will effect the surface, usually, quite suddenly.

Sand filling was done in many of the mines to support the stopes, to protect surface structures and to extinguish mine fires. For the closed mines, accurate information on the sand-filled stopes is not always available. Too, the sand fill in a stope may not be complete, may compact to a degree, or even shift and move by failure of mine pillars. It may also become redistributed during the process of mine flooding.

Because of the uncertainties in predicting subsidence, the installation of a network of survey monuments over the critical areas is recommended. Periodic leveling surveys of the monuments would yield a positive indication of subsidence by gradual surface settling if it occurs. This simple method of subsidence monitoring can be done by the communities of the Iron River valley for minimal cost. The technique is described in more detail in the Recommendation section.

REFERENCES

Allen, Alice S. (1969), Geologic Settings of Subsidence, "Reviews in Engineering Geology II", Geol. Soc. Am., pp. 305-342.

Allen, R. C. (1910), The Iron River Iron-Bearing District of Michigan, publ. 3, Geol. Series 2, Mich. Geol. & Biol. Surv., p. 151.

Dutton, C. E. (1969), Geology and Magnetic Data for the Central Iron River Area, Michigan, Rept. of Inves. 5, Michigan Geol. Survey, p. 17.

James, H. L., Dutton, C. E. and Wier, K. L. (1967), Geology and Magnetic Data for Northern Iron River Area, Rept. of Inves. 4, Michigan Geological Survey, p. 46.

James, H. L., Dutton, C. E., Pettijohn, F. J. and Wier, K. L. (1968), Geology and Ore Deposits of the Iron River-Crystal Falls District, Iron County, Michigan, USGS, pp. 570, 134.

James, H. L. and Wier, K. L. (1969), Geology and Magnetic Data for the Southeastern Iron River Area, Michigan, Rept. of Inves. 6, Michigan Geological Survey, p. 30.

Johnson, Allan M. and Frantti, Gordon (1976), "Study of Mine Subsidence and Acid Water Drainage in the Iron River Valley, Iron County, Michigan - Status of Initial Work", Institute of Mineral Research, Michigan Technological University, Houghton, Mich., 113 p.

Olson, Donald J. (1977), Subsidence in the Iron River Mining District, Iron County, Michigan, Unpublished thesis, Dept. of Geology and Geological Engineering, Michigan Technological University, Houghton, Mich., 105 p.

Reed, R. C. (1975), Michigan Iron Ore Shipments through 1974 - One Thousand Million Tons, Michigan DNR, Geological Survey Div., Circ. 12, p. 12.

Lake Superior Iron Ores (1938), Lake Superior Iron Ore Association, Hanna Bldg., Cleveland, Ohio, p. 364.

Lake Superior Iron Ores, 2nd ed. (1952), Lake Superior Iron Ore Association, Cleveland, Ohio, p. 326.

GEOPHYSICAL STUDIES

Underground mining disturbs the state of equilibrium of rock and causes a redistribution of stresses with concentrations around mine openings. The accompanying changes in earth strain often show up as a downward deflection or an actual fall of weakened roof rock into the voids. With time, this process of deformation migrates upward until surface subsidence occurs.

Although subsidence has been studied for over 100 years in Europe and 60 years in the United States (Vongpaisal, 1973), no general method has been developed by which ground movement can be predicted as a function of geological structure, physical properties of materials and geometry of openings. Studies of the mechanics of caving in situ are needed in order to develop a basis for prediction of subsidence, especially for steeply-inclined openings.

Keeping in mind this state-of-the-art of the understanding of subsidence and recognizing that the Iron River valley contains a highly complex geologic environment, the following two generalized objectives of the geophysical feasibility studies related to subsidence were identified: 1) to investigate applicable geophysical methods for delineating the present position of underground openings (which are approximately described in the composite mine maps), and 2) to search for parameters which aid in explaining the physical mechanism of the subsidence process and which can be recognized as warning signals of impending subsidence.

Earlier cases of subsidence in the district suggest that three dominant mechanisms are operating; namely, 1) piping, wherein surface settlements occur as underlying alluvium flows (with the aid of ground water) through rock fractures into underground voids, 2) massive sinking of segments of strata, in the form of graben-like structures, where overlying unstable rock subsides or drops into old workings, and 3) surface displacements associated with the sliding of rock mass into old stopes and compaction of buried overburden strata (from which ground water is partially depleted by mining operations).

The degree to which these mechanisms manifest themselves either independently or collectively, as well as the induced effects of hydrologic phenomena such as hydrocompaction, swelling, changing pore pressure and water impounding, are poorly understood. It is important to note that all three mechanisms are characterized either by material transport, material settlement or stepwise geologic displacements.

With this tentative field model, applicable geophysical techniques based on principles of seismology, gravity, radar, resistivity and thermal-infrared imagery were considered. In evaluating a particular method for cavity detection, it was anticipated that the following conditions near the excavated zone must be satisfied to some degree: 1) a contrast in physical properties, 2) a cavity system ideally in a homogeneous medium, and 3) a sufficient cavity size-to-depth ratio (maximum depth to ten times the opening dimension).

Thermal-infrared imagery and ground-penetrating radar are both restricted to maximum depths of about 30 feet, so they were rejected because of excessive stope burial. Resistivity was not explored because of the unavailability of adequate deep-sounding resistivity equipment and the expectation of multiple factors affecting in situ resistivity measurements.

Five methods based on principles of seismology and gravity were outlined for investigation. These are:

1. Seismic Refraction Technique
2. Gravity Modeling Technique
3. Wave Perturbation Technique

4. Microseismic Technique

5. Seismic Reflection Technique

Seismic refraction and gravity modeling were applied with conventional procedures using available equipment. A wave perturbation technique, about which no known previous application had been attempted in field subsidence problems, was explored using an available microearthquake seismograph. This was supplemented with an early project acquisition of a second matched microearthquake seismograph and later with the acquisition of a third system. A microseismic method based on an established procedure was applied using the same set of instruments employed in the wave perturbation study. Finally a seismic reflection technique was first briefly explored with the aid of an instrument on short loan from a manufacturer. Subsequently a multi-channel seismograph incorporating current technological advantages was secured and a more thorough investigation of the reflection technique was carried out during the final months of the project.

All geophysical measurements were made with surface installations in the interest of exploiting methods that could be implemented without the cost and complexity of going into boreholes or underground mines (impossible in the case of abandoned mines). Similarly, the ultimate goal of this investigation is to recommend, if possible, a practical technique that can be routinely applied by technicians to monitor the progress of pre-subsidence diagnostic events at crucial sites within the district.

Discussions of the geophysical feasibility studies follow and are subdivided according to the five techniques being examined. A substantial portion of this work was presented in an earlier interim technical report (Johnson and Frantti, 1976) and in a master of science thesis (Johnson, 1977). A general treatment of the final seismic reflection investigation is also covered in a departmental Independent Study Report (Pardini, 1978).

Seismic Refraction Technique

Background. The seismic refraction method is widely described in geophysical literature. In this technique elastic waves generated in the earth, for example, by mechanical means or explosive charges, travel through the earth and are recorded by a series of detectors located along the surface at various distances from the source. Signals from the detecting devices are displayed on a visual recorder in conjunction with an accurate set of time lines. Raw data from this system can be readily analyzed to determine wave velocity as a function of depth in the earth. By careful analysis it is possible to determine the depth to zones of contact between distinctly different materials or areas of change in physical properties within a given horizon. Perhaps the most serious constraint on refraction methods is the requirement that velocities increase with depth for principal interpretation. Thus, in the conventional procedure, a velocity reversal such as at the top of a buried void would violate this constraint.

A useful variation in conventional refraction procedures makes use of a study of amplitude changes along ray paths and the correlation of these changes with imperfections such as cavities or fracture zones. This requires an accurately-calibrated instrumentation system ideally in combination with a directional energy source and at least 24 directional recording channels. Turpening (1976) achieved some success with this method in a specialized study concerning detection of fluid cavities at a coal gasification site encompassed by a relatively uniform geological environment. Although these requirements exceed the capabilities of our refraction equipment, we examined this approach in a limited way as discussed under the wave perturbation section.

Field procedure. For penetrations up to a 75-foot depth, Bison Signal Enhancement Seismgraphs, Models 1575B and 1570B, were used with a manual thumper as energy source. Signals are stored digitally in memory allowing the summation of repeat blows which reinforces the desired signal and partially cancels random noise. With this system, traverse lines 100 feet in length were established with a geophone at each end. Repeat blows were carried out with the thumper advancing in both directions along the line at intervals ranging from 2 to 10 feet. Resulting waveforms were observed and read on a cathode ray tube display with no permanent recording of the signal waveform.

Deep penetration was obtained with a portable Century Refraction Seismograph using explosive energy sources and recording 12 channels of data on permanent photographic film. The normal field procedure consisted of laying out a 550-foot geophone cable along a straight course and connecting a vertical geophone at each of 12 connection points spaced 50 feet apart along the cable. One to two pounds of explosives were tamped and detonated in 5-foot deep shot holes at each end of the line.

A geophone arrangement such as this with a shot point at both ends of the line is referred to as a Reversed Refraction Spread and was routinely used in the survey. A reversed spread allows determination of dip in subsurface interfaces and a 550-foot spread length provides effective penetration to about 200 feet of depth. Two modifications to the standard spread were tested and proved useful on occasion. Reducing geophone spacing to 25 feet provided better definition of the velocities in the shallow overburden and expanding the array by offsetting shot holes (on-line) up to 200 feet from the end geophones increased the effective depth of penetration to about 350 feet.

Interpretation. In the data analysis, arrival times of waves at each geophone location are read from the Bison display or from the Century photographic seismogram, samples of which are illustrated in Figure 26. In this figure time runs from left to right with the arrival of energy at each geophone indicated by a sudden displacement of a trace offscale. Seismogram (a) illustrates the typical pattern for a single three-layer earth model. The breaks in the third trace from the top of seismogram (b) and in the seventh trace from the top of seismogram (c) demonstrate the type of offset in arrival times that can result from low velocity zones, depressed overburden strata or down-dropped bedrock blocks.

Seismogram readings were programmed for computation on the MTU Univac 1110 computer using programs described by Mooney (1976) or by Scott, Tibbetts and Burdick (1972) in which layer thicknesses beneath each geophone are adjusted by an iterative process involving ray tracing. Where assumptions in the machine programs are not satisfied in the field data, manual travel time curves are prepared and interpreted with desk top calculators.

Five general areas where refraction surveys were conducted are shown in Figure 27. A concentration of 31 shots on deep refraction lines shown in Figures 28 and 29 were made in two areas with 12 of them in the Dober-Isabella area where 5 reversed spreads (labelled A-E) were tested and 19 in the Mineral Hills-Davidson area where 9 reversed spreads (labelled F-N) were tested. Depth-to-bedrock contours are illustrated for these areas in Figure 30. A general northwesterly dip in the Dober-Isabella vicinity is noted with no unusual indications in the subsurface integrity. The pattern of contours for the Mineral Hills-Davidson area is somewhat asymmetrical. Refraction profiles for spreads M and L suggest the possibility of a depression or down-drop in bedrock to the north with erratic variation in deep velocities. The surface expression in this area contains a 6-foot scarp trending west north west and intersecting the approximate center of spread M. Erratic travel time data make a precise interpretation

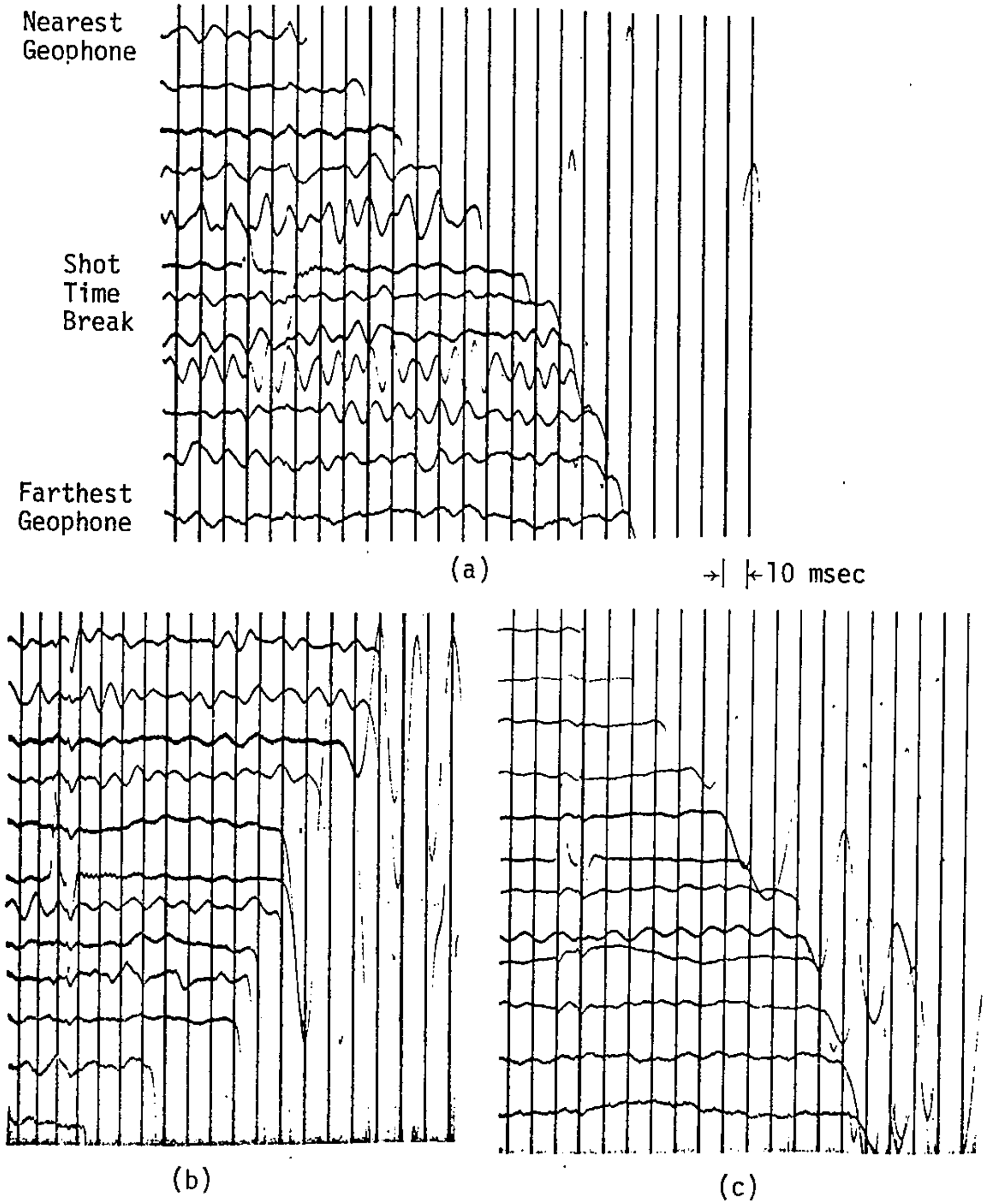


Figure 26. Photocopies of Three Refraction Seismograms as Described in the Text

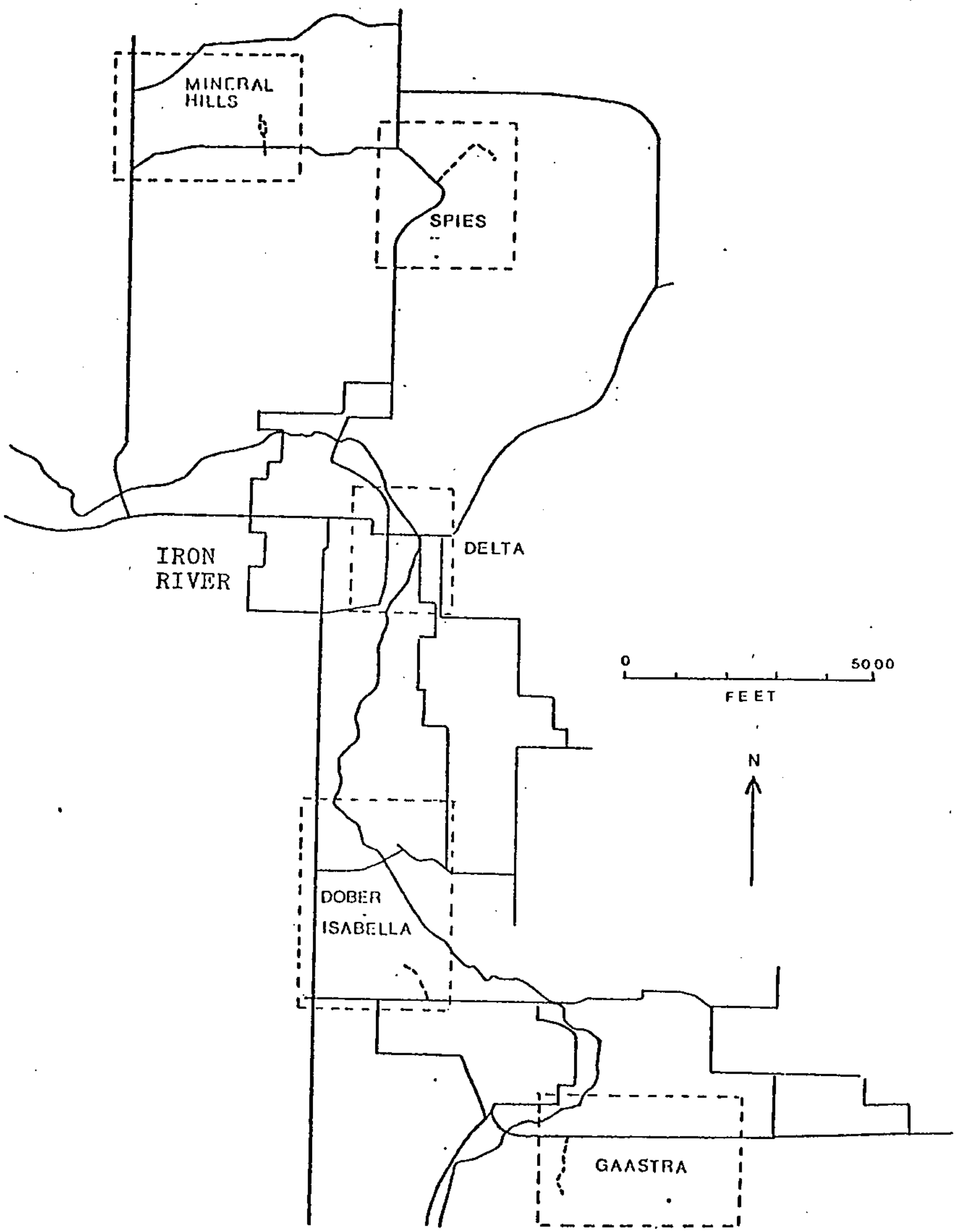


Figure 27. Location Map Showing Five General Areas Where Refraction Surveys were Conducted

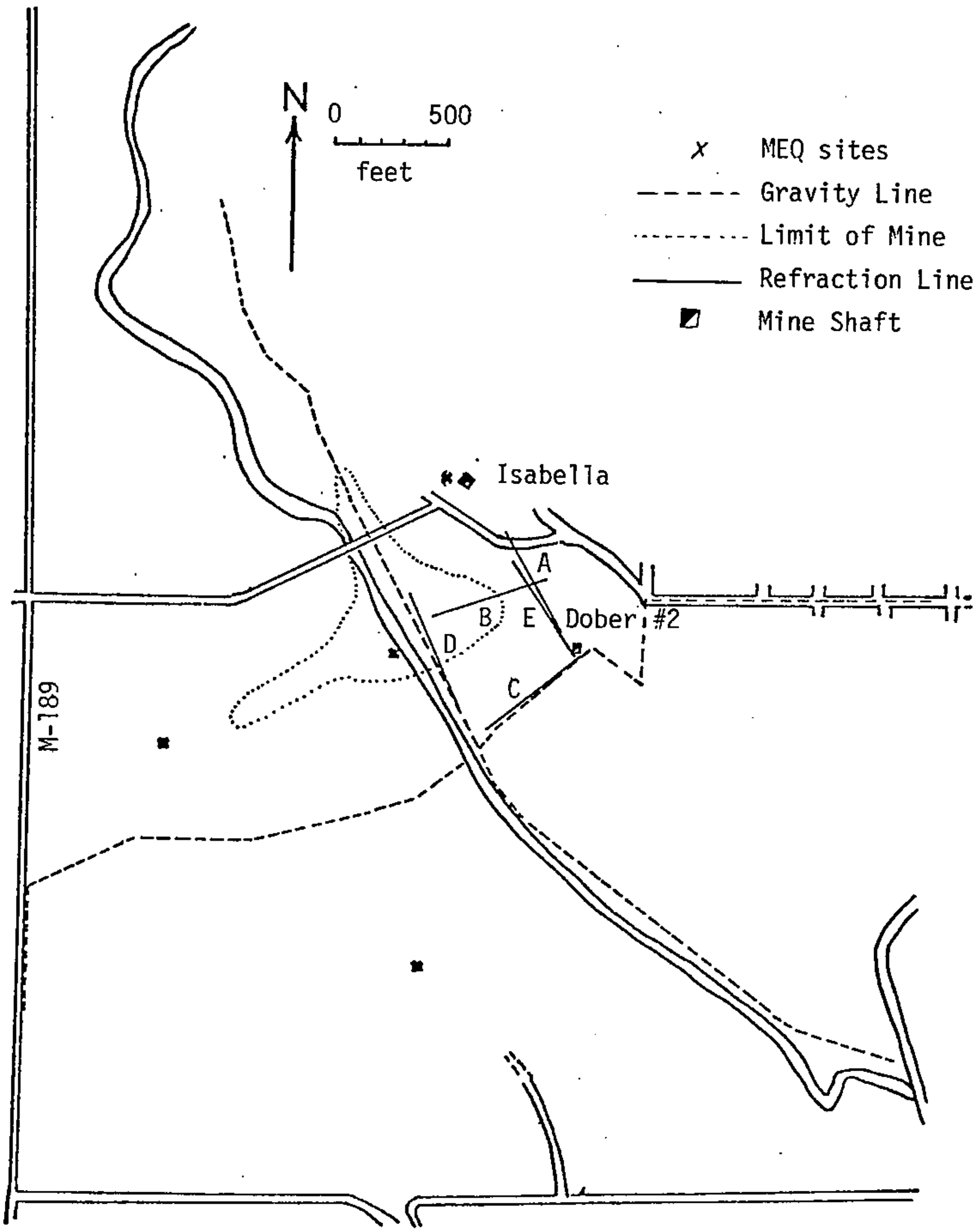


Figure 28. Map of Dober-Isabella Area Showing Locations of Geophysical Measurements

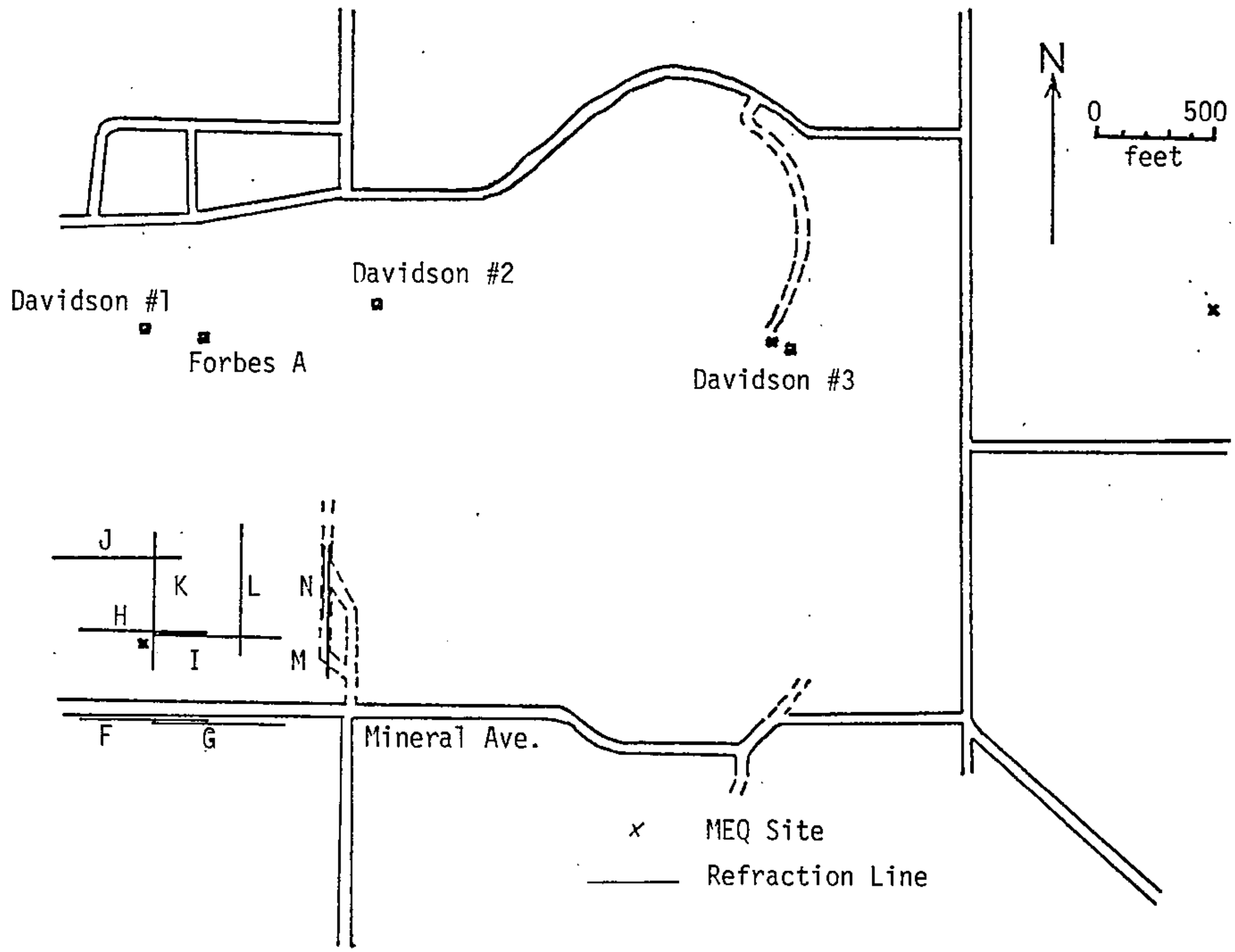


Figure 29. Map of Mineral Hills-Davidson Area Showing Locations of Geophysical Measurements

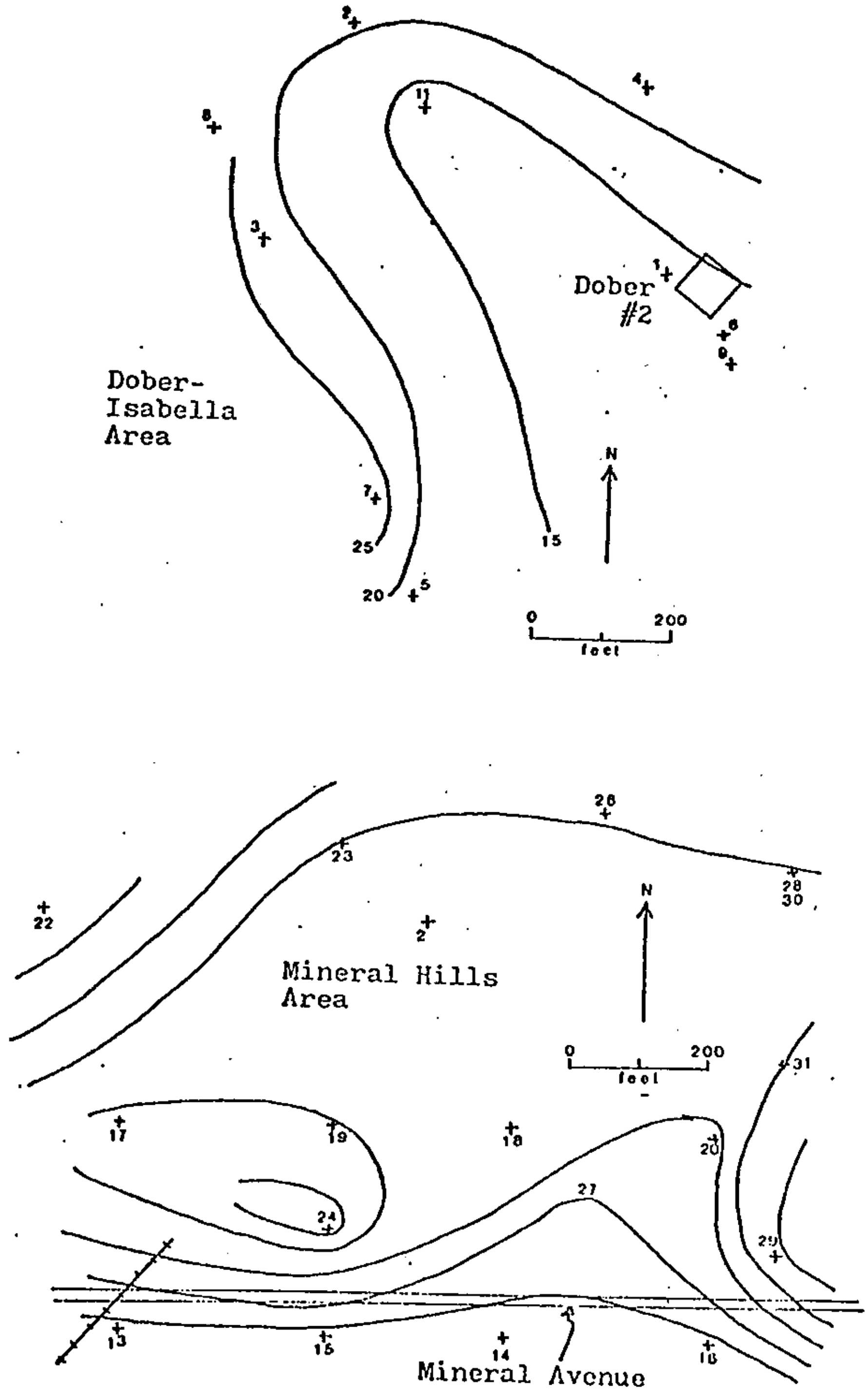


Figure 30. Contoured Depths to Bedrock Based on Refraction Surveys are Shown for the Dober-Isabella and Mineral Hills Areas. Shot locations and numbers are indicated by symbol plus with adjacent number.

difficult. Several shallow refraction lines were carried out to supplement the near-surface interpretation. A noticeable decrease in alluvium velocity is observed to coincide with the position of a surface crack at a point 460' east of the intersection of Mineral Avenue with the old railroad grade and 100' south of the avenue. Along this same traverse a more pronounced velocity decrease occurs 70' south of the avenue suggesting the strong possibility of a similar crack at depth without current surface expression.

Several additional refraction lines, referenced in the section on reflection, were established primarily to gather preliminary velocity measurements for interpretation of reflection data. A particular line over the Young Mine of the Buck Group shows an anomalous bowl-shaped depression in the hardpan layer which otherwise is relatively flat-lying in this area, thus suggesting evidence for subsurface settlement over the Young Mine.

Gravity Modeling Technique

Background. The gravity method is based on the fact that any pair of masses in the universe attract one another, the attraction being described by a force or, through a common law of physics, by an acceleration (common unit is milligal or 10^{-3} cm/sec^2). In geophysics it is common to determine the change in acceleration from point to point by weighing a small known mass at each location and comparing the change from its weight at a known reference (base) point. These measurements are made with a portable gravimeter which is obviously manufactured to be very sensitive to small changes in gravity.

The raw data from this instrument after preliminary processing to eliminate the known effect of elevation and latitude can be interpreted to reveal the presence of lateral density variations, such as mass excesses due to dense rock formation or mass deficiencies due to large underground cavities. A stringent constraint on this technique results from the fact that gravity at a point is an integrated affect; that is, the total attraction of all mass systems beneath and near the observation point are combined in the measurement. Thus, gravity is generally used in a regional way or with targets much larger than underground mine openings.

There are only about 7 gravity meters in North America with the precision necessary for conducting microgravity surveys for small targets. An alternative procedure is to use a conventional gravimeter with a station spacing considerably less than the lateral dimension of targets, such as mine cavities in this case. The observed anomaly obtained from actual measurements in the field is then compared with a theoretical anomaly calculated for a particular model of the mine. Subsidence can be simulated by shifting the model closer to the surface, adjusting the upward migration of the system until a best-fit is obtained between the observed and calculated data.

This approach was used in the feasibility study of the gravity technique.

Field procedure. The Dober-Isabella area was chosen for this experiment because the best level-by-level mine maps were available at the time for this property and the detailed maps were needed in constructing a mine model.

As shown in Figure 28, two traverses were laid out approximately at right angles crossing just south of the Dober shaft. Water-filled pits prevented a crossing directly over the mine. Approximately 250 stations were surveyed and leveled (to ±0.1') along these lines at intervals of 25 feet near the center and increasing to 100 feet near the outer limits. Leveling was referenced to a nearby benchmark.

Measurements were taken with a departmental Worden Portable Gravimeter manufactured by the Houston Technical Laboratories and having a scale constant of 0.0548 milligal per scale division. The time of each reading was recorded and base station readings were repeated at least four times per day to permit the determination of instrument drift.

Interpretation. In the data analysis, raw gravity readings for each station were programmed with data describing the station locations and elevations, and computations were carried out on the MTU Univac computer. The computer program (GEOPHYSICS*XQT GRAVITY) makes all necessary corrections (drift, elevation, latitude and datum) and plots the Bouguer gravity, or the corrected gravity at each station relative to a base value.

Bouguer gravity values for these traverses are shown in Figure 31 (the north or N25W line) and in Figure 32 (the east or N65E line). The line striking N25W passes more directly over the old Dober Mine complex, whereas the line striking N65E passes just southeast of the Dober shafts. Irregularities in station alignment on the actual traverses were adjusted by linear interpolation in projecting data on the N25W and N65E lines. There is an apparent low gravity anomaly of about 2 milligals (with respect to the regional trend) on the N25W profile with the mine structure centrally positioned in this anomaly. At the precise position of the shaft a low microgravity anomaly of about 0.3 milligal is suggested with respect to a smoothed curve. The N65E profile on the other hand shows the projected position of the mine to be along the flank of a low gravity anomaly with a local magnitude with respect to the smoothed trend between 0.2 and 0.3 milligals.

An approximate model of the Dober Mine from the first to the eleventh levels was designed on the basis of mine level maps. The 3-dimensional mine opening was approximated by a series of contours at different depths. Each contour was fitted to a polygon and converted to a lamina by assigning an

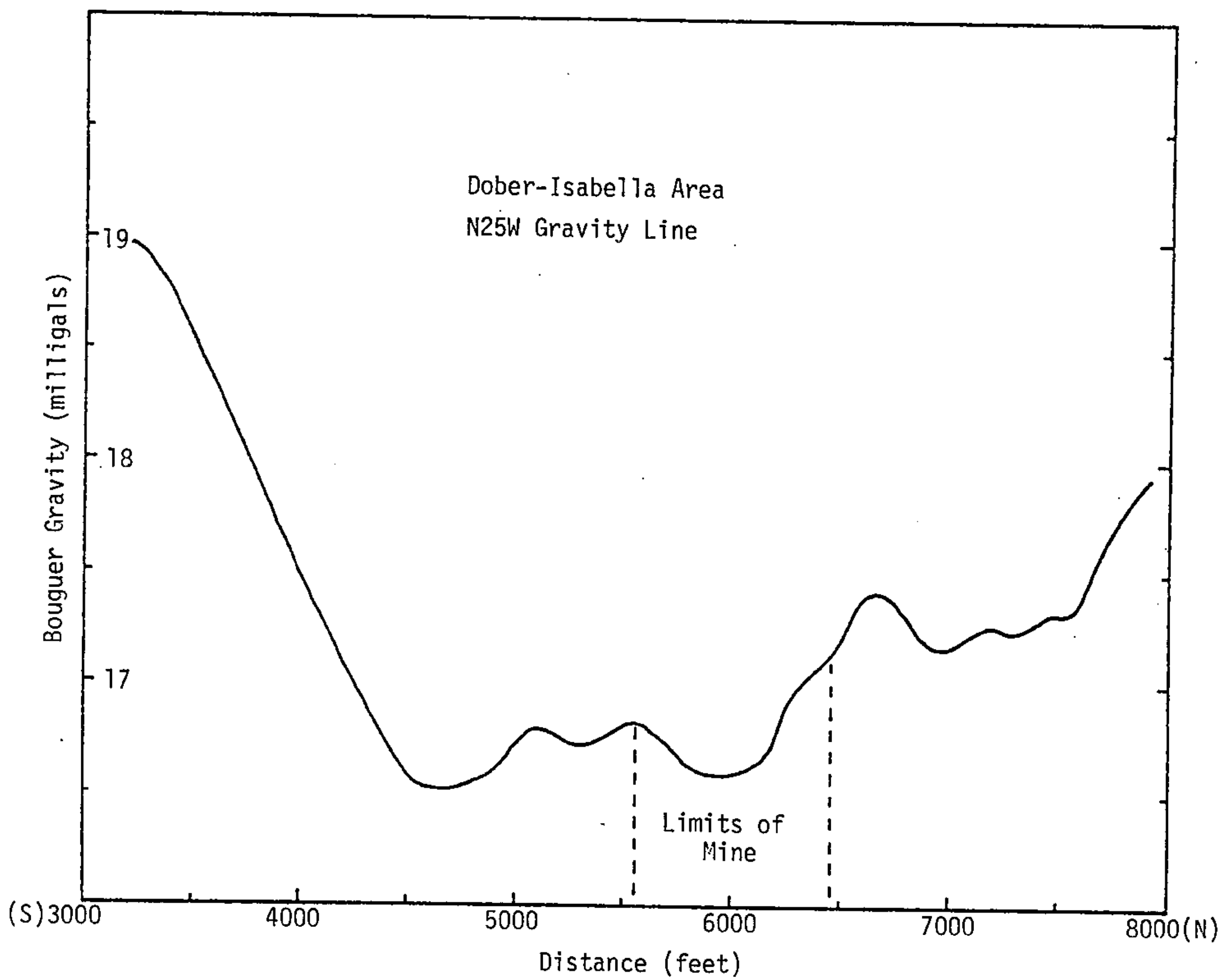


Figure 31. Reduced-Scale Tracing of the Computer Printout of the Bouguer Gravity Profile, Line N25W.

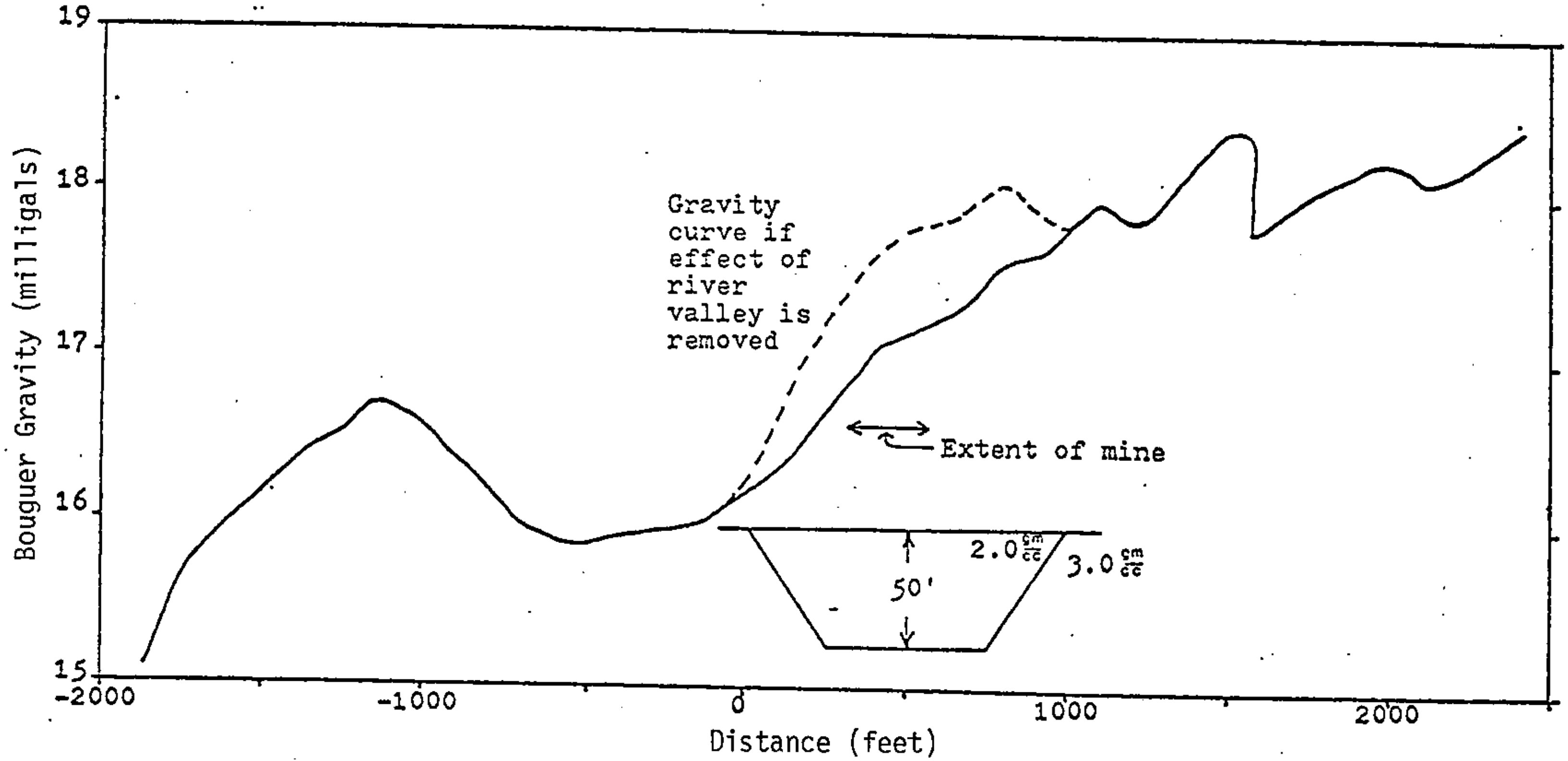


Figure 32. Bouguer Gravity Profile for the N65E Line is Shown with the River Valley Correction and Valley Model

appropriate thickness. A computer program described in detail by Talwani and Ewing (1960) was used to determine the gravitational effect at the surface of each lamina and to integrate the effects of all laminas to obtain the total gravity anomaly. The Bouguer gravity for this model was calculated assuming the openings were in their mapped positions (first level down 133 feet, etc.). For the case of a density contrast of 1.5 gm/cc, based on an average value of 3 gm/cc (Wyble, 1958) for surrounding host rock and 1.5 gm/cc for a water-filled sand mix in the stopes, the calculated gravity contours are shown in Figure 33 indicating a maximum anomaly of 0.23 milligals. Another computation was made by shifting the entire mine model 100 feet closer to the surface (simulating subsidence). This resulted in a maximum anomaly of 0.48 milligals with a gravity contour pattern shown in Figure 34.

No attempt was made to model the affect of local geology because of its complexity and imprecise description. However, the affect of the alluvium-filled river valley aligned with the mine setting was computed as shown in Figure 32. A valley model was based on field observations and refraction measurements, and its gravitational affect was computed with a two-dimensional gravity program titled GEOPHYSICS*XQT GRAV2D.

As a further example, the gravity effect of the same mine model with density contrast reduced to 1.0 gm/cc was computed and yielded a maximum value of 0.17 milligals for the mapped position and 0.22 milligals for the case of upward migration by 100 feet.

No combinations of the gravity profiles from computer modeling followed the detailed peregrinations of the observed gravity. Thus, while the gravity profiles (especially the line directly over the mine shaft) encouragingly showed low values in the general location of the mine openings, it was not

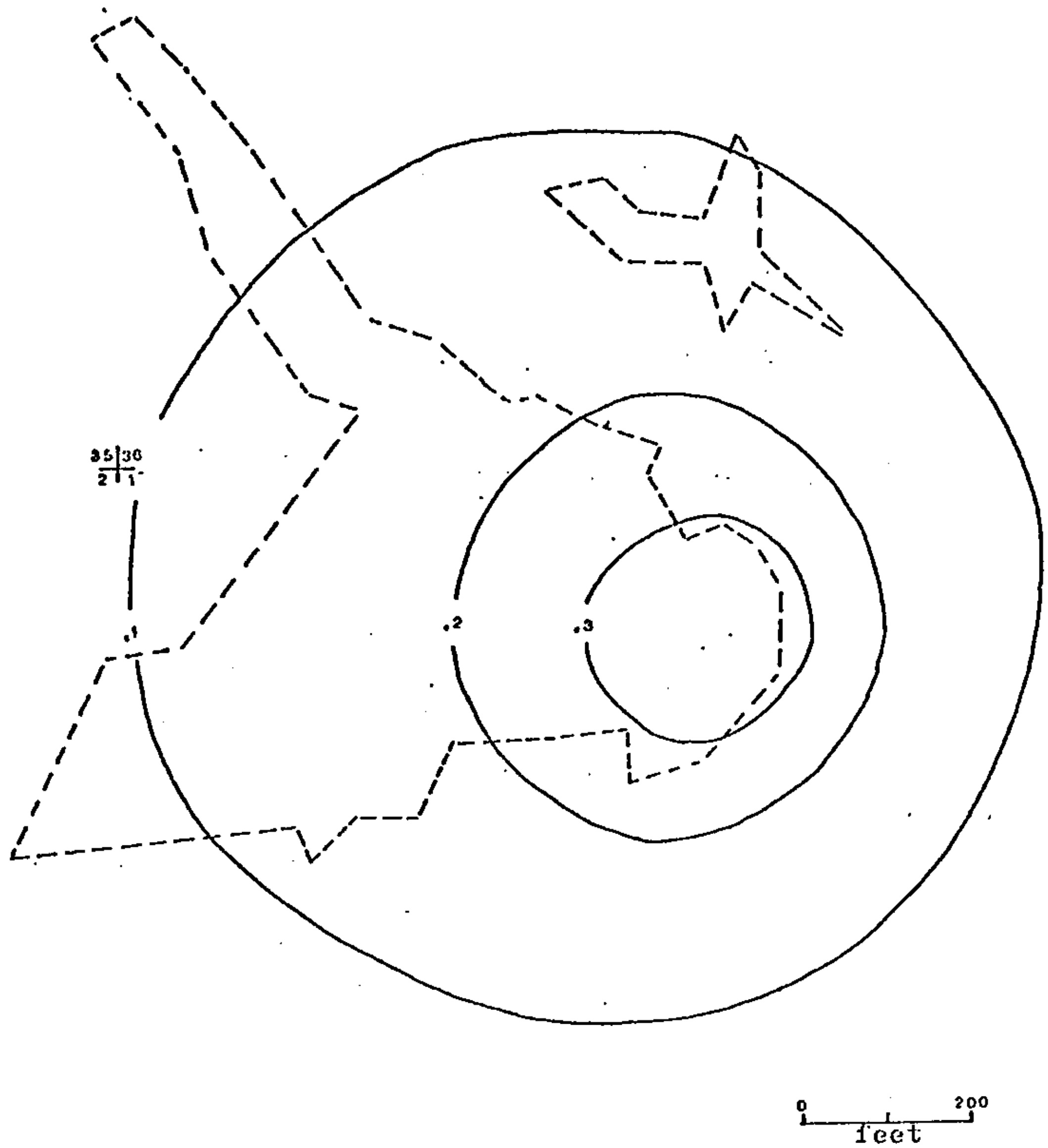


Figure 33. Calculated Bouguer Gravity is Contoured at 0.1 Milligal Intervals for the Dober Mine Model. The outline of the maximum extent of stoping is projected to the surface and shown by dashed line.

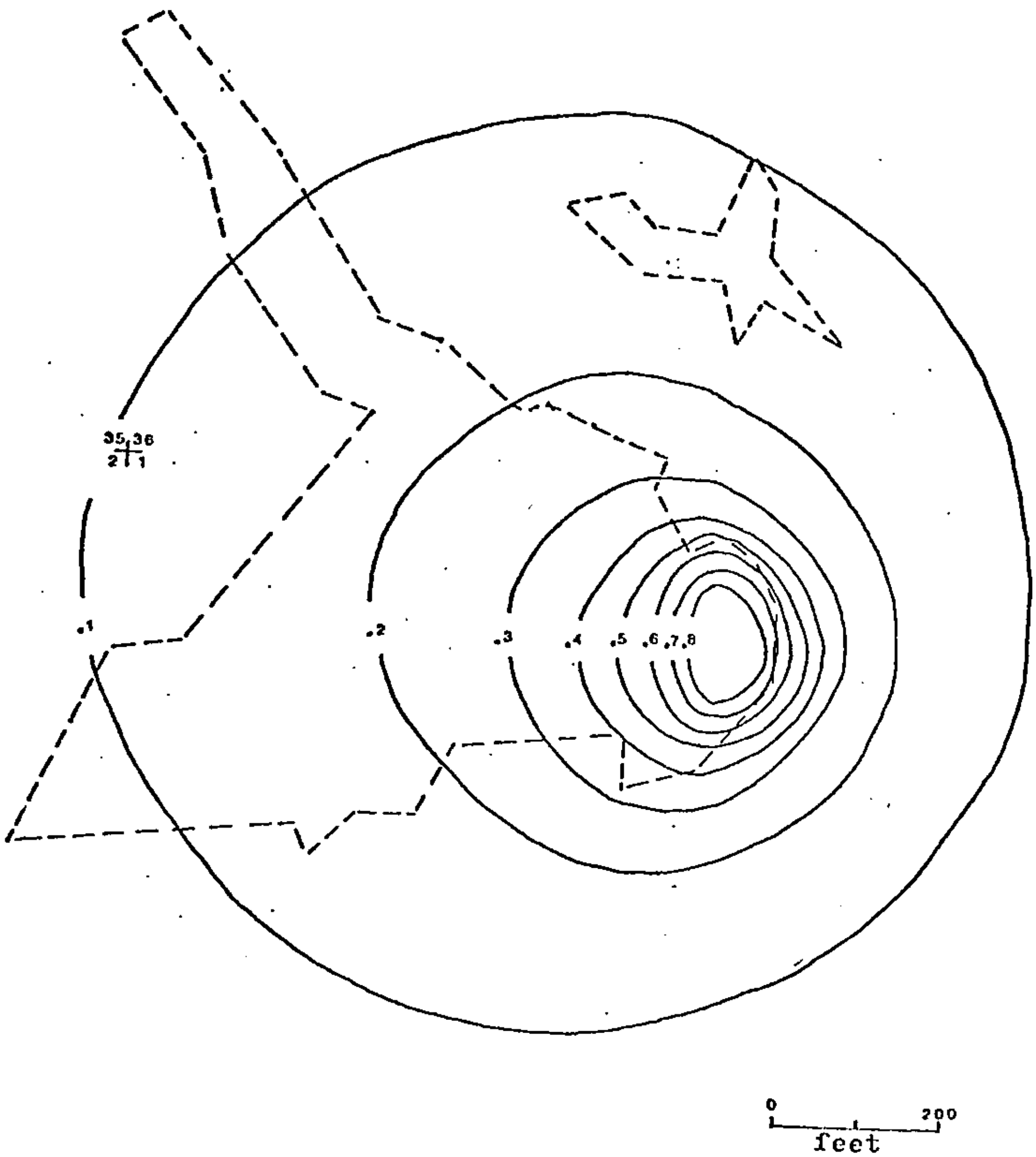


Figure 34. Calculated Bouguer gravity is contoured at 0.1 milligal intervals for the Dober Mine model which has been shifted 100 feet upwards to simulate subsidence. The dashed line locates the surface projection of the limits of stoping.

possible to duplicate the total observed gravity anomaly by modeling. Furthermore, though the magnitude of expected mine gravity is sufficient to be detected by a conventional gravimeter, it is evident that the changes brought about by a subsiding mine may or may not fall within the precision of such instruments.

Wave Perturbation Technique

Background. Inhomogeneities in the earth are known to affect the transmission of elastic waves. In general, the effects are most pronounced when the primary wavelength of the wave is approximately equal in size to the gross space dimension of the perturbing (disturbing) structure. This phenomenon is used by seismologists in studies of the earth. As the size of disturbing structures becomes smaller, the frequencies effected get higher.

Prior to the start of this project, the Geophysics Group at Michigan Tech, as reported by Frantti (1975) had successfully recorded large mine blasts from Marquette County with a single portable microearthquake recorder set-up in Houghton County. The source-receiver distances were about 100 km which was sufficient for the compressional, shear and surface waves to become separate, distinct arrivals on the seismogram due to their velocity differences. It was noted that when source and receiver were located on opposite sides of the underground mines, the relative wave traces of Rayleigh and shear waves differed, apparently, from the case where both were on the same side of the mines. We suggested a strong possibility that mine openings were measurably affecting those waves within the passband of recording (often 0.5 to 10 hz).

Rykunov and Thhukh (1972) showed by model studies that local structure will effect the character of surface waves. Since the mines near Iron River are tabular and steep-dipping, the model that aptly approximates them is a slot.

These authors showed that as the depth of a slot increases, the amplitude of surface waves decreases and the frequency shifts to a lower value, which suggests a qualitative agreement between their model results and our field observations.

The energy content of surface waves recorded near Iron River from Marquette County explosions peaks at about 1 or 1.5 hz. At a nominal velocity of 3 km/sec, this corresponds to a wavelength of about 2000 m, which is about three times the typical depth of Iron County mines. However, a substantial fraction of surface wave energy is confined to within one-half of a wavelength of the surface, or 1000 m in this case. This is about 1½ times the typical mine depths. In other words, it is reasonable to expect that surface waves, and perhaps shear waves, will be measurably attenuated (lowered) and frequency-shifted by the mine openings.

On this basis, the Wave Perturbation Technique was used to examine the integrated scattering and diffractive affect of mine cavities on the amplitude/frequency character of seismic waves, which is the first known attempt to apply this rationale in a field subsidence study.

Field procedure. A portable microearthquake seismograph, Sprengnether model MEQ-800-A, used in conjunction with a Mark Products L-4C vertical seismometer, was available in the department for this study. The system operates on internal chargeable batteries so it may be used anywhere in the field. An internal chronometer affixes accurate time marks on the record which is synchronized with WWV time signals for correlation with absolute time. The overall frequency response of the system, 0.2 to 100 hz, can be adjusted by internal filters which enable optional pre-filtering at 30, 10 and 5 hz on the upper end and up to 5 hz on the low end. Amplifier gains of 60 db to 120 db in 6 db steps are featured and system calibration is actuated through an internal calibration coil in the seismometer. A matched instrument was initially purchased on this project so that measurements could be made with two stations during the first phase of the project. Subsequently, an additional system was acquired and permitted the operation of a tripartite array during the second phase of the project.

The field procedure consisted of recording signals from large mine blasts (from 60 to 100 km away) with one instrument on the source side and one on the shadow side of a mine. When 3 systems were available, the recording configuration was either three elements on-line or tripartite (triangular). Sites were selected as far as possible from cultural noise sources such as highways and industrial centers. Geophones were set up on bedrock when available or on reasonably stable bases such as large, in-place rocks and abandoned building piers. Site selection was a problem in the Iron River valley because of the predominance of thick glacial alluvium.

As shown in Figure 35, 15 recording sites were occupied in areas comprising mine complexes known as Mineral Hills-Davidson, Spies-Johnson, Dober-Isabella and Young-Buck. Approximately 50 recordings were obtained. Records from the Mineral Hills-Davidson area were plagued by a strong periodic signal generated by the surface crusher at the operating Sherwood Mine, which severely limited gain ranging. A similar but less severe problem prevailed in the Spies-Johnson area because of its proximity to vehicular traffic on highway U.S. 2.

Interpretation. Photocopies of original seismograms from the drum recorders are illustrated in Figures 36 and 37. Time runs from the upper left to the lower right along each trace. Raised marks which align diagonally across the record are one minute apart. The first arriving wave for each signal is the compressional (P) wave. A lower-frequency, higher-amplitude event arriving about 10 seconds later is a surface wave (Rayleigh or Lg) and the distinct phase coming in just ahead of Lg is the shear (SV) wave. Visual differences in signal characteristics

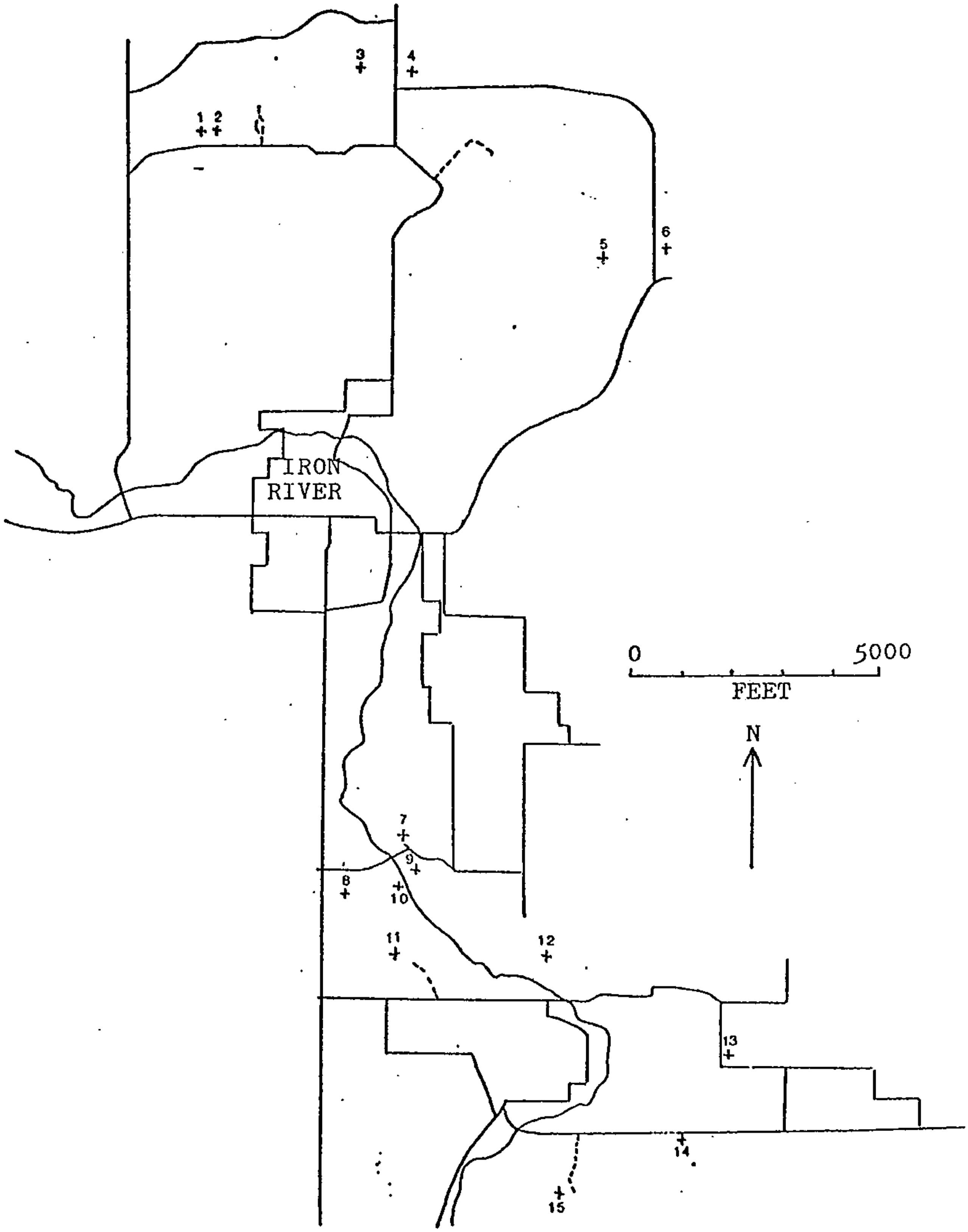
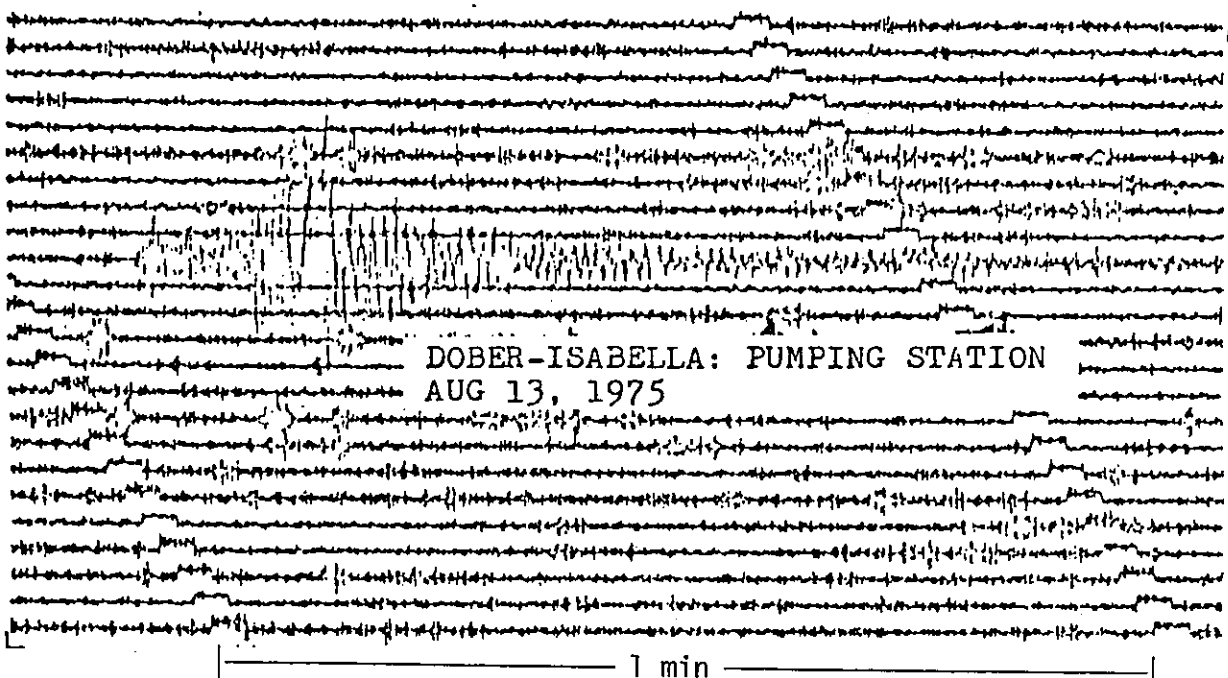
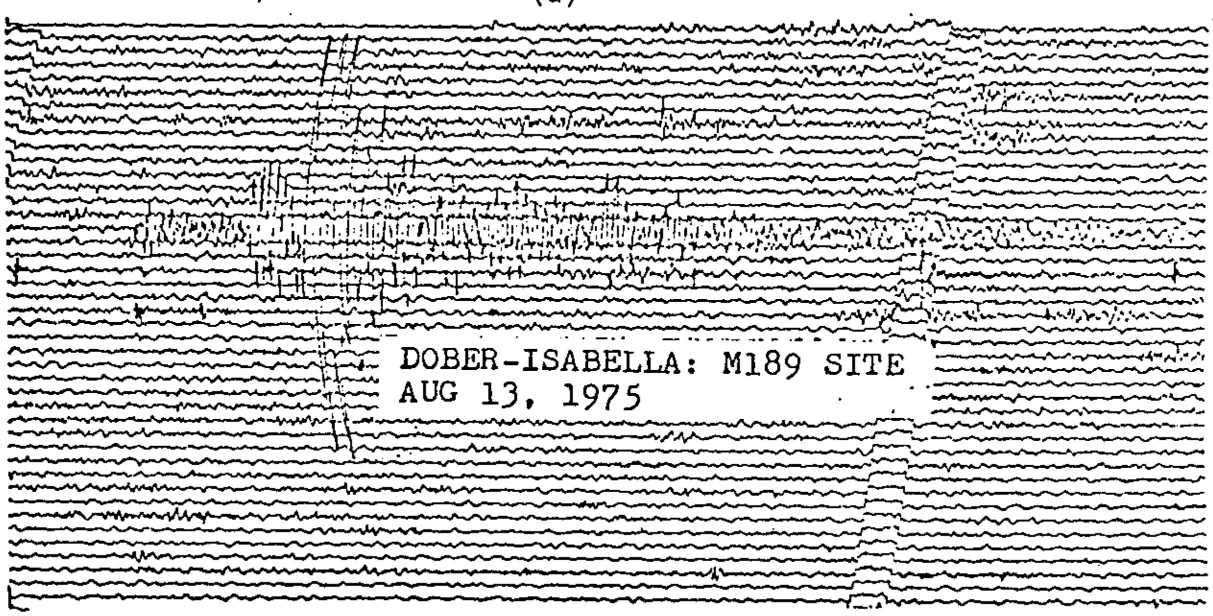


Figure 35. Map of Recording Sites Used for MEQ Monitoring in the Iron River District



(a)



(b)

Figure 36. Photocopies of Original Seismograms from the MEQ Recorders; (a) Laterally-Offset Site and (b) Shadow Site.

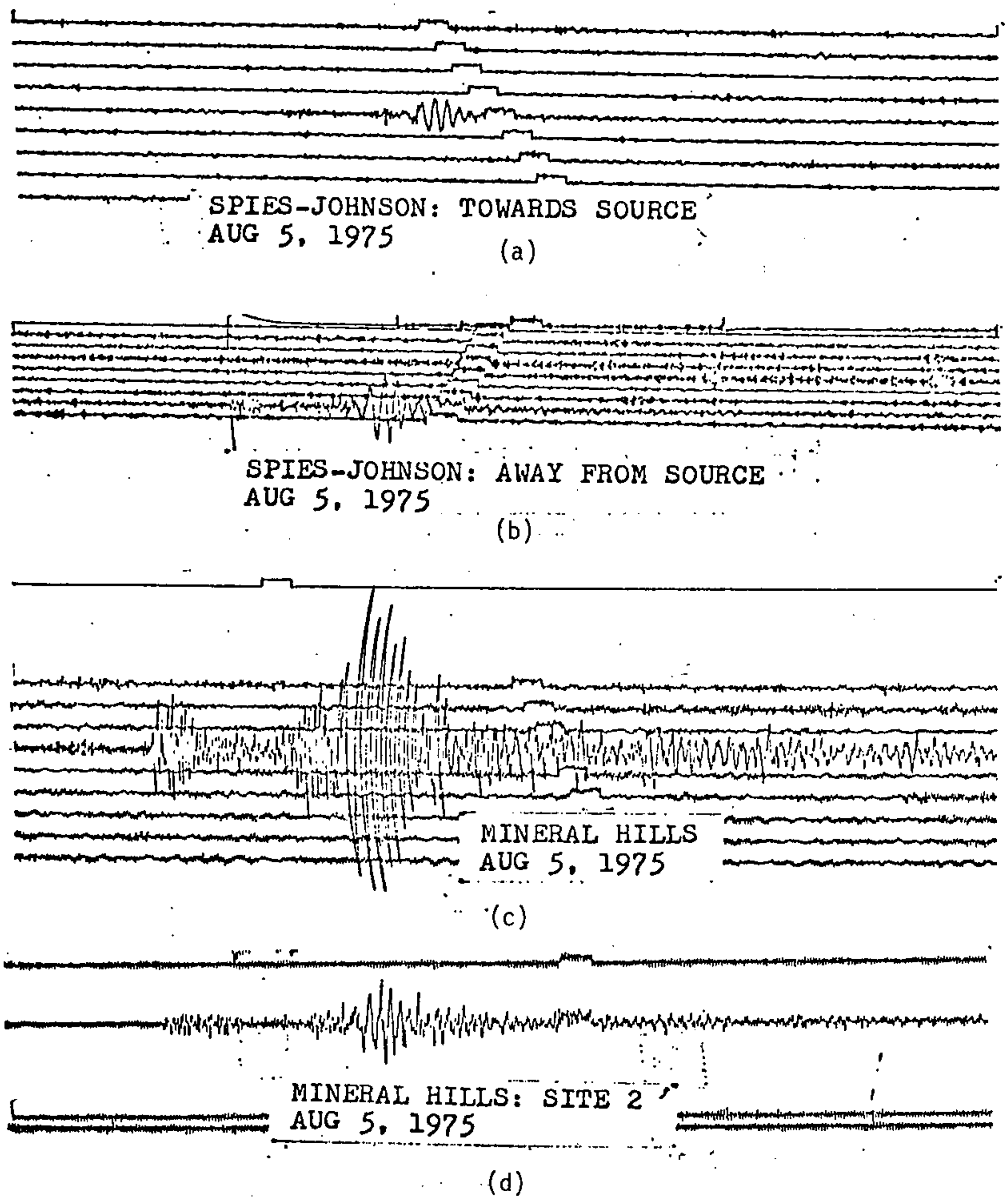


Figure 37. Photocopies of Original Seismograms from the MEQ Recorders; (a) and (c) Near-Side Sites and (b) and (d) Shadow-Side Sites.

are apparent as one compares the near-side with the shadow-side recordings for each of the locations shown. Measurements of maximum amplitudes are measured directly from these traces and corrected for system response to generate data for amplitude analysis.

For frequency analysis, it is necessary to measure amplitudes at discrete and closely-spaced intervals along the entire envelope of a given wave phase. To expedite this process, photo enlargements were made of the section of waveform being analyzed, as shown in Figure 38. A mechanical digitizer was constructed to extract sequential measurements along the trace. This device corrected for the arcuate movement of the drum-pen system which is not rectilinear on the MEQ-800 seismograph. The digitized data were processed on the MTU Univac 1110 computer with an Autocovariance and Power Spectral Program titled MTU*BIOMED.BMD02T. The output of this program is a plot of relative power at discrete frequencies.

Generating digital data from hardcopy analog records with a mechanical digitizer is an exceedingly time-consuming process. The process was optimized by concentrating on the surface wave (Lg) which was the most efficient and clear window on the signal trace. The Lg phase transmits very effectively throughout most of the earth's crust and thus has definite advantages if it proves to convey the information that one is seeking. In the maximum amplitude analysis, all phases (P, S and surface) were examined.

Computer plots of power spectral density for the complete set of digitized records are illustrated by five typical pairs of data shown in Figures 39, 40 and 41. The spectra generally display a maximum power between 1 and 2 hz with lesser peaks up to 8.6 hz, the Nyquist frequency. The overlayed pairs of spectra suggest an apparent shift in maximum power towards lower frequency for the recording obtained on the shadow side of the mine, although the shift is not

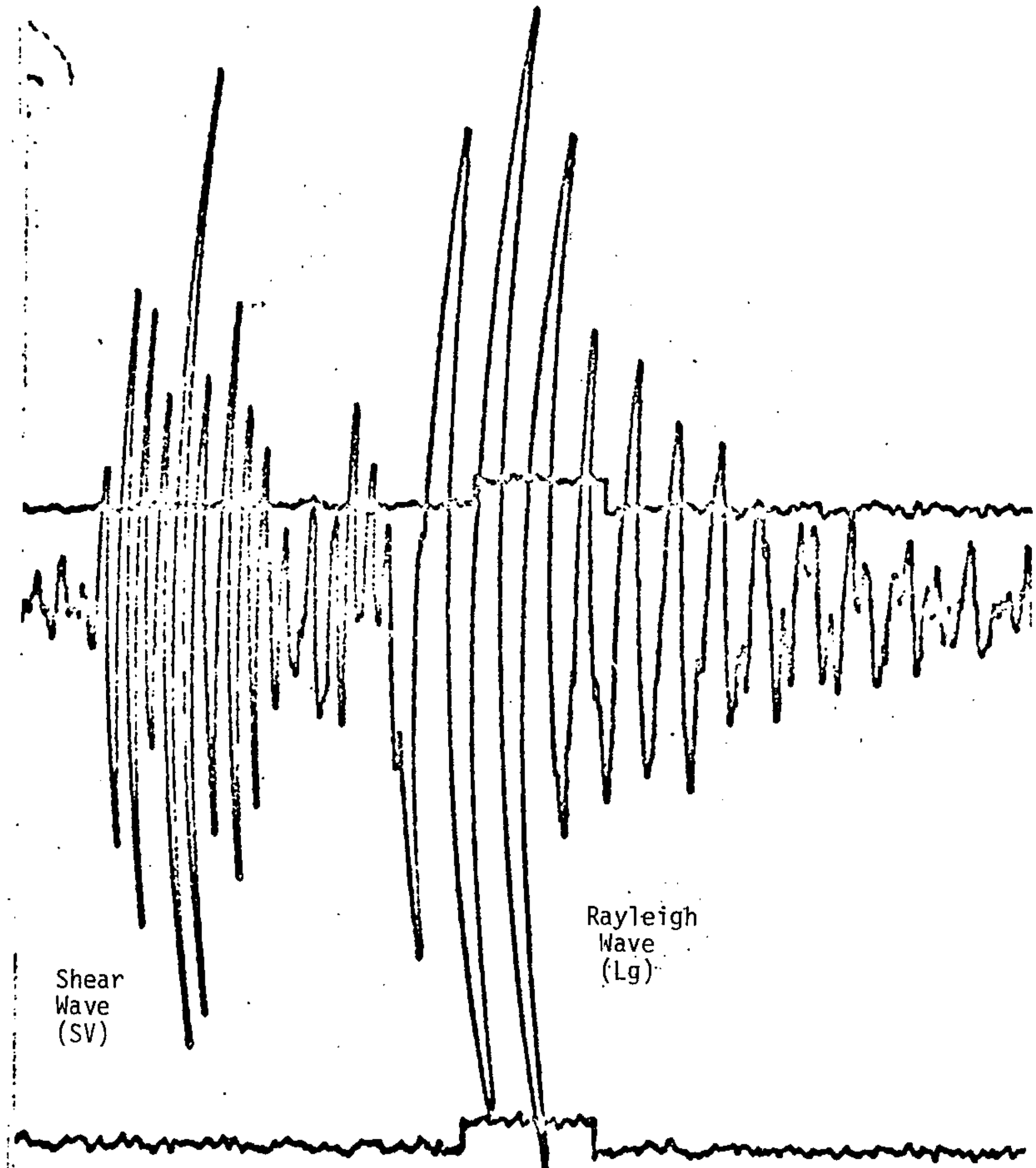


Figure 38. Photocopy of a Magnified Section of an Original MEQ Seismogram as Used in Record Digitizing

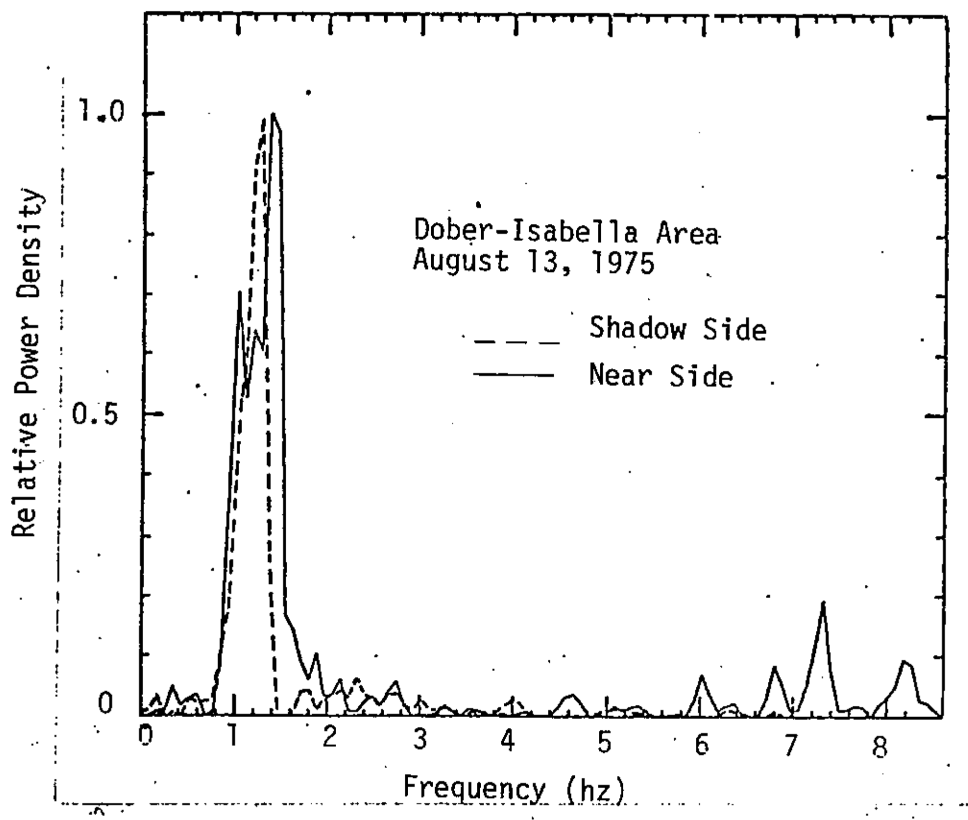


Figure 39. Reduced-scale Tracing of a Computer Printout of the Relative Power Spectral Density for a Pair of Recordings in the Dober-Isabella Area

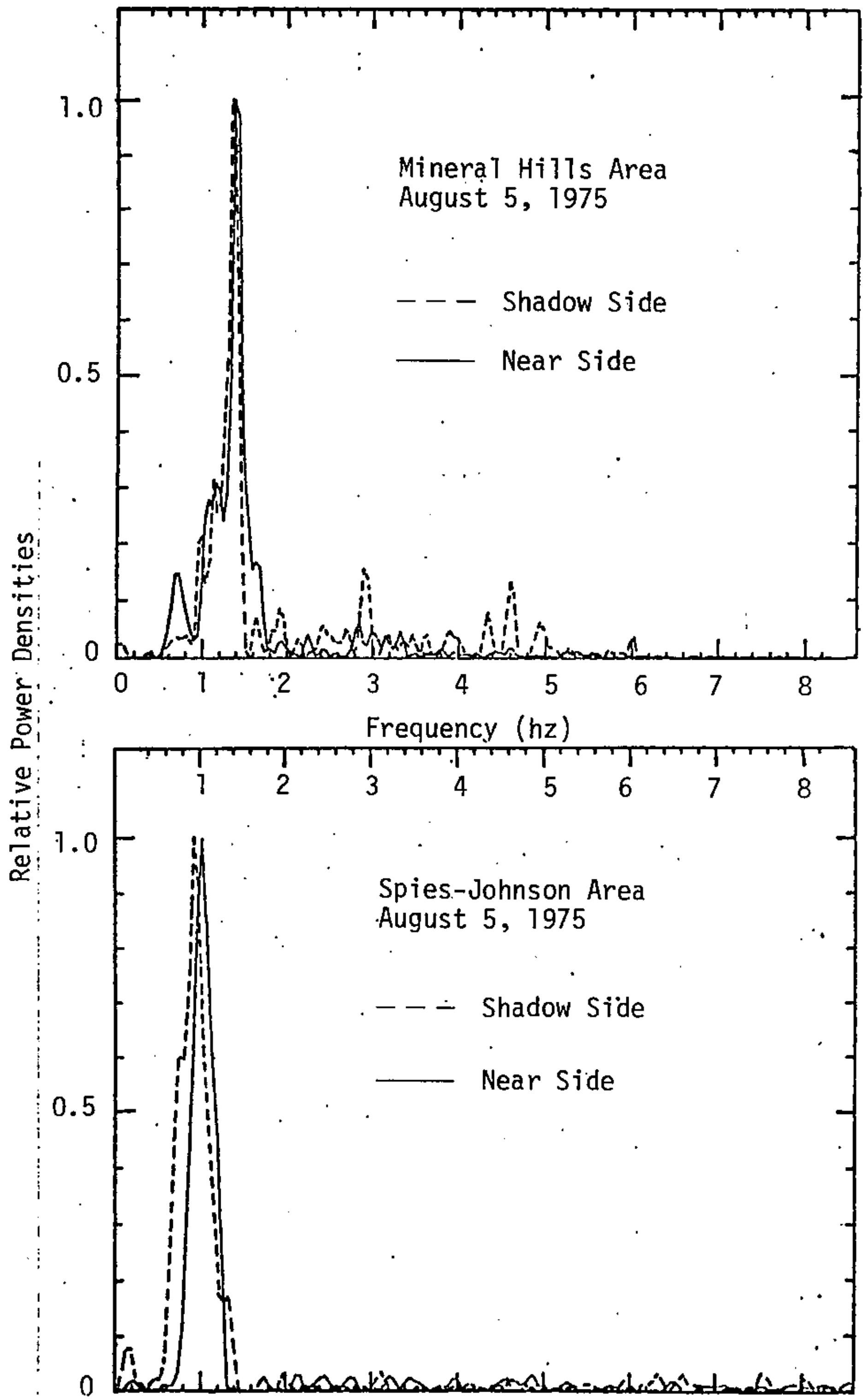


Figure 40. Reduced-Scale Tracings of Computer Printouts of Relative Power Spectral Densities

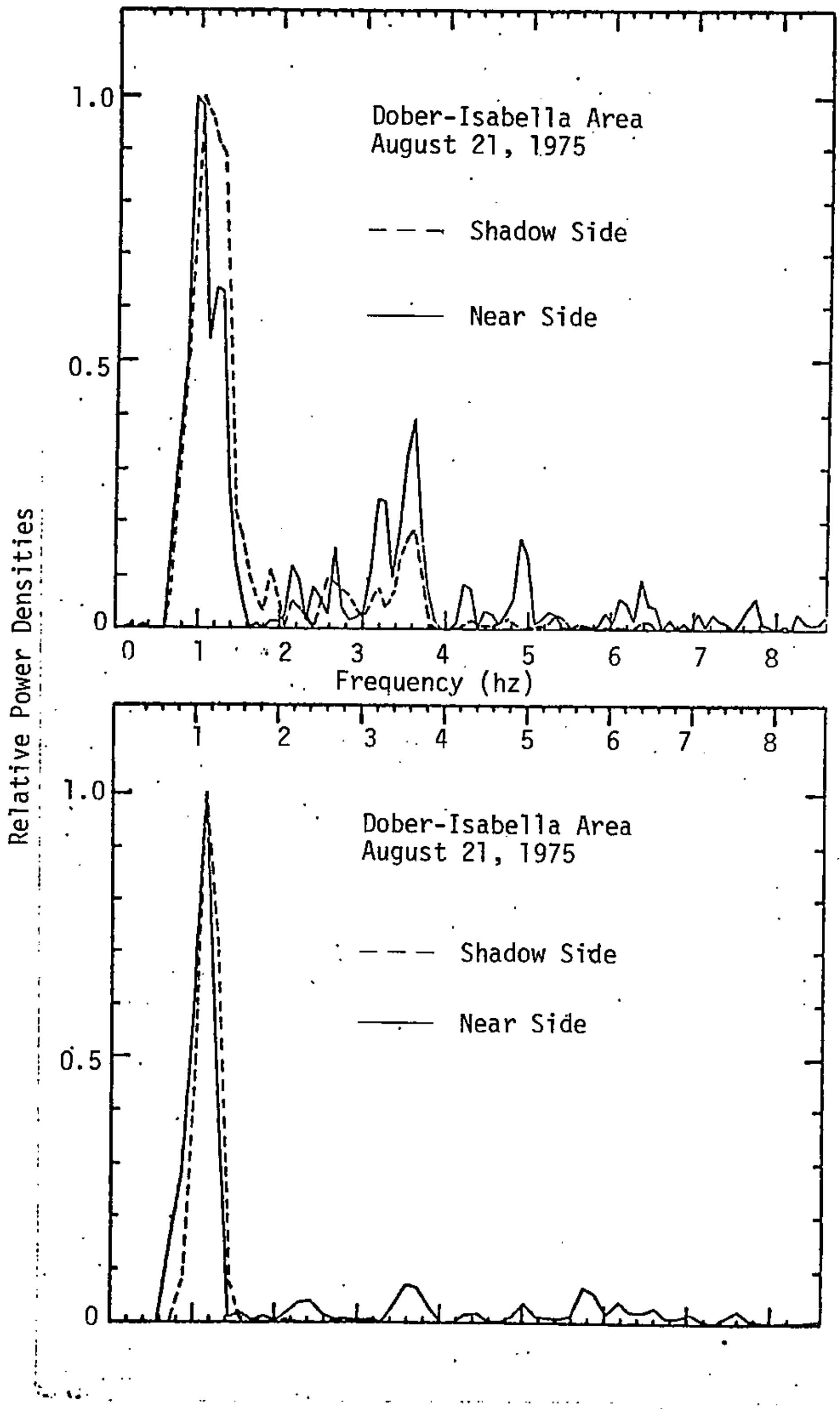


Figure 41. Reduced-Scale Tracings of Computer Printouts of Relative Power Spectral Densities

very large and not completely consistent. An initial inspection of these data was carried out by having the computer read the precise frequency of the peak of the power curve. This set of readings is illustrated in Table 1 where it can be seen that the peak frequency often, but not always, shifts towards a lower value for the shadow side. It is suggested that the rather narrow band of frequencies contained in the most energetic part of Lg is partly responsible. The narrowness of this band can typically be seen in the enlarged recording of Figure 38.

Another way of examining the frequency data is by measurement of the "width" of the spectral peak. Information preferrentially conveyed by higher frequencies will be more readily extracted this way, since the spectral width is responsive to the frequency distribution about the peak. This was explored by measuring the breadth of the spectral peak at its half-power points and taking the ratio of this parameter (the near side divided by the shadow side). Thus a ratio exceeding unity indicates that attenuation has developed with transmission across the mine. The data is shown in Table II where it can be seen that a statistically-significant result emerges. The ratio has a mean value of 1.27 $\pm$0.10 at the 80% confidence level and 1.27 $\pm$0.14 at the 90% confidence level. Thus in future applications we urge that record digitization extend into the high frequency coda of Lg and some measure other than specific peak frequency should be used as the judgement criterion.

The second aspect of the wave perturbation study is a comparison of the maximum amplitude of each wave type as recorded on opposite sides of a mine with respect to the source. This measurement is made without regard to frequency. Table III lists the measurements for compressional (P), shear (S) and surface (Lg) waves and corresponding ratios of each to compare the shadow side to the near side. Because of the scatter in the measurements, it is difficult to

Table I

Lists the computer-determined frequency of the point of maximum power in the spectra for near-side and shadow-side mine seismograms.

Record Identification	Location		Frequency (hz)
7225	Dober	Near Side	1.104
		Shadow Side	1.106
7235	Mineral Hills	Near Side	1.062
		Shadow Side	1.413
8055	Mineral Hills	Near Side	1.304 - 1.391
		Shadow Side	1.293 - 1.379
8055	Spies	Near Side	1.042
		Shadow Side	0.955
8135	Dober	Near Side	1.406
		Shadow Side	1.217
8215-1	Dober	Near Side	1.058
		Shadow Side	0.995
8215-2	Dober	Near Side	1.235
		Shadow Side	1.149
6246	Dober	Near Side	1.230
		Intermediate	1.058
		Shadow Side	1.148
7026	Dober	Near Side	0.991
		Intermediate	1.056
		Shadow Side	0.972
8056	Dober	Near Side	1.056
		Shadow Side	1.142

Table II

Lists the width of the spectral peak (at its half-power points) for the spectra of near-side and shadow-side mine seismograms and the corresponding ratio of the width measurements.

Record Id.	W_N	W_S	R	
8056 DOB	7.5	7.2	1.04	W_N = width of near side
7026 DOB	7.8	5.6	1.39	W_S = width of shadow side
8246 DOB	10.6	8.5	1.25	$R = W_N \div W_S$
8215-1 DOB	5.5	5.4	1.02	n = no. of samples = 15
8215-2 DOB	9.6	4.9	1.96	$\overline{R}$ = mean value of R = 1.27
8135 DOB	10.9	6.0	1.70	t_{80} = 80% value, students' t distribution
8055 MIN	7.1	4.9	1.45	= 1.34
8055 SPI	9.0	6.2	1.45	t_{90} = 90% value, students' t distribution
7235 MIN	8.4	8.2	1.02	= 1.76
7225 DOB	5.9	5.2	1.13	$S = [\Sigma(R-\overline{R})^2 \cdot (n-1)^{-1}]^{\frac{1}{2}}$
8135 ISA	6.8	4.1	1.66	$\overline{R}_{80} = 1.27 \pm t_{80} \cdot S \cdot n^{-\frac{1}{2}}$
8055 DAV	2.2	2.1	1.05	$= \underline{1.27 \pm 0.10}$
8055 JOH	3.9	4.1	0.95	$\overline{R}_{90} = 1.27 \pm t_{90} \cdot S \cdot n^{-\frac{1}{2}}$
8215 ISA	6.1	6.2	0.98	$= \underline{1.27 \pm 0.14}$
8215 DOB(2)	4.0	3.8	1.05	

Table III

Lists the maximum amplitudes for P, S and Lg waves and ratios of the amplitudes comparing shadow-side to near-side mine seismograms.

Record Id.	Location	Ap	As	ALg	Rp	Rs	RLg	Rs-p	Rs-Lg
7305 MIN	Near Side	60	56	116				0.93	0.48
	Shadow Side	50	44	80	0.83	0.79	0.69	0.88	0.55
8055 MIN	Near Side	18	23	55				1.28	0.42
	Shadow Side	28	44	124	1.56	1.91	2.25	1.57	0.35
8055 SPI	Near Side	6	12	24				2.00	0.50
	Shadow Side	10	12	26	1.67	1.00	1.92	1.20	0.26
8075 SPI	Near Side	45	70	75				1.56	
	Shadow Side	48	60	50	1.07	0.86	0.67	1.25	
8135 DOB	Near Side	24	37	77				1.54	
	Shadow Side	8	20	64	0.33	0.54	0.83	2.50	
8215 DOB	Near Side	24	40	38				1.67	1.05
	Shadow Side	19	25	48	0.79	0.63	1.26	1.32	0.52
8215 ISA	Near Side	34	48	66				1.41	1.38
	Shadow Side	8	28	70	0.24	0.58	1.06	3.50	0.40
9185 DOB	Near Side	28	64	96				2.29	0.67
	Shadow Side	30	75	92	0.71	1.17	0.96	3.75	0.82
6106 DOB	Near Side	14	30	45				2.14	0.67
	Intermediate	5	13	30	0.36	0.43	0.67	2.60	0.43
	Shadow Side	6	13	40	0.43	0.43	0.89	2.17	0.33
6156 DOB	Near Side	50	70	65				1.40	1.17
	Intermediate	15	30	28	0.30	0.43	0.43	2.00	1.07
	Shadow Side	25	40	42	0.50	0.57	0.65	1.60	0.95
6246 ISA	Near Side	10	44	70				4.40	0.63
	Shadow Side	15	35	103	1.50	0.80	1.47	2.23	0.34
6256 BUC	Near Side	10	20	40				2.00	0.50
	Intermediate	10	40	38	1.00	2.00	0.95	4.00	1.05
	Shadow Side	5	15	25	0.50	0.75	0.63	3.00	0.60
6306 BUC	Near Side	18	50	80				2.78	0.63
	Shadow Side	18	30	75	1.00	0.60	0.95	1.67	0.40
7016 DOB	Near Side	20	77	126					
	Intermediate	30	80	80	1.50				
	Shadow Side	25	80	80	1.25				
7016 ISA	Near Side	15	30	66				2.00	0.45
	Shadow Side	23	40	60	1.53	1.33	0.81	1.74	0.67
7026 DOB	Near Side	12	19	25				1.58	0.76
	Shadow Side	12	19	25	1.00	1.00	1.00	1.58	0.76
7076 BUC	Near Side	14	25	45				1.79	0.56
	Intermediate	7	18	20	0.50	0.72	0.44	1.11	0.90
	Shadow Side	15	28	28	1.07	1.12	0.62	1.89	1.00

Table III (continued)

Record Id.	Location	Ap	As	ALg	Rp	Rs	RLg	Rs-p	Rs-Lg
7086 DOB	Near Side	40	65	70				1.63	0.93
	Intermediate	55	112	124	1.38	1.72	1.77	2.04	0.90
	Shadow Side	40	80	117	1.00	1.20	1.67	2.00	0.68
8056 DOB	Near Side	25	105	100				4.20	1.05
	Shadow Side	18	63	77	0.72	0.60	0.77	3.50	0.82
8196 ISA	Near Side	16	63	110				3.94	0.57
	Intermediate	34	140	104	2.13	2.22	0.95	4.12	1.35
	Shadow Side	36	94	92	2.25	1.49	0.84	2.61	1.02

recognize any systematic variations. Therefore, a statistical analysis was performed as shown in Table IV. Within the confidence limits shown, it is not possible to recognize a systematic change in parameters based on maximum amplitude with one exception. At the 90% confidence level, the maximum amplitude ratio of shear wave to surface wave is 0.76 ±0.16. Maximum amplitudes are of course readily extracted from seismic traces. Based on these results, we are encouraged in future work to concentrate maximum amplitude investigations on the shear wave to surface wave ratio.

However, recently a computer program, used for computing amplitude ratios of body waves (P, SV and SH), was modified to simulate mine voids by introducing water-filled cavities (Bingham, 1978). Applying this program to particular models of several crucial areas near Iron River consistently showed very sharp peaks over a frequency range 3.2 to 3.8 hz, as shown in Figure 42. This implies that frequency-dependent amplitude ratios of body waves, P and S, and horizontal shear waves (SH) or Love waves, may well carry diagnostic information on the cavity position. In several amplitude cases analyzed in Tables III and IV, the exclusion of just 1 or 2 extreme readings of a total set would lead to a statistically-significant result. Thus the data indicate a potential usefulness of body wave amplitudes in this connection and emphasize the need to involve the frequency dependence by using spectral ratios.

Microseismic Technique

Background. Seismic signals have been observed to radiate from zones in the crust of the earth where stress is accumulating or where soil and rock are disturbed. Often those signals are forerunners to a subsequent major event. For example, the number of microearthquakes (small events) in a stressed region has often been observed to increase prior to a major earthquake. The number of

Table IV

Lists the statistical analysis of data comparing the shadow-side to the near-side for P, S, Lg and ratios s/p, s/Lg.

	P	S	Lg	Rs-p	Rs-Lg
	1.56	1.91	2.25	1.23	0.83
	1.67	1.00	1.92	0.60	0.52
	1.07	0.86	0.67	0.80	0.50
	0.33	0.54	0.83	1.62	0.29
	0.79	0.63	1.26	0.79	0.22
	0.24	0.58	1.06	2.48	0.64
	0.71	1.17	0.96	1.64	0.91
	0.36	0.43	0.67	1.21	1.20
	0.30	0.43	0.43	1.43	0.63
	0.50	0.75	0.63	1.50	1.49
	1.00	0.60	0.91	0.60	1.00
	1.53	1.33	1.00	0.87	1.61
	1.00	1.00	0.44	1.00	0.73
	0.50	0.72	1.67	0.62	0.78
	1.00	1.20	0.77	1.22	
	0.72	0.60	0.95	0.83	
	2.13	2.22		1.04	
n -	17	17	16	17	14
$\bar{X}$ -	0.91	0.94	1.03	1.15	0.76
t_{90} -	1.75	1.75	1.75	1.75	1.76
t_{80} -	1.34	1.34	1.34	1.34	1.34
S -	0.56	0.51	0.52	0.49	0.36
90% -	0.91±0.24	0.94±0.21	1.03±0.23	1.15±0.21	0.76±.17
80% -	0.91±0.18	0.94±0.17	1.03±0.17	1.15±0.16	

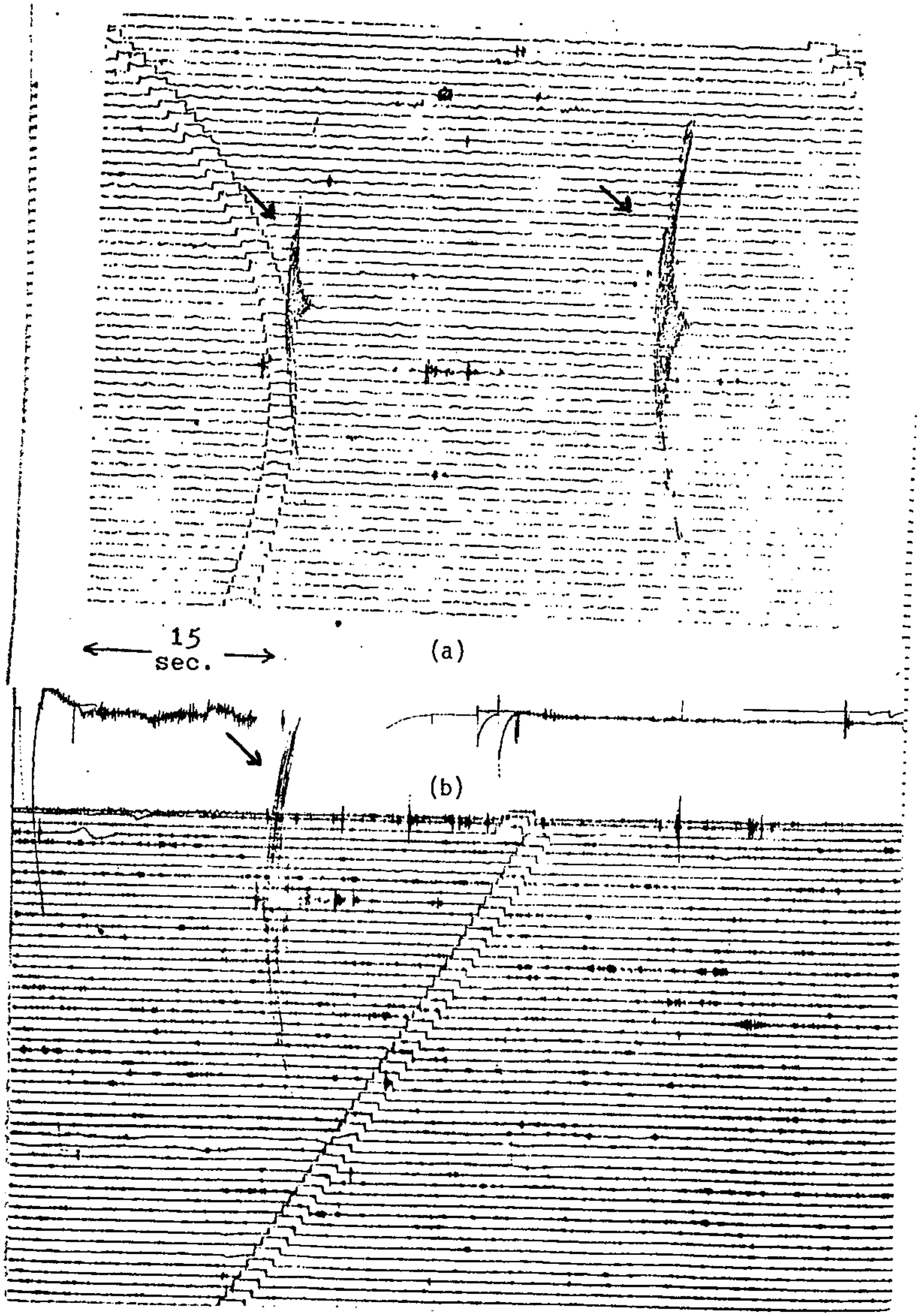


Figure 42. Photo-seismograms of natural, high-frequency signals showing similar characteristics for (a) a source in the Dober-Hiawatha Mine complex and (b) a rockburst in the Quincy Mine north of Hancock, MI - both recorded on nearby MEQ instruments.

microsignals originating in a large embankment has been observed to increase prior to a major earthslide. The microsignal generation in a mine roof has been observed to increase prior to a roof collapse. All of these observations have been the basis for the design of practical monitoring systems.

Our geophysics group in a project at the White Pine Mine, as described by Gibbons (1975) and Frantti (1975), has detected seismic signals as low as a few hertz which apparently relate to geological disturbances in the mine roof complex. This is in contrast to investigations such as by Obert and Duvall (1945), Brown and Singh (1966), and Scholtz (1968), who correlated failure in rock to microseismic signals at frequencies well above 100 hz.

Monitoring very high frequency microsignals requires the location of sensors close to the expected source since earth materials absorb high frequencies very rapidly. Because of thick overburden in our study area, this would mean drilling holes for emplacement of sensors, an option that was averted for reasons discussed earlier.

Monitoring signals below 30 hz could in principle be accomplished at the surface since signals in this range propagate effectively over the necessary distances. Because of supporting evidence for this lower frequency range, which correlates with the passband of the MEQ-800 seismograph, it was determined that the feasibility of a microearthquake surface monitoring technique should be investigated in this subsidence study. In principle, this method could furnish a measure of the impending threat of subsidence in an area since the data relate to the statistics of the level of activity as indicated by the radiation rate of microsignals from stressed or disturbed soil and rock. This is in contrast to the other techniques under study which examine static conditions and parameters rather than dynamic ones.

Field procedure. The same instrumentation as described and used in the Wave Perturbation study is also used in gathering data for the Microseismic Technique. The general requirement is to position the three MEQ seismographs a few kilometers apart in a triangular array above the shallow stopes of a mine. The spread geometry should be large enough to distinguish the difference in arrival time at each site for a common signal originating within or near the mine. On the other hand, excessive station separation could head to low-level signals being recorded on just a single instrument which prevents the precise location of the source (a minimum of three recordings are needed for triangulation).

Fifteen recording sites used for this study are shown in Figure 35. These cover the general mine areas known as Mineral Hills-Davidson, Dober-Isabella, Spies-Johnson and Young-Buck. As previously mentioned, recording time at Mineral Hills-Davidson was severely limited because of noise from the Sherwood Mine crusher and likewise at Spies-Johnson because of highway U.S. 2.

A total of 750 hours of recording time were generated for this study. Records obtained for the Wave Perturbation investigation were also used. Instruments were operated for continuous periods of 24 hours, 12 hours or 6 hours at intermittent intervals of time. The 6-hour records were made at four times the recording speed used for the longer runs, which expanded the signals for easier frequency analysis. Night time operation is favored by lower noise level. Daytime operation was necessary for monitoring blast signals from distant sources.

Interpretation. All recordings were diligently searched for short-duration signals having nearly coincident arrival times and similar characteristics. Spike-like signals would ascribe to events having only high frequencies, perhaps dominantly beyond the passband of the instruments, and would indicate a source very close to the recorder (such as from small movements in soil or rock). Short duration signals with abrupt arrival breaks and otherwise similar to recordings of microearthquakes would indicate sources of compact size and reasonably close to the recording sites (such as from sudden, massive rock failures). Elongated signals with a slow buildup and decay could imply either more distant events or more spread-out source mechanisms (such as separations or adjustments along extended roof strata in an underground mine).

With just a few exceptions, the absence of signals, as described above, from the microseismic records suggests that there were very little, if any, disturbances or adjustments occurring in nearby mines during our monitoring periods. The sensitivity of the recording array was reaffirmed by conducting small test explosions throughout the network and by examining the system's response to disturbances generated at local industrial centers. Seismic signals would be much more effectively radiated by small disturbances at depth in rock or in consolidated soils than in surface unconsolidated alluvium.

The exceptions mentioned above were detected during the summer of 1976 before the third seismograph was available, thus precluding a reasonable source determination. On two separate days, signals with characteristics of a local natural origin were recorded at the sites numbered 8 and 11 of Figure 35. The amplitude at site 11 was an order of magnitude larger than at site 8, indicating a likely origin in the mine complex just north of Caspian. Also on another day, four events were recorded at site 8 with a waveform again suggesting natural origin. Unfortunately this happened at a time when the second seismograph was being operated for surveillance reasons in another part of the district, so the events were detected at just a single station. Two of these signals arriving about 30 seconds apart are shown in Figure 43. They consist of short bursts of high frequency energy with an impulsive beginning and rapid decay, implying a local origin. The signals can be compared to an event, shown in Figure 43,

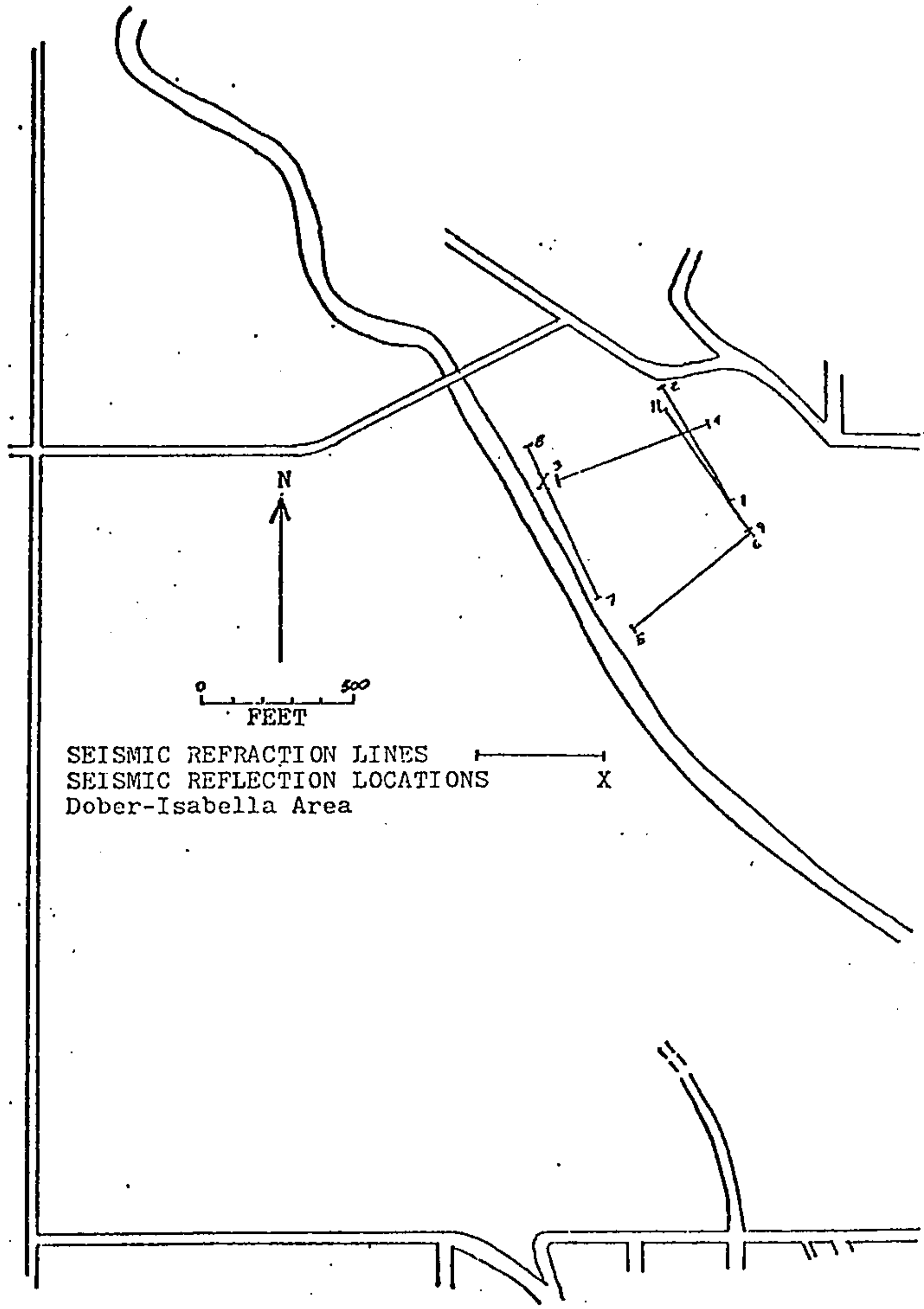


Figure 43. Map of the Locations of Seismic Refraction Lines (numbered solid lines) and Preliminary Seismic Reflection Measurements (marked x) in the Dober-Isabella Area.

which was generated by a rockburst in the Quincy Mine near Hancock, Michigan and recorded about 400 meters away in the Arcadian Adit. The signals correlate very closely in waveform characteristics.

Seismic Reflection Technique

Background. The petroleum companies have been using seismic reflection methods for many years in the search of geological targets at depths of thousands of meters. However, deep surveys have an advantage over shallow surveys since the waves traveling horizontally from the energy source disappear long before the reflected waves return to the detectors from great depth. Because this is not so for shallow work, the application of shallow reflection techniques has only recently endured practical success due to developments in instrumentation and data processing procedures.

Cook (1965) achieved some success in detecting reflections from shallow, liquid-filled cavities by using horizontally-polarized shear waves. However, his procedure involved (1) a specialized energy source, which would be impractical for repetitive use, and (2) a correlation of cavity reflections with reflections from a good marker horizon below the cavity, which is usually only possible in flat-bed structures.

Lepper and Ruskey (1976) described an effective application of shallow seismic reflections in mapping the tops of coal seams and various associated geologic features. They did not consider underground voids, however, and selected study areas with desirable and well defined characteristics.

The energy of a seismic wave penetrating the earth, upon reaching an obstacle such as a large cavity, will be divided into a transmitted wave, transformed waves and reflected wave. For plane wave transmission along a near-vertical path, we can reasonably ignore the transformed waves. The degree of reflection from an interface is dependent on the contrast in acoustic impedance across the contact. For example, a measure of reflectance from the boundary of two homogeneous media is given by coefficient R where $R = [c_2\rho_2 - c_1\rho_1][c_2\rho_2 + c_1\rho_1]^{-1}$. In this expression c_1, c_2 are seismic velocities and ρ_1, ρ_2 are densities and subscript one denotes the medium on the side from which the wave is incident. Thus we can expect good reflection from the top of a cavity and also a phase reversal (R is negative) since $c_2\rho_2 < c_1\rho_1$. It is important to note that the smaller the physical size of the reflecting surface, the higher the frequency must be for the incident wave. In other words, the incident wave must be dominated by wavelengths less than the diameter of the reflection surface if substantial reflection is to be achieved.

From the expression for R above, it is evident that reflections will occur wherever there is a contrast in acoustic impedance. Thus in addition to the desired target (top of underground cavity), other interfaces such as ledge surface, interfaces within the glacial overburden and geological interfaces within the medium surrounding the mine will produce reflections. These must be distinguished from the stope reflections.

Furthermore, sources such as explosives or mechanical devices will not only generate down-going waves, but also horizontally-traveling waves. Procedures must be devised to reduce the affects of horizontal waves on the detectors since they will still be present at the time when reflections arrive from shallow targets.

The enhancement features of modern seismographs and simple field procedures to reduce the undesirable affects were used in this study to explore the Seismic Reflection Technique in measuring the position of underground cavities.

Field procedures. For a period of 10 days late in the first phase of this project (August, 1976), a model 1575B Automatic Signal Enhancement Seismograph was made available courtesy of Bison Instruments Incorporated of Minneapolis. This instrument stores the seismic waveform for each source impact in digital memory. Thus one can add the waveforms from several impacts to reduce noise levels (since noise arrives at random times) and to increase the intensity of true reflections (since signals arrive at the same time). Also, this seismograph has the capability of introducing a time delay between the time of impact and subsequent time of waveform summation. Using this feature, a correction (called normal moveout - NMO) can be made for the time difference that results from a small change in wave path when the impact point is moved. These instrument capabilities make possible field procedures for data gathering which enhance the success of seismic reflection studies of shallow targets.

Using the Bison Seismograph, preliminary measurements were made in six areas; namely, 1) Young-Buck, 2) Dober-Isabella, 3) Delta, 4) Homer-Cardiff, 5) Mineral Hills-Davidson and 6) Spies-Johnson. The locations are shown in Figures 44-48. Initial refraction measurements were made in each location to determine subsurface velocities of various layers as needed for evaluation of reflection data. Following this, a survey was made with the Bison Seismograph in which on-line recordings were obtained with a single geophone for several impact points spaced a few meters apart. These measurements were used to determine the wavelength of the horizontally-traveling wave. A general reflection survey was then carried out by surveying traverse lines over the projected position of shallow stopes as determined from composite mine maps. Different configurations of geophones were tried with the typical array being 6 detectors equi-spaced over a length corresponding to one wavelength of the surface wave.

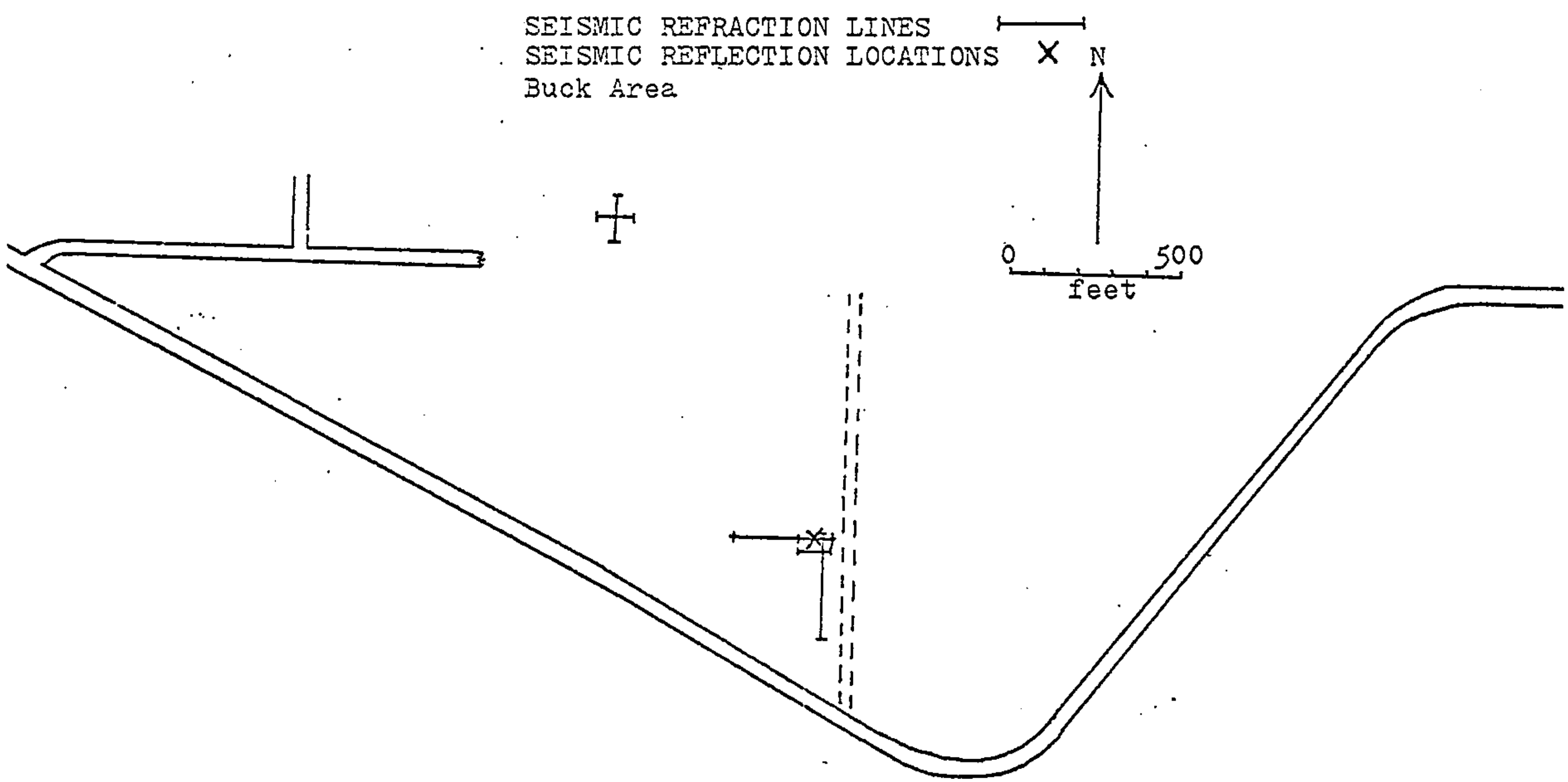


Figure 44. Map of the Locations of Seismic Refraction Lines (solid line) and Preliminary Seismic Reflection Measurements (marked x) in the Buck Area.

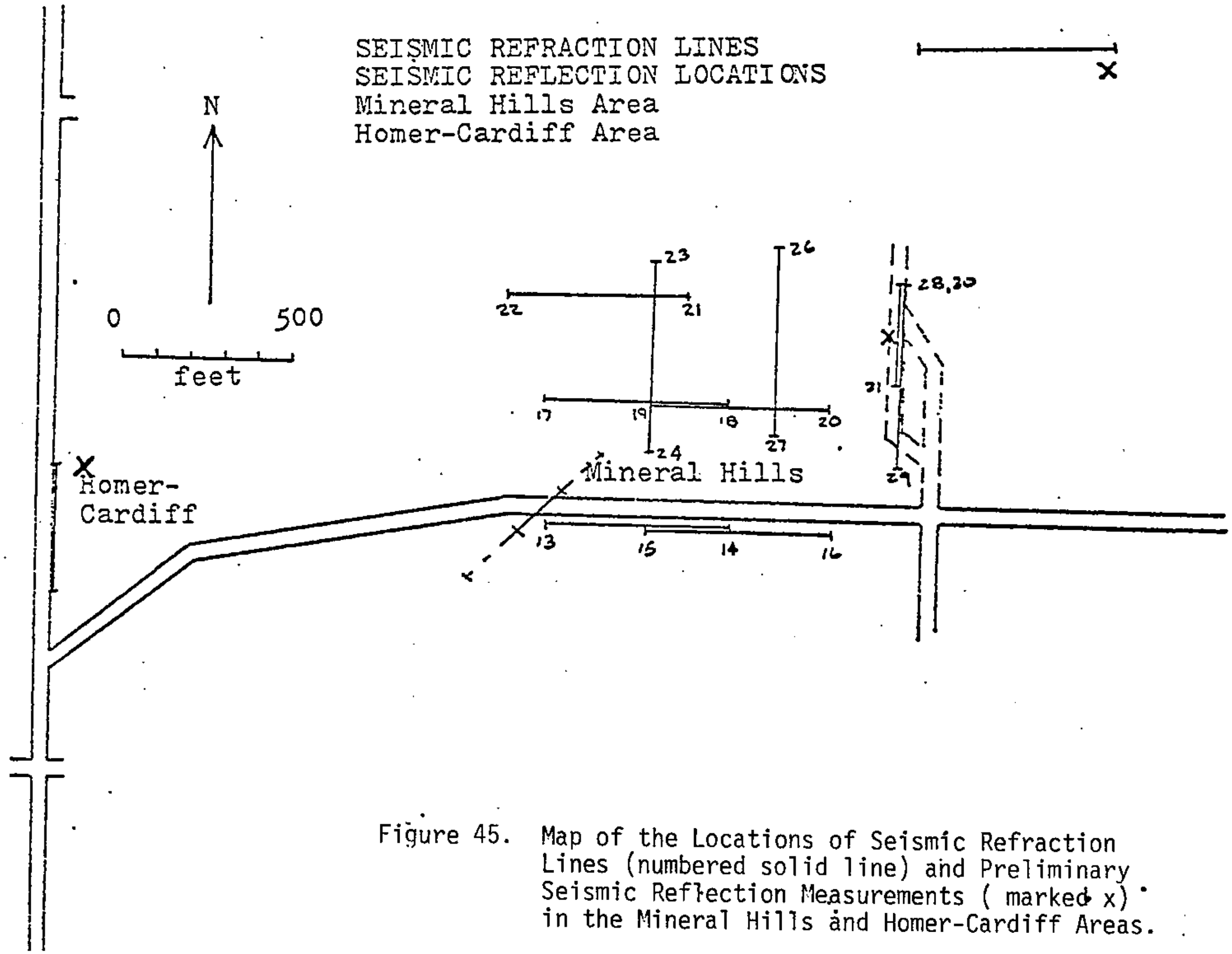


Figure 45. Map of the Locations of Seismic Refraction Lines (numbered solid line) and Preliminary Seismic Reflection Measurements (marked x) in the Mineral Hills and Homer-Cardiff Areas.

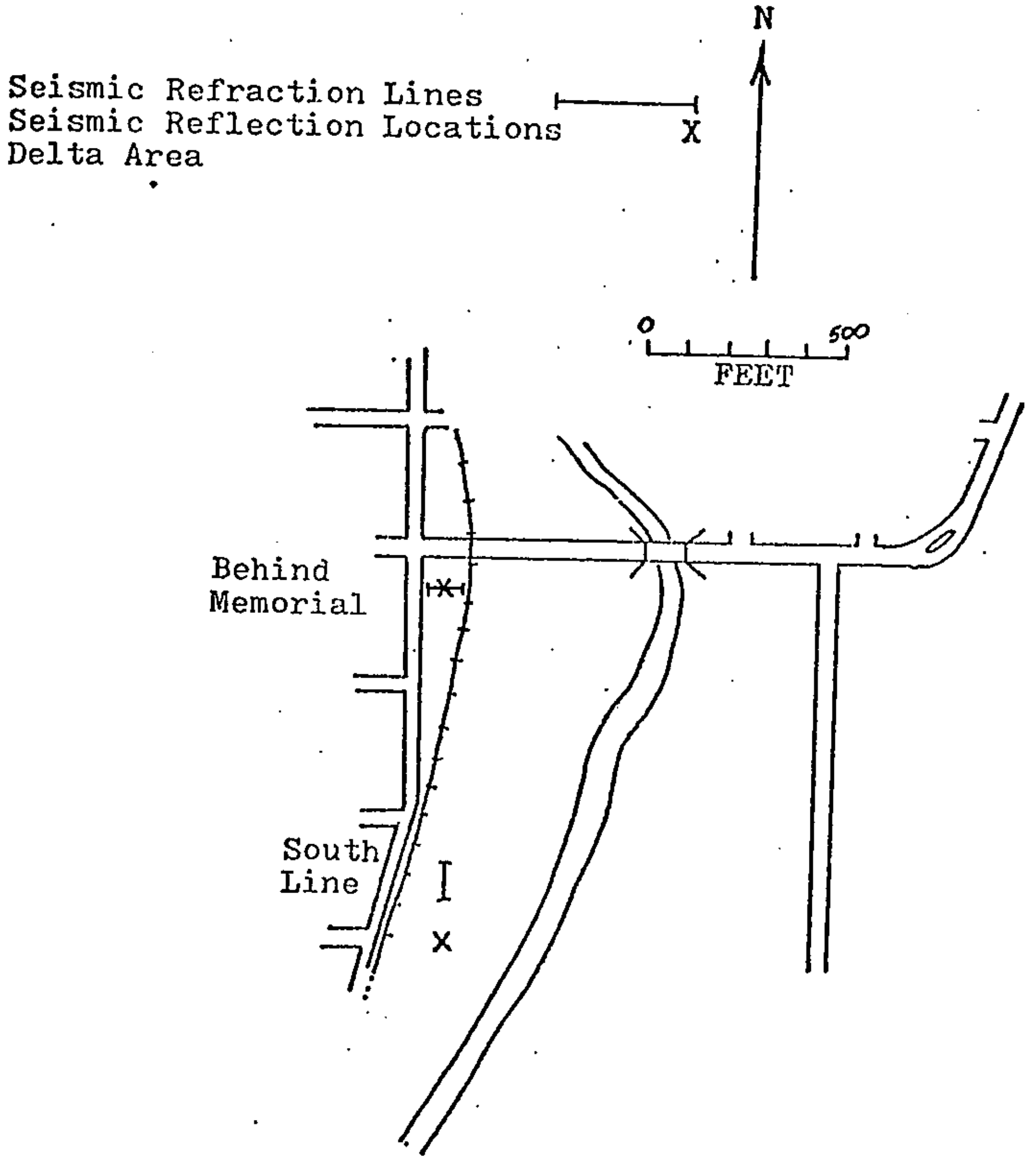


Figure 46. Map of the Locations of Seismic Refraction Lines (solid line) and Preliminary Seismic Reflection Measurements (marked x) in the Delta Area.

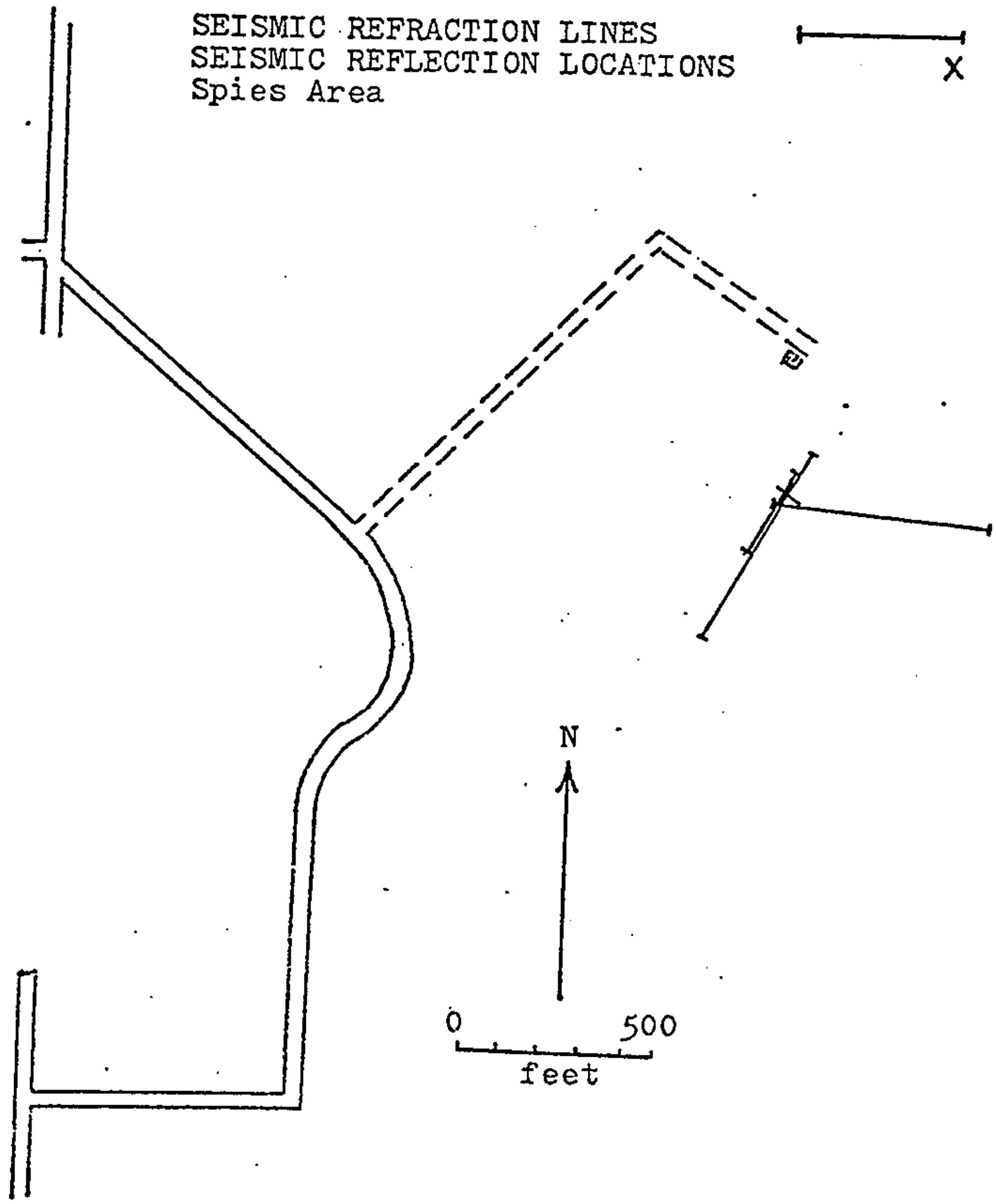


Figure 47. Map of the Locations of Seismic Refraction Lines (solid line) and Preliminary Seismic Reflection Measurements (marked x) in the Spies-Johnson Area.

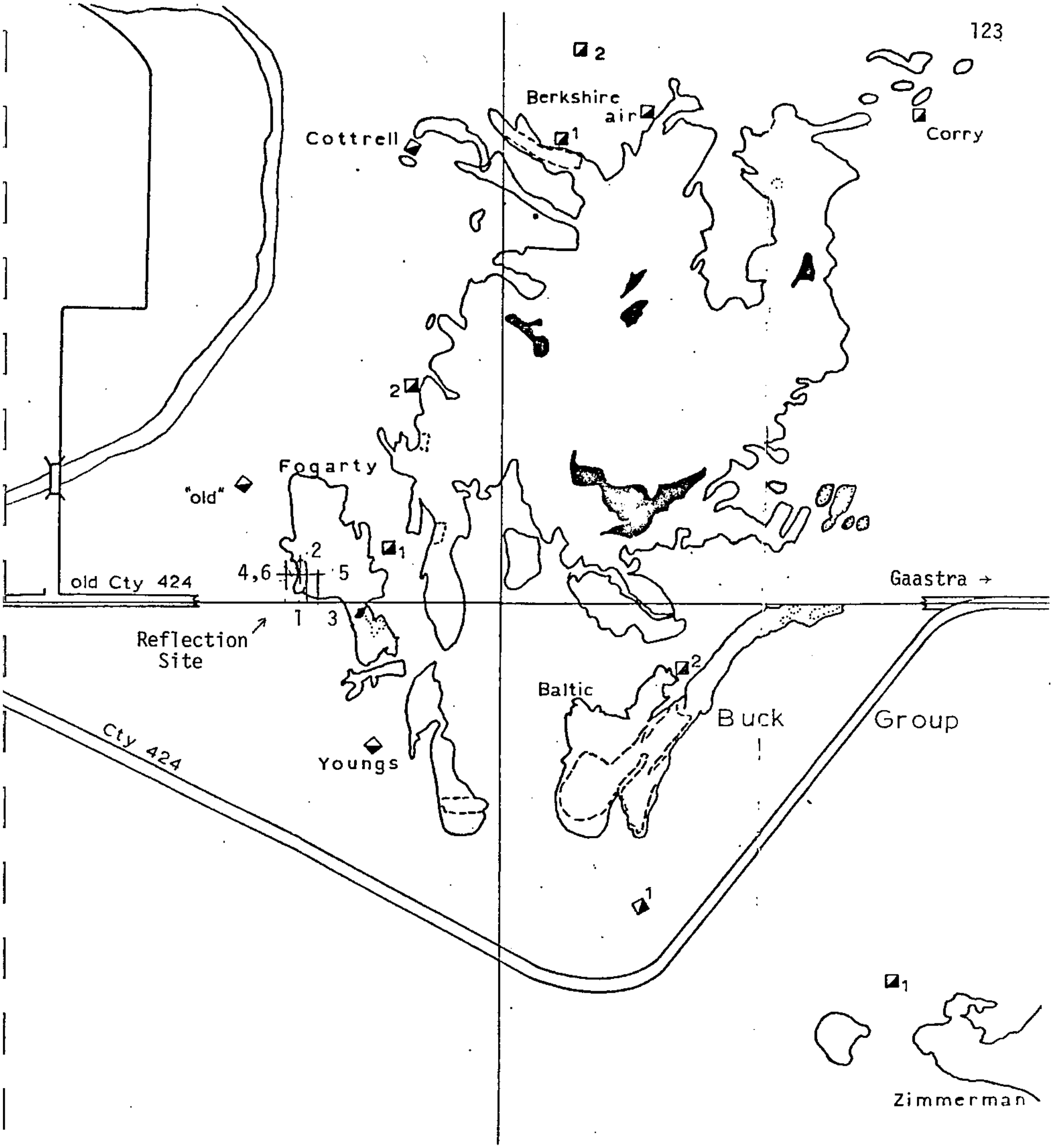


Figure 48. Map of the Locations of the Seismic Lines for the Final Reflection Study in the Young-Buck Area.

Repeated impacts were delivered to the ground with a 30-pound thumper at successive points along the line proceeding away from and towards the geophone array.

In June of 1977 a Multi-Channel Signal Enhancement Seismograph, model ES-1200 manufactured by Nimbus Instruments, became available in the department. In addition to offering the features of the Bison seismograph, this instrument has 12 channel capability and produces a permanent record of the data.

The Nimbus seismograph was used during the last few months of the project to conduct more detailed measurements of the Seismic Reflection Technique. Since there was not enough time to investigate all of the eleven areas judged to be critical, we selected seven sites that represented the typical range of depths and overburden thicknesses and that were free of current interferring activities such as construction projects. The sites are referred to by mine names as follows: 1) Young-Buck, 2) Dober-Isabella, 3) Hiawatha, 4) Delta, 5) Cardiff, 6) Homer-Wauseca and 7) Baker. These are shown in Figures 49-53.

The routine measurement procedure already described was followed, namely refraction survey, simple profiling to determine the wavelength of interferring surface waves and finally the general reflection survey. In this case where estimated stope depths exceeded about 250 or 300 feet, small explosive charges (in 3 to 5-foot holes) were used as the energy source. Various array configurations were explored. A typical array, as shown in Figure 54, contained 12 groups of 6-element subarrays with individual arrays distributed over a distance equivalent to one wavelength of surface interferring waves.

Table V contains descriptions of survey lines for the seven areas and line numbers as shown in Figures 49-53.

Interpretation. All reflection data were corrected for normal moveout; that is, for the difference in time between a vertical path and non-vertical path

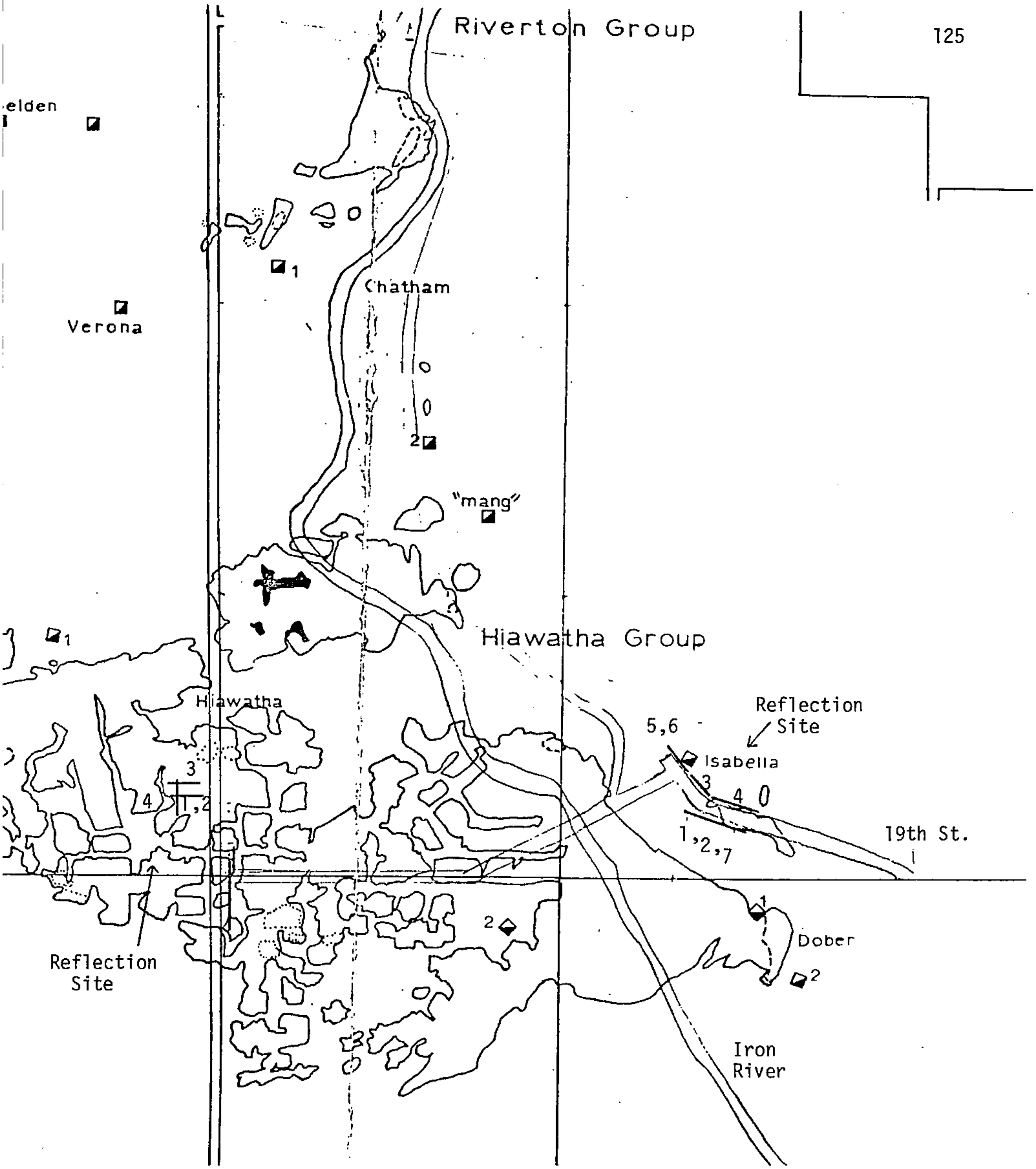


Figure 49. Map of the Locations of the Seismic Lines for the Final Reflection Study in the Dober-Isabella and Hiawatha Areas.

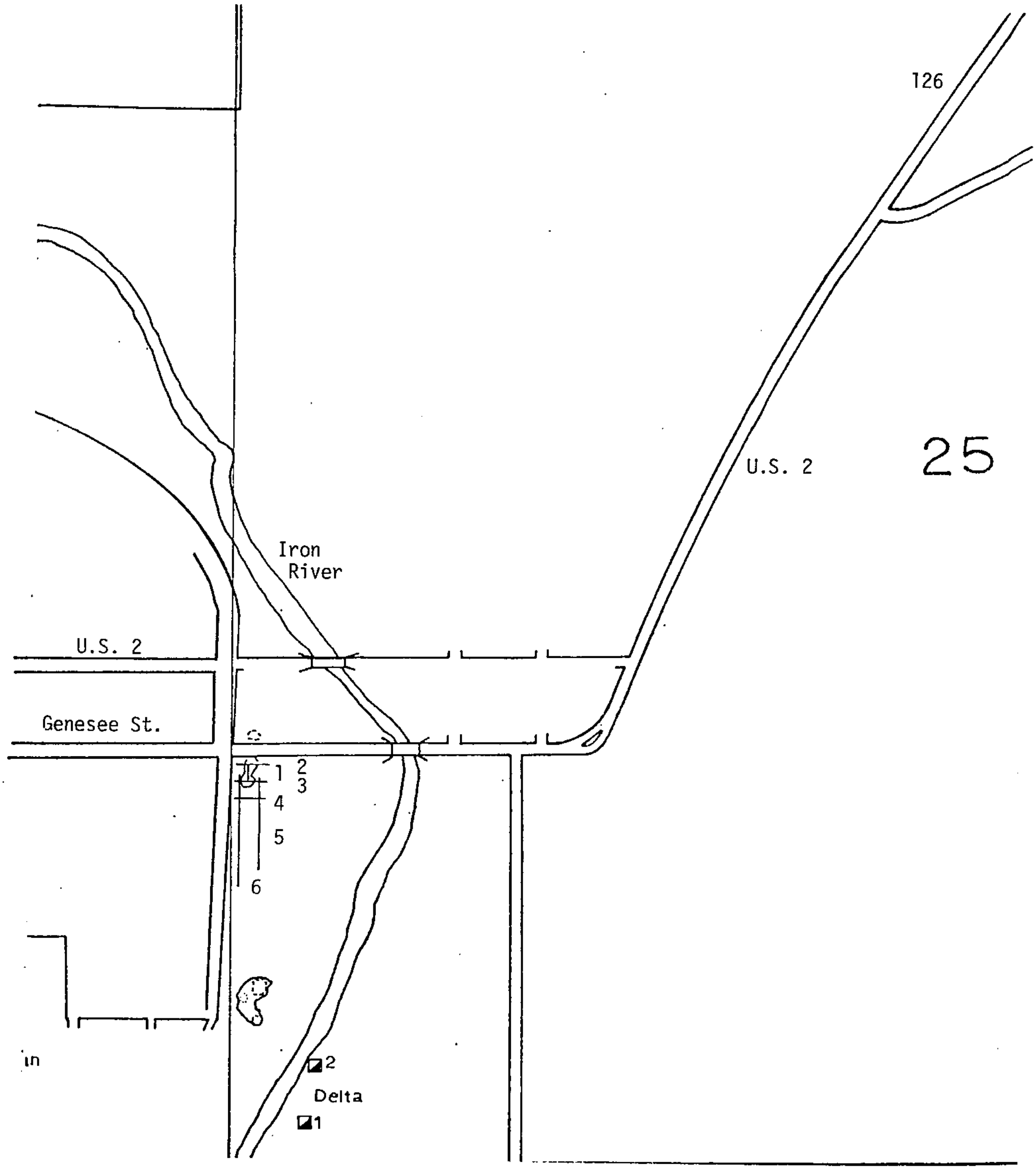


Figure 50. Map of the Locations of the Seismic Lines for the Final Reflection Study in the Delta Area.

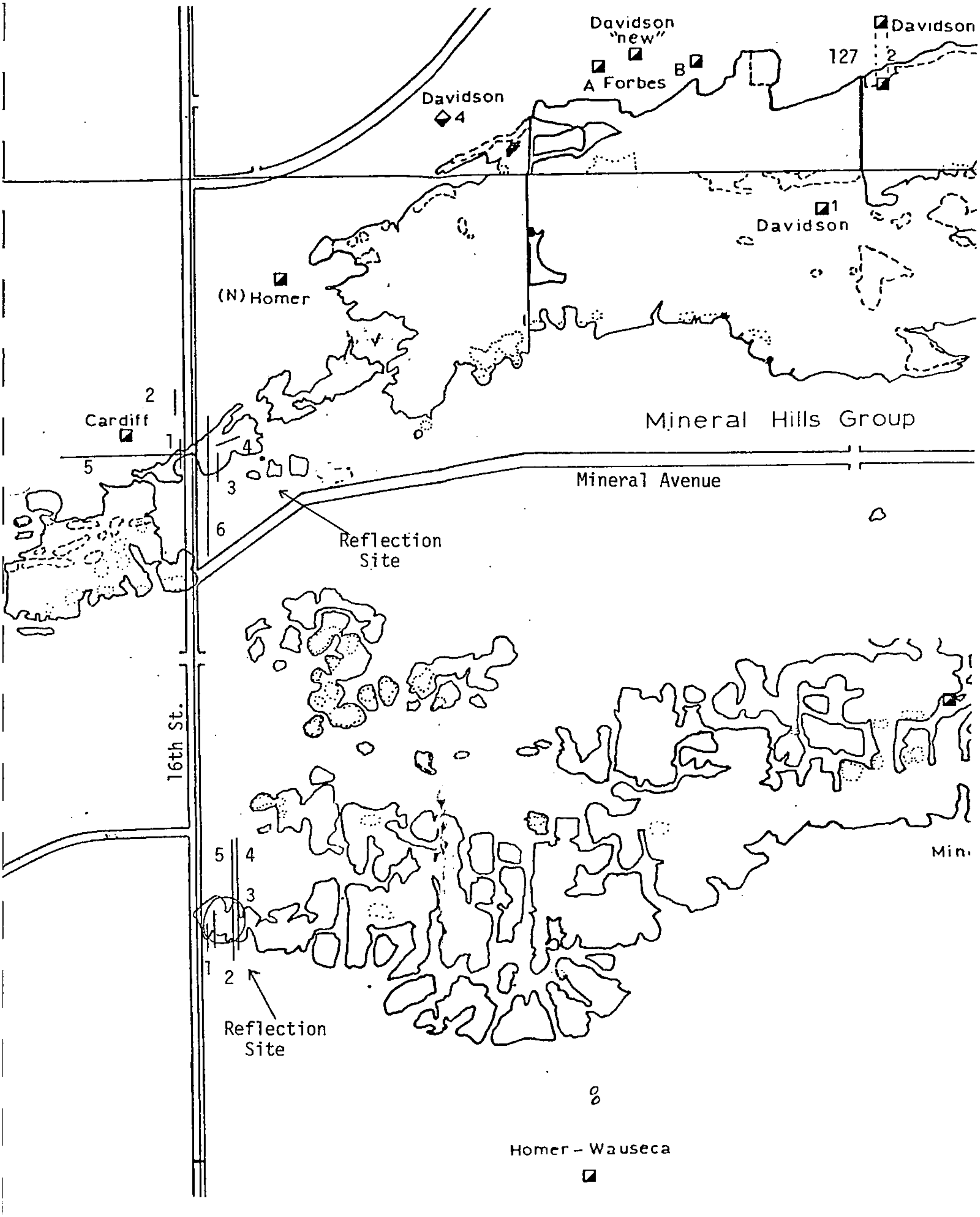


Figure 51. Map of the Locations of the Seismic Lines for the Final Study in the Cardiff and Homer-Wauseca Areas.

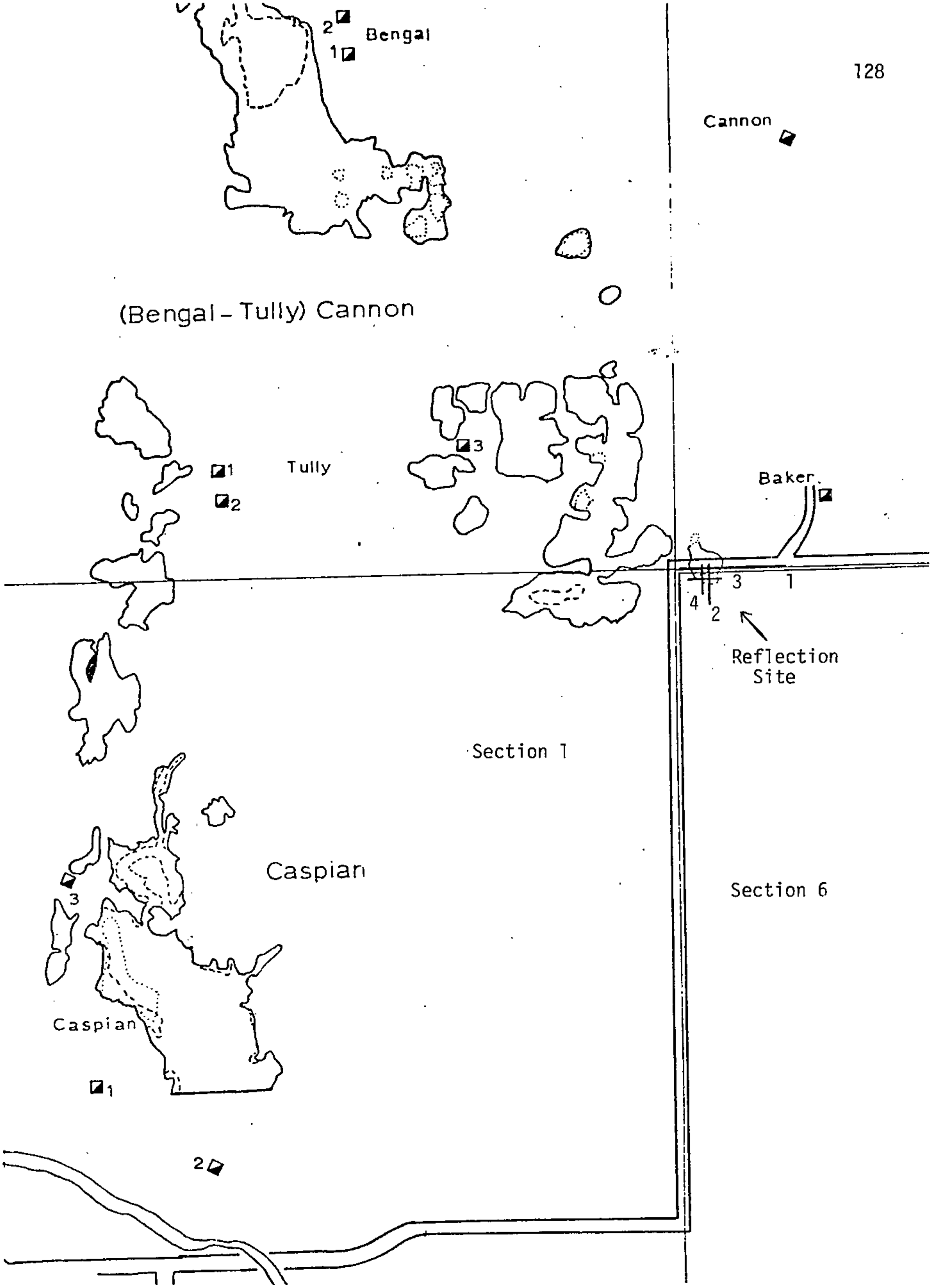


Figure 52. Map of the Locations of the Seismic Lines for the Final Reflection Study in the Baker Area.

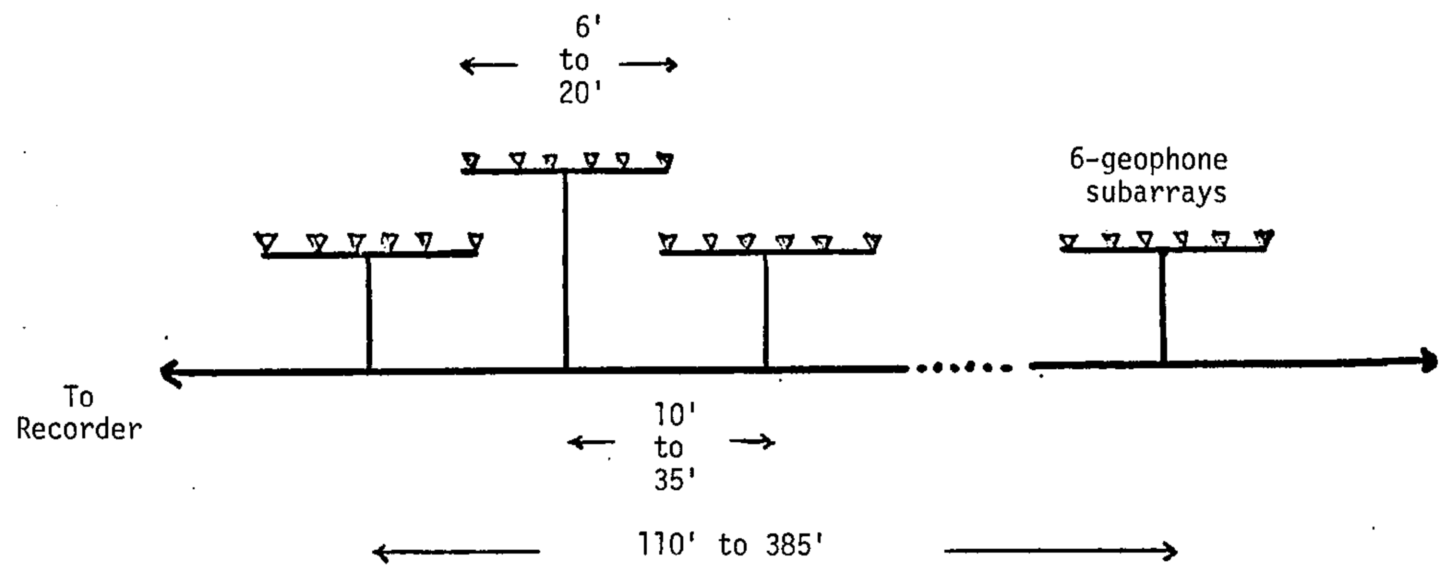


Figure 53. Typical Array Used in the Final Reflection Study Showing the Configuration of Geophone Subarrays Used to Reduce Noise by Spatial Filtering in the Field.

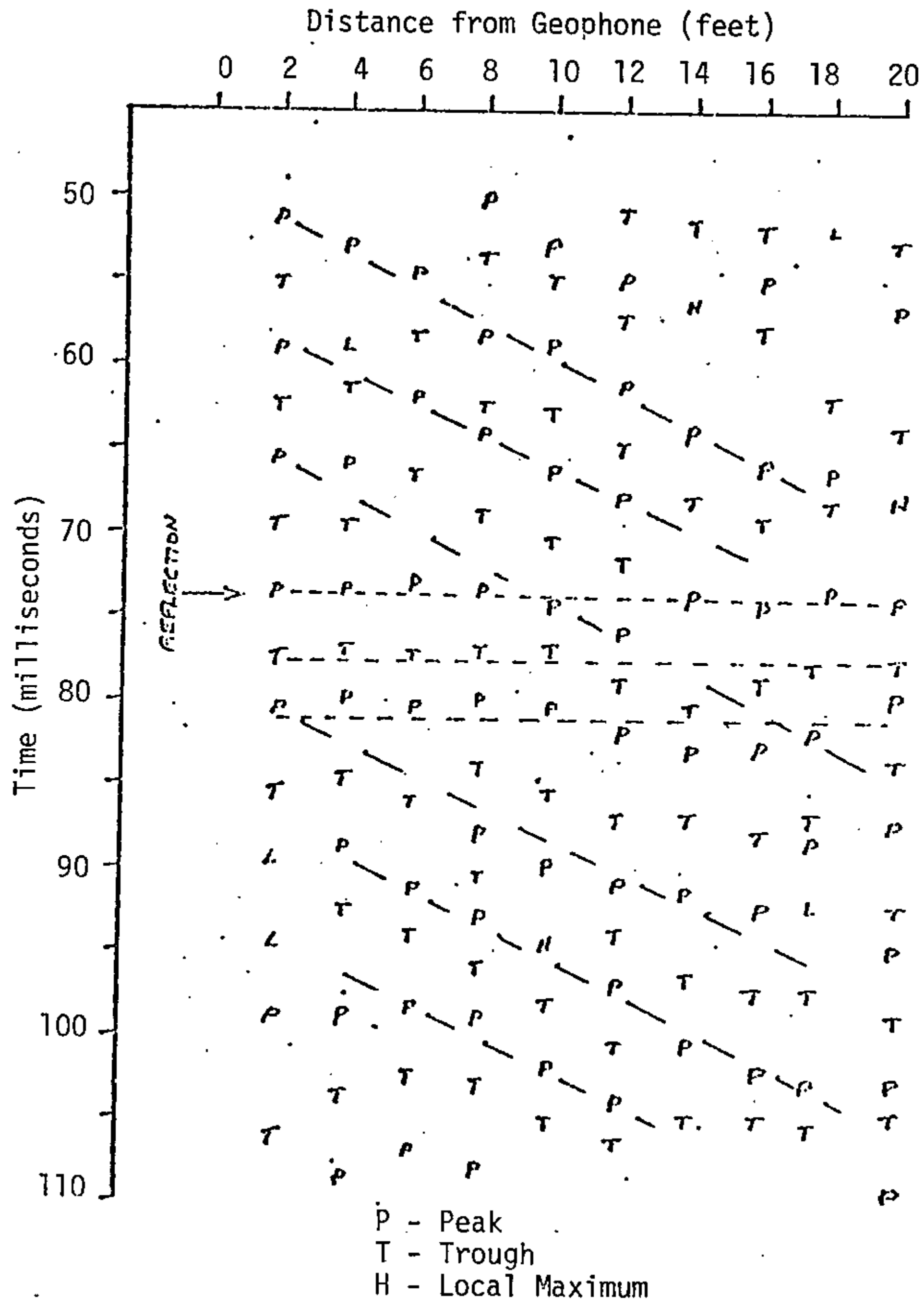


Figure 54. Typical Plot of Preliminary Seismic Reflections Obtained with a Single-Channel Seismograph Showing a True Reflection at 74 Milliseconds and Direct Seismic Arrivals (non-reflections) Along Diagonal Alignments.

Table V

Lists the locations of survey lines and reference coordinates for each of the seven areas at which reflection data were obtained with the Nimbus seismograph.

Line Number	Type Survey	Line Description
(1) Young-Buck (Reference: S.E. corner, sec. 1, R35W, T42N)		
1	N-S Reflection	7+00W, 0+05N to 1+55N
2	N-S Reflection	7+25W, 0+72N to 1+60N
3	N-S Reflection	6+60W, 0+30N to 1+20N
4	N-S Reflection	7+75W, 0+50N to 1+40N
5	E-W Reflection	1+00N, 6+62W to 7+50W
6	N-S Refraction	7+75W, 0+40N to 1+10N
(2) Dober-Isabella (Reference: Intersection, centerline, 19th Street and Wash. Avenue)		
1	Refraction	19th St., 7+00NW to 8+40NW
2	Reflection	19th St., 0+32S to 7+00NW
3	Reflection	19th St., N side, 8+68NW to 7+58NW
4	Reflection	19th St., N side, 8+68NW to 9+78NW
5	Refraction	19th St., N side, Front of Isabella shaft, 150' long
6	Reflection	19th St., N side, Front of Isabella shaft, 150' long
7	Reflection	19th St., 0+32S to 7+00NW
(3) Hiawatha (Reference: Intersection, centerline, 19th Street + M-189)		
1	E-W Reflection	3+20N, 0+60W to 1+20W
2	E-W Refraction	3+20N, 0+60W to 2+00W
3	E-W Reflection	3+55N, 0+60W to 1+70W
4	N-S Reflection	1+60W, 2+45N to 3+55N
5	N-S Refraction	0+72E, 1+00N to 2+00S
6	N-S Reflection	0+70E, 0+20N to 1+30N
(4) Delta (Reference: Intersection, E side River St. and S side U.S. 2)		
1	N-S Reflection	0+70E, 0+45S to 1+00S
2	E-W Reflection	0+30S, 0+55E to 1+15E
3	E-W Reflection	1+00S, 0+30E to 0+90E
4	E-W Reflection	1+35S, 0+30E to 0+90E
5	N-S Refraction	0+30E, 0+98S to 2+48S
6	N-S Refraction	0+40E, 0+90S to 2+70S
(5) Cardiff (Reference: Intersection, centerline, 19th St. and Mineral Ave.)		
1	N-S Reflection	0+60W, 4+50N to 5+60N
2	N-S Reflection	0+40W, 7+20N to 8+30N
3	N-S Reflection	1+10E, 3+90N to 5+00N
4	N-S Reflection	5+63N, 2+16E to 5+35N, 1+10E
5	E-W Refraction	5+60N, 0+35W to 5+35W
6	N-S Refraction	1+10E, 0+95N to 7+35N

Table V (cont.)

Line Number	Type Survey	Line Description
(6) Homer-Wauseca (Reference: Intersection, centerline, 16th St. and road W at E quarter corner, sec. 22, R35W, T42N)		
1	N-S Reflection	0+75E, 3+00S qo 4+50S
2	N-S Reflection	0+50E, 3+45S to 4+50S
3	Reflection	Center at 1+15E, 3+50S; radius, 75'
4	N-S Refraction	1+50E, 0+00S to 4+50S
5	N-S Refraction	1+10E, 0+30S to 5+00S
(7) Baker (Reference: Intersection, centerline, roads on N and W boundaries, sec. 6, R34W, T42N)		
1	E-W Refraction	0+15S, 0+50E to 4+30E
2	N-S Reflection	1+25E, 0+25S to 1+35S
3	E-W Reflection	0+35S, 0+98E to 1+75E
4	N-S Reflection	0+75E, 0+35S to 1+10S

that results from changing the geophone-to-impact distance. In the preliminary analysis with the Bison seismograph, this correction was determined from a weighted average of the velocity along the entire vertical section based on individual layer thicknesses and velocities. During the subsequent analysis with the Nimbus seismograph, the correction was based on the interval layer thicknesses and velocities.

The basic procedure of data acquisition followed the Common-Depth-Point (CDP) method of reflection seismology. The procedure used is referred to as PSUEDO-CDP since generally only the source was moved, whereas in a TRUE-CDP survey both source and detector are moved simultaneously.

In the preliminary analysis, a modified method of interpretation was used to circumvent the single-channel limitation of the Bison instrument and its lack of permanent recording. For each source-to-detector distance the waveform on the cathode ray tube was manually recorded by plotting the position of individual peaks and troughs against time. With the data corrected for NMO (normal moveout), reflections from particular horizons would be recorded at particular times and show up as diagonal alignments across the graph at angles dependent on their velocity. An example of this data is shown in Figure 55 where a reflection is indicated at 74 milliseconds and extraneous signals are depicted by diagonal alignments.

A summary of the preliminary reflection results is shown in Table VI for the areas outlined in Figures 44-48. In the table the estimated depths to top of mine are only approximate as they are based on available map information. Although it was not always possible due to surface complications, an effort was made to work above the shallowest stopes. There are probable reflections from mine cavities in the areas of Dober-Isabella, Mineral Hills-Davidson and Spies-

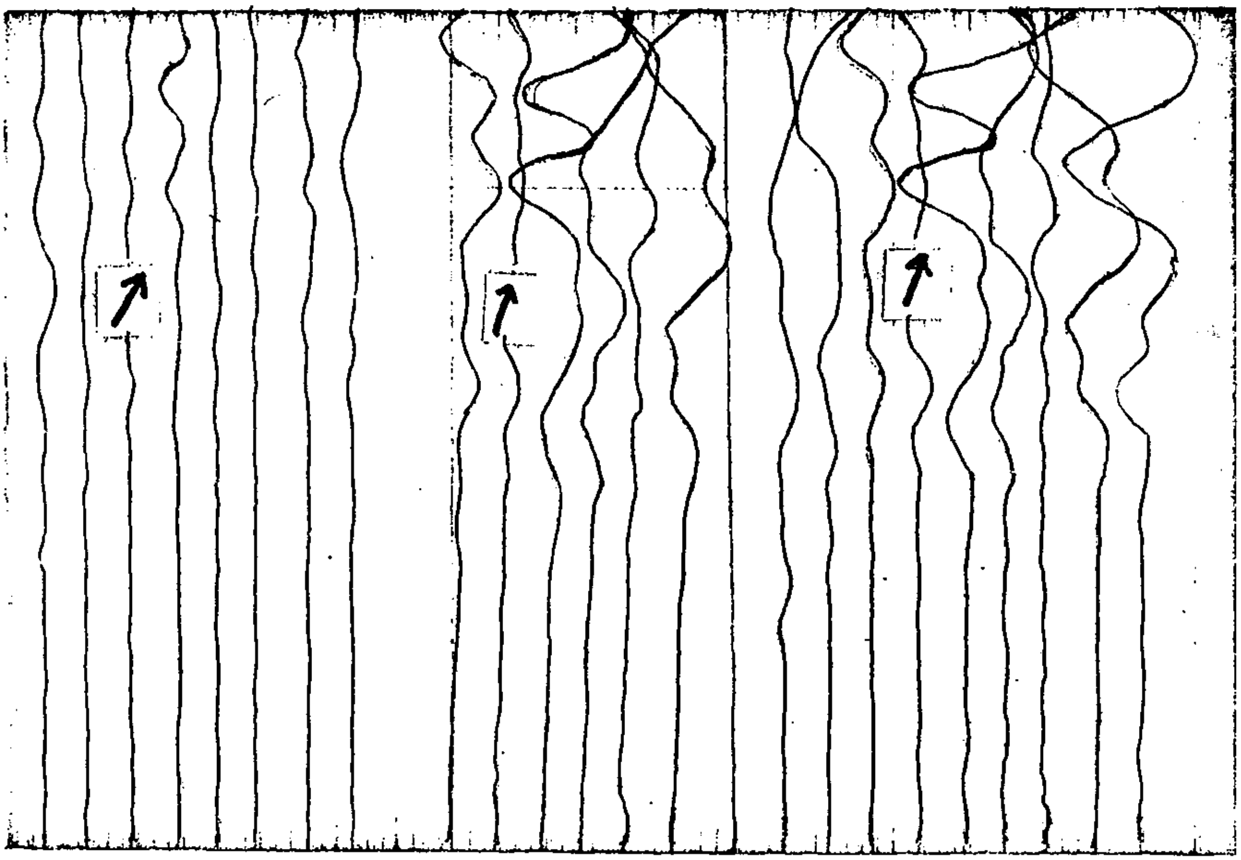


Figure 55. Photocopies of Three Reflection Records for the Dober-Isabella Area Showing the Enhancement of a Stope Reflection, Depicted by Arrows, as Repeat Hammer Blows are Summed (from a to c).

Table VI

Summary of Preliminary Reflection Measurements
Made With the Bison Seismograph

Area	T	D_c	D_b	D_m	Comments
(1) Young-Buck (500' N)	52	139	49	200	Possible reflection from fractured rock above stope
(2) Dober-Isabella (Refraction Shot #3)	125	480	22	400	Reflection questionable due to excess depth for thumper source
Dober-Isabella (Old RR tracks)	75	264	19	200	Probable reflection from mine cavity
(3) Delta (Memorial)	97	293	50	200	Questionable reflection - possible multiple
(4) Homer-Cardiff	97	146	140	500	Reflection is probably from bedrock
(5) Mineral Hills-Davidson	80	265	75	350	Probable reflection from mine cavity
(6) Spies-Johnson	55	102	102	200	Bedrock reflection
	95	286	102	200	Probable mine reflection

T = reflection time in milliseconds
D_c = depth determined from reflection time in feet
D_b = depth to bedrock from refraction survey in feet
D_m = estimated depth to top of mine in feet

Johnson and possible stope reflections at the Delta and Young-Buck sites.

In the final investigation of the reflection method, the Nimbus seismograph was used at seven sites previously described and shown in Figures 49-53. Greater versatility in data handling and array configurations is possible with this 12-channel instrument. Experiments to optimize these parameters were conducted primarily at the earliest sites studied. At mine depths greater than about 275 feet, explosives were needed to strengthen the seismic source, which made the field work progress more slowly. Permanent records of field measurements made it possible to perform additional treatment of data in the laboratory. The results are summarized by area in Table VII. The earth model for each area is determined from initial refraction surveying. The parameters in Table VII are described as follows:

V_1 = velocity of layer 1 in ft/sec

V_2 = velocity of layer 2 in ft/sec

V_b = velocity of upper bedrock in ft/sec

D_1 = thickness of layer 1 in ft

D_2 = thickness of layer 2 in ft

T_1 = 2-way travel time to the base of layer 1 in milliseconds

T_2 = 2-way travel time to the base of layer 2 in milliseconds

T = 2-way travel time to the top of the stope of indicated depth

Estimated depth = distance in ft to the stope as determined from mine maps

Estimated time = reflection time in milliseconds for estimated depth

Measured time = reflection time in milliseconds from seismograms

Calculated depth = distance in ft to stope based on the measured time

In presenting the data shown in Table VII, we have not included several

Table VII

Summary of the Reflection Data Obtained in Seven Areas with the Nimbus Seismograph

(1) Young-Buck

Earth Model: V_1 = 1200 T_1 = 17
V_2 = 2500 T_2 = 24
V_b = 8500 T = 56 (stope at 160')
D_1 = 7 T = 63 (stope at 190')
D_2 = 17

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
1	poor	ES 14	stope	160	56	57/60	170/178
1	fair	ES 14	?			75	242
2	none						
3	poor	ES 16	stope	190	63	65	199
4	poor	ES 12	?			68	212
5	none						

(2) Dober-Isabella

Earth Model (lines 3,4,6):

V_1 = 1450 T_1 = 12
V_2 = 3800 T_2 = 27/24
V_b = 17,700 T = 43 (stope at 195')
D_1 = 7.1 T = 77 (stope at 495')
D_2 = 28.2/21.9

Earth Model (lines 2,7):

V_1 = 700 T_1 = 19
V_2 = 4400 T_2 = 40
V_b = 14,400 T = 129 (stope at 695')
D_1 = 6.7
D_2 = 45.7

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
2	none						
3	good	ES 16	stope	495	77	61/67	358/410
3	fair	ES 16	stope multiple			109	778
4	poor	ES 14	stope multiple			120/125	875/964
6	good	several	stope	195	43	40/48	168/239
6	good	several	interbed multiple			65	
6	good	several	deeper stope			75/70	439/371
7	poor	ES 80	stope	695	129	110	556

Table VII (cont.)

(3) Hiawatha

Earth Model (line 6):

V_1 = 1660 T_1 = 3
V_2 = 6700 T_2 = 15
V_b = 9000 T = 394 (stope at 1750')
D_1 = 2.6
D_2 = 40

Earth Model (lines 1,3,4):

V_1 = 625 T_1 = 7
V_2 = 2100 T_2 = 18
V_3 = 4800 T_3 = 30
V_b = 8700 T = 96 (stope at 330')
D_1 = 2.3
D_2 = 11.4
D_3 = 29.3

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
1	good	4	dipping stope	330	96	75/90	239/304
1	good	4	bedrock multiple		60	56/66	
3	fair	3	dipping stope	330	96	85/100	282/347
3	fair	3	?			120/125	444/466
4	none						

(4) Delta

Earth Model: V_1 = 1700 T_1 = 28
V_2 = 5200 T_2 = 40/47
V_b = 8000 T = 73 (stope at 180')
D_1 = 16.9 T = 86 (stope at 230')
D_2 = 27.6/45.9

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
1	good	ES 24	bedrock	44	40	44	58.6
1	fair	ES 26	stope	230	88	98	275
1	good	ES 28	stope multiple		146	152	
2	fair	ES 24-2	stope	230	86	90	244
2	poor	ES 20-2	?			120/129	364/400
3	fair	several	stope	180	73	76	192
3	good	several	?			125	375
4	good	ES 10	bedrock	44	40	39/46	44/64

Table VII (cont.)

(5) Cardiff

Earth Model (lines 3,4):

V_1 = 1600 T_1 = 44
V_2 = 4050 T_2 = 88
V_b = 8750 $\bar{T}$ = 237 (stope at 775')
D_1 = 33.9
D_2 = 92.3

Earth Model (lines 1,2):

V_1 = 1400 T_1 = 7
V_2 = 4200 T_2 = 54/50
V_b = 8750 $\bar{T}$ = 159 (stope at 570')
D_1 = 8.7
D_2 = 102/90.5

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
1	poor	2	dipping stope	570	159	150/185	532/685
2	poor	3	Riverton Iron Fr.	500	143	130/185	445/635
3	none						
4	none						

(6) Homer-Wauseca

Earth Model: V_1 = 900 T_1 = 9
V_2 = 2200 T_2 = 26
V_3 = 3600 T_3 = 74/90
V_b = 8500 $\bar{T}$ = 426 (stope at 1570')
D_1 = 5.3
D_2 = 18.5
D_3 = 85.7/114.6

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
1	none						
2	poor	2	?			205/212	624/662
3	fair	3	bedrock multiple		180	190	
3	fair	3	?			246	799

Table VII (cont.)

(7) Baker

Earth Model: $V_1 = 1380$ $T_1 = 5$
$V_2 = 2300$ $T_2 = 16$
$V_3 = 3900$ $T_3 = 32$
$V_4 = 5300$ $T_4 = 48$
$V_b = 9300$ $T = 88$ (stope at 281')
$D_1 = 6.9$
$D_2 = 12.3$
$D_3 = 30.8$
$D_4 = 43.2$

Line Number	Event Quality	Record Number	Reflection Target	Estimated Depth	Estimated Time	Measured Time	Calculated Depth
2	fair	ES 14	bedrock multiple		96	92	
3	good	ES 16	stope	281	88	70	232
4	fair	ES 26	stope	281	88	68/70	214/232

bedrock reflection measurements since these were not the prime target of the reflection study. As a general rule, the reflection records must be described as being noisy, as indicated by the two sample records shown in Figures 56 and 57. This results from two principle causes. First, the total spread length on the surface had to be kept reasonably short since rather small targets were being sought. Thus the geophones continue to "ring" from surface waves when the reflection events are arriving from depth. Second, complex geologic layering in the areas also gives rise to reflections and to multiples (signals which bounce back and forth between boundaries before being recorded) which add to the recorded waveform forming complex patterns. However, it does appear that reflections from certain mine cavities were recorded.

In the Young-Buck area, reflections were probably recognized from two old stopes at depths within ±10% of the estimated position. These are in an area that has been closed to public use.

In the Dober-Isabella area, reflections were quite likely received from three old stopes south of the Isabella shaft area along 19th Street. The calculated depths range from 168 to 556 feet and are shallower than the estimated depths based on old mine maps.

Along the west side of highway M-189 just north of the 19th Street junction, reflections are indicated from two dipping stopes of the Hiawatha Mine. The reflection depths, ranging from 239 to 347 feet, compare with 330 feet as determined from mine maps.

In the critical area south of Genesee Street near the old Memorial, reflections appear to be recognized from three stope locations in the Delta Mine with depths within ±15% of the estimated positions from maps.

In the Cardiff area measurements were carried out on the west side of 16th

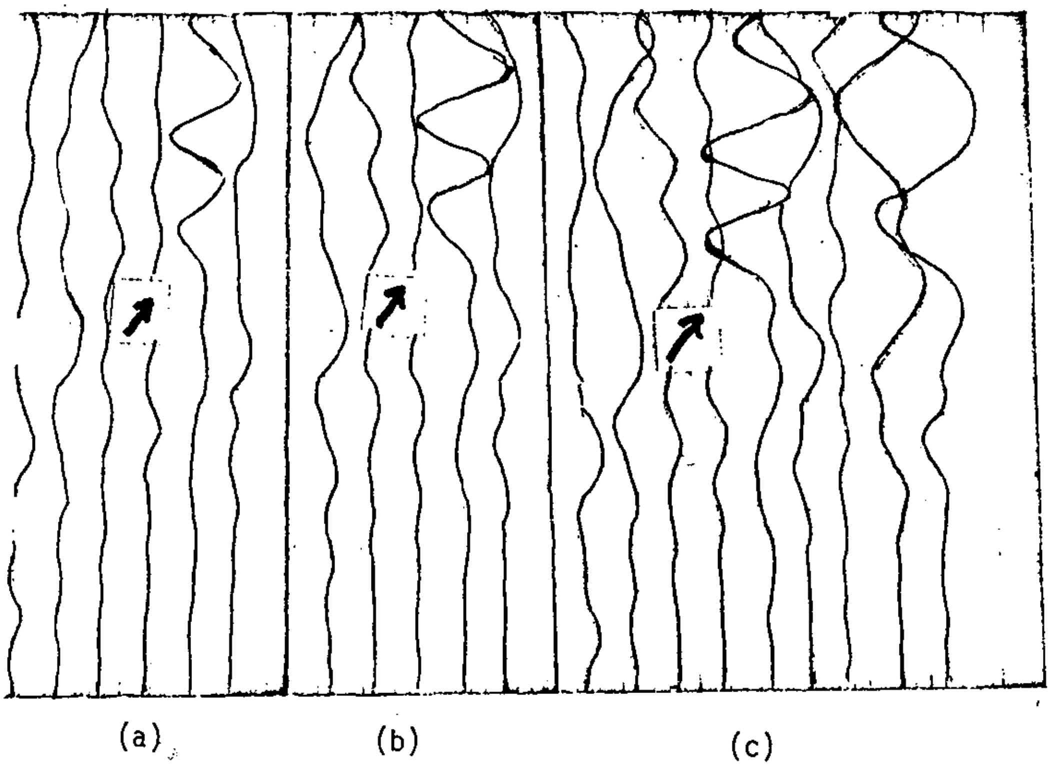


Figure 56. Photocopies of Three Reflection Records for the Hiawatha Mine Showing the Enhancement of a Stope Reflection, Depicted by Arrows, as Repeat Hammer Blows are Summed (from a to c).

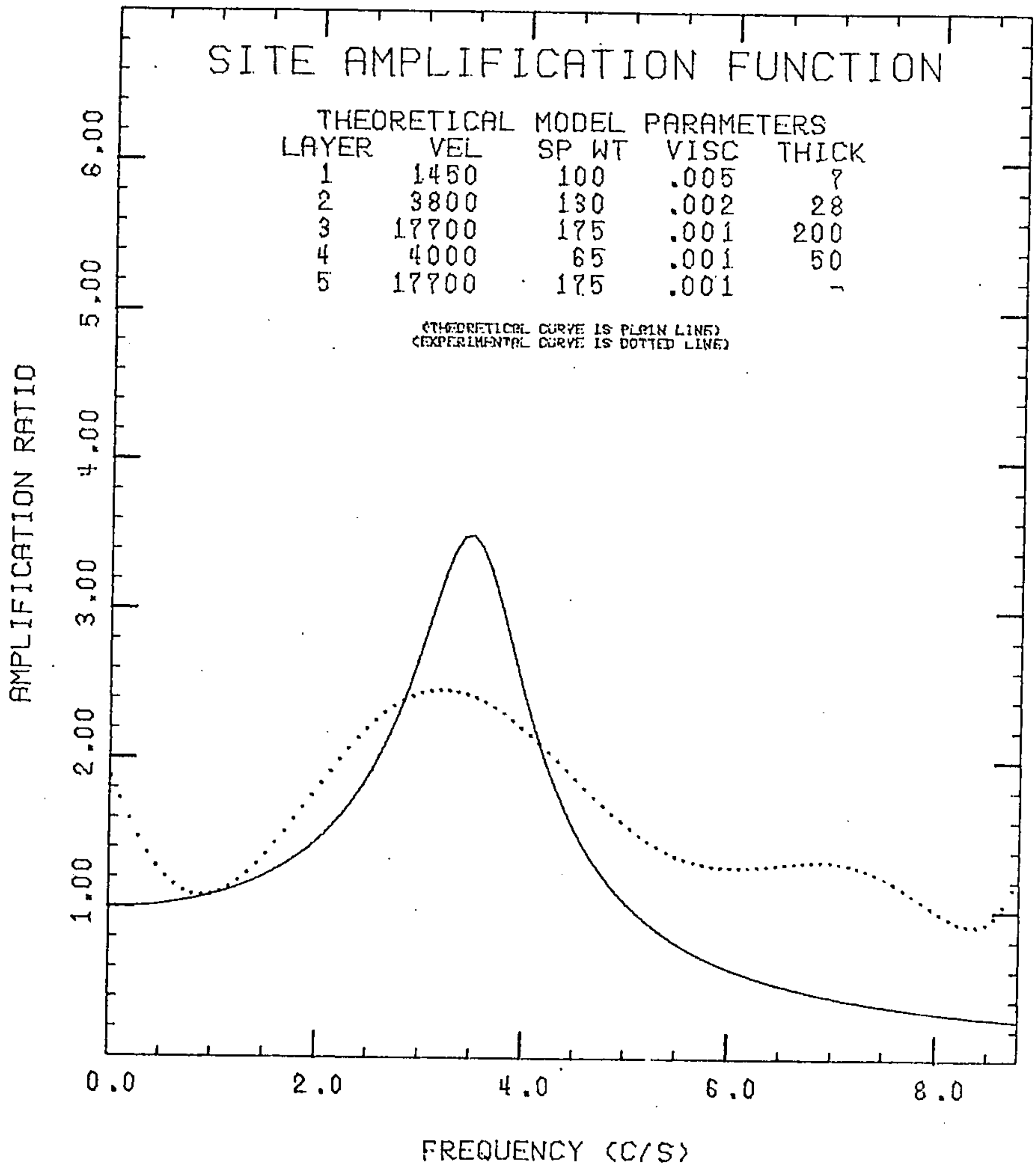


Figure 57. A Sample of the Computer Printout of the Theoretical (solid line) and Actual Field (dotted line) Amplification Ratios for P-waves Resulting from a Field Model of Four Layers Over a Half Space. British engineering units.

Street just north of Mineral Avenue which indicate stope depths approximately 10% less than the map predictions.

Along the east side of 16th Street south of Mineral Avenue, two possible reflections were picked up near the Homer-Wauseca complex with measured depths greater than 600 feet.

In the Baker area measurements were made near the northeast corner of section 1 just southeast of the corner of the main road. Here two probable reflections were recognized from old stopes which measure 50 feet shallower than the mapped depth of 281 feet.

Unfortunately there is no location in the district where the present configuration of an old stope is sufficiently defined so that the site could be used for "calibrating" the reflection system. Thus it is not possible to ascertain the reliability of reflection depth-estimates. A bore hole in one or more of the surveyed areas is needed to certify the current position of the back of the old stopes.

REFERENCES

Bingham, Michael (1978), Personal communication.

Brown, J. W. and Singh, M. M. (1966), "An Investigation of Microseismic Activity in Rock Under Tension", Trans. Soc. of Mng. Eng., V. 235, pp. 255-265.

Cook, John C. (1965), "Seismic Mapping of Underground Cavities Using Reflection Amplitudes", Geophysics, V. XXX, No. 4, pp. 527-538.

Frantti, G. E. (1975), "Seismissions and Surface Waves Related to Geologic Structures", Proceedings, Conference on Microseismic and Acoustic Emissions, Penn. State Univ., June 9-11.

Gibbons, M. G. (1975), "Low Frequency Microseismic Investigation of Roof Stability in the White Pine Mine", Michigan Technological University, M.S. Thesis.

Johnson, Allan M. and Frantti, Gordon (1976), "Study of Mine Subsidence and Acid Water Drainage in the Iron River Valley, Iron County, Michigan", Michigan Technological University, Institute of Mineral Research, IMR Report R-250.

Johnson, Donald W. (1977), "Geological Investigations of Subsidence in Mines Near Iron River, Michigan", Dept. of Geol. & Geol. Eng., Michigan Technological University, M.S. Thesis.

Lepper, C. Melvin and Ruskey, Frank (1976), "High-Resolution Seismic Reflection Techniques for Mapping Coal Seams from the Surface", U.S. Bureau of Mines, TPR 101.

Obert, L. and Duvall, W. (1945), "Microseismic Method of Predicting Rock Failure in Underground Mining, Part I, General Methods", U.S. Bureau of Mines, R.I. 3979.

Pardini, Anthony C. (1978), "An Investigation of Mine Subsidence in the Iron River Area of Michigan Using Shallow Seismic Reflection Techniques", Independent Study Report, Dept. of Geol. & Geol. Eng., Michigan Technological University.

Rykunov, L. N. and Tkhukh, F. V. (1972), "A Study of the Affect of Local Heterogeneities on the Rayleigh Wave Field", Izvestya, Physics of the Solid Earth, No. 5, pp. 65-71.

Scholtz, C. H. (1968), "The Low-Magnitude Relation of Micro-Fracturing in Rock and its Relation to Earthquakes", B.S.S.A., V. 58, No. 1, pp. 399-415.

Talwani, Manik and Ewing, Maurice (1960), "Rapid Computation of Gravitational Attraction of Three-Dimensional Bodies of Arbitrary Shape", Geophysics, V. XXV, No. 1, pp. 203-225.

Turpening, Roger M. (1976), "Cavity Detection by Means of Seismic Shear and Compressional Wave Refraction Techniques", Environmental Research Institute of Michigan, Report 116400-1-F, Contract E(29-2)-3614, Ann Arbor, Michigan.

Vongpaisal, Somchet (1973), "Prediction of Subsidence Resulting from Mining Operations", Ph.D. Thesis, Dept. of Mng. & Mt. Eng., McGill University.

Wyble, C. O. (1950), "A Study of the Regional Gravity of the Southwestern End of the Iron River District, Iron River, Michigan", Michigan College of Mining & Technology, M.S. Thesis.

ACID WATERS

Acid water drainage has been a pollution problem in the Iron River District since the mines were opened. When many mines were operating, acid waters pumped from them caused the Iron River to run red. In more recent years as mines closed and pumping ceased acid water drainage abated. 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, 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 level - 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 fill around mine workings came into direct contact with the elevated ground waters and acid waters issued from this source too.

At the Dober Mine, rising waters were more than a pollution problem. An iron sewer line feeding the Stambaugh sewage plant to the south was corroded by the acid waters. The acid entered the line and severely upset the sewage treatment process. At the same time concern was expressed for the safety of the Stambaugh plant regarding the effect of acid water on its concrete substructure.

Upon recommendation by Jack Van Alstine of the Geological Survey Division and Joseph Bal of the Water Quality Division, Department of Natural Resources, several steps were taken to solve the immediate problems. A drainage ditch cut from the Dober pit to the Iron River lowered water levels around the sewage plant and plastic pipe inserted into the corroded sewer line solved that problem. However, acid waters continued to flow into the Iron River.

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 Water Quality Division show that trout and other fish and aquatic organisms can and do live in the clouded waters. However, several local residents stated that the flesh of the trout is not good to eat. Too, 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 extremely fine precipitates are 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 boundary between Michigan and Wisconsin. It is also the northern border of the 650,000 acre Nicolet National Forest. A 1974 report issued by Nicolet National Forest personnel documents the pollution by chemical analysis and by low level, colored aerial photography (Hunt, 1974).

Background

Acid drainage is a common occurrence in Appalachian coal mines. Sulfide minerals, notably pyrite and marcasite (FeS_2) are closely associated with the coal. Oxidation of the sulfides in the presence of air and water produces sulfuric acid and soluble ferrous sulfate:

Dunn Creek slate. Actually, the Wauseca member can be considered to be similar to a metamorphosed low grade Precambrian coal (Tyler, et.al., 1957). As in Appalachian occurrences, oxidation of the extremely fine-grained pyrite in the Wauseca member upon exposure to air and moisture produces acid and dissolves iron. Thus, although the setting of the two occurrences is different, pyrite oxidation and resulting acid drainage are similar.

Oxidation of the pyrite can be extremely rapid, even to the point where fires occur. Fires were very common in the mines of the Iron River District when black slates were exposed in mining. Spontaneous combustion of surface piles of black slate also occurred on mine dumps. Even drill cores of the pyrite-bearing slate oxidized rapidly. After a few years of storage, originally solid cores were reduced to a loose mass of black and white powder (James, et.al., 1968).

Numerous studies of pyrite oxidation have elucidated the most significant factors affecting acid production (Smith and Shumate, 1970; Shumate, et.al., 1971). They are:

1. Pyrite is the most important mineralogical form of FeS_2 in acid production.
2. Specific surface of the pyrite material available for oxidation is important.
3. Factors important to the rate of pyrite oxidation in nature are: a) higher temperatures, b) increased oxygen concentration, c) higher surface area of pyrite, d) presence of iron oxidizing bacteria, and e) concentrations of dissolved ions including sulfate and ferrous and ferric iron.

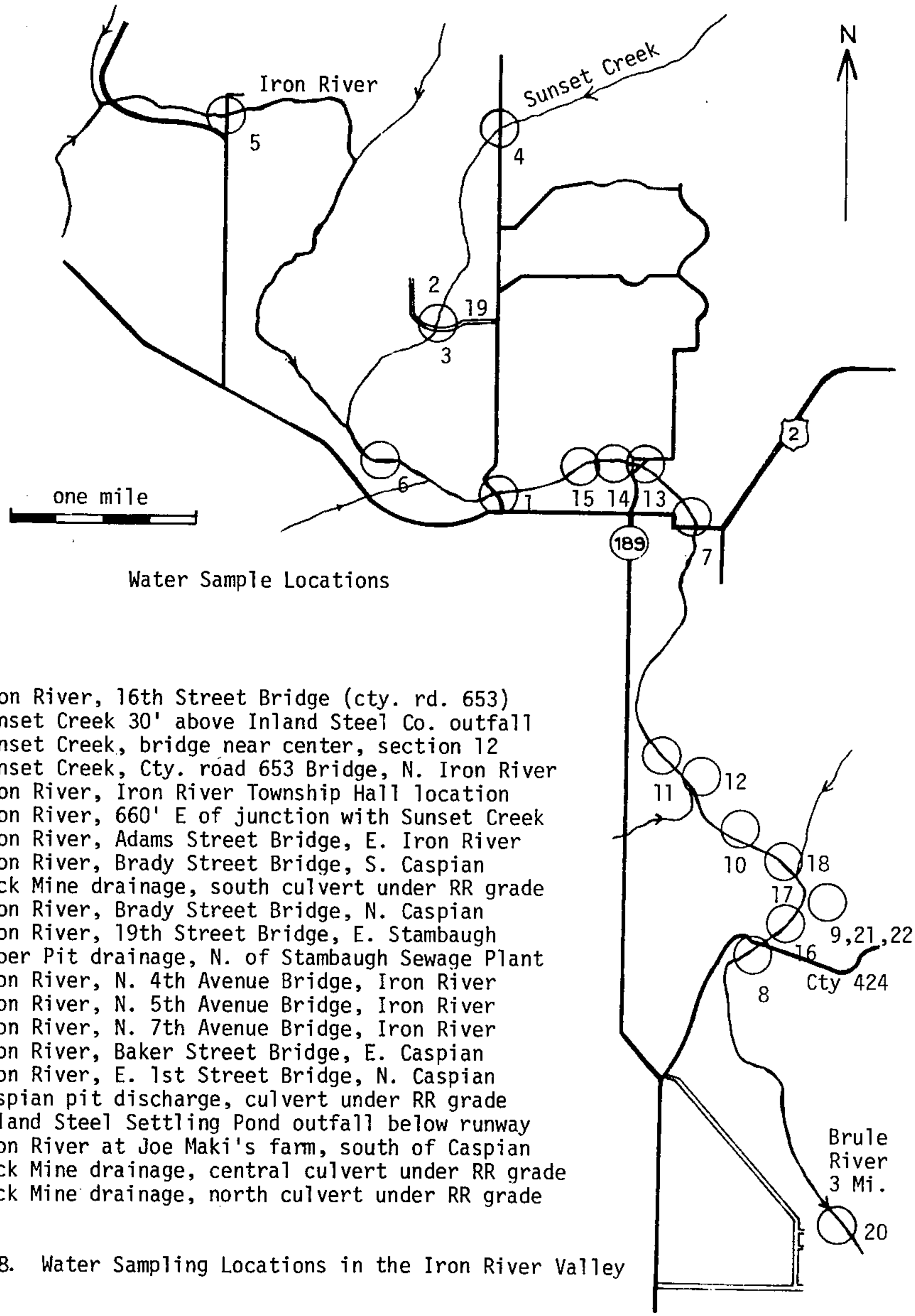
Acid waters also attack and dissolve other minerals. High concentrations of manganese, magnesium, calcium, sodium and other elements can occur. If minerals containing the more toxic elements such as arsenic, cadmium and mercury are present, they pose an added threat.

Periodic Water Sampling and Analysis

Periodic sampling and analysis of waters from the Iron River, its tributaries and acid drainage sources was initiated early in the project. This work was continued through 1976 and 1977. The purpose of this work was to identify the sources and magnitudes of the acid drainage entering the Iron River. This was largely accomplished during the 1975 and early 1976 period and the data was presented in the 1976 status report (Johnson and Frantti, 1976). The original network of 17 sample sites was expanded to 19 when two more acid drainage channels were discovered on the Buck Mine Group property in 1976. Sampling from these 19 sites was continued to confirm the earlier results and to assess seasonal effects over a longer period of time. The locations of the sample sites are shown in Figure 58.

Two water samples were collected at each location and stored in 500 ml polyethylene jars. The sample to be used for chemical analysis in the lab was acidified with 2.5 ml of nitric acid to keep dissolved solids in solution. The other sample was immediately checked for temperature, specific conductance and pH, the remainder being kept for acidity titrations. During summer months, acidity samples were kept on ice in an insulated cooler until they could be run in the lab. Acidity was determined by titrating to a phenolphthalein endpoint with a standard NaOH solution. Acidity values are represented as the milligrams of $CaCO_3$ to neutralize the acid. Iron, manganese and sulfate were also analyzed in the lab; aluminum was run on the more acid samples.

Findings. Results of analyses run on waters collected from the Iron River



Water Sample Locations

Sample No.	
1	Iron River, 16th Street Bridge (cty. rd. 653)
2	Sunset Creek 30' above Inland Steel Co. outfall
3	Sunset Creek, bridge near center, section 12
4	Sunset Creek, Cty. road 653 Bridge, N. Iron River
5	Iron River, Iron River Township Hall location
6	Iron River, 660' E of junction with Sunset Creek
7	Iron River, Adams Street Bridge, E. Iron River
8	Iron River, Brady Street Bridge, S. Caspian
9	Buck Mine drainage, south culvert under RR grade
10	Iron River, Brady Street Bridge, N. Caspian
11	Iron River, 19th Street Bridge, E. Stambaugh
12	Dober Pit drainage, N. of Stambaugh Sewage Plant
13	Iron River, N. 4th Avenue Bridge, Iron River
14	Iron River, N. 5th Avenue Bridge, Iron River
15	Iron River, N. 7th Avenue Bridge, Iron River
16	Iron River, Baker Street Bridge, E. Caspian
17	Iron River, E. 1st Street Bridge, N. Caspian
18	Caspian pit discharge, culvert under RR grade
19	Inland Steel Settling Pond outfall below runway
20	Iron River at Joe Maki's farm, south of Caspian
21	Buck Mine drainage, central culvert under RR grade
22	Buck Mine drainage, north culvert under RR grade

Figure 58. Water Sampling Locations in the Iron River Valley

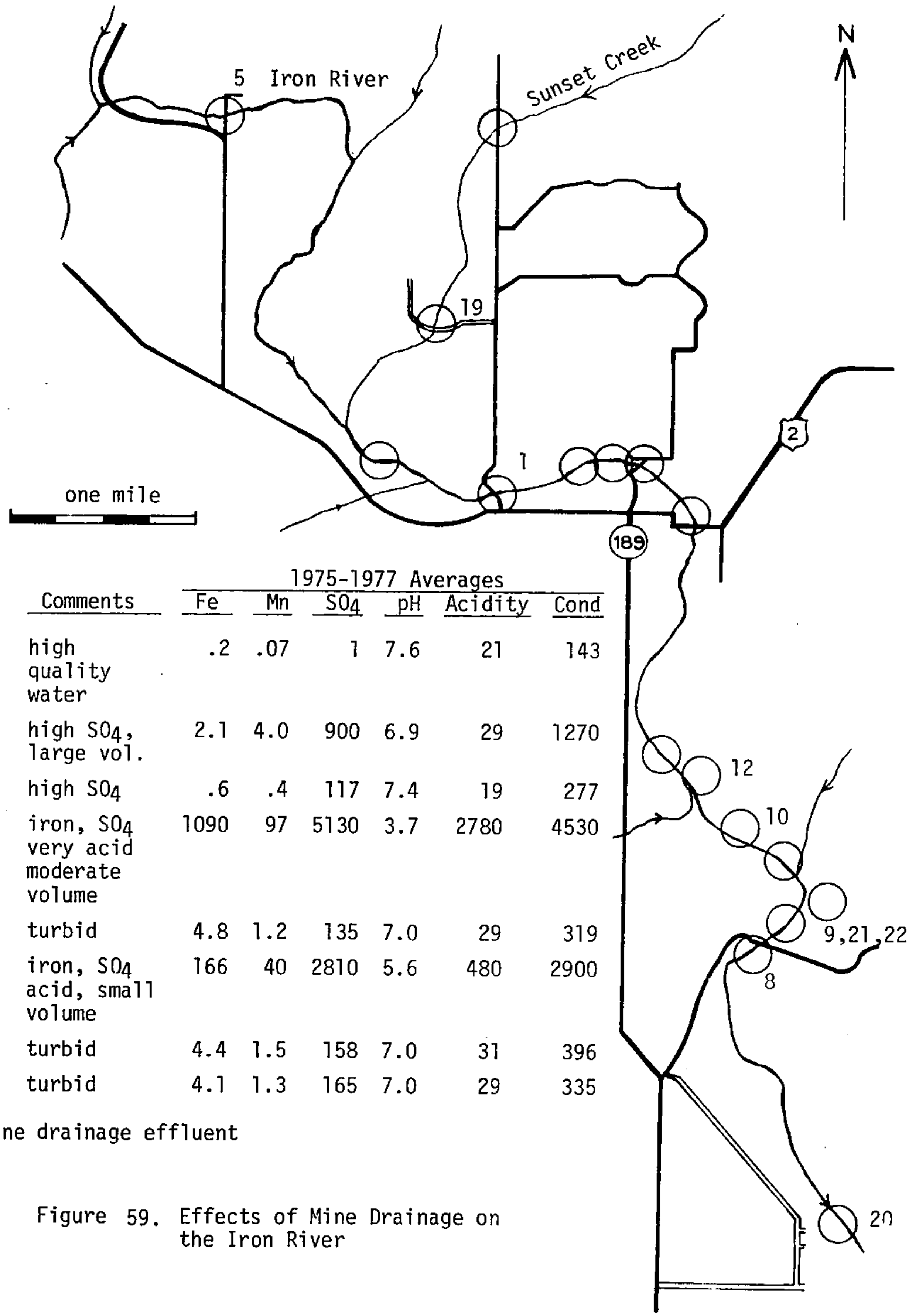
and its tributaries throughout 1976 and 1977 are tabulated in Tables A-4 - A-10 in the Appendix. The yearly average for 1975 is also included. Comparisons of these values with corresponding sample locations (Figure 58) show quite markedly the effects of acid drainage on Iron River waters.

Sample #5 (Figure 58), the control point sample, collected from the bridge just north of the Iron River Township Hall is low in dissolved solids and low in conductivity. This sample represents Iron River waters before contamination by acid water and sewage effluents. Samples taken downstream from this location are not so pristine. Below the confluence of Sunset Creek at location #6 (Figure 58) dissolved solids become higher, although the river remains clear. Overflow from the series of settling ponds maintained by the Sherwood Mine, although lowered in iron and manganese, retains high sulfate levels. These are reflected by higher specific conductance values. Aside from chlorinated sewage wastes from the City of Iron River, no further changes in the quality of the waters takes place until the river flows through the Dober-Hiawatha Mine location west and south of Stambaugh.

Just below the 19th Street bridge (sample point #11, Figure 58) acid waters from the flooded Dober Mine on the east bank drain into the Iron River. Samples of this drainage (#12) establish it as the worst acid drainage pollution in the Iron River valley. Reference to Tables A-4 - A-10 (Appendix) show this drainage to be highly acid and to contain large quantities of dissolved solids, iron, manganese, aluminum and sulfate. The effect on the Iron River is instantaneous. At the point the water enters the Iron River a plume of insoluble iron and aluminum hydroxides ("yellow-boy") discolors the waters along the east bank as the drainage is swept into the current. In only a relatively short distance the acid waters are mixed completely with the river water making the river cloudy with suspended "yellow-boy". Farther downstream, just east of Caspian, more acid water from the Buck group of properties enters the river. This drainage (Samples 9, 21 and 22), although acid, is not as concentrated as that from the Dober Mine and it has a less noticeable effect on the Iron River. No other occurrences of acid drainage into the river were found.

At the County Road 424 bridge south of Caspian, the last road bridge in Michigan over the Iron River, waters of the Iron River are noticeably degraded. Colloidal precipitates of "yellow-boy" cloud the water with a yellow-brown suspension. Submerged rocks and aquatic vegetation are coated with a yellow-brown sludge and high water marks on the concrete bridge abutment are clearly marked with an ocherous line. A few miles south these turbid waters enter the Brule River which serves as the Wisconsin-Michigan border. Pollution of the Brule River by the Iron River has been documented by a report published at the Nicolet National Forest Headquarters in Rhinelander (Hunt, 1974). As was pointed out in this report, the effects of the acid drainage are more-or-less limited to problems with the finely divided precipitates which discolor the waters and coat submerged objects. Iron River waters have sufficient natural buffering capacity to neutralize the acid quite rapidly. This is confirmed by the near neutral pH's recorded downstream from the acid drainage. However, the average pH value for the years 1975 to 1977 upstream from the Dober Mine are about a half a pH-unit higher than those downstream (7.5 above versus 7.0 below) so there is a slight lowering of pH (Table A-4, Appendix). Similarly, acidities, conductivities and dissolved solids contents are higher downstream below the drainages than upstream.

This description of degradation of the Iron River in its course through the mining district may be quantified by reference to Figure 59 in which average water analyses made during the period 1975-1977 recorded for key points along



Sample #	Comments	1975-1977 Averages					
		Fe	Mn	SO_4	pH	Acidity	Cond
5	high quality water	.2	.07	1	7.6	21	143
19*	high SO_4, large vol.	2.1	4.0	900	6.9	29	1270
1	high SO_4	.6	.4	117	7.4	19	277
12*	iron, SO_4 very acid moderate volume	1090	97	5130	3.7	2780	4530
10	turbid	4.8	1.2	135	7.0	29	319
9*	iron, SO_4 acid, small volume	166	40	2810	5.6	480	2900
8	turbid	4.4	1.5	158	7.0	31	396
20	turbid	4.1	1.3	165	7.0	29	335

*mine drainage effluent

Figure 59. Effects of Mine Drainage on the Iron River

the Iron River are summarized.

Mine Drainage - Quantitative Effects

Using flow rates from drainages and analyses of the waters, amounts of iron, manganese and sulfate entering the Iron River were calculated. Yearly averages of elemental concentration were taken from Tables A-7, A-8 and A-9 (Appendix) and the flow rates were from field measurements taken throughout the year. Each of the drainages contributing dissolved solids to the Iron River is covered in turn from upstream to downstream.

Inland's outfall. Overflow from settling ponds installed by Inland Steel Co. at its Sherwood Mine was sampled just below the weir before it empties into Sunset Creek. Sherwood Mine pumps an average of 9.2 million gallons of water a day from its operations[1]. Of this, approximately one sixth is water pumped from the Sherwood and adjacent Homer-Wauseca Mines. These mineralized waters are mixed with ground waters pumped from three relatively shallow surface wells. These wells dewater the overburden, greatly lowering the amount of acid water that would otherwise be pumped from the mine. The mixed waters flow westerly into holding ponds installed by Inland Steel Company. Retention time in the two series-connected ponds promotes oxidation of the iron and neutralization of the waters by mixing and exposure to air. Water from the second pond draining into Sunset Creek meets effluent standards of the State of Michigan and the Federal Environmental Protection Agency.

Total solids in pounds per day for 1975 were calculated to be:

---

(1) Telephone communication with B. Caverson, Engineer, Sherwood Mine, April, 1976.

Total Solids	Yearly Average mg/l	#/day
Iron	1.97	151
Manganese	3.87	297
Sulfate	898	69,000

The total amount of sulfate and manganese entering the Iron River for the years 1975 through 1977 are essentially the same as the 1975 measurements. The average total iron content was somewhat higher than the 1.97 mg/l average in 1975; to 2.17 mg/l in 1976 and 2.57 mg/l in 1977 for a three year average of 2.14 mg/l. The higher iron concentrations do not proportionately reflect higher quantities entering the Iron River, however, as 1976-1977 were dry years and lesser volumes of water were pumped during the dry periods.

With the cessation of mining operations at the Sherwood Mine scheduled for mid-July of 1978, flow from this source will stop.

Dober Mine drainage. In 1975 using an average flow rate of 120 gpm from the Dober Mine pit, the following amounts of dissolved solids were calculated to flow into the Iron River each day:

Total Solids	1975 Avg. mg/l	#/day
Iron	1125	1620
Manganese	151	217
Sulfate	5130	7410

In the initial study period flow rates of acid drainage were calculated using the float-velocity method. This method involved recording the velocity of flow with a float over a short length of channel and using the cross sectional area of the channel to compute the volume of flow. Due to irregularities in the drainage channel and approximations made in the measurements, the flow rates obtained were only approximate. Flow rates from the Dober Mine pit in 1975 ranged from a low of 90 gpm to a high of 150 gpm, depending upon season and precipitation conditions. The average value of 120 gpm may have been somewhat high, as the float velocity method favors high values. More accurate measurements of flow were desired so a V-notched weir was installed in the channel draining the Dober Mine pit in the fall of 1976. The flow through the weir was monitored periodically since that time.

Much lower values of flow were recorded from the V-notched weir installation in late 1976 and early 1977 compared to the 1975 measurements. These lower flow rates are attributed to the extended drought through this period. Freezing conditions further restricted flow rates during the winter of 1976-1977. Even with more normal precipitation conditions in the spring of 1977, ground water tables were lowered and flows were not back to normal. Calculated amounts of iron entering the Iron River, based on flow rates and chemical analyses from the Dober Mine drainage in late 1976 and 1977, are as follows:

Date	Flow (gpm)	Iron (mg/l)	Total Iron (#/day)
Nov. 10, 1976	31	1310	480
Feb. 2, 1977	20*	820	197
Mar. 10, 1977	20*	143	34
Oct. 25, 1977	45*	1160	625

*Estimated flow rates

An estimation of flow rate was necessary several times because of waters by-passing the weir dam through the angular and porous rock debris lining the Dober drainage ditch, or because of waters back up from beaver dams downstream on the Iron River, and finally because of corrosion of the steel weir plate by the acid (Oct. 25, 1977 reading).

Some of the very low values of iron are due to dilution by fresh surface waters, either runoff or backed-up river waters. With water tables rising to more normal levels, acid flow from the Dober Mine pit should approach predrought amounts.

Amounts of iron, manganese and sulfate entering the Iron River from the Dober Mine pit in pounds per day based on averages for 1975 through 1977 and a 50 gpm flow rate are:

Dissolved Solid	3-Year Average mg/l	#/day
Iron	1090	654
Manganese	97	58
Sulfate	4860	2918

Buck Mine group acid drainage. With the float-velocity method, an average flow rate of acid drainage from the Buck Mine area in 1975 was about 25 gpm, although during spring runoff flow was in excess of 100 gpm. Using the 25 gpm figure, the following weights of iron, manganese and sulfate were calculated to flow into the Iron River in 1975:

Total Solids	Yearly Avg. mg/l	#/day
Iron	186	56
Manganese	46	14
Sulfate	2810	843

More detailed work on the Buck Group slate piles was done during the summer of 1976. In addition to the acid drainage channel monitored throughout 1975 (site #9), two more channels were discovered to the north (#21 and #22). They flow at higher rates but have lower dissolved solids contents and are less acid than the channel designated #9. V-notched weirs were installed in the three channels during the fall of 1976. Periodic measurements of the flow rate and chemical analyses of the waters were used to calculate the amounts of dissolved iron, manganese and sulfate originating from these sources.

For the 1976-1977 period the average flow of acid drainage from the Buck Group slate piles was 441 gpm. Of this total, 54 gpm came from sample site #9, 136 gpm from sample site #21 and 251 gpm from sample site #22. Analyses show that although the flow from site #9 is lowest of the three, it is the most acid and contains the highest level of dissolved solids, averaging 120 mg/l Fe, 31.9 mg/l Mn and 2515 mg/l $SO_4^=$. The central drainage channel from the Buck Mine slate piles, #21, ranks second in concentration with average values of 15.9 mg/l Fe, 11.1 mg/l Mn and 1605 mg/l $SO_4^=$. The northernmost drainage channel (sample site #22) with the highest flow rate has the lowest concentration with average values of 6.4 mg/l Fe, 5.73 mg/l Mn and 1700 mg/l $SO_4^=$ (data from Table VIII).

Total amounts of iron, manganese and sulfate in acid waters flowing from the Buck Mine slate piles based on the 1976-1977 measurements and an average total flow rate of 441 gpm are as follows:

Dissolved Solid	#/day
Iron	117
Manganese	56
Sulfate	9750

These data are presented in more detail in the section on the Buck Mine Group and in Table VIII.

Combined Effect of Acid Drainage

The total effect of all acid and mineralized water drainages entering the Iron River is shown in Table IX as average daily amounts of iron, manganese and

Table VIII

Flow Rates and Iron, Manganese and Sulfate Concentrations of Acid Drainages from the Buck Mine Complex in 1976 and 1977

Date Sampled	Sample Site	Flow		Iron			Manganese			Sulfate		
		GPM	% of Total	mg/l	lb/day	% of Total	mg/l	lb/day	% of Total	mg/l	lb/day	% of Total
11/10/76	9	52	11.6	132	82	61.7	33.1	20.7	33.9	2500	1561	16.1
"	21	128	28.4	19.7	32	24.0	13.8	21.2	34.8	1720	2644	27.2
"	22	270	60.0	5.8	19	14.3	5.90	19.1	31.3	1700	5512	56.7
Totals	-	450	100.0	-	133	100.0	-	61.0	100.0	-	9717	100.0
2/2/77	9	58	12.6	97	68	66.7	28.6	19.9	42.1	2500	1741	17.9
"	21	145	31.5	12.1	21	20.6	8.20	14.3	30.2	1620	2821	28.9
"	22	257	55.9	4.1	13	12.7	4.24	13.1	27.7	1680	5185	53.2
Totals	-	460	100.0	-	102	100.0	-	47	100.0	-	9747	100.0
3/10/77	9	64	14.2	109	83	62.9	33.1	25.4	42.1	2420	1860	19.7
"	21	122	27.0	15.8	23	17.4	11.4	16.7	27.7	1530	2242	23.7
"	22	265	58.8	8.0	26	19.7	5.76	18.3	30.2	1680	5347	56.6
Totals	-	451	100.0	-	132	100.0	-	60	100.0	-	9449	100.0
8/18/77	9	41	10.2	142	70	70.0	32.8	16.2	30.3	2640	1300	15.3
"	21	150	37.4	16.0	14	14.0	10.8	19.5	36.5	1550	2792	32.9
"	22	210	52.4	7.8	16	16.0	7.02	17.7	33.2	1740	4388	51.8
Totals	-	401	100.0	-	100	100.0	-	53	100.0	-	8480	100.0
Averages	9	54	12.0	120	76	65.0	31.9	20.6	37.1	2515	1615	16.6
(Arithmetic)	21	136	31.0	15.9	23	19.7	11.1	17.9	32.2	1605	3028	31.1
	22	251	57.0	6.4	18	15.3	5.73	17.1	30.8	1700	5108	52.3
Total Average	-	441	100.0	-	117	100.0	-	56	100.0	-	9750	100.0

sulfate in pounds per day for the three year period, 1975 through 1977. For the three year period, on the basis of iron, the Dober Mine drainage discharged on the average 654 pounds of iron per day or 71% of the total from all sources. The remaining iron came from the Sherwood Mine (151#/day average or 16%) and the Buck Mine drainage (117#/day or 13%). Relatively greater percentages of manganese and sulfate originate from the Sherwood Mine operation than from the Dober and Buck Mines; however, these discharges do not violate federal or state effluent standards. Sherwood Mine is scheduled to stop pumping in mid-July 1978. As a result, there will no longer be any flow of mineralized water from this source.

Seasonal Effects

During the 1975 sampling period it was established that acid drainage from abandoned mine sources was at its peak during spring runoff. At this time because of the very high runoff the greatest quantities of dissolved solids are carried into the Iron River. It is true that in mid to late summer the absolute concentrations of iron, manganese and sulfate in the drainage are higher, but due to lower flow rates, the overall effect is not as great.

These observations of the harmful effects of acid drainage are based on the concentration of iron. Discoloration of the Iron River by the finely divided insoluble iron hydroxides (yellow-boy) and the coating of submerged objects by these precipitates are the result.

Trace Elements in Acid Drainage

Acid waters formed from the oxidation of pyrite may also react with other minerals. Highly acid waters can be very reactive. In addition to iron and sulfate from pyrite, the waters may dissolve and carry large quantities of other elements. If toxic elements are present in sufficient quantity, the acid drainage

Table IX

Daily Calculated Amounts and Relative Percentages
of Iron, Manganese, and Sulfate
Entering the Iron River 1975-1977

	Source			
	Inland's Outfall	Dober Mine	Buck Mine	Totals
Fe, #/day	151	654	117	922
% of total	16	71	13	100
Mn, #/day	297	58	56	411
% of total	72	14	14	100
SO_4, #/day	69000	2918	9750	81668
% of total	84	4	12	100

may present a much more serious threat than from the usual acid conditions and resulting "yellow-boy" precipitation. Consequently, a more complete analysis of elements present in acid waters entering the Iron River was desired so that this possibility could be checked.

A bulk sample of acid water (pH = 4.4) was collected from the Dober Mine pit in July 1975. It was further acidified with nitric acid to keep the ions in solution and analyses were run on a large number of elements: Al, Mn, Na, K, Sr, Ni, Cu, U, Hg, Zn, Cd, Mg, Si, Pb, Cl and P. Results of the analyses are listed in Table X.

Besides high values of sulfate and iron from the pyrite, the water also contains high concentrations of magnesium, calcium and aluminum, probably from the minerals dolomite, calcite and from aluminum-bearing clays present in the iron formation and footwall slate. Manganese no doubt comes from manganese oxides commonly associated with the iron ore. The alkaline elements sodium and potassium may be leached from clays or may be present in brines which are indicated by the presence of chlorine. Silica may also originate from the clays. Nickel, zinc, copper, lead and cadmium are present at low levels, a few parts per million or less. Minor occurrences of chalcopyrite ($CuFeS_2$), galena (PbS) and sphalerite (ZnS) account for copper, lead and zinc, respectively. Cadmium is geochemically very similar to zinc and may be present in small amounts as greenockite (CdS). Nickel minerals have not been reported from the Iron River District, but are probably present in small quantities as sulfides, as pentlandite or millerite. Surprisingly nickel was higher at 2.7 ppm than Zn, Cu or Pb for which minerals have been reported.

Uranium was found in mines of the district as uraninite (James, et.al., 1968). Uraninite is found at the basal portion of the Riverton Iron formation in the

Table X

Concentrations of Elements
in Dober Mine Acid Water

Element/ Compound	Concentration (mg/l)
SO_4	6400
Fe	1500
MgO	719
CaO	436
Al_2O_3	201
Mn	85
SiO_2	70
Cl	40
Na	20
K	10
Ni	2.7
Zn	2.0
Sr	0.7
Cu	0.6
Pb	0.05
Cd	0.02
PO4	trace
U_3O_8	<4
Hg	nil

black slates. Detectable levels of U were expected in the acid drainage because it is soluble in sulfuric acid; however, no U was indicated at a concentration of 4 ppm, the level of sensitivity of the colorometric technique used.

No mercury was detected using a sensitive atomic absorption analysis. Phosphorus was present at only trace level in solution, although phosphorus-bearing apatite is present in the ore. However, ferric iron present in high concentrations in the acid waters combines with the phosphate ion to form an insoluble precipitate.

Apparently no large quantities of toxic metals are present in the acid waters draining from the Dober Mine. For the elements analyzed this would include Pb, Cd and Hg. Arsenic was not analyzed; however, no arsenic compounds have been reported from the district.

Fate of Dissolved Solids

High concentrations of sulfate, iron and other elements are characteristic of acid drainage. These species remain in solution as long as the drainage is strongly acid. Upon neutralization, insoluble residues form. In the Iron River District neutralization takes place when acid waters mix with surface waters of the Iron River.

Upon neutralization, both iron and aluminum rapidly precipitate as hydroxides, both being extremely insoluble. Aluminum is more insoluble than iron and comes from solution first. The sulfate ion is present in very high concentration in acid drainage waters. However, it would tend to remain in solution when diluted with fresher water unless large amounts of calcium ions are present, in which case gypsum ($CaSO_4 \cdot 2H_2O$) would form. Gypsum precipitation would continue until concentrations of calcium and sulfate fall below the solubility product of gypsum.

Manganese, geochemically similar to iron, forms insoluble hydroxides; however, elevated pH's and higher oxidizing potentials are required to precipitate manganese than iron. Thus, soluble iron and aluminum concentrations are quickly lowered by precipitation in neutralized acid drainage waters, but manganese remains in solution at higher concentrations (relative to original concentration). These facts probably explain the presence of manganese nodules in Green Bay; acid drainage from the Iron River District could very well be the source. This does not imply that all of the manganese was transported since mining originated. Surface weathering of manganese-enriched iron formation has occurred for millions of years and transport into Lake Michigan, at least for thousands of years since the last glaciation. Of course, much higher levels of manganese have been released in the last hundred or so years by mining activity, than by former natural geologic processes.

Statistical Correlation of Water Analyses

The large number of analyses performed on the Iron River water samples during the term of the project suggested that some form of statistical treatment would be useful to make accurate statements and to establish levels of correlation between groups of data.

Correlation coefficients calculated for the water data can be thought of as a measure of the strength of the linear relationships between pairs of variables; the closer the coefficient is to 1.000 the more perfect is the relationship between variables. For example, acidity correlated with iron at a value of 0.962. This is a very high correlation and indicates that a good linear relationship exists between iron concentrations and acidity values. Variables for which correlation coefficients were determined included chemical analyses and the lab and field measurements. Table XI ranks pairs of variables showing a high degree of correlation in the order of their correlation for analyses run on Iron River

Table XI

Correlation Coefficients Between Selected Analysis Pairs on Iron River District Waters and Acid Drainages

Correlation	Coefficient	Variable Pair
1	.962	acidity - iron
2	.945	conductivity - sulfate
3	.956	manganese - sulfate
4	.945	manganese - iron
5	.931	conductivity - manganese
6	.925	acidity - manganese
7	.916	sulfate - iron
8	-.910	pH - sulfate
9	-.903	pH - conductivity
10	.899	acidity - aluminum
11	.893	acidity - conductivity
12	.892	aluminum - iron
13	.880	conductivity - iron
14	-.874	pH - manganese
15	-.829	pH - acidity

waters, its tributaries and acid drainages in 1975. These correlations do not occur by chance. They are significant at least at the 95% level of confidence.

The very high levels of significant correlation shown between the different analyses and measurements establishes the usefulness of the analytical techniques used to detect and monitor acid drainage in the Iron River District. If the data were divided into subpopulations, say by isolating the acid drainages from river waters, it is likely that even higher correlations would be found.

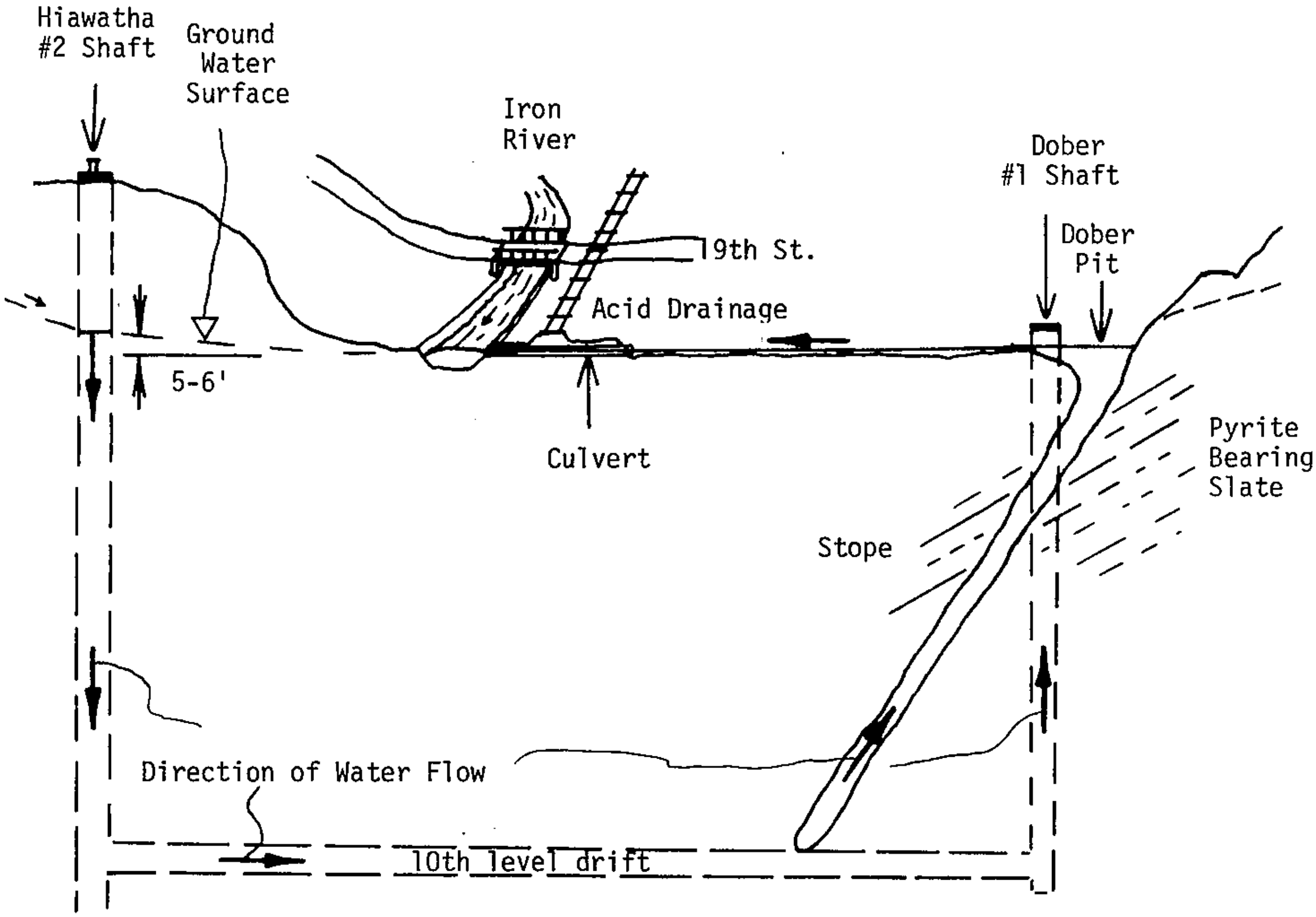
Acid Drainage from the Dober-Isabella-Hiawatha Mine Complex

Initial work established acid drainage from the Dober Mine pit to be the major source entering the Iron River from abandoned mine sources (Johnson and Frantti, 1976). On the basis of iron content it was calculated that approximately 90% of the acid entering the Iron River came from the Dober Mine. The model proposed for acid drainage involved an observed imbalance in level of the waters between the interconnected Hiawatha Mine workings on the west and the Dober Mine on the east. Fresh waters apparently recharged the Hiawatha Mine producing sufficient head differential to cause flow through the workings and resulting acid drainage from the Dober Mine pit which is collared at lower elevation in the Iron River valley. Flow from the Dober Mine pit goes directly into the Iron River.

Major evidence supporting this concept of acid drainage included: 1) the 4 to 6 foot higher elevation of waters in the Hiawatha #2 shaft over the Dober Mine pit; 2) fresh non-mineralized waters in the Hiawatha #2 shaft in at least the upper 300' compared to the Dober Mine where acid waters were present at the surface; 4) the upwelling and flowage of acid water from the Dober Mine pit. Furthermore, the flow rates of the acid drainage were of essentially the same magnitude as the reported pumping from the Hiawatha Mine when it was operating - on the order of 100 to 150 gpm. A schematic representation of this model is shown in Figure 60.

More detailed work was needed to understand the hydrologic regime in the mine complex and more specifically how acid waters were generated and moved. With this information the feasibility of correcting the acid drainage problem could be assessed. With these goals in mind a plan of study of the Dober-Isabella-Hiawatha Mine Complex was developed and begun. Since it was not possible to enter the flooded mines, the investigation involved working with available data preserved on the mine maps, obtaining information through discussions with former mine captains and superintendents and the measuring, monitoring and analysis of waters flowing from the Dober pit. In addition, sampling of mine waters from accessible mine openings, assessments of precipitation and runoff records, and field measurements over the mine complex that would affect recharge and runoff were done. These efforts and the results obtained from them are discussed in the following sections.

Deep sampling of Hiawatha #2 shaft. On June 17, 1976, waters in the ladder compartment of the vertical Hiawatha #2 shaft were sampled at 100 foot intervals to a depth of 600 feet below the water surface. On that day the water level was 37.0 feet below the concrete cap. The sampling was done with a one liter Kemmerer sampler. (The Kemmerer sampler consists of a cylindrical tube suspended on a line. Tapered stoppers at each end are tripped closed at the desired depth by dropping a weight down the line. It is the standard sampling tool to collect water samples from depth in lakes and oceans.) At 600 feet the Kemmerer sampler became wedged and was recovered with difficulty. The shaft had been sounded with a weighted line previously and a major obstruction was encountered at 1240', but



Looking North

Figure 60. Schematic Representation of Acid Drainage from the Dober-Hiawatha Mine Complex

only a minor one at 600 feet. An isometric sketch showing the relationship of the various shafts to the Dober-Hiawatha-Isabella Mine Complex is shown in Figure 60.

The water samples were analyzed for pH, specific conductance and acidity. They were found to be progressively more mineralized with depth. At 100 feet the pH was 7.2; specific conductance, 580 μmhos/cm and acidity, 100 mg $CaCO_3$/l. At a depth of 500 feet the pH was 6.6, specific conductance, 2020 μmhos/cm and the acidity, 240 mg $CaCO_3$/l. Between 500 and 600 feet a tremendous change occurred. At the 600 foot depth the pH dropped to 3.8 and the specific conductance and acidity increased to 7000 μmhos/cm and 7200 mg $CaCO_3$/l, respectively (see Table XII). These results indicated an interface between upper fresh waters and lower acid waters was somewhere between 500 and 600 feet below the water surface in the Hiawatha #2 shaft. More detailed information on the location of the acid-fresh water interface and the acid waters at depth was needed.

Subsequently the cap over the ore haulage compartment of the Hiawatha #2 shaft was penetrated with a diamond coring drill and the opening enlarged with a jack-hammer. The resulting one foot wide opening in the steel rail reinforced cap was sounded with a weighted line to a depth of over 1600 feet with no obstructions encountered.

On August 17, 1976 water samples were collected from the Hiawatha #2 shaft at 100' intervals from 500 feet to 1200 feet below the water surface level. In order to more accurately locate the acid-fresh water interface, sampling was done at 25 foot intervals between 500 and 600 feet. The original intent was to sample to 1600 feet, the line capacity on the sample hoisting device; however, the Kemmerer sampler was lost when the wire line broke in the attempt to recover the 1300 foot sample. On that day, the water level was 37.7 feet below the surface of the concrete cap.

The acid-fresh water interface was located between 525 and 550 feet below the water level in the shaft. Chemical analyses and the conductivity and pH measurements confirmed this interface. With increasing depth to 1000 feet the waters became more acid and had higher values of dissolved solids. From 1000 to 1200 feet the pH's were slightly less acid (4.0 versus 3.7) but dissolved iron and sulfate contents continued to increase to their highest value of 2080 and 8670 mg/l, respectively. All analytical data from the two days of sampling are listed in Table XII.

Comparison of the analyses of waters at 525 feet with those at 550 feet (above and below the acid-fresh water interface) showed iron to increase by a factor of 44 (38 to 1680 mg/l), and sulfate by a factor of nearly 7 times (1130 to 7290 mg/l); alumina increases many fold from a trace to 296 mg/l and manganese over two times from 43 to 94 mg/l. Much more striking is the increase in iron content; at 1200 feet water depth with an iron concentration of 2080 mg/l it is 55 times the concentration at 525 feet water depth (38 mg/l).

Penetration of Churn drill hole 2-45. Churn drill hole 2-45 is located on the Hiawatha #1 property about 300 feet southeast of the Hiawatha #1 shaft (Figure 61). This raise was formerly used for sand filling of stopes below the 7th level. A cross sectional view on a mine map shows the 30 inch diameter shaft to be vertical to the 7th level where it dog legs into the stope at a depth of about 700 feet. A small galvanized steel shed is built over the raise to which the enclosed sand fill conveyor line is attached.

Several other sand filling raises are present on the Hiawatha #1 property; however, in discussions with Mr. Reginald Raymond who was involved in the capping of shafts on the Hiawatha property, he indicated this was the only raise that

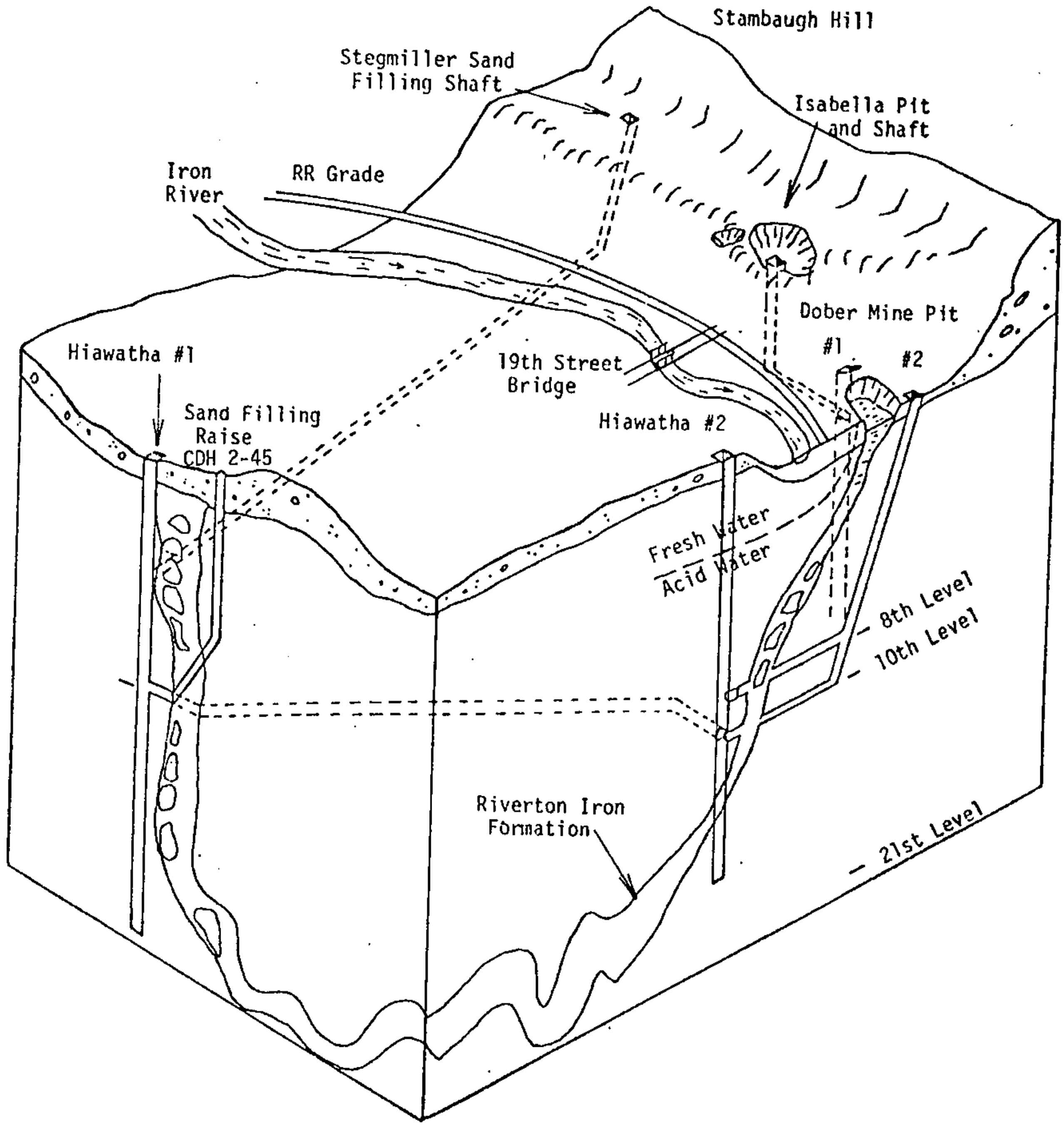


Figure 61. Isometric Sketch of the Hiawatha-Dober-Isabella Mine Complex - Looking Northeast

Table XII

Characterization of Waters in the Hiawatha #2 Shaft

Sampled	Depth (feet) Below Cap	Depth (feet) Below Water Level	pH	Specific Conductance	Acidity °C	mg/l Fe	mg/l Mn	mg/l Al_2O_3	mg/l $SO_4^=$
6/17/76	137	100	7.2	580	100	-	-	-	-
6/17/76	237	200	7.1	490	40	-	-	-	-
6/17/76	337	300	6.6	2000	200	-	-	-	-
6/17/76	387	350	6.6	2000	220	-	-	-	-
6/17/76	537	500	6.6	2020	240	-	-	-	-
6/17/76	637	600	3.8	7000	7200	-	-	-	-
8/17/76	563	525	6.7	1600		38	43	tr.	1130
8/17/76	588	550	3.8	5900		1670	94	296	7290
8/17/76	638	600	3.7	5900		1680	91	307	7430
8/17/76	738	700	3.7	5900		1670	95	299	7030
8/17/76	838	800	3.7	5900		1680	96	299	7500
8/17/76	938	900	3.8	5900		1680	86	291	7410
8/17/76	1038	1000	3.7	6200		1870	102	304	8190
8/17/76	1138	1100	4.0	6800		1970	99	250	8450
8/17/76	1238	1200	4.0	6800		2080	103	280	8670

would be reasonably easy to penetrate. His recollection was that the circular raise was sealed with a steel plate and a thick concrete plug.

On August 24 and 25, 1977 the concrete raise plug was drilled with a portable diamond drill with an EX size diamond bit (1½" hole). At 10 feet the steel plate was encountered and this was drilled through with a 1-3/16" carbide tipped bit after drilling a 3/8" pilot hole.

A weighted line was lowered into the raise. No obstruction was encountered until the weight reached a depth of 680', the depth where mine maps show the raise to dog leg into the upper part of the stope at the 7th level. The raise was water filled to a point 54.95 feet below the surface of the raise cap.

A specially constructed small diameter water sampler, similar to a Kemmerer sampler, was used to sample the water in the raise. A single sample taken from a depth of 318' below the surface plug was tested for pH and conductivity. It had a pH of 5.1 and a specific conductance value of 1170 μmhos/cm which would indicate it to be lightly mineralized. The 318 feet was the maximum length of line on the sampler.

Mine maps show a connection between this raise and the Hiawatha #1 shaft on the 4th level. The 4th level drifts are in turn connected with stopes at this level. Thus, if pumping is done from the sand filling raise, only waters on the 4th and higher levels should be most affected.

<u>Monitoring water levels in the Dober-Hiawatha Mine Complex</u>. In August of 1976 a level survey was made between the Hiawatha #1 and #2 shafts, Churn drill hole (CDH) 2-45 and a staff gage which was installed in the Dober pit. Measurements of the ground water levels at these openings were made for nearly one year beginning in June, 1976. The results of these measurements are shown in Figure 62. Not shown in Figure 62 are the water levels in CDH 2-45 because they were so

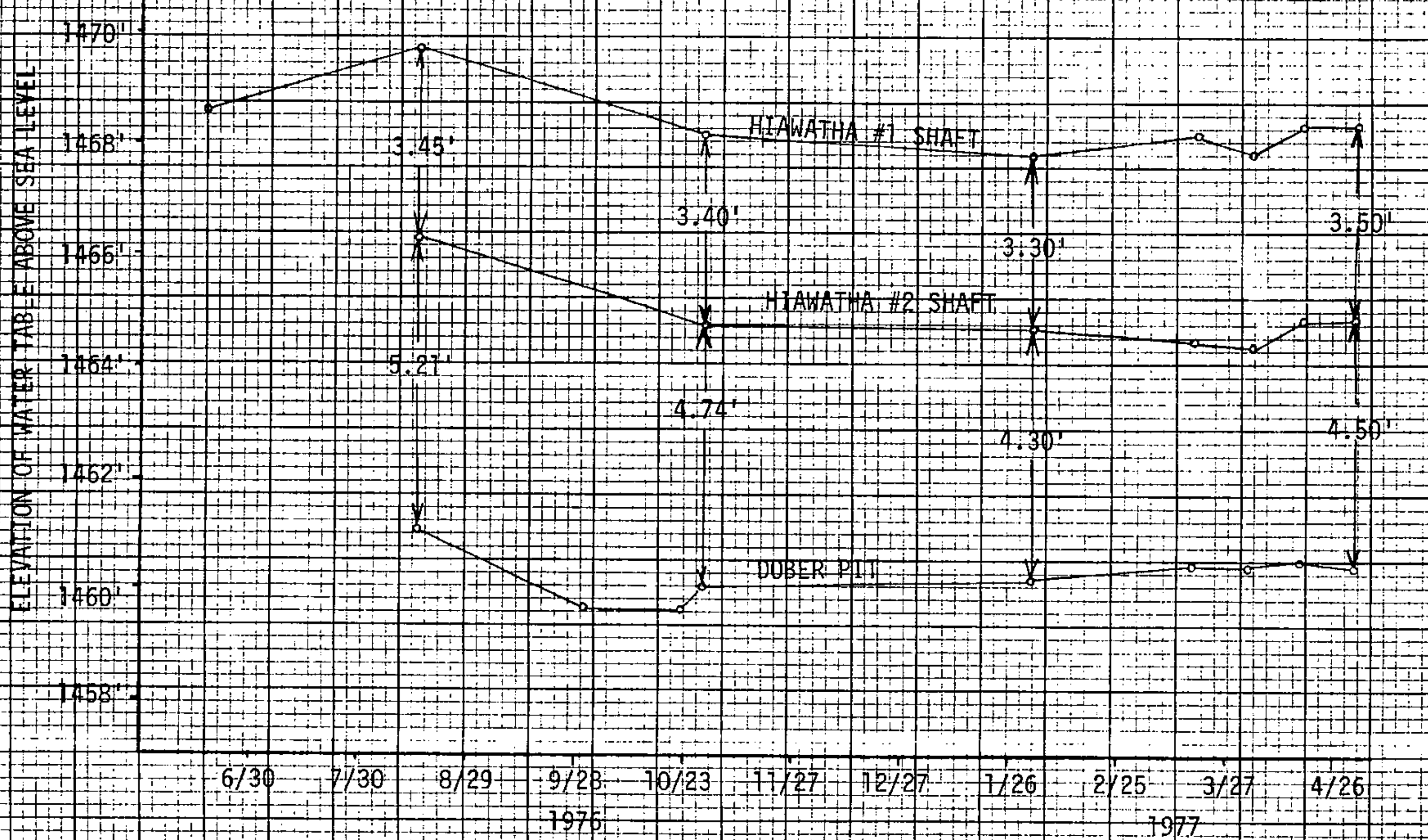


Figure 62. Water Level Observations in the Hiawatha-Dober-Isabella Mine Complex from June 1976 through April 1977

similar to those of the nearby Hiawatha #1 shaft. In CDH 2-45 the measurements were begun in February 1977 being 0.3 feet higher than the Hiawatha #1. However, by mid-March 1977 the water level in CDH 2-45 was 0.25 feet lower and finally equilibrated with the water in the Hiawatha #1 shaft by early April 1977.

Water levels in the Hiawatha #1 shaft may be described as gradually rising until mid-summer 1976 and then declining during the fall and winter. The first rise of water levels in the mine complex in the spring corresponds to the early rainfall which occurred before the snow melted in early March 1977. A short period of decline was then followed by a rise in the ground water level by May 1977 to an elevation just short of the June 1976 water level.

Water levels in the Hiawatha #2 shaft may be described as declining directly with the water levels in the Hiawatha #1, but not responding to the mid-March 1977 rise in water level. Response to recharge in the mine complex did not manifest itself until the middle of April 1977. During the decline of water levels the head differentials between the Hiawatha #1 and the Hiawatha #2 gradually approached each other from 3.45 to 3.40 to 3.30 feet. After the spring 1977 recharge they gradually increased to a head differential of 3.50 feet.

Water levels in the Dober pit were somewhat complicated due to the installation of a V-notch weir in the ditch draining to the Iron River which raised the water level in the pit somewhat. The decline of water levels in the Dober pit diverged rapidly from those of the Hiawatha #1 and #2 shafts until the weir was installed on October 28, 1976. Figure 62 shows that the water level in the Dober pit had been equilibrating and gently rising in a subdued profile most similar to the Hiawatha #1 shaft water level. Head differentials between the Dober Mine pit and the Hiawatha #2 shaft had decreased throughout the fall and winter from 5.21 feet to 4.74 feet (on 11/2/76) to 4.30 feet in late January 1977 and finally in the spring of 1977 increased 4.40 feet after having come as close as 3.90 feet before water levels began to rise in the Hiawatha #2 shaft. The maximum reading when the weir was operating properly (the nappe of the water was contracting properly and not being influenced by the downstream water level) was 138 gpm and occurred on April 26, 1977.

Water level variations in mine shafts due to water density variations. Water level variations between the Dober Mine pit and the Hiawatha #2 shaft were related to a "U" tube concept by Johnson and Frantti (1976). The 4 to 6 foot head on the Hiawatha #2 shaft compared to the Dober Mine pit level was attributed to a balancing effect because of differences in the densities of the two columns of water. More detailed work during 1976 and 1977 allows some quantification of these results. Deep sampling of the Hiawatha #2 shaft disclosed the fresh water interface at about 540' below the water surface. Thus approximately 540 feet of fresh water is elevated from 4 to 6 feet higher than the column of acid water in the Dober "leg" of the tube. From this data a density can be calculated for the heavier mineralized water if the assumption is made that the two "legs" are balanced:

$$\text{S.G. acid water} = \frac{540}{536} = 1.0075$$

This calculated density of 1.0075 g/cc for the mineralized water is extremely close to the density obtained from Dober Mine pit water by measuring the dissolved solids content. A sample of Dober pit water collected in February of 1977 had dissolved solids content of 7070 ppm. By adding the dissolved solids weight to that of pure water (S.G. = 1.0000), the S.G. of the acid water is 1.0071. On February 2, 1977 the water level difference between the Dober Mine pit and the Hiawatha #2 shaft was 4.30 feet, or just slightly more than the 4.0 feet used in the calculation. Thus, very close agreement exists between the estimated value and the calculated value.

It is possible to calculate the depth of a fresh water-acid water interface in the Hiawatha #1 shaft in a similar fashion. On February 2, 1977 the water level in the #1 shaft was 3.30 feet above the level in the #2 shaft, or a total of 7.60 feet above the water level in the Dober Mine pit. If a simple proportion is used to relate the relative depths of the interfaces, the result is as follows:

$$\frac{4.30' \text{ head}}{540' \text{ column}} = \frac{7.60' \text{ head}}{X' \text{ column}}$$

where X = 954' of 'fresh' water column in Hiawatha #1 shaft

The actual depth of the interface may be somewhat less, as frictional losses in the mine drifts and shafts are ignored as is the possibility that the head forcing the acid waters from the Dober may be part of this elevation difference. Deep sampling of the Hiawatha #1 Mine will be needed to check this estimate.

Discharge from the Dober Mine pit. On October 4, 1976 a V-notched weir was installed in the Dober Mine pit drainage so more accurate measurements of flow could be made from the pit. Results of periodic measurements of flow rates are reported in the section on Periodic Water Analysis. During late winter and early spring of 1977 daily measurements of flow rates were recorded (March 12 - April 29) and compared to the precipitation amounts as recorded at the Stambaugh Sewage Treatment Plant. These results are displayed in Figure 63. Unfortunately, because of high water in the Iron River backing up into the drainage channel, reliable measurements of flow could not be obtained for most of April. These questionable readings are indicated as a dashed line in Figure 63. Solid lines connect the reliable readings.

It is apparent from these data that flow from the Dober Mine pit responds

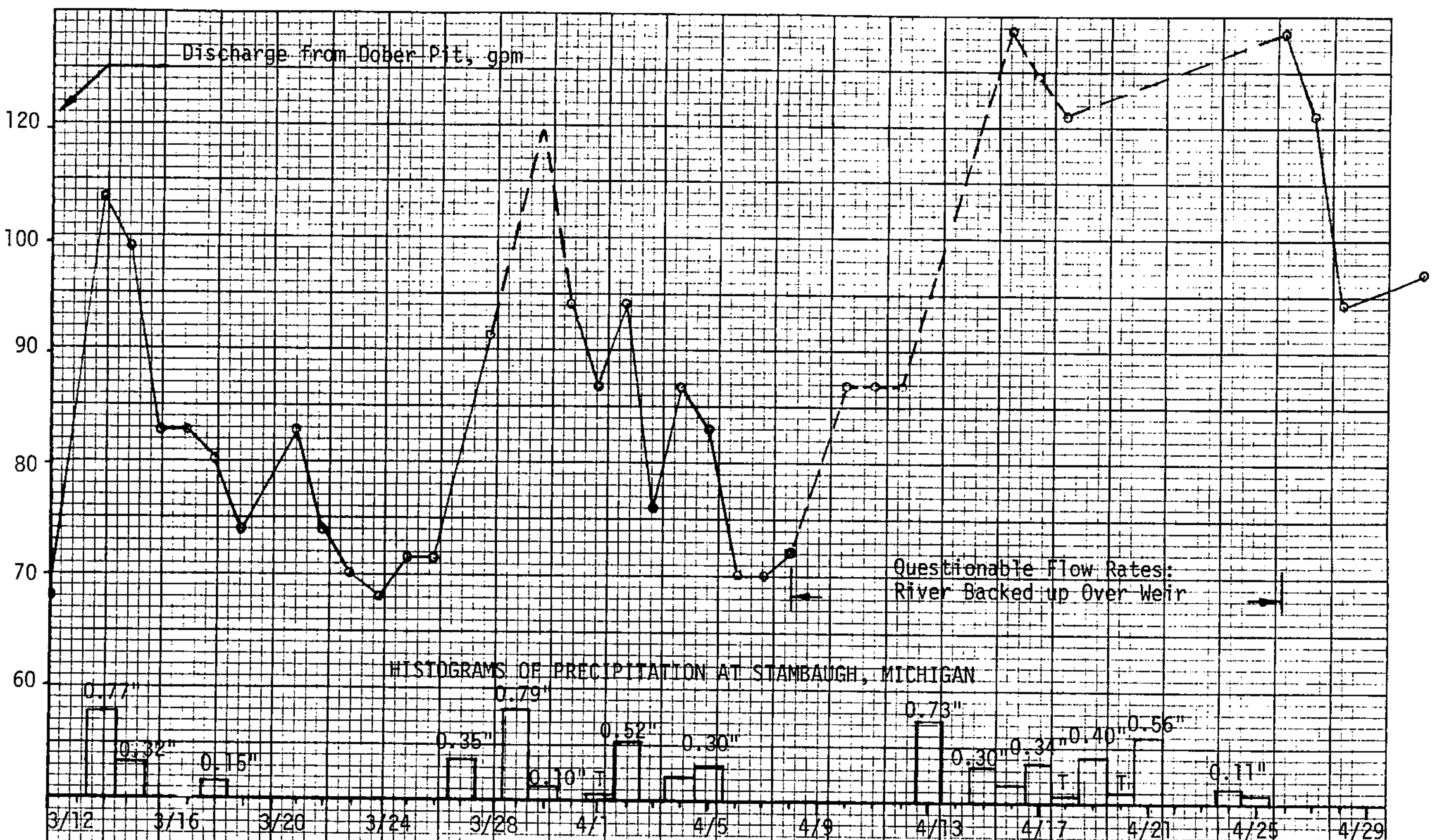


Figure 63. Results of Daily Readings of the Weir on the Dober Pit, and the Corresponding Histograms of Precipitation Recorded at Stambaugh, Michigan for the Period March 12, 1977 to May 1977

almost immediately to precipitation. This would be due to direct runoff into the pit area. However, there exists a longer term relationship also. Cregger (1977) concluded that a lag time of about one month occurred between precipitation recharge over the Hiawatha Mine workings on the west and increased flow from the Dober Mine pit. This time lag was calculated from measured permeability values of both the iron formation and overlying glacial material on the Hiawatha #1 property.

Conclusions from work on the Dober-Hiawatha-Isabella Mine Complex. Based on the additional work done on the Dober-Isabella-Hiawatha Mine Complex in 1976 and 1977, the model described in the 1976 status report (Johnson and Frantti, 1976) is confirmed and strengthened. The model is one of recharging fresh waters entering the Hiawatha workings on the west forcing acid waters through the mine and to the surface in the Dober Mine pit and flow into the Iron River.

The flow rate from the Dober Mine pit is influenced considerably by precipitation. During the spring melting snow and rains combine to produce the greatest acid flow.

Head differences between water levels in the mine complex are attributable largely to density differences of the waters. In the Dober Mine heavy mineralized waters in effect cause a thick (500 feet and more) blanket of fresh water in the Hiawatha workings to lie at a higher elevation. Slight imbalances in this head caused by recharging surface waters produces flow from the Dober Mine pit.

It is possible that pumping from the surface in the vicinity of the Hiawatha properties may eliminate the imbalance and either stop or greatly reduce acid drainage from the Dober Mine pit.

Factors Affecting Acid Drainage from the Buck Group of Mines

Acid drainage from the Buck Mine Complex was identified in the earlier work (Johnson and Frantti, 1976). Results of this early work showed that approximately 10 percent of the acid drainage entering the Iron River from abandoned mines originated from this source. The Buck Mine Complex is located east of Caspian on the east side of the Iron River. Here extensive piles of pyrite-bearing black slate fill low areas in the Iron River valley.

The Buck Group of Mines for the purpose of this report includes the Fogarty, Cottrell, Berkshire and Buck properties. Officially the Buck Group is a complex of mines including the Baltic, Zimmerman, DeGrasse and the above listed mines with the exception of the Cottrell. The Cottrell was a shallow, separately operated mine. The locations of these properties are shown in Figure 64.

Three well defined channels drain acid waters from the slate piles into the Iron River. Acid waters seep from the lower western margin of the piles and collect in ponds behind elevated railway grades. The waters flow under the grade through three culverts. From the railway grades the drainages flow several hundred feet more-or-less directly into the Iron River (Figure 65).

Limited earlier work on the Buck Mine Complex suggested acid drainage had its origin primarily from surface and near-surface ground waters flowing from the elevated east margin of the piles through the piles and seeping from the lower western toe of the piles into the Iron River. The oxygenated waters would react with the abundant pyrite in the slate to form sulfuric acid.

Mapping Buck Group of Mines slate piles. The first step in studies of the acid drainage from the slate piles over the Buck Group of Mines was to produce a map of the waste rock piles and acid drainage channels at a suitable scale.

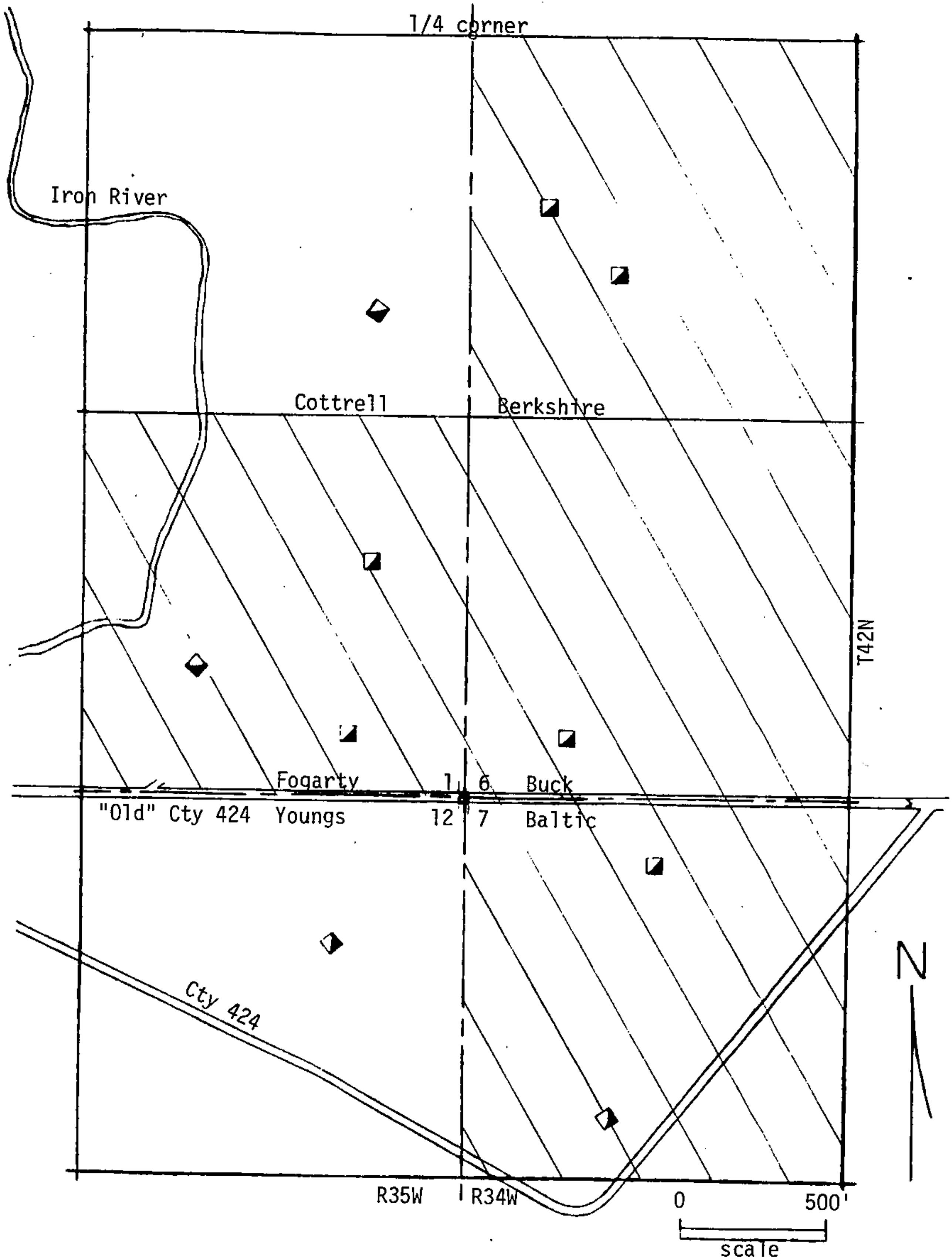


Figure 64. Relationship of Mine Properties Forming the Main Body of the Buck Group (shaded)

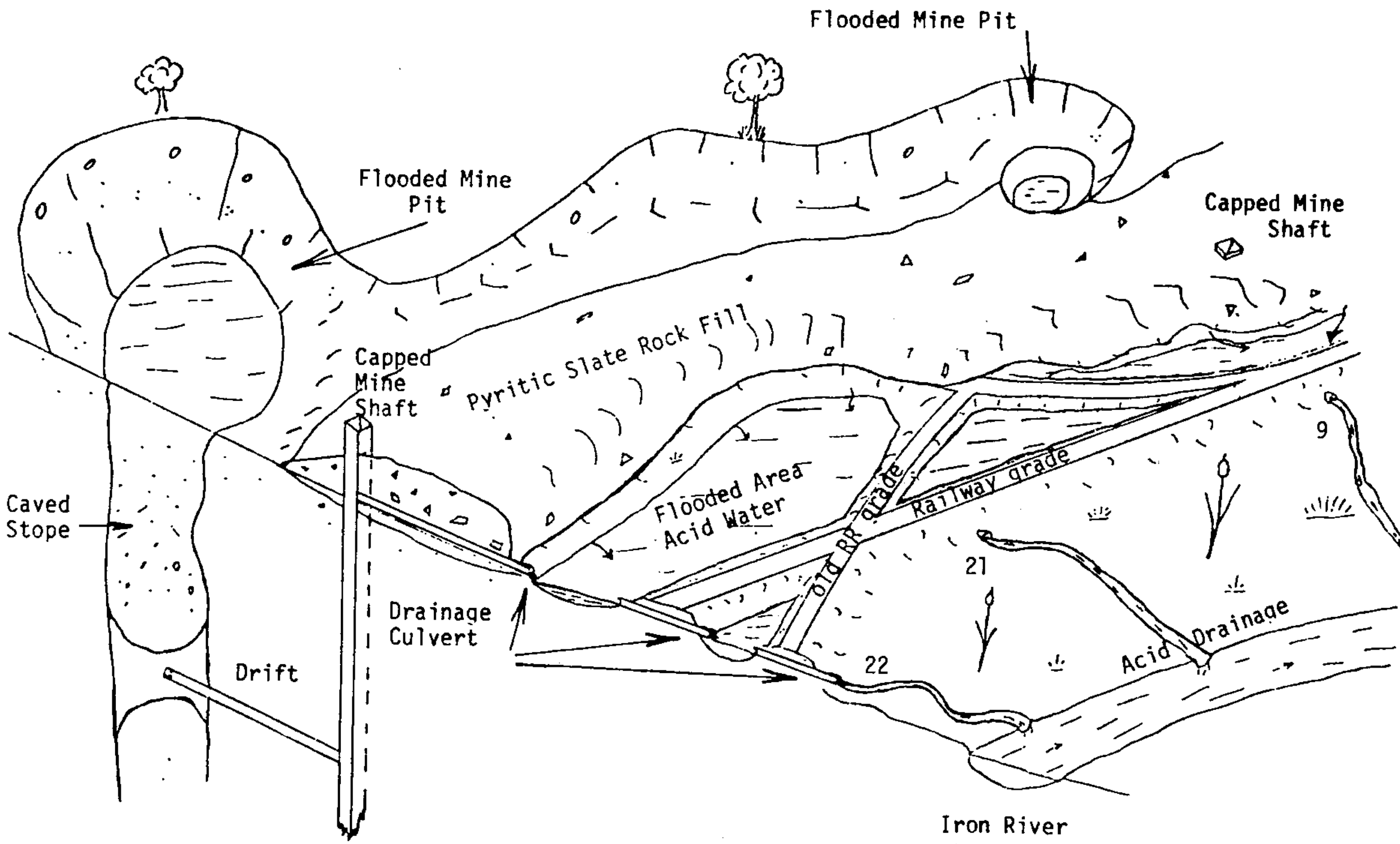


Figure 65. Schematic Cross Sectional Oblique View of Acid Drainage from Buck Group of Mines Surface Waste Piles (looking southeast)

In June of 1976 a pace and compass map of the area was made. The area underlain by waste rock fill is nearly one half mile long and up to 600 feet wide. The black slate piles are flanked by high ground on the east and by low marshy ground on the west along the Iron River. Numerous subsidence pits dot the area along the eastern area of the piles and several pits extend into the piles. One small circular pit lies within the area of the piles. Many of the subsidence pits are flooded. Waters flow from the higher area on the east to the Iron River on the west, across and through the slate piles. These features are shown on the map in Figure 66.

During June of 1976 a leveling survey of the Buck Group of Mines waste piles was done. Results of the survey showed a 26 to 27 foot difference in elevation between water filled subsidence pits on the elevated east margin of the piles compared to the elevation of the Iron River on the east. Elevations of acid water seeps at the base of the western margin of the waste piles are approximately midway between these two elevations. Profiles of two cross-sections through the Buck waste piles are shown in Figure 67 (see Figure 66 for the cross-section locations).

Auger sampling and analysis of Buck Group waste piles. Information on the sulfur content of the Buck Group waste piles was needed to determine the potential for acid drainage from this source. A sampling grid was devised and auger samples from 15 locations on the piles were collected. The augering was done during the summer of 1976 using a truck-mounted drill rig with a small diameter auger string (2½ inch). Efforts were made to auger through the slate fill at each site; however, timbers and large rocks at the base of the piles precluded these efforts in several holes. The depths varied from as little as 2 feet near the margins of the pile to more than 15 feet in one location.

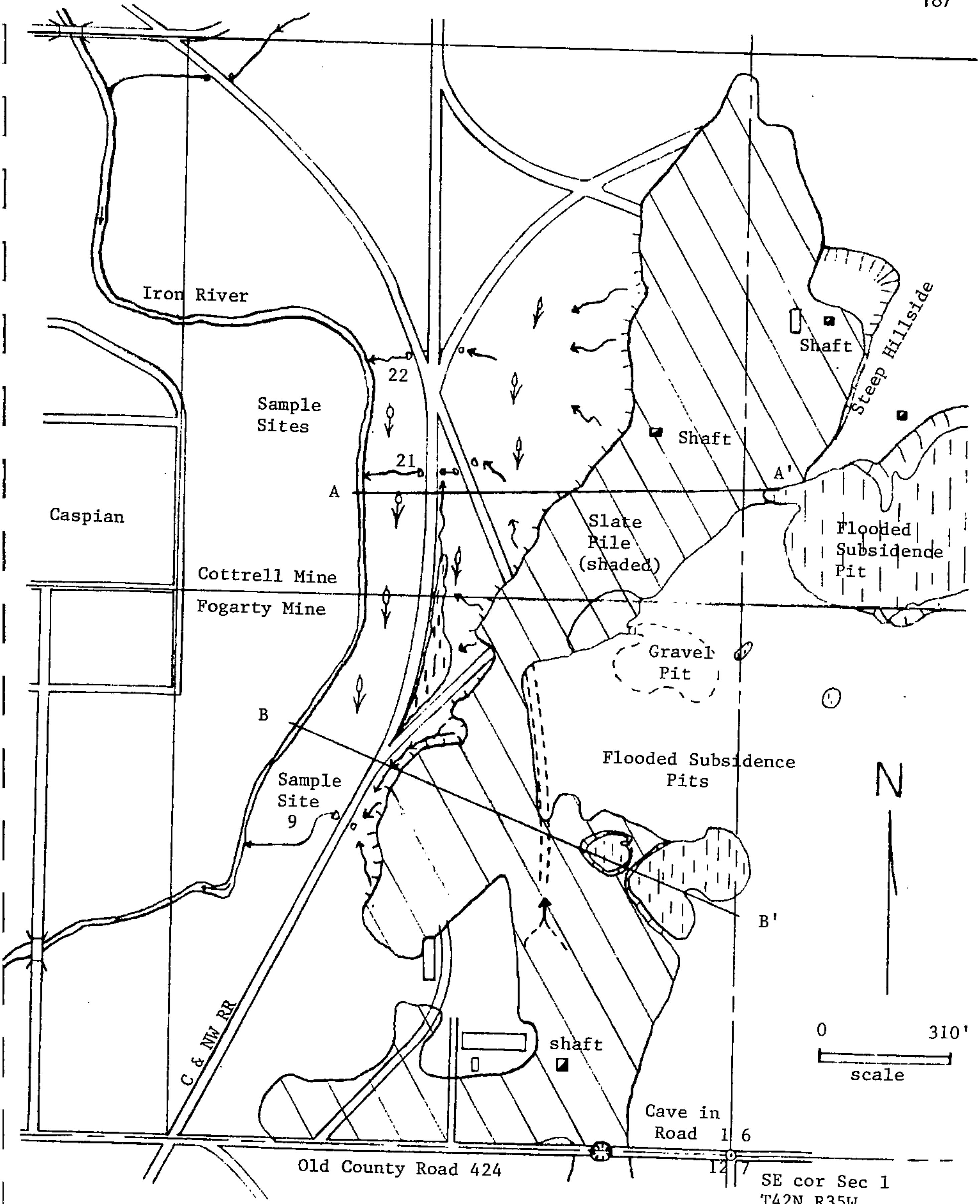


Figure 66. Map of the Buck Group Slate Piles

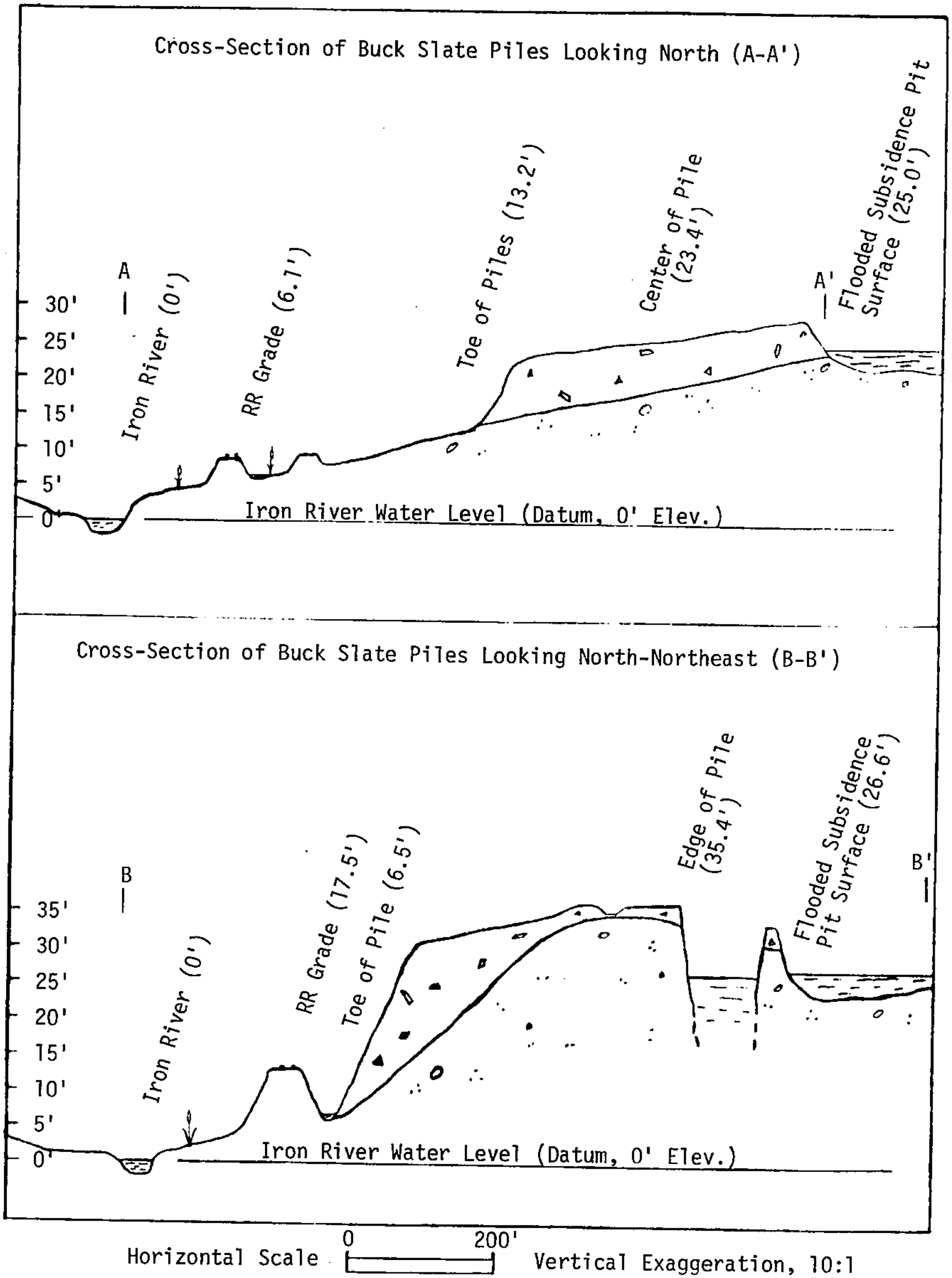


Figure 67. Cross-Sectional Views of Buck Slate Piles (see Figure 66)

Within the accuracy limits of the 14-hole sampling grid, a fairly representative suite of samples was obtained. Material augered from each hole was sampled separately when any obvious change in color or texture was observed. A total of 18 samples from the 14 holes were prepared for analysis.

Following drying and sample preparation, each sample was analyzed for total sulfur. The analyses ranged from a low of 0.9% to a high of 9.8% sulfur.

Based on field observations and the sulfur analyses, the surface piles were divided into 13 areas on the map. The average sulfur content for each area was calculated from auger samples taken within the area.

The areas were planimetered from the map and with depths from the auger and the edges of the piles, the volumes of each area were calculated. These volumes were converted to pounds of slate for each area assuming a bulk density of 105 pounds/ft^3 for the slate. The pounds of sulfur for each area were then calculated by multiplying the average percent sulfur times the volume. Total sulfur in the piles is simply the sum of sulfur in each area.

The figures used in the above calculations are reproduced in Table XIII. A plan map showing the areas and average sulfur percentages of each are in Figure 68. It is obvious from the map of Figure 68 that some areas are much richer in sulfur. The north area of the pile was used formerly to stockpile ore, therefore it contains less sulfur.

Based on these calculations, the volume of the Buck Group waste piles is 129,000 cubic yards and contains 10.2 million pounds of sulfur. If this quantity of sulfur was converted to sulfuric acid, 31.1 million pounds of concentrated sulfuric acid would be produced. Furthermore, if the sulfur is calculated as pyrite (FeS_2), the oxidation of the pyrite would generate directly 8.86 million pounds of iron (4,430 short tons).

Table XIII

Volume and Sulfur Content
of Buck Mine Complex Slate Piles

Area Number	Surface Area (Ft^2)	Average Depth of Slate (Ft)	Slate Volume (Yd^3)	Sulfur %	Sulfur[4] lb/Segment
1	51,000	7.5	14,167	4.35	1,747,000
2	25,200	2.5	2,333	1.93	128,000
3	34,200	4.0	5,067	4.42	635,000
4	15,600	4.0	2,311	3.70[1]	242,000
5	19,200	4.75	3,378	5.72[2]	548,000
6	22,200	7.0	5,756	8.07	1,317,000
7	28,800	8.0	8,533	0.91	220,000
8	58,800	4.0	8,711	9.78	2,415,000
9	54,000	2.5	5,000	0.22	31,000
10	139,800	2.0	10,356	0.93	273,000
11	151,200	3.75	21,000	0.21	125,000
12	99,000	6.0	22,000	0.44	274,000
13	45,000	8.5	14,167	3.57	1,434,000
14	84,600	2.0	6,267	4.42[3]	785,000
Total	828,600 = 19 acres	-	129,046	-	10,174,000

[1]% S weighted from 4 analyses

[2]% S weighted from 2 analyses

[3]% S estimated to be similar to Area 3

[4]Sample Calculation for Area 1 is:

$14,167 \text{ yd}^3 \times 2,835 \text{ \# Slate/yd}^3 \times .0435 \text{ S} = 1,747,000 \text{ \#S}$

Note: Bulk density of slate estimated using S.G. of 2.8 and 40% voids: i.e., $2.8 \times 62.4 \text{ \#/ft}^3 \times 0.6 = 105 \text{ \#/ft}^3$

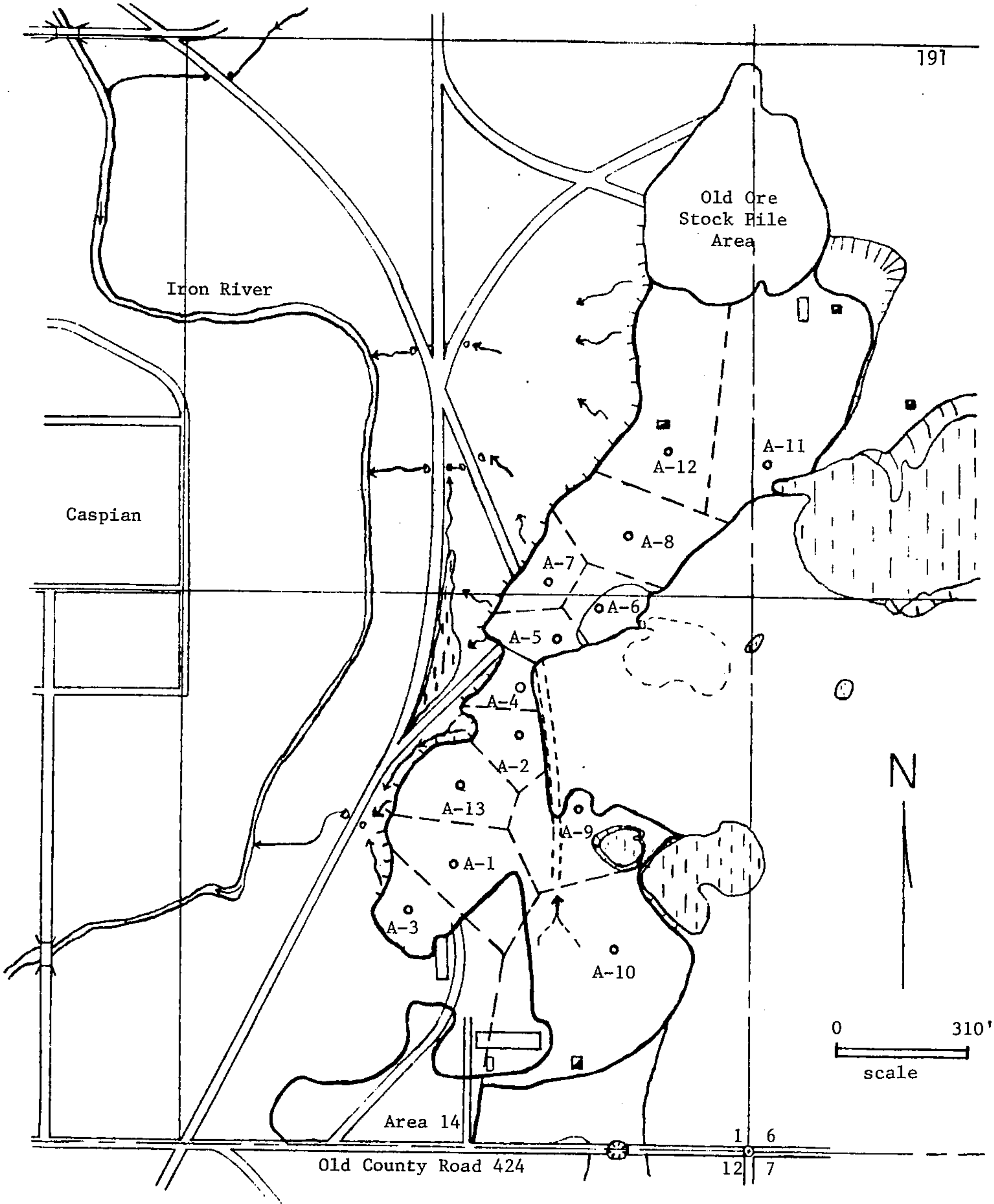


Figure 68. Auger Hole Locations and Areas Included in Sulfur Content Calculations for Buck Slate Piles

Although these calculations are only approximations and a number of assumptions are made, such as all of the sulfur being present as pyrite and the complete oxidation of this pyrite occurring, the above figures provide a realistic estimate of the potential for acid drainage from the leaching of waste rock in the Buck piles. This may even be on the conservative side as the sulfuric acid generated will react with other minerals to dissolve more iron. Moreover, acid drainage from within the mine voids under the slate piles is not considered in these calculations and it is possible that acid originates from this source also.

Acid drainage from the Buck Mine Complex. As mentioned previously, acid waters collect from seepages on the western margin of the waste rock pile. The waters flow from the ponded seepage behind the railway and railway spur grades through three culverts. The sample numbers of the culverts are from south to north as numbers 9, 21 and 22 (see Figure 66).

V-notched weirs were installed at each of the drainage culverts in the late fall of 1976. Periodic measurements of the flow rates coupled with chemical analyses of the waters were used to calculate the amount of iron flowing into the Iron River from these sources. The results of these measurements and analyses are listed in Table VIII. General discussions concerning the relative contribution of acid drainage from each of the drainage channels is included in the section on Periodic Water Sampling and Analysis in the Buck Mine Group Acid Drainage subdivision. There it was noted that although most of the iron (76#/day or 65%) came from drainage site #9, it accounted for only 12% of the total flow.

Sample sites #21 and #22 accounted for only 23 and 18 pounds of iron per day, respectively (20% and 15%), while accounting for 31% and 57% respectively of the total flow. Thus, in Table VIII an inverse relationship is indicated between iron content and flow rate.

Caution must be exercised in this assumption, however. If the sulfate values of the various drainages are compared with the flow rates, a much closer relationship is observed. These following data are abstracted from Table VIII.

Source	Flow Rate (gpm)	%	Sulfate (mg/l)	%
#9 (South)	54	12	1615	16.6
#21 (Central)	136	31	3028	31.1
#22 (North)	251	57	5108	52.3

Note that the percentage of sulfate is nearly identical to the percentage of flow rate for each drainage source. The conclusion to be drawn from these observations on flow rates versus iron and sulfate contents is significant. Sulfate in the acid water, unlike iron, is not easily precipitated out - it tends to remain in solution. Iron, on the other hand, is readily precipitated when it comes in contact with oxygen and fresh water. From these relationships it is probable that waters with high sulfate levels were originally more acid and contained proportionately more iron. For the drainages from the Buck Mine area this would rank the acid drainage potential in the order #22, #21 and #9, just the opposite of the observed values (on the basis of iron).

To explain this situation, extensive precipitation of iron is required from the waters comprising drainage #22 and to a lesser extent from waters comprising drainage #21. Field evidence suggests this to be the case. Ponded areas exist between the toe of the waste piles and the drainage culverts under the railway tracks for drainage #21 and #22. At sample site #9 the toe of the slate pile is very near the drainage culvert. Rather large amounts of "yellow-boy" (iron hydroxide precipitates) have built up in these ponded areas over the years. Apparently the process is continuing. Below sample site #9 west of the railway grades, deltas of the "yellow-boy" are also present, demonstrating how readily the iron oxidation and precipitation occurs. The pond areas of "yellow-boy" precipitation can be seen on the map of Figure 66.

Conclusions from the work on the Buck Mine Group acid drainage source. Results of the sampling and analysis work on the Buck Mine black slate piles shows the piles contain large quantities of sulfur (10.2 million pounds) that could form as much as 31.1 million pounds of sulfuric acid. It is also observed that surface and near-surface ground waters flow through the black slate piles and into the Iron River under a rather steep gradient from east to west. It is logical to assume that significant quantities of acid are generated as the oxygenated waters pass through the piles and react with the iron sulfide present in them. However, the rather large total volume of mineralized water coming from the surface piles suggests some of the drainage may originate from within the mines underlying the piles.

Acid drainage, in terms of iron entering the Iron River, would be much worse were it not for the retention time in ponded areas east of the railway grade for drainages #21 and #22 on the central and northern areas of the piles. This retention time promotes oxidation of the iron and the resultant formation of iron hydroxide hydrate precipitates.

REFERENCES

Cregger, David M. (1977), Flow of Acid Mine Water in the Abandoned Hiawatha-Dober-Isabella Mine Complex, Iron River District, Michigan, Unpublished thesis, Dept. of Geology and Geological Engineering, Michigan Technological University, Houghton, Mich., 127 p.

Hunt, Cliff (1974), Iron River-Brule River Report, Unpublished report by USDA Forest Service, Nicolet National Forest, Rhinelander, Wis., p. 23.

Johnson, Allan M. and Frantti, Gordon (1976), "Study of Mine Subsidence and Acid Water Drainage in the Iron River Valley, Iron County, Michigan - Status of Initial Work", Institute of Mineral Research, Michigan Technological University, Houghton, Mich., 113 p.

Schumate, K. S., Smith, E. E., Dugan, P. R., Brant, R. A. and Randles, C. I. (1971), Acid Mine Drainage Formation and Abatement, Ohio State University Res. Foundation, FWPCA Grant No. 14010 FPR, EPA, p. 82.

Smith, E. E. and Shumate, K. S. (1970), Sulfide to Sulfate Reaction Mechanism, Ohio State University Res. Foundation, RWPCA No. 14010 FPS, Supr. Doc. Wash., D.C., p. 115.

Tyler, S. A., Barghoorn, E. S. and Barrett, L. P. (1957), Anthracitic Coal from Precambrian Upper Huronian Black Shale of the Iron River District, Northern Michigan Geol. Soc. Am. Bull., V. 68, No. 10, pp. 1293-1304.

Van Alstine, Jack (1973), Acid Mine Water Problem at Stambaugh, File Report, 15 pages plus Appendix, Mich. Geol. Survey.

APPENDIX

BACKGROUND

The West Iron County communities comprised of Iron River, Stambaugh, Caspian, Gaastra and Mineral Hills owe their origin to the discovery of iron ore in 1851. The initial discovery is credited to a Mr. Harvey Mellen, a United States land surveyor. A metal plaque marks the site of his discovery at the west base of Stambaugh Hill just south of the old Iron River mine, later named Riverton, in the Iron River valley.

However, it was not until 1882, some 31 years later, that the first shipment of ore was made from the Iron River and Namaino mines on a spur of the Chicago and Northwestern Railroad. From the first shipments in the fall of 1882 of 31,600 tons of ore the Iron River District had shipped more than 147 million tons of ore from nearly 50 different operations by 1974. With the closing of the Homer and Wauseca mines owned by M. A. Hanna Company in 1969, the Sherwood Mine of Inland Steel Company became the only operating mine in the District, or for that matter, in Iron County. The Sherwood mine produces approximately 375,000 long tons of direct-shipping ore per year and employs approximately 125 men in its underground operation in Iron River.

Study Area

The area encompassed by the study is in west Iron County comprising the southeast part of Iron River Township, the southeast part of Bates Township and a northern portion of the eastern extension of Stambaugh Township. Township locations in Iron County and the limits of the study area are shown in Figure A-1.

The five communities within this area are the cities of Iron River, Stambaugh, Caspian and Gaastra and Mineral Hills Village. According to statistics in the 1974-75 Iron County Directory population figures are:

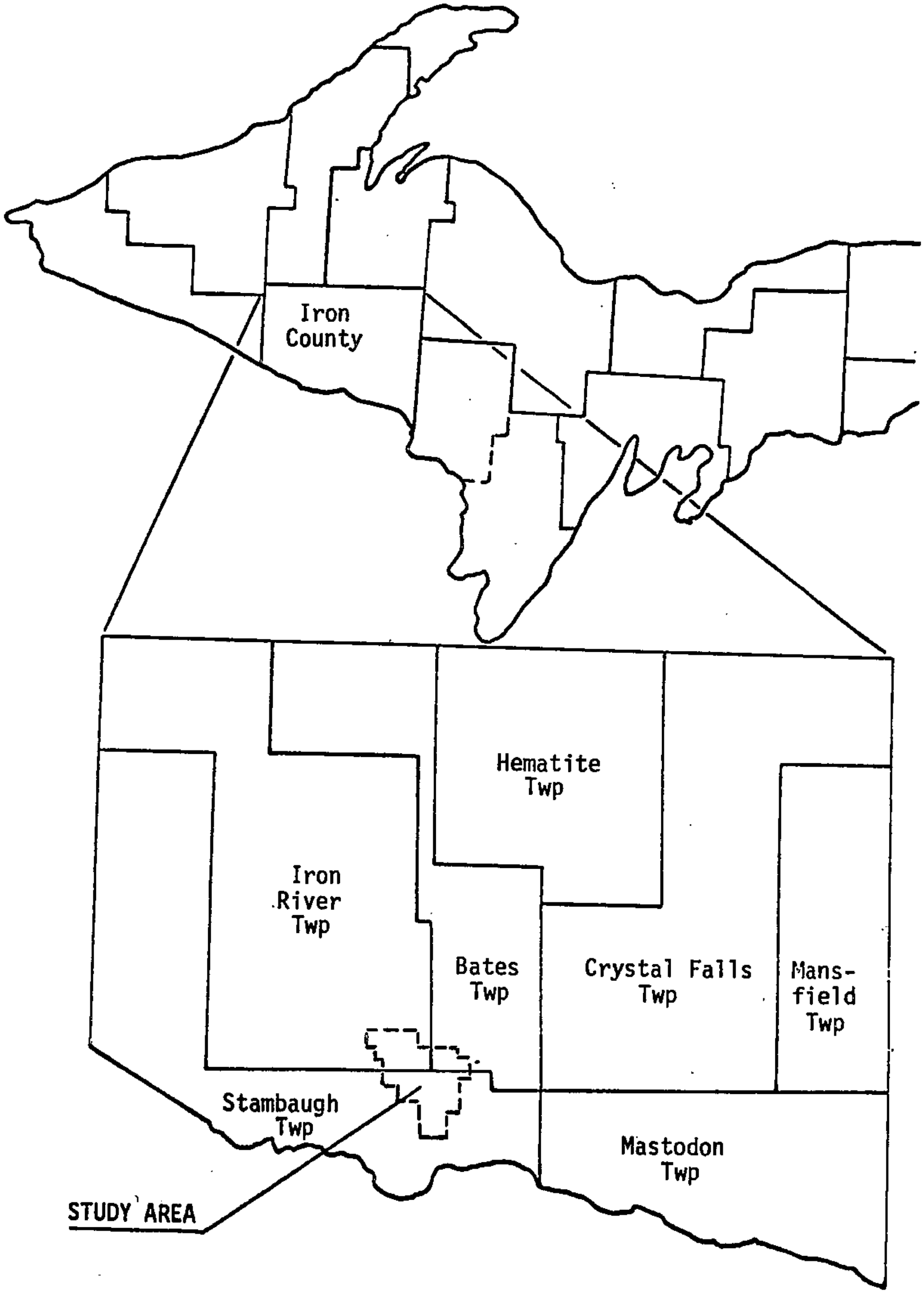


Figure A-1. Study Area in Iron County, Michigan

City of Iron River		2,684
City of Stambaugh		1,458
City of Caspian		1,165
City of Gaastra		479
Mineral Hills Village		234
Bates Township		980
Iron River Township		1,164
Stambaugh Township		947
	Total	9,111 (66% of County)
1970 Iron County Census		13,813

The relationship of the towns to each other and other general geographic features are shown on the map of Figure A-2.

General Geology

As an aid to understanding the distribution of mines in the district, the nature of subsidence and the origin of acid drainage, a brief sketch of the local geology is helpful. Most of the following descriptions are abstracted from U.S. Geological Survey Professional Paper 570, the most recent publication on the Iron River District.

The iron-bearing rocks of Iron County of interest to this report comprise a complexly folded series of sedimentary rocks of middle Precambrian age known as the Menominee Iron Range. In Iron County, the Menominee Range forms a roughly shaped triangle, one leg of which extends between Crystal Falls and Iron River, a second trending southeast of Iron River and a third running south of Crystal Falls into Wisconsin. The Range extends southeasterly into Michigan again, paralleling the Menominee River in Menominee County. In Iron County it is referred to as the West Menominee Range or simply the Iron River-Crystal Falls District (see Figure A-3).

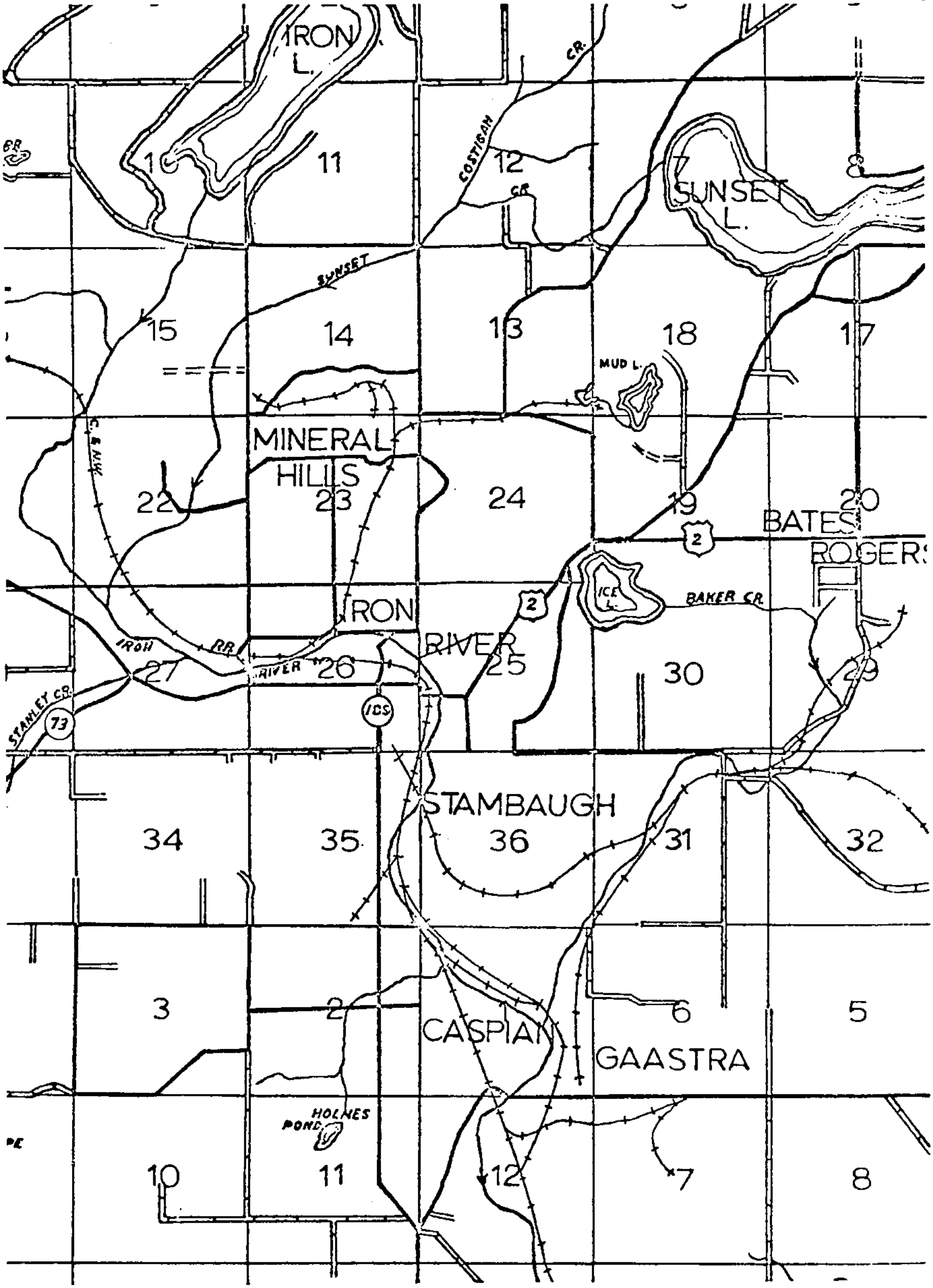


Figure A-2. Geographical Features of the Iron River District

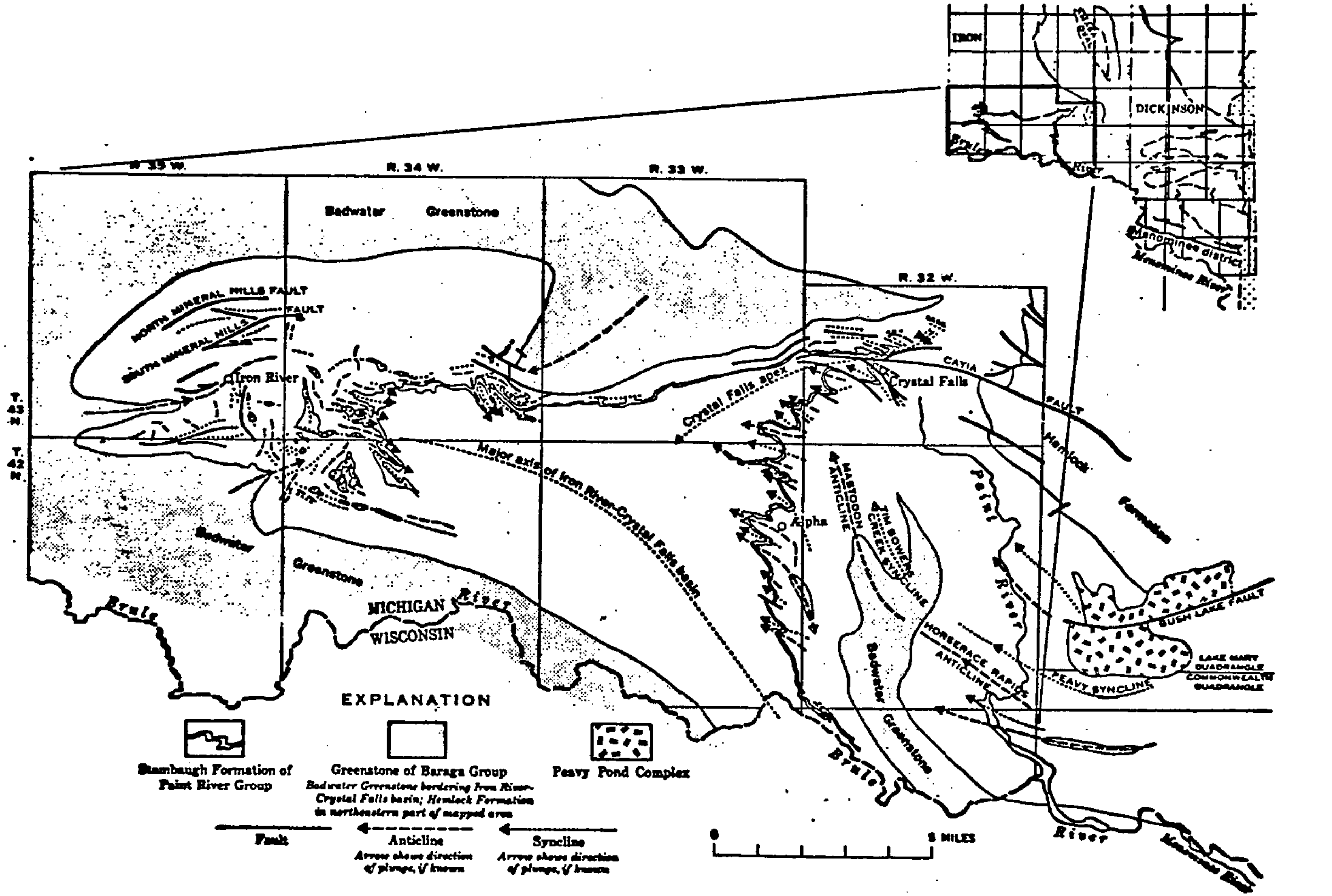


Figure A-3. West Menominee Iron Range: Iron River-Crystal Falls District Showing Structure Source: USGS Prof. Paper 570 (1968) p. 80

The strata comprising the Menominee Range in the Iron River District are the five formations of the Paint River Group of the Upper Animikie Series of rocks. Stratigraphic relationships and thicknesses of these strata are shown in Table A-1.

Table A-1

Rock Units of the Iron River-Crystal Falls District

Younger	Rock Unit			Estimated Thickness (Feet)
Middle Precambrian	Animikie Series	Paint River Group	Fortune Lake Slate Stambaugh Formation Hiawatha Graywacke Riverton Iron Formation Dunn Creek Slate	4,000+ 100 0-500 10-800 400-1500
		Baraga Group	Badwater Greenstone Michigamme Formation Amasa Formation Hemlock Formation	0-15,000 6,000 1,800 6,000+
Older		Chocolay Group	Saunders Formation	1,000+

Source: USGS Prof. Paper 570 (1968) p. 17

Brief descriptions of formations comprising the Paint River Group from bottom to top follow. The upper part of the Dunn Creek Slate and the Riverton iron formations are of particular interest as they are the formations encountered in the mines.

Dunn Creek Slate: A grey sericitic slate and siltstone about 500 feet thick in the Iron River District, but thicker towards the east. Uppermost part is a black pyritic-graphitic slate, sometimes intensely sheared. In the vicinity of Iron River typically a breccia up to 30 feet thick. The presence of abundant fine grained pyrite in the Wauseca member is the cause of acid drainage and mine fires -- both the result of pyrite oxidation.

Riverton Iron Formation: This formation directly overlies the Dunn Creek Slate and is named from the first production of ore from the Riverton Iron Mine. Ore is mined only from iron-enriched portions of the Riverton where original thin-bedded siderite has been oxidized and chert has been replaced. Thicknesses of the iron formation range from 150 to 300 feet in the Iron River District; however, it is not all ore. As much as half may be slaty iron formation and pyritic slate. Post-sedimentary erosion has thinned the formation in its western end. In the Cardiff mine the formation thins to 50 feet in the most westerly workings, and farther to the south and west drill holes show only 10 feet of thickness.

Hiawatha Graywacke: This clastic unit containing slate, siltstone and conglomerate-breccia facies overlies the Riverton Iron formation. The formation is thickest in the Iron River District--as much as 500 feet thick.

Stambaugh Formation: This formation is best characterized as a silicified or cherty slate. It is estimated to be some 100 to 200 feet thick in the vicinity of Iron River. The presence of magnetite in the upper part of the Stambaugh formation has allowed it to be traced magnetically through the extensive glacial cover. In fact, its magnetic character has greatly facilitated mapping the geology where glacial deposits conceal the bedrock.

Fortune Lakes Slate: This formation is the uppermost of the Paint River Group. Little is known of the Fortune Lakes slate formation except for the lower several hundred feet from exposures in the eastern part of the district where it is principally slate and graywacke. The thickness is estimated to be in excess of 4,000 feet.

Glacial Deposits

Very few areas of bedrock are exposed in the Iron River District. Thick glacial deposits of sand, gravel and till mantle more than 99% of the District to thicknesses in excess of 300 feet deep, although 100 to 200 foot thicknesses are more common. Bedrock exposures are rare. They are known only in the Iron River valley south of the City of Iron River and at the bottom of some mine subsidence pits.

Generally speaking, poorly consolidated sands and gravels are overlain by a fairly continuous sheet of quite competent boulder till. In many mine caves the overlying till containing large boulders stands in near vertical walls whereas the sandy lower units slump to form more gentle slopes. These relationships greatly influence mine drainage, drilling, shaft sinking and subsidence.

Structure

Concerning structure, James, et al (1968, p. 78, 80) state:

> "The structure of the Iron River-Crystal Falls District, though tremendously complex in detail, is relatively simple in broad outline. The district proper is a deep basin, rudely triangular in shape .... The sedimentary strata are intensely folded, more so perhaps than those of any other area in the Lake Superior region. Dips of less than 60° are scarce and overturning is common. Many faults with throws measureable in thousands of feet have been recognized and many more doubtless exist....
> ....The sedimentary strata within the basin are intensely distorted. All the strata are involved, but the thinly bedded units, expecially the Riverton Iron-Formation, are more noticeably deformed than the more massive units.....The folds have steeply dipping axial planes and most are overturned....
> ....in the vicinity of the City of Iron River, the dominant trend of folds ranges systematically from westerly in the southeastern part of the area, to northerly in the central part, to easterly in the northern part."

Major structural features of the West Menominee Iron Range including the Iron River District are shown in Figure A-3. A highly generalized sketch of typical relationships between folded Paint River Group strata and overlying glacial deposits in the Iron River District is shown in Figure A-4.

Ore and Ore Bodies

Not all of the Riverton Iron-Formation is ore. Only zones that have been enriched in iron values by oxidation of primary siderite and by replacement of chert are ore. This alteration and replacement occurs in irregular pods and lenses within the iron formation but some broad forms of ore control are recognized. Most of the ore occurs in the basal part of the iron formation and is in direct contact with the underlying pyritic-graphite slate of the Wauseca member.

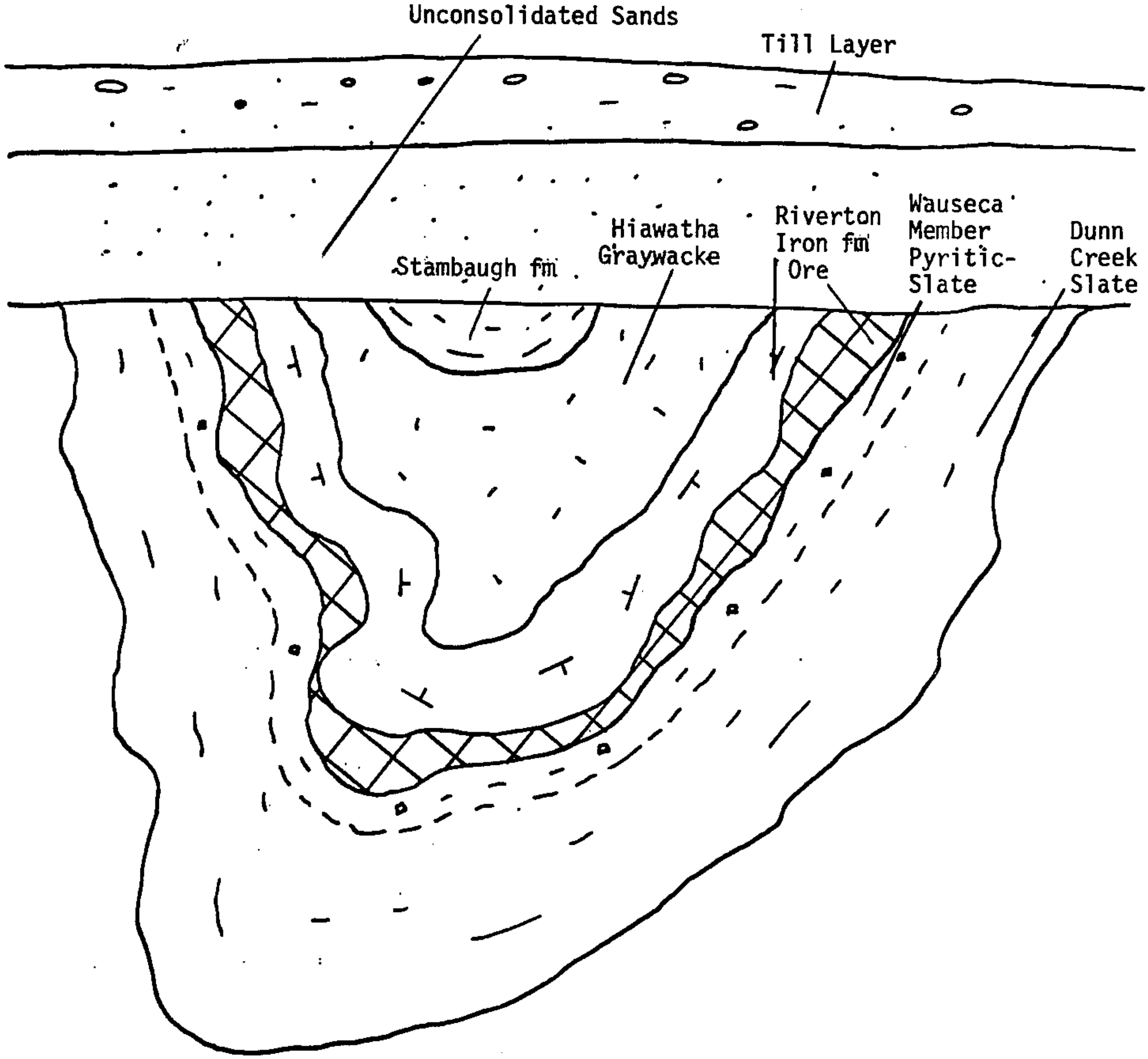


Figure A-4. Generalized Geologic Relationships of Folded Paint River Group and Glacial Deposits in Iron River District

All deposits from which adequate information is available show the ore to be continuous from depth to the bedrock surface (often buried by glacial till). Structural changes in the attitude of the iron formation often correlate with the limits of the ore, particularly with depth. Laterally the ore may grade into unoxidized iron formation.

Most mined ore has come from tabular bodies 100 feet or more in thickness and hundreds to thousands of feet in vertical or lateral directions. This distribution of the ore is responsible for the large underground openings employed in mining.

Complex folding of the strata causes the ore bodies to vary greatly in attitude from flat lying to vertical and often overturned so that the stratigraphically lower pyritic-graphite slate may actually lie in the hanging wall.

Typical ore from the Iron River District is very porous and yellow to bluish red, the former color due to goethite and the latter hematite. Most of the ore is soft enough to auger, but layers and pods of hard goethite ore occur in some deposits.

The ore is described as a direct shipping, old range, non-Bessemer high phosphorous ore. Published analyses of ore from nine operations in the Iron River District are listed in Table A-2. Ore from mines in the district is enriched in manganese - notably the Bengal (Cannon) and Rogers mines. As a result, acid waters from the mines have high manganese concentrations.

Minor to rare occurrences of a number of other minerals have been reported; including sphalerite (ZnS), urananite or pitchblende (UO_2), galena (PbS) and chalcopyrite ($CuFeS_2$). These minerals are found in the basal part of the Riverton iron formation where it is in contact with the Wauseca member of the Dunn Creek slate.

TABLE A-2

Analyses of Iron Ore from the Iron River district of Michigan

Mine	Davidson Group	James	Buck Group	Spies	Bengal	Homer	Hiawatha No. 1	Hiawatha No. 2	Wauseca
Total tons of shipment from which composite sample taken.	337,518	178,586	435,687	257,838	145,587	500,000	347,731	243,154	500,404
Date of Shipment	1950	1950	1950	1949	1950	1950	1950	1950	1950
	Chemical analyses (percent)								
SiO_2	7.15	7.76	9.75	6.84	6.55	7.65	4.92	6.39	6.19
Al_2O_3	2.63	1.68	3.31	2.29	3.89	4.71	2.61	3.22	3.78
Fe_2O_3	77.75	77.43	76.43	82.08	79.00	75.58	79.81	77.45	78.78
FeO	1.99	2.16	2.61	.30	.72	2.86	2.61	3.15	1.98
MgO	.50	.51	1.25	.21	2.04	.71	.70	.90	.39
CaO	.45	.54	1.67	.09	1.04	.93	.97	1.03	.51
Na_2O	.02	.01	.00	.00	.02	.05	.00	.03	.11
K_2O	.32	.14	.34	.16	.24	.37	.21	.27	.18
H_2O-	.17	.18	.22	.29	.21	.19	.12	.08	.14
H_2O+	7.46	7.85	2.31	6.47	3.84	4.71	6.44	5.74	6.07
TiO_2	.10	.07	.18	.10	.15	.18	.10	.14	.11
CO_2	.35	.16	.02	.42	.52	.08	.22	.22	.06
P_2O_5	.99	.99	1.12	.57	.83	.85	1.09	1.00	1.11
S	.07	.08	.10	.08	.08	.36	.10	.12	.22
MnO	.19	.19	.12	.20	.93	.12	.15	.15	.19
C	.13	.10	.16	.18	.13	.43	.15	.19	.36
Total	100.27	99.85	99.59	100.28	100.19	99.78	100.20	100.08	100.18

SOURCE: James, et al (1968) Geology and Ore Deposits of the Iron River-Crystal Falls District, Iron County Michigan, USGS P.P. 570 (p. 109)

Sources of Information

The problems of mine subsidence and acid water drainage affecting the communities of the Iron River District are actually problems that mining companies faced during the development and operation of the mines. These problems were worked on to varying degrees by each company and reports of several of these efforts have been made available for this study.

Subsidence studies made by U.S. Bureau of Mines personnel on the Sherwood Mine property is one of these reports. Mr. Robert Edwards, Superintendent of the Sherwood Mine, kindly released this report for our use. Notes and letters on file at the Michigan Geological Survey from some of the earlier mining operations provided additional insites into water drainage and subsidence problems for the Rogers Mine in its early stages of development.

A comprehensive report on ground water entitled "Ground Water Problems of the Iron River District" by Wilbur Stuart, C. V. Theis and George Stanley published in 1948 by the Michigan Geological Survey is a particularly useful reference. Their purpose was to study ground water phenomena in the district so this knowledge could be used to reduce mining costs related to mine water problems.

R. C. Allen's 1910, 151 page report entitled "The Iron River Iron-Bearing District of Michigan", published by the Michigan Geological and Biological Survey (Publication 3, Geological Series 2), comprehensively covers the geology of the district as it was known then. The district was young then, being only into its 28th year of production. The report covers some of the early mining history and documents information on the earliest mining operations.

Three reports, part of a larger series of eight covering the Iron River-Crystal Falls District, describe the geology and mining operations in the

Iron River District. These reports were published by the Michigan Geological Survey, and are available from their Lansing office. The reports are:

Report of Investigation 4 - Geology and Magnetic Data for Northern Iron River Area (1967), H. C. James, C. E. Dutton and K. L. Wier, 46 p.

Report of Investigation 5 - Geology and Magnetic Data for the Central Iron River Area, Michigan (1969), C. E. Dutton, 17 p.

Report of Investigation 6 - Geology and Magnetic Data for the Southeastern Iron River Area, Michigan (1969), H. L. James and K. L. Wier, 30 p.

The two volumes entitled Lake Superior Iron Ores published by the Lake Superior Iron Ore Association in 1938 and 1952 provided a wealth of information on mining operations and iron ore shipments from the various mines.

A United States Geological Survey publication, Professional Paper 570, Geology and Ore Deposits of the Iron River-Crystal Falls District, Iron County, Michigan (1968) by H. L. James, C. E. Dutton, F. J. Pettijohn and K. L. Wier (134 p.), describes in detail the geology and theories of origin for the ores of the district. It is the most recent work on the district.

Joseph Bal of the Water Resources Commission, Escanaba office, has been concerned with the effects of pollution from acid water drainage for many years. Reports of tests, observations and attempts made to correct acid drainage from his files were made available to this study.

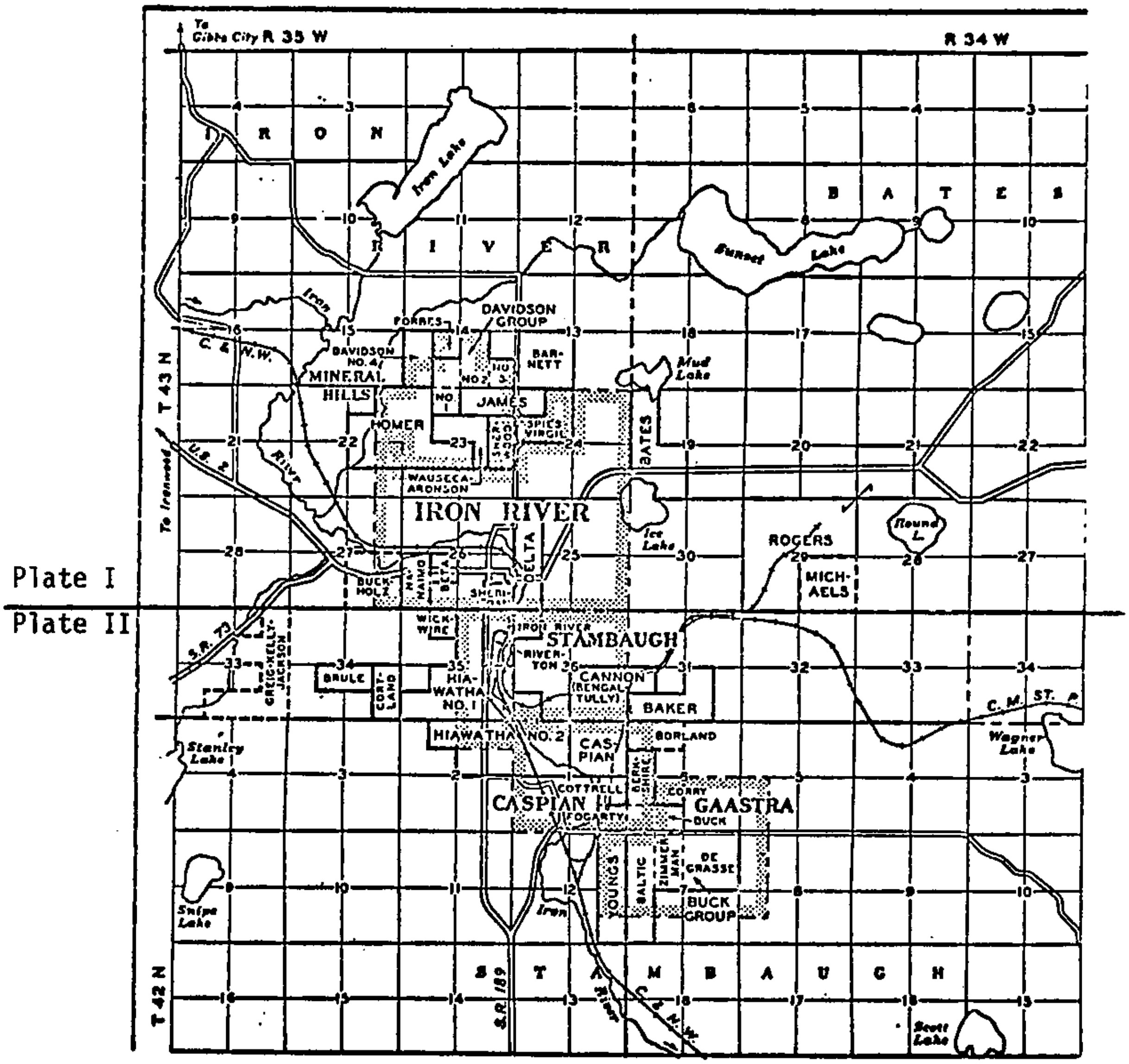
Jack Van Alstine of the Michigan Geological Survey, Marquette office, has also been concerned with aspects of acid drainage - particularly the effects of rising water levels and acid drainage on the operation of the Stambaugh Sewage Treatment Plant and corrosion of feeder lines to the plant. Work done by Van Alstine and Bal on these problems is covered by a file report incorporating significant amounts of data from tests that document the nature of the problem in the vicinity of the sewage plant quite well. The report by Van Alstine, "Acid Mine Water Problem at Stambaugh", has been of particular usefulness to the part of this study concerned with acid water drainage.

Mines

Some 55 separate mining operations are on record in the Iron River District. Some of them amounted to no more than a shallow shaft and limited exploration drifts, whereas others became major producers, shipping millions of tons of ore. Almost without exception the mines had vertical shafts, and were mined with some type of open stope or caving method. Peculiar to the Iron River District was the land ownership in forty acre blocks or combinations of them. Locations of the mining properties are shown on the map of Figure A-5.

The history of mine ownership in the district is very complex and although of interest, it is not germane to this report. However, each of the mining properties or individual "forties" has a name. Many of these individual mines were incorporated at a later date into a larger complex under singular ownership. Major recent operators in the district were the M. A. Hanna Company, Pickands Mather and Company, Cleveland-Cliffs Iron Company and Inland Steel Company. Of these, only Inland Steel Company remains active at its Sherwood Mine; however, it is scheduled to cease mining by mid-summer of 1978.

Major groupings of operations include: 1) the Buck group of mines owned and operated by Pickands Mather and Company comprising the Buck, Fogarty, Berkshire, Baltic, Zimmerman and De Grasse properties, 2) the Hiawatha Mine complex consisting of the Hiawatha #1 and #2, Dober and Isabella properties owned and operated by M. A. Hanna Co. Likewise M. A. Hanna Co. integrated the Homer, Cardiff and Wauseca properties into the Homer-Wauseca group in the



Source: Lake Superior Iron Ores Second Edition 1952

Figure A-5. Map of Mined Properties in the Iron River District western part of the Mineral Hills area, 3) the Davidson group of mines consists of four properties integrated by Pickands Mather and Company with the James Mine, 4) Cleveland-Cliffs Iron Company owned and operated the Spies group of mines consisting of the Spies, Virgil, Spies-Virgil and Spies-Johnson Mines, and 5) the Cannon Mine, owned by M. A. Hanna, is the combined Bengal and Tully properties.

Each of the mines or groups of mines is listed in Table A-3 along with the shipments of ore from each.

Table A-3

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: R. C. Reed (1975), Michigan Iron Ore Shipments Through 1974 - One Thousand Million Tons (p. 9) Mich. DNR Geol. Surv. Div. Circ. 12, 12 p.

Table A-4

pH Measurements
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	7.0	-	7.7	6.8	7.4	-	6.9	7.0	7.6	7.2	7.0	7.4
2	6.7	-	7.2	7.2	7.5	-	6.9	7.0	7.3	7.2	7.0	7.2
3	6.3	-	6.9	6.9	6.9	-	6.8	6.0	7.3	6.8	6.4	7.0
4	6.9	-	7.5	7.4	7.5	-	7.4	7.0	7.5	7.3	7.2	7.4
5	6.9	-	7.9	7.3	7.2	-	7.4	6.5	7.9	7.3	7.0	7.6
6	6.8	-	8.0	7.4	7.3	-	7.5	6.5	7.8	7.4	7.0	7.5
7	7.0	-	7.7	7.5	7.1	-	7.3	7.0	7.8	7.3	7.2	7.5
8	6.6	-	6.7	7.0	7.1	-	7.3	7.0	7.1	6.9	7.1	7.0
9	6.0	-	5.1	5.3	5.9	-	6.0	6.2	5.5	5.6	6.1	5.6
10	6.1	-	6.6	7.0	7.1	-	7.3	7.0	7.2	6.7	7.2	7.0
11	6.1	-	7.5	7.2	7.1	-	7.4	7.0	7.6	7.0	7.2	7.3
12	5.6	-	3.2	2.6	3.4	-	3.2	1.5	4.1	3.7	2.4	3.7
13	-	-	-	-	-	-	-	-	7.8	-	-	7.8
14	-	-	-	-	-	-	-	-	7.8	-	-	7.8
15	-	-	-	-	-	-	-	-	7.8	-	-	7.8
16	6.8	-	6.6	7.1	7.3	-	6.7	7.0	7.1	7.0	6.9	7.0
17	6.0	-	6.7	7.5	7.3	-	7.1	7.0	7.1	6.9	7.1	7.0
18	5.9	-	7.9	7.5	7.4	-	7.0	7.8	7.6	7.2	7.4	7.4
19	6.4	-	7.0	6.7	6.9	-	6.9	6.2	7.1	6.8	6.5	6.9
20	6.7	-	6.9	7.1	7.1	-	7.2	7.0	7.1	7.0	7.1	7.0
21	-	-	6.4	6.5	6.8	-	6.6	6.5	-	6.6	6.6	6.6
22	-	-	6.5	6.6	6.9	-	6.8	6.5	-	6.7	6.7	6.7

*Six sampling trips in 1975.

Table A-5

Acidity Values, mg/l $CaCO_3$
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	20	20	30	15	25	-	20	15	16	22	18	19
2	30	10	20	20	20	-	20	15	17	20	18	18
3	30	10	60	20	30	-	20	30	33	30	25	31
4	20	10	20	20.	25	-	10	15	22	19	13	19
5	30	10	20	15	25	-	15	15	23	20	15	21
6	20	15	20	20	20	-	15	20	25	19	18	22
7	30	15	30	20	20	-	10	20	24	23	15	22
8	40	20	25	30	30	-	20	20	36	29	20	31
9	430	750	525	400	400	310	350	370	535	501	343	482
10	35	20	30	30	20	-	20	20	33	27	20	29
11	25	20	25	30	30	-	20	20	25	26	20	25
12	2850	3350	3950	3950	3400	325	900	2875	2897	3500	1367	2784
13	-	-	-	-	-	-	-	-	27	-	-	27
14	-	-	-	-	-	-	-	-	30	-	-	30
15	-	-	-	-	-	-	-	-	25	-	-	25
16	30	20	25	20	25	-	25	25	28	24	25	26
17	50	20	40	20	25	-	25	15	30	31	20	29
18	60	-	40	40	50	-	55	35	43	48	45	45
19	20	30	30	30	20	-	25	25	33	26	25	29
20	50	15	40	30	30	-	20	25	27	33	23	29
21	-	-	125	150	130	125	120	110	-	135	118	127
22	-	-	205	140	145	110	125	120	-	163	118	141

*Six sampling trips in 1975.

$$\text{mg/l } CaCO_3 = \frac{A \times N \times 50{,}000}{\text{ml sample}}$$

where A = ml NaOH titrant
N = normality of NaOH

NOTE: Titrations done at ambient temperature to a phenolphthalein endpoint.

Table A-6

Specific Conductance, micromhos/cm
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2 **	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	210	130	391	400	270	-	230	300	279	280	265	277
2	84	52	180	212	150	-	130	155	169	136	143	152
3	590	170	112	1310	830	-	850	1050	815	602	950	754
4	81	50	160	190	140	-	120	163	118	124	142	124
5	110	78	201	181	120	-	120	158	149	138	139	143
6	212	122	343	423	255	-	205	290	245	271	248	255
7	223	165	392	420	260	-	240	293	291	292	267	288
8	280	210	600	650	345	-	315	400	391	417	358	396
9	2200	3180	3010	3420	2300	-	2650	2950	3000	2820	2800	2900
10	51	180	500	480	275	-	250	312	350	297	281	319
11	50	140	400	445	280	-	250	310	318	263	280	291
12	2750	4500	6200	7100	4020	-	1550	2800	4990	4910	2180	4530
13	-	-	-	-	-	-	-	-	317	-	-	317
14	-	-	-	-	-	-	-	-	283	-	-	283
15	-	-	-	-	-	-	-	-	280	-	-	280
16	272	200	540	640	330	-	320	410	414	396	365	400
17	235	178	381	462	270	-	260	315	342	305	288	319
18	342	-	620	720	395	-	420	580	560	519	500	535
19	930	1250	1490	1450	1030	-	1080	1250	1340	1230	1170	1270
20	266	200	590	670	320	-	320	400	266	409	360	335
21	-	-	2460	2830	1750	-	2000	2200	-	2350	2100	2280
22	-	-	2500	2810	1900	-	2350	2450	-	2400	2400	2400

*Six sampling trips in 1975.

**No conductivities run on Feb 2 samples.

Table A-7

Iron (Total) Analyses, mg/l Fe
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	0.60	0.51	0.33	0.18	0.38	-	0.32	0.27	0.84	0.40	0.30	0.59
2	0.31	0.28	0.48	0.62	0.22	-	0.42	0.40	0.33	0.45	0.41	0.36
3	1.69	1.13	1.44	1.53	2.55	-	2.29	2.00	0.90	1.67	2.15	1.39
4	0.18	0.13	0.21	0.18	0.15	-	0.19	0.12	0.18	0.17	0.16	0.17
5	0.14	0.29	1.12	0:13	0.21	-	0.31	0.32	0.11	0.38	0.32	0.24
6	0.36	0.30	0.18	0.24	0.32	-	0.29	0.74	0.22	0.28	0.52	0.29
7	0.57	2.06	0.30	1.34	0.40	-	0.38	1.87	0.35	0.93	1.13	0.69
8	3.78	5.33	9.01	3.60	3.33	-	1.56	2.31	4.81	5.01	1.94	4.44
9	151	258	182	135	132	97.0	109	142	186	172	116	166
10	4.46	6.05	15.1	1.44	2.63	-	1.10	1.81	4.85	5.94	1.46	4.75
11	1.07	0.63	3.13	0.58	0.65	-	0.56	0.80	0.54	1.21	0.68	0.82
12	794	1470	1610	1270	1310	820	143	1160	1125	1290	707	1090
13	-	-	-	-	-	-	-	-	0.32	-	-	0.32
14	-	-	-	-	-	-	-	-	0.32	-	-	0.32
15	-	-	-	-	-	-	-	-	0.31	-	-	0.31
16	3.82	5.61	8.46	3.86	3.14	-	2.01	1.94	5.36	4.98	198	4.69
17	3.41	5.87	17.9	1.25	2.52	-	4.20	1.37	6.38	6.19	2.79	5.75
18	0.15	-	0.11	0.39	0.14	-	0.15	0.28	0.08	0.20	0.22	0.14
19	2.59	2.21	1.51	1.50	3.03	-	2.86	2.27	1.97	2.17	2.57	2.14
20	2.36	4.84	10.2	1.65	2.56	-	1.48	1.26	4.79	4.32	1.37	4.08
21	-	-	17.8	14.5	19.7	12.1	15.8	16.1	-	17.3	14.7	16.0
22	-	-	7.22	3.17	5.80	4.1	8.02	7.84	-	5.40	6.65	6.03

*Six sampling trips in 1975.

Table A-8

Manganese Analyses, mg/l Mn
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	0.48	0.12	0.37	0.45	0.66	-	0.48	0.29	0.43	0.42	0.39	0.42
2	0.03	0.01	0.05	0.06	0.02	-	0.06	0.02	0.05	0.03	0.04	0.04
3	2.15	0.33	2.84	3.78	3.33	-	3.14	3.00	2.44	2.49	3.07	2.55
4	0.04	0.01	0.06	0.08	0.04	-	0.05	0.01	0.06	0.05	0.03	0.05
5	0.02	0.09	0.38	0.06	0.04	-	0.04	0.03	0.05	0.12	0.04	0.07
6	0.47	0.02	0.29	0.52	0.57	-	0.37	0.61	0.29	0.37	0.49	0.35
7	0.44	0.32	0.33	0.49	0.60	-	0.45	1.31	0.42	0.44	0.88	0.50
8	1.31	0.84	1.70	2.07	1.53	-	1.04	1.11	1.59	1.49	1.08	1.47
9	38.7	41.2	39.7	36.7	33.1	28.6	33.1	32.8	45.5	37.9	31.5	39.8
10	1.06	0.74	3.03	0.99	0.99	-	0.74	0.85	1.28	1.36	0.80	1.24
11	0.81	0.34	1.12	0.74	0.78	-	0.64	0.53	0.65	0.76	0.59	0.68
12	65.1	93.2	100	101	90.1	63.0	30.9	83.0	121	89.9	59.0	96.6
13	-	-	-	-	-	-	-	-	0.37	-	-	0.37
14	-	-	-	-	-	-	-	-	0.32	-	-	0.32
15	-	-	-	-	-	-	-	-	0.34	-	-	0.34
16	1.30	0.83	1.79	1.51	1.48	-	1.06	0.98	1.60	1.38	1.02	1.43
17	0.94	0.73	2.54	0.95	1.04	-	0.93	0.70	1.85	1.24	0.82	1.46
18	0.68	-	0.29	0.22	0.93	-	0.10	0.31	0.56	0.53	0.21	0.49
19	3.79	3.49	4.39	4.32	4.30	-	4.14	3.72	3.87	4.06	3.93	3.95
20	1.04	0.78	1.57	1.20	1.36	-	0.95	0.73	1.43	1.19	0.84	1.25
21	-	-	-	12.0	13.8	8.20	11.4	10.8	-	12.9	10.1	11.2
22	-	-	7.17	5.09	5.90	4.24	5.76	7.02	-	6.05	5.67	5.86

*Six sampling trips in 1975.

Table A-9

Sulfate Analyses, mg/l $SO_4^{=}$
Iron River Valley Water Sampled 1975-1977

Sample Number	1976					1977			Averages			
	Jan 29,30	Apr 20	Jun 22,23	Aug 25	Nov 10	Feb 2	Mar 10	Aug 18	1975*	1976	1977	Total
1	100	32	120	160	160	-	120	120	117	114	120	116
2	1	1	1	3	1	-	10	1	7	4	6	5
3	474	83	580	830	780	-	730	740	544	550	735	575
4	1	1	1	1	1	-	-	1	7	1	1	2
5	1	1	1	1	1	-	-	1	4	1	1	1
6	103	27	80	160	140	-	90	120	84	102	105	94
7	98	40	110	160	150	-	110	110	117	112	110	114
8	159	78	200	230	-	-	160	150	158	167	155	160
9	2600	2900	2700	2530	2500	2500	2420	2640	2810	2650	2520	2690
10	120	67	150	170	160	-	110	120	135	133	115	131
11	104	38	110	160	150	-	110	110	110	112	110	111
12	4270	4900	5700	6240	6160	4460	1810	3690	5130	5450	3320	4860
13	-	-	-	-	-	-	-	-	94	-	-	94
14	-	-	-	-	-	-	-	-	95	-	-	95
15	-	-	-	-	-	-	-	-	86	-	-	86
16	161	80	200	220	220	-	160	160	148	177	160	160
17	115	67	140	160	160	-	120	120	177	128	120	150
18	83	-	50	90	80	-	90	870	90	76	480	150
19	819	810	920	960	980	-	970	1330	898	898	1150	937
20	120	75	180	210	200	-	150	150	165	157	150	160
21	-	-	1740	1690	1720	1620	1530	1550	-	1720	1570	1640
22	-	-	1760	1720	1700	1680	1680	1740	-	1730	1700	1710

*Six sampling trips in 1975.

Table A-10

Aluminum Analyses, mg/l Al_2O_3
Iron River Valley Water Sampled 1975-1977

Sample Number	1976 Jan 29,30	1976 Apr 20	1976 Jun 22,23	1976 Aug 25	1976 Nov 10	1977 Feb 2	1977 Mar 10	1977 Aug 18	Averages 1975*	Averages 1976	Averages 1977	Averages Total
1	-	-	-	-	0.76	-	-	-	-	0.76	-	0.76
2	-	-	-	-	0.40	-	-	-	-	0.40	-	0.40
3	-	-	-	-	3.12	-	-	-	0.9	3.12	-	1.22
4	-	-	-	-	-	-	-	-	-	-	-	-
5	-	-	-	-	-	-	-	-	-	-	-	-
6	-	-	-	-	0.73	-	-	-	-	0.73	-	0.73
7	-	-	-	-	0.92	-	-	-	-	0.92	-	0.92
8	-	-	-	-	1.37	-	-	-	-	1.37	-	1.37
9	12.5	33.6	16.8	6.38	8.29	5.19	2.70	17.9	12.0	15.5	8.60	12.5
10	-	-	-	-	1.54	-	-	-	-	1.54	-	1.54
11	-	-	-	-	1.39	-	-	-	-	1.39	-	1.39
12	195	217	270	233	480	157	141	174	114	279	157	182
13	-	-	-	-	-	-	-	-	-	-	-	-
14	-	-	-	-	-	-	-	-	-	-	-	-
15	-	-	-	-	-	-	-	-	-	-	-	-
16	-	-	-	-	1.60	-	-	-	-	1.60	-	1.60
17	-	-	-	-	1.49	-	-	-	-	1.49	-	1.49
18	-	-	-	-	0.64	-	1.82	4.55	-	0.64	3.19	2.34
19	2.00	0.10	2.58	-	2.60	-	-	-	0.8	1.82	-	1.21
20	1.64	0.10	3.57	-	1.89	-	-	-	-	1.80	-	1.80
21	-	-	1.52	1.18	1.06	0.94	1.49	1.71	-	1.25	1.38	1.32
22	-	-	1.63	0.83	0.85	0.76	1.06	1.65	-	1.10	1.16	1.13

*Six sampling trips in 1975.