

Report of Investigations 8453

**Documentation and Analysis
of a Massive Rock Failure
at the Bautsch Mine, Galena, Ill.**

By Jack Touseull and Charles Rich, Jr.



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PREFACE

A large number of rock failures occur in underground mines and civil engineering projects each year. Some of these failures are of such magnitude as to affect the entire underground structure, or part of the structure. Each of the rock failures is, in effect, a fullscale in situ test of the rock in a particular situation.

Rock has been classified on the basis of mechanical and/or geological properties; however, very little information relating these classifications to specific mining problems--such as large rock failures--is available. Therefore, this investigation documents the occurrence of large rock failures and combines documentation with an analysis of failure, using supporting theory, laboratory studies, and other data to classify underground stability.

In a January 1971 final report entitled, "Definition of the Most Promising Lines of Research in Rock Mechanics," by a Commission of the International Society of Rock Mechanics, six subjects concerning rock failures were identified as having the highest priority. The present research project was selected on the basis of two of the research subjects: "Determination of Strength and Deformability of Fissured or Massive Rock Masses as a Function of Time," and "Correlation Between the Mechanical Properties of Rock and Geological and Petrological Data." The suggested "best approach" of the Commission was utilized to achieve the objective of the research project; that is, large-scale testing and documentation of the geology, petrological and mechanical data, and engineering experience in rock.

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DOCUMENTATION AND ANALYSIS OF A MASSIVE ROCK FAILURE AT THE BAUTSCH MINE, GALENA, ILL.

by

Jack Touseull¹ and Charles Rich, Jr.²

ABSTRACT

On November 15, 1972, the Bautsch mine, a lead-zinc mine in Paleozoic dolomites, experienced a massive rock failure involving 3 to 5 million tons. Because this failure was large and extended to the surface, it was included in the Federal Bureau of Mines investigations on "Massive Rock Failures."

Analysis of the rock mechanics and mode of failure revealed that failure at the Bautsch mine was the result of the interrelationship of many factors. Factors related to the failure were found to be external and internal to the mining environment. Unlike internal factors, external factors were not apparent and, therefore, many external factors were investigated; some of which are not normally considered in rock mechanics analyses. External and internal factors determined to be of significant importance were: (1) precipitation, (2) fractures, (3) plastic clay layer, (4) topography, (5) rock alteration, (6) bedding, and (7) mining zone dimensions.

Because of the conditions at the mine, failure could have been predicted without extensive instrumentation. Application of basic geologic and engineering principles to the internal and external factors could have predicted failure. Alternately, failure would, in all probability, have been delayed by years if, after 1962, mining had been curtailed in the area of failure.

INTRODUCTION

On November 15, 1972, the Bautsch mine—a lead-zinc mine in Paleozoic dolomites—experienced a massive rock failure³ (fig. 1) that led to the closure of the mine. A room-and-pillar mining system was being utilized at a depth between 160 and 400 feet (48.4 to 121.9 meters). Average extraction ratios were 81 percent in the failure area. Excessive extraction ratios was ruled out as a possible cause of the failure because many of these openings in the

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³A massive rock failure is a failure of the rock mass, either intentional (block caving) or unintentional (roof falls, floor heave, or subsidence), around underground openings involving areas in excess of thousands of square feet or hundreds of cubic yards.



FIGURE 1. - Surface failure over the Batsch mine looking south.

failure area had been stable for 10 years or more. Therefore, an alternate model of failure was needed to explain the failure.

Because of the size of the failure, the mine was included in the Federal Bureau of Mines Research Program. This report documents the geology, mining method, and sequence of rock failures and relates these factors to current knowledge in rock mechanics so as to present a plausible explanation for failure.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the Eagle-Picher Industries, Inc., in Galena, Ill. particularly H. H. Hammon, manager, and A. E. Viscan, regional geologist, for their cooperation in this investigation.

LOCATION AND CLIMATE

The Bautsch mine is located approximately 5 miles south-southeast of Galena, Ill. and 1 mile east of the Mississippi River (fig. 2). This area is a part of the Upper Mississippi Valley Zinc-Lead District (9).⁴

The climate of the area is cool-temperate with heavy snows and considerable periods of subzero temperatures (14). Temperatures are usually 20° to 30° F (-7° to -1° C) in the winter and 65° to 75° F (18° to 24° C) in the summer. The first and last frost generally occur in late September and late April, respectively. Annual precipitation (appendix A) is about 34 inches (86.4 centimeters) and is usually well distributed, however, there are periods when rainfall greatly exceeds the monthly average (appendix B).

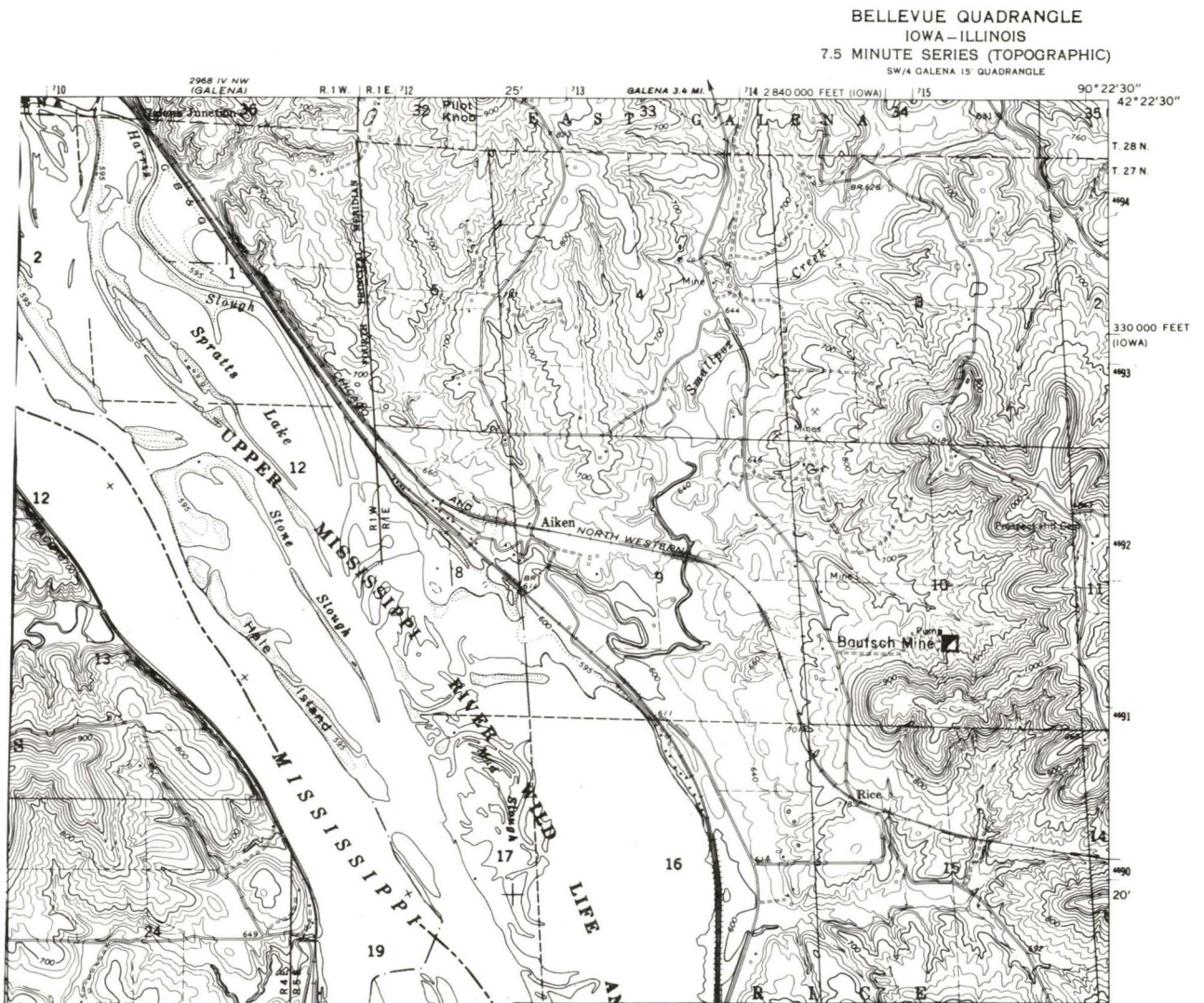


FIGURE 2. - Location and physiography of the Bautsch mine.

⁴Underlined numbers in parentheses refer to items in the list of references preceding the appendixes.

GENERAL PHYSIOGRAPHY

The area around the Bautsch mine is absent of any glacial deposits or glaciations; and as a result, this region has been designated the "driftless area." However, Pleistocene bench and terrace gravels, sands, and clays are common in the valleys.

The gently rolling relief ranges between 700 and 800 feet (213 and 244 meters) above sea level, but a number of low escarpments and isolated hills increase this on a local basis by about 200 feet (61 meters). One such hill lies directly over the southern end of the mine (fig. 2).

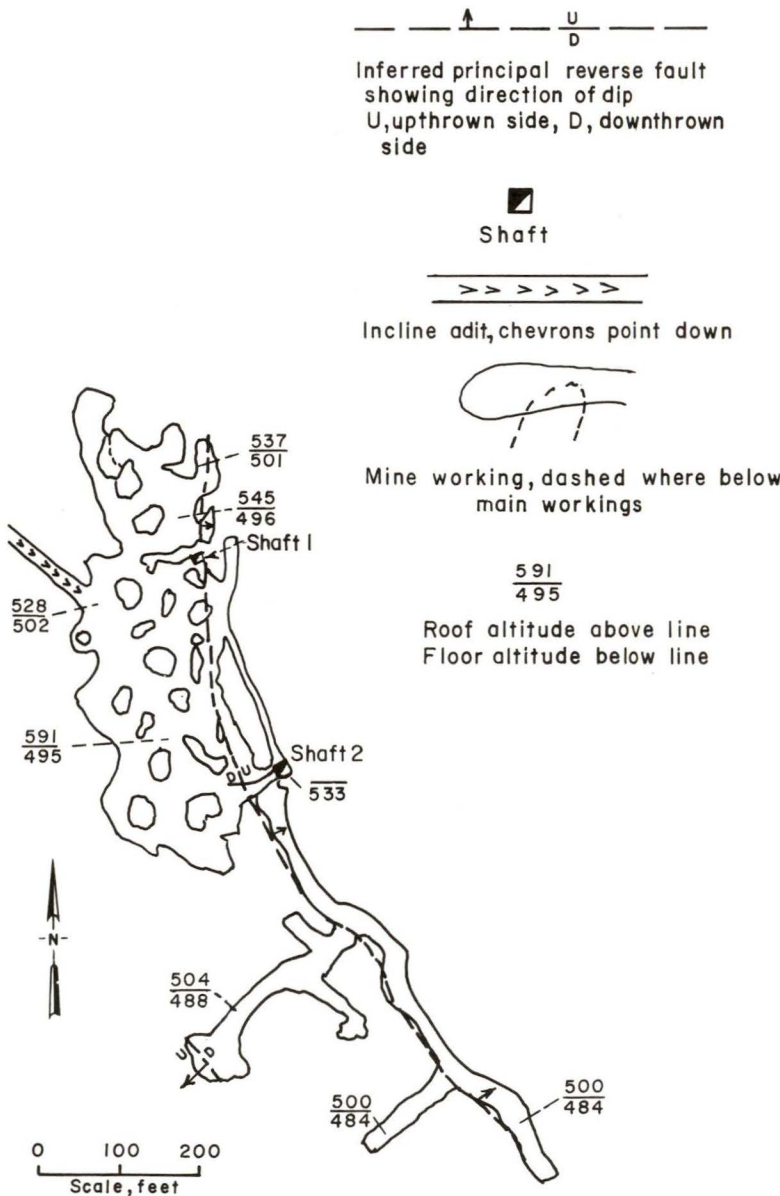


FIGURE 3. - Map of Bautsch mine.

A dendritic network of intermittent and perennial streams, all tributaries to the Mississippi River, drains the area of the Bautsch mine.

HISTORY OF THE BAUTSCH MINE

The ore body was found in 1944 (18) and put into operation in 1946 by Tri-State Zinc, Inc. Exploratory drilling at that time indicated an ore body of more than 2,000,000 tons (1,816,000 metric tons), making the ore body the largest known in the district.

In 1949, the mine comprised an area of over 2.56 acres (10,359 square meters) and consisted of two shafts and a truck incline (fig. 3). Water was being pumped from the mine at a rate of about 1,500 gal/min (5,677 liters/min).

According to company information, the first signs of ground movement occurred underground in 1961 or 1962. Pillars A, B, and C failed near the center of the mine (fig. 4).

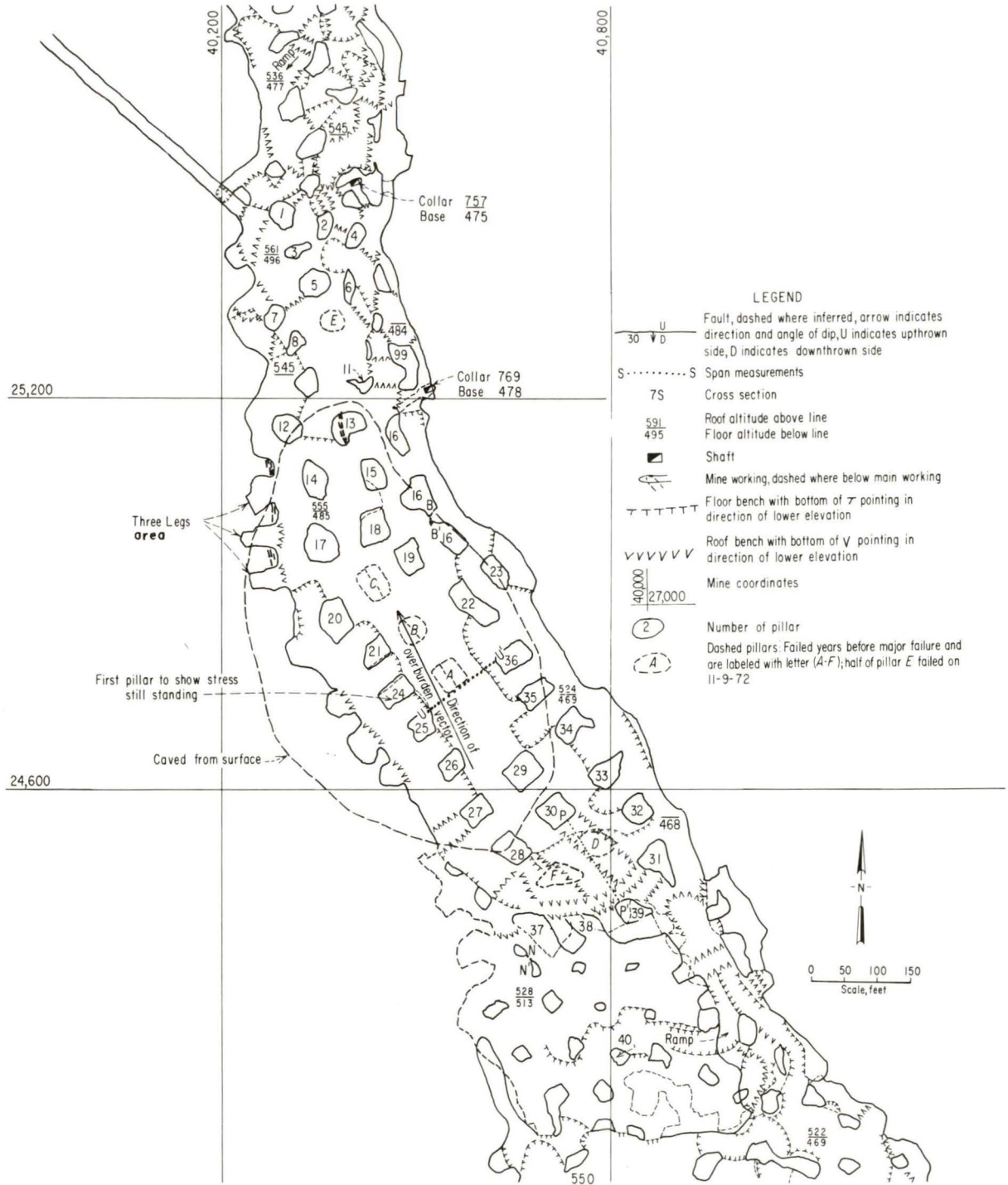


FIGURE 4. - Batsch mine failure area.

From 1963 to 1968, operations at the mine were terminated, and the mine was allowed to flood. Flooding did not intrude all the workings, but only encompassed the southern end of the mine to about 100 feet (30.5 meters)

north of shaft 2. After dewatering in 1968, it was discovered that pillar D had failed during flooding by tipping over intact (private communication from Eagle-Picher Industries, Inc.).

The first serious signs of ground movement in the form of pillar slabbing occurred in the south end of the Bautsch mine on September 9, 1972. Slabbing from various pillars continued until October 13 when sections of brows began to fall. The size of these failures and the rate of activity increased and necessitated that all mining in the south end be halted on November 9. This was followed by pillar failures and the massive failure on November 15. (See appendix C for a more detailed chronology.)

The failure extended to the surface and involved an area of 5.04 acres ($\approx 204,000$ square meters) and an estimated 3 to 5 million tons (2.72 to 4.54 million metric tons) of rock. The resulting massive failure completely cut off access to the central and southern end of the mine and led to an early closing of the mine in May of 1972.

MINE DESCRIPTION

A room-and-pillar mining method was used at the Bautsch mine. Ore was broken by conventional drilling and blasting and loaded into trucks by means of electric shovels and front-end loaders. A truck incline and two shafts were utilized for haulage, access, and ventilation. Mining was at a depth of 160 to 400 feet (48.8 to 121.9 meters), with an average depth of 250 feet (76.2 meters) in the failure area.

Depending on the area of the mine, the pillars were irregular or rectangular in shape and randomly or regularly spaced. Pillar dimensions ranged from approximately 10 to 50 feet (3 to 15.2 meters) horizontally from 10 to 130 feet (3 to 39.6 meters) vertically. Unsupported spans ranged from approximately 20 to 130 feet (6.1 to 39.6 meters). Also, floor and back elevations are very irregular (figs. 5-6).

In the area of failure (fig. 4), the pillars were generally rectangular and regularly spaced; however, at the southern and northern ends, the pillars were rectangular and irregular in shape (figs. 5-6), respectively. Average dimensions of pillars in the failure area were 92 feet (28 meters) vertically and 36.75 feet (11.2 meters) horizontally. Average spans in the area were 75 feet (25.5 meters), with the mine's maximum span of 130 feet (39.6 meters) along section line U-U' in figure 4.

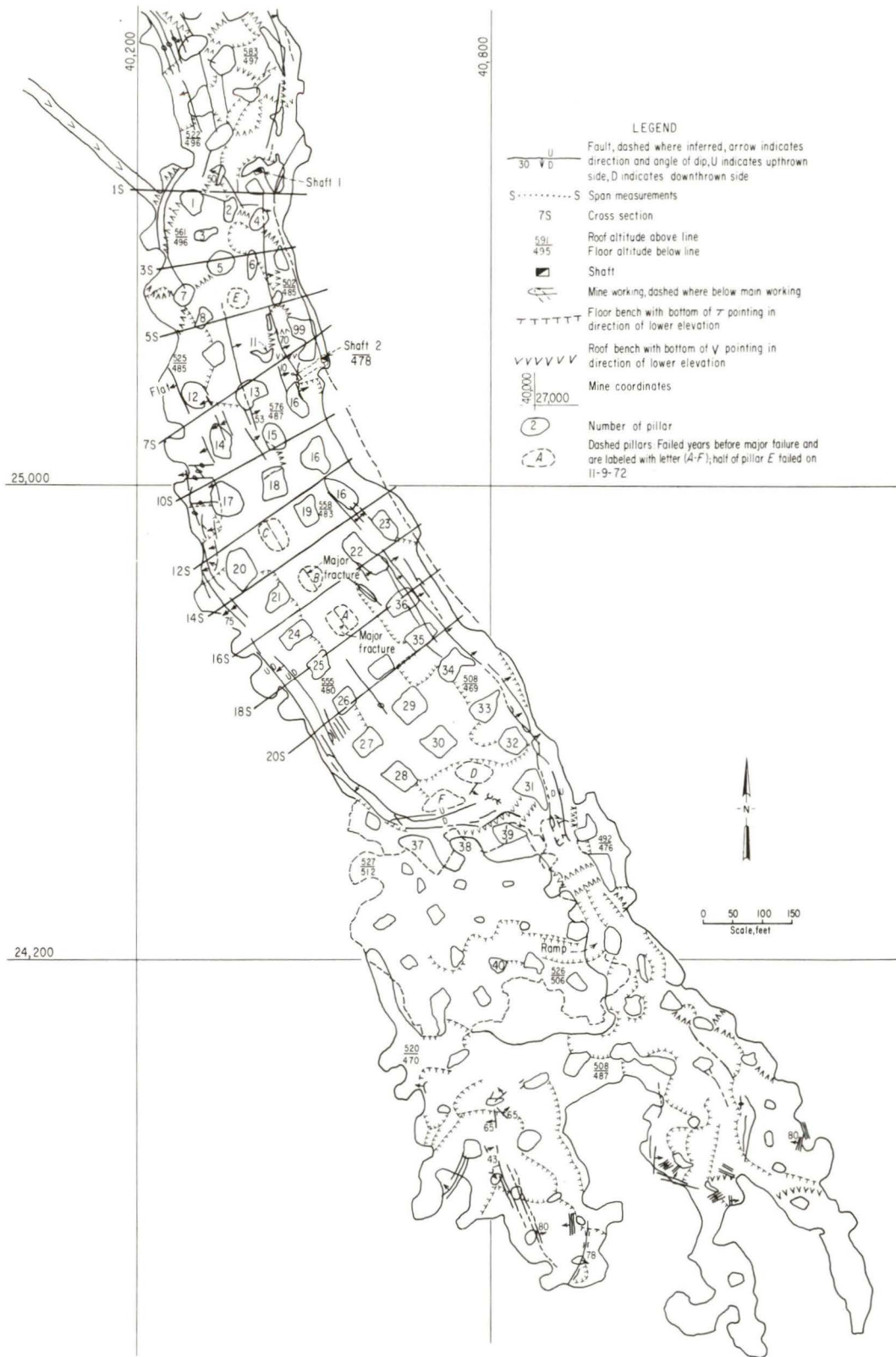


FIGURE 5. - Batsch mine geology—south.

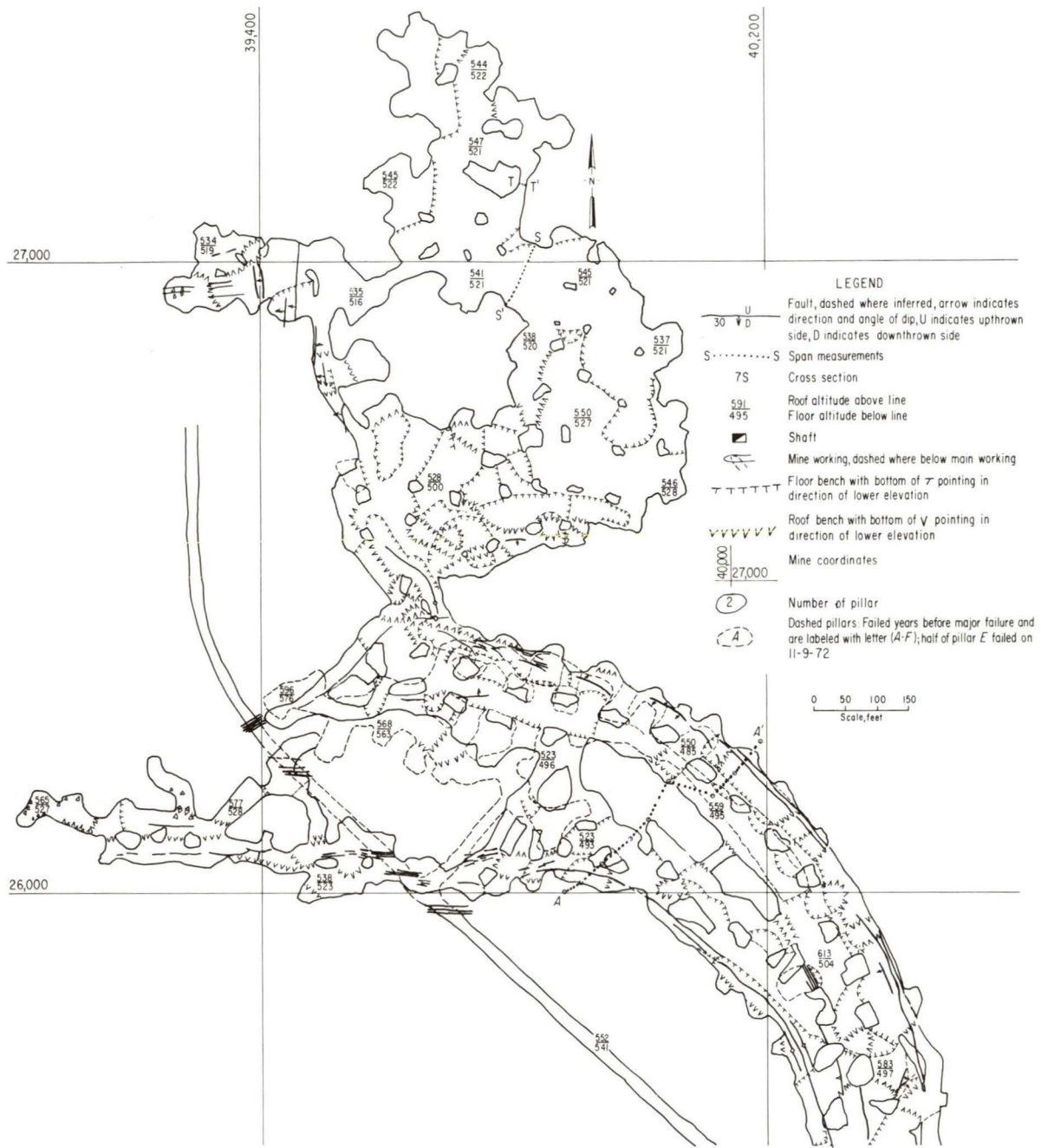


FIGURE 6. - Batsch mine geology—north.

GEOLOGY

An understanding of the geology at the mine is critical in determining the relationship of geologic factors to the massive failure. A brief review of the regional and local geology pertaining to the failure follows.

General Regional Geology

Regional Stratigraphy

In general, the rocks of the district (fig. 7) are Late Cambrian to Early Silurian sedimentary sandstones, dolomites, limestones, and shales, with a total thickness of about 1,800 feet (549 meters). Large and numerous caverns and sinkholes were formed in the dolomites of the Prairie du Chien Group and, to a lesser extent, in the Galena Dolomite and Silurian formations.

Regional Structure

Structurally, the Upper Mississippi Valley Zinc-Lead District is an uplifted, gently southerly sloping area, bounded by the Wisconsin dome, Wisconsin Arch, Savanna-Sabula anticline, and the Forest City basin (fig. 8).

	System	Series	Group or formation	Description	Approximate thickness, feet	
SILURIAN	Middle		Hopkinton Dolomite	Dolomite, buff, cherty, <i>Pentamerus oblongus</i> common	190+	300+
		Lower	Kankakee Formation	Dolomite, buff, cherty	45-50	
ORDOVICIAN	Upper		Edgewood Dolomite	Dolomite, gray, argillaceous	9-116	108-240
			DISCONFORMITY	Shale, blue, dolomitic, phosphatic, depauperate fauna at base		
	Middle		Maquoketa Shale			
		Galena Dolomite		Dolomite, yellowish-buff, thin-bedded, shaly	40	225
				Dolomite, yellowish-buff, thick-bedded	80	
				Dolomite, drab to buff, cherty	105	
			Decorah Formation	Dolomite, limestone, and shale, green and brown, phosphatic nodules and bentonite near base	35-40	
			Platteville Formation	Limestone and dolomite, brown and grayish, green sandy shale and phosphatic nodules at base	55-75	
	Lower		St. Peter Sandstone	Sandstone, quartz, coarse, rounded, local anomalous variations in thickness	28-340	280-340
			DISCONFORMITY	DISCONFORMITY		
		Prairie du Chien Group (undivided)	Dolomite, light-buff, cherty, sandy near base and in upper part, shaly in upper part	0-240		
CAMBRIAN			Trempealeau Formation	Sandstone, siltstone, and dolomite	120-150	
			Franconia Sandstone	Sandstone and siltstone, glauconitic	110-140	

FIGURE 7. - Stratigraphic column of the Upper Mississippi Valley District.

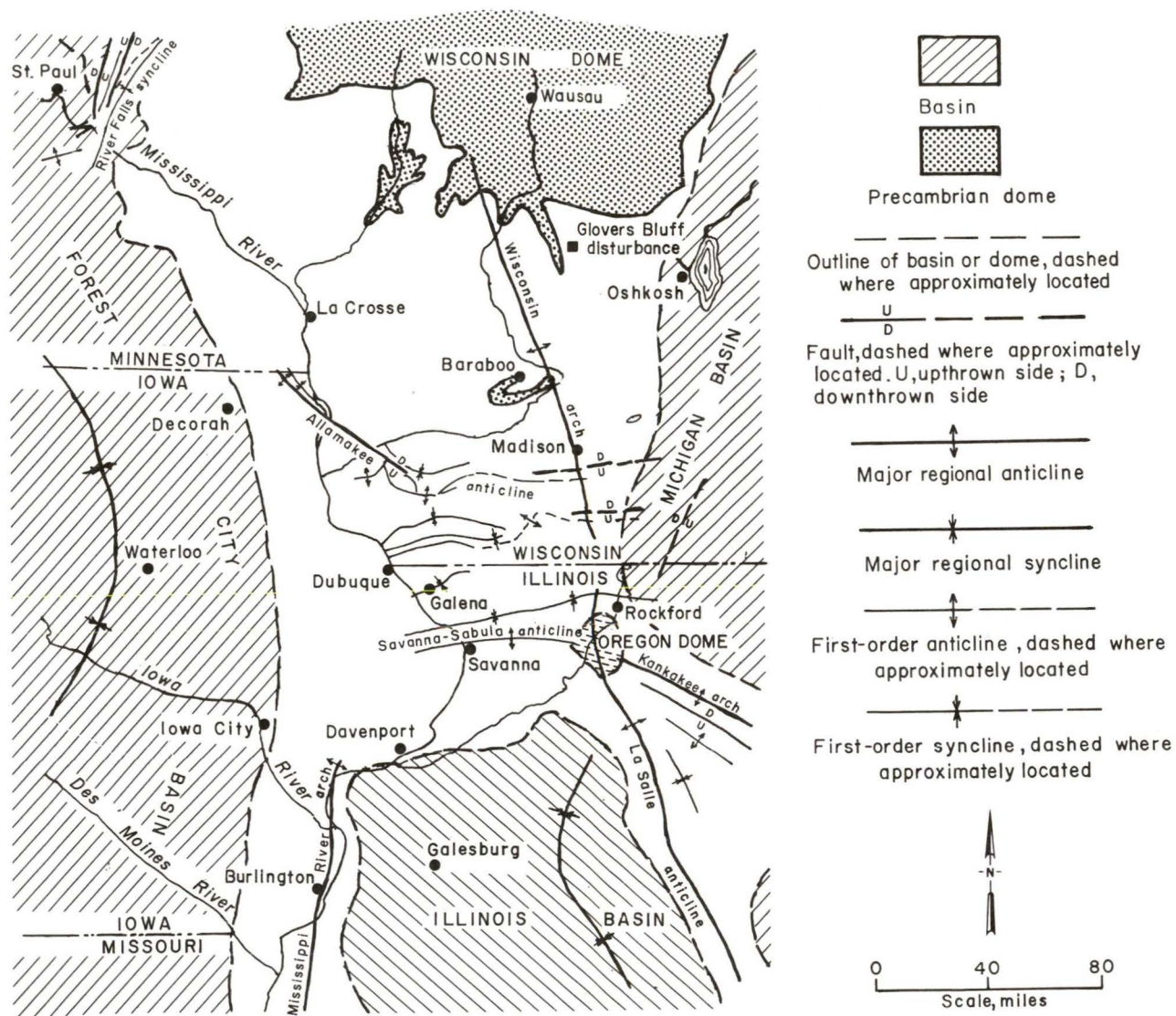


FIGURE 8. - Generalized diagram showing the major structural features of the region and relationship within the district.

The rocks of the district are folded into low, broad undulations that trend northeastward, eastward, or northwestward and can be grouped into three orders of magnitude: first, second, and third. The folds are asymmetrical in form; and in general, the northern limb of the folds dips more steeply than the southern limb. The greater inclination of the limbs toward the north and northeast, along with the orientation of joint sets, strongly suggests that lateral compressional forces acted principally in the N-S, and to a lesser extent, the NE-SW directions.

Most of the faults in the district are reverse, bedding-plane, normal, or shear faults. Displacements are generally of magnitudes less than 10 feet (3 meters), but a few are larger (9).

The reverse and bedding-plane faults are zones of fracturing along the limbs of second- and third-order folds. These faults are situated not only along the limbs of the folds, but also commonly around the ends of the folds, forming general arcuate patterns (9). Most of the reverse faults flatten downward and join underlying bedding-plane faults; generally in the Spechts Ferry Shale. Interconnection with bedding-plane faults also occurs in the beds above, forming a general interconnected system (fig. 9), with the dips of the reverse faults, nearly everywhere, toward the bordering anticlinal areas. Without exception, the reverse faults appear to be caused by compression rather than collapse, but the bedding-plane faults are a result of tectonic stresses producing bedding-plane movement in incompetent members—particularly the Spechts Ferry—and along the limbs of folds (9).

All the rock formations in the district contain well-developed vertical and inclined joint sets. The vertical joints of the district all appear to

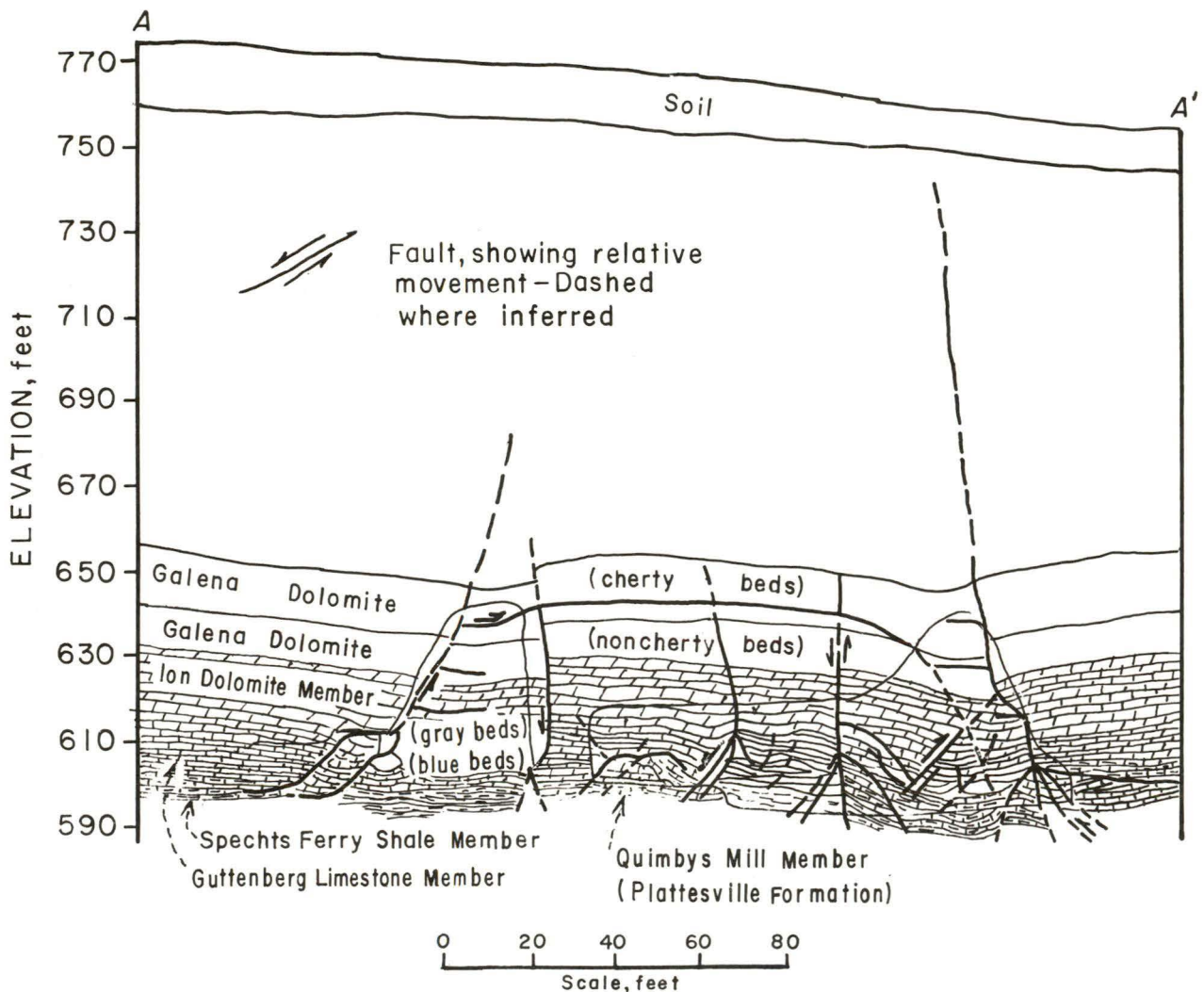


FIGURE 9. - Structural complexity and thinning in the incompetent beds of the Lower Decorah.

have resulted from compressional forces during the period of regional deformation, whereas, the incline joints appear to be related to local folding and reverse faults.

The vertical joints basically comprise three sets, referred to here as J_1 , J_2 , and J_3 . The J_1 set consists of mainly tensional release joints that trend in the direction of the fold axis. The J_2 and J_3 sets are tight, conjugate shear joints that form an acute angle approximately bisected by the plane perpendicular to the fold axis.

The incline joints consist mainly of two sets that are referred to here as J_4 and J_5 . These joints are generally localized and strike parallel to the limbs of individual folds, dipping 40° to 60° toward and away from the fold axes. Most of these joints zigzag across the bedding and occur in closely spaced zones. Joint set (J_4)-dipping away from the synclinal axis-is tight, while joint set (J_5)-dipping toward the synclinal axis-is more open and irregular.

Regional Economic Geology

The district mineral deposits are classified as: (1) pitch-and-flat, (2) gash vein, (3) stock works, (4) bedded replacements, (5) solution-collapse breccias, (6) fissure veins, and (7) ore-lined vugs. Of these types, the first two are the most common (8-9).

Average percentage of ore minerals in the productive areas of the district are 5 percent for zinc, 0.5 percent for lead, and 8 to 15 percent for iron (9, 18).

Supergene enrichment of the primary sulfide ores are common where deposits are within 30 to 100 feet (9.1 to 30 meters) of the present land surface. The oxidized zone generally continues for a few feet below the water table, but extends as much as 100 feet (30 meters) below the water table along some open fractures.

The origin of the ore has been debated for many years, but recent developments favor a hydrothermal origin. Ore deposition probably originated from a mixture of heated connate and magmatic water, the latter probably being the small fraction.

Regional Wall Rock Alteration

In the immediate vicinity of the deposits, the ore-bearing solutions have formed alteration halos in the host limestones, and to a lesser extent, the dolomites. Alteration is of five types: solution of carbonate rocks, silicification, dolomitization, clay-mineral alteration, and the formation of sanded dolomites. The last type of alteration means dolomites were altered to a friable or incoherent mass of crystals by ore-bearing solutions and ground-water weathering.

Solutioning of the carbonate rocks has caused considerable thinning of favorable beds, resulting in the opening of fractures, and leaving only an argillaceous residuum and, in places, formation of tumble breccias. (See appendix E for detailed effects of alteration on specific formations and members.)

Regional Hydrogeology

All the Paleozoic sedimentary rocks of the district, except the St. Peter Sandstone and Quimbys Mill Member of the Platteville Formation, have very low primary permeabilities. However, owing to the widespread faults and joints, an interconnected fracture system between permeable beds produces high secondary permeabilities. Combined with the enlargement of fractures by solutioning, water movement is essentially unimpeded, both vertically and laterally.

Geology of the Bautsch Mine

Local Stratigraphy

The Maquoketa Shale and part of the Galena Dolomite comprise the overburden at the Bautsch mine. The mining zone encounters rocks from the McGregor Member of the Platteville Formation, up into the Galena Dolomite (fig. 10). In general, the mine stratigraphic section is composed of thin- to thick-bedded limestones, dolomites, shales and a thin clay bed (Spechts Ferry), with a significant bentonite content. (For a detailed lithologic description, see appendix E, and mine cross sections in appendix F.)

Local Structure

The mine is developed along a synclinal trough known as the Bautsch-Black Jack trough. This trough is an undulating, northwest trending second-order fold, with a length of less than 3 miles (4.8 kilometers) and a width of less than 500 feet (152.4 meters). Although the general trend is northwest, the fold axis varies from N-NW to W (figs. 4-5). This is probably because of modification of the second-order fold by third-order folds in the trough.

Reverse and bedding-plane faults, as described under the regional structure section, are common (figs 5 and 9, and appendix F). The cross sections in appendix F and in figure 9 show the contrast between the more steplike, weaker fault zone on the SW limb of the syncline, and the more numerous straighter reverse faults on the NE limb.

Owing to the undulating fold axis, the strike of the release and conjugate joint sets will vary along the fold, but will have the same orientation to the fold axis. In addition, observations made of joints in the mine indicated that they are tight. Because mining, overburden pressures and/or weathering could have closed or altered the joints' appearance, it would be more reasonable to assume the regional joint descriptions.

Formation of the Bautsch-Black Jack trough was by minor northeastward compressive forces during the period of district folding. Release joints

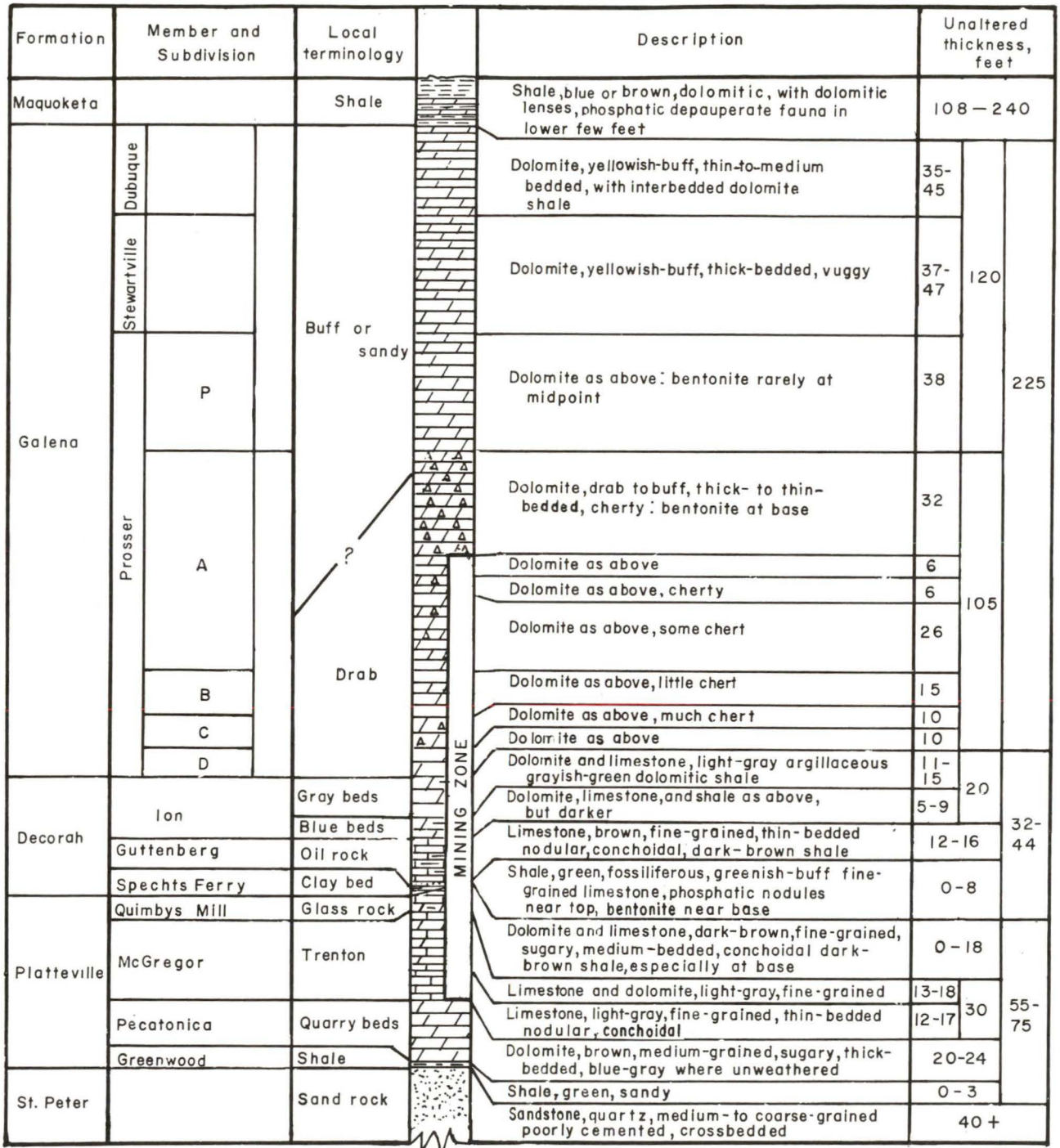


FIGURE 10. - Detailed stratigraphic column of the formations in the zinc-lead district.

along the fold axis suggests that the compressive forces have relaxed in that direction, at one time or another, but does not necessarily mean that these forces are still relaxed.

Local Economic Geology

The main ore body is a linear pitch-and-flat deposit with ore in both east and west dipping-pitch zones, and accompanying core ground. However, gash vein lead is found in the lower Galena Formation.

Ore occurs in all beds from the McGregor Member of the Platteville Formation upward, to about 70 feet (21.3 meters) above the base of the Galena Dolomite, approximately 140 feet (42.7 meters). The ore is primarily high-grade sphalerite, with minor amounts of galena occurring mainly in veins, replacements, and as some breccia ore.

Mineralization becomes leaner toward the north, although the mineralized structure, not fully prospected, continues to the Grey ore body 1,000 feet (305 meters) to the north. The southern end of the ore body also becomes leaner and lies directly beneath a hill capped by the Maquoketa Formation (18).

Local Wall Rock Alteration

The Bautsch mine ore body is notable not only for its large size, but also for the unusually large amount of solution thinning that has led to marked accentuation of all the lithologic units (fig. 11). For example, two adjacent vertical drill holes obtained 13 and 7 feet (4 and 2.1 meters) of drill core for the Guttenberg Member, respectively.

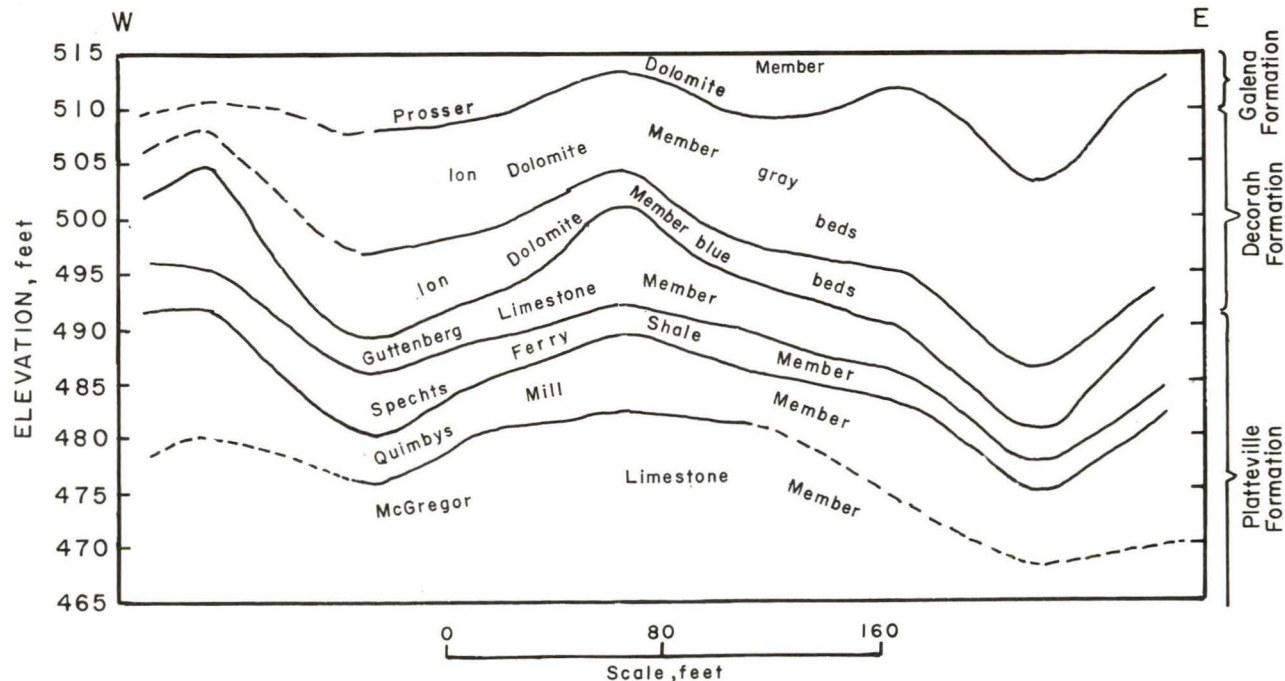


FIGURE 11. - Cross section midway between shafts 1 and 2 of the Bautsch mine showing solution thinning of pre-Galena beds.

Locally, solution sags, breccias, and collapse breccias are abundant in the ore body. Also, it appears from observations of the dolomites that at least "sanding" alteration has taken place.

Local Hydrogeology

Although the McGregor Member is a recognized aquifer in the district and mine, most of the other beds present are also adequate aquifers. This is primarily due to the fracture system and secondary openings.

Prior to mining at the Bautsch mine the water table was at the Maquoketa Shale-Galena Dolomite contact. Because of mining, drawdown had sufficiently depressed the water table—temporarily, if not permanently—to a new elevation of 495 feet (151 meters). This was evident during the period from 1963 to 1968 when mining activity ceased, and natural flooding of the mine did not occur above that elevation, even though this flooding was 100 feet (30.5 meters) below the level of the Mississippi River. The only plausible explanation for this fact is a closed trough-type structure which is hydrologically isolated.

Also, it might be expected that infiltration rates of ground water into the soil on the northern slope of the hill, overlying the mine (northern hemisphere), would be much higher due to lower evapotranspiration rates.

MECHANICS OF MASSIVE ROCK FAILURE

In order to analyze the Bautsch mine massive rock failure, many factors were examined. Some factors directly related to the failure were overburden composition, depth, fracture patterns, mining spans, and pillar dimensions. Some factors not directly related to the mine, but whose influences were, included earth tremors, hydrology, and topography. The following detailed analysis attempts to determine the relationship between these various factors and the massive failure.

Earth Tremor Analysis

A possible, although remote, factor is an earth tremor that occurred on the morning of September 15, 1972. The epicenter registered 3.7 on the Richter scale (VI on the Modified Mercalli intensity scale) and occurred about 74 miles (118.4 kilometers) SE of the Bautsch mine (fig. 12), at a depth of 3.1 miles (5 kilometers). However, because of the small intensity (IV-V) felt at the mine and because no further progression of ground instability occurred until 2 weeks after, the conclusion was that any compression and dilation of water-bearing rock, as a result of the seismic waves, did not, in all probability, contribute significantly toward failure (6).

Hydrological Analysis

Rainfall data (appendixes A and B) for the Bautsch mine, considering recharge and evapotranspiration (appendix G), show a direct correlation with failure activity and the time at which failure occurred. That is, times of increased failure activity or activation of failure activity occurred during

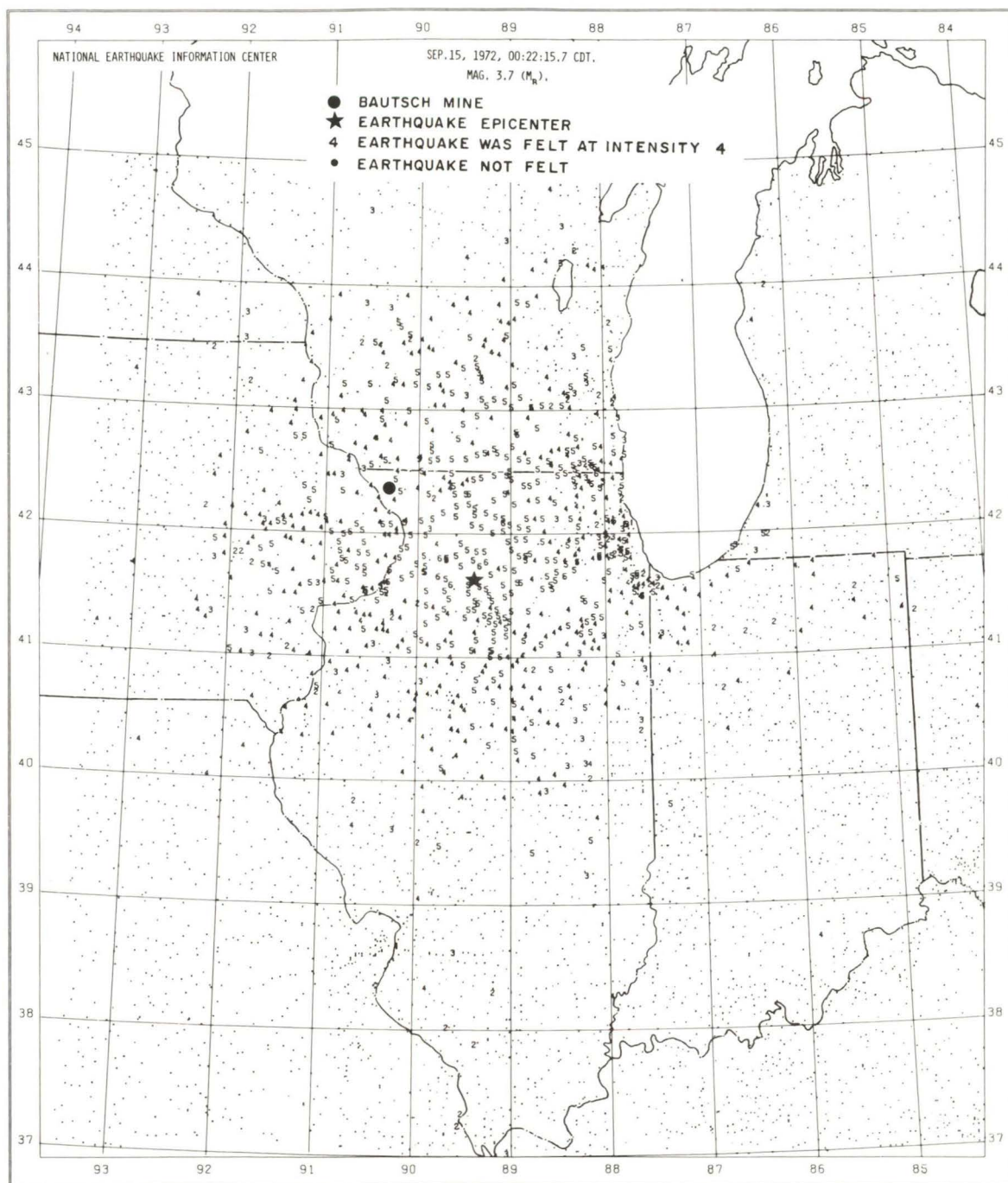


FIGURE 12. - Location and area affected by Illinois earthquake of September 15, 1972.

periods that showed unusually large amounts of precipitation being available for ground-water recharge (7). Periods of high recharge in general, were 1961, 1962, 1965, 1968, and 1972; 1961, 1962, and 1972 correspond to when failure activity was first noted and the final failure occurred. As for the high discharge periods during 1965 and 1968, no observations were possible because the

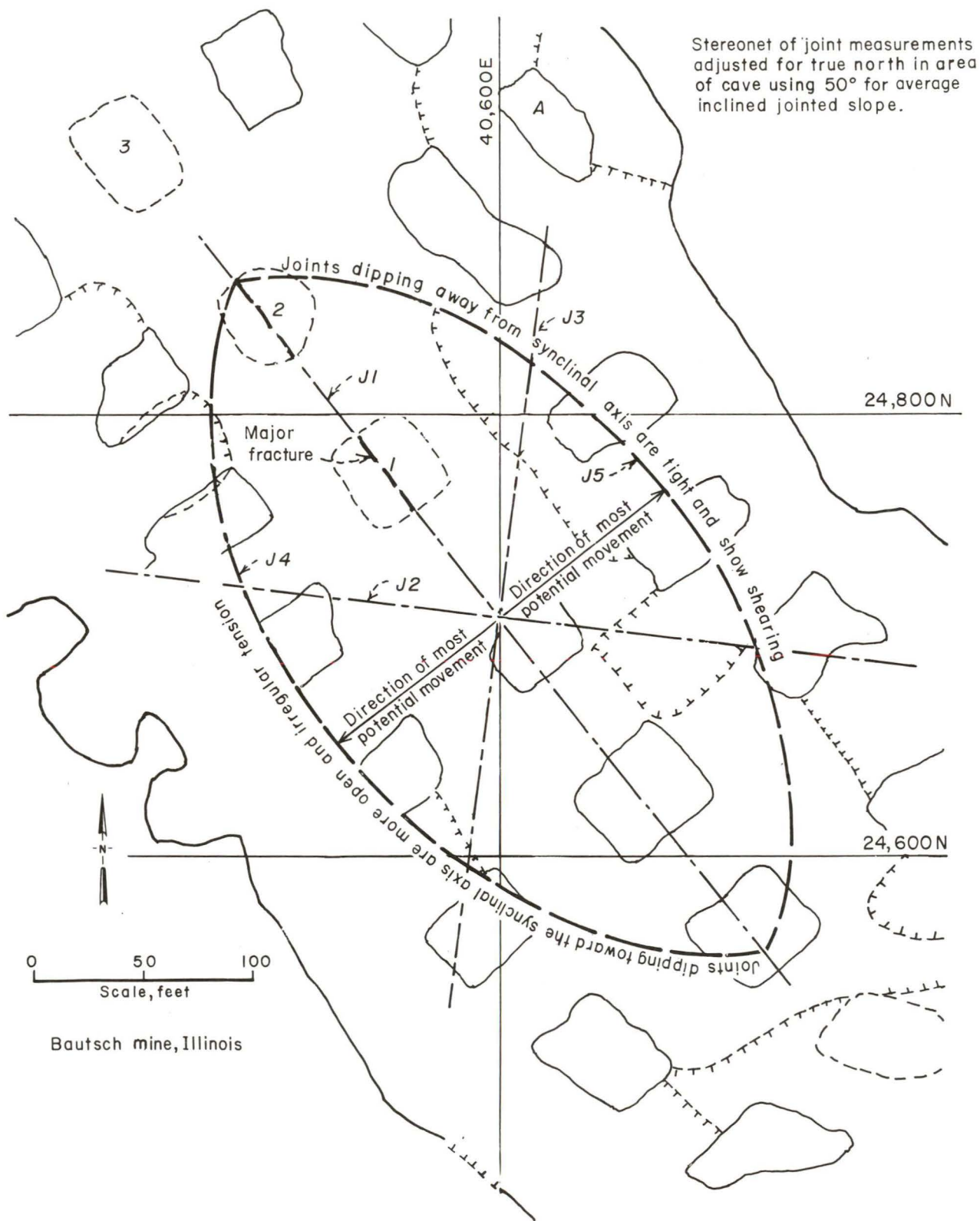


FIGURE 13. - Stereographic projection of joints in area of failure.

mine was flooded. However, it was observed after the mine was dewatered in the latter part of 1968, that the area of instability had increased. This was based on the observed failure of pillar D.

The effect of large amounts of moisture introduced into the overburden essentially decreased the safety factor of the supports, by increasing the moisture content of the overburden and clay layer (increased unit weight), and lubricating potential failure surfaces. Also, the occurrence of the failure under the north slope of the hill suggests that the effect of the lower evapotranspiration rate on ground-water recharge, and hence the effects of ground water recharge, may have influenced failure.

Fracture Analysis

From an analysis of the fractures at the mine, it was evident that these features affected the mode of failure and the strength of supports. For example, a stereographic plot of joint set readings (including inclined sets) taken on the surface, in the area of failure, was made and corrected for true north. When the plot was overlaid on the area of failure (fig. 13), the following relationships were observed: (1) the direction of potential movement along sets J_4 and J_5 was approximately perpendicular to the long dimension of the mine; (2) vertical set J_1 projected directly along the major fractures underground; and (3) vertical sets J_2 and J_3 are orientated so that they can act as release surfaces for block movement.

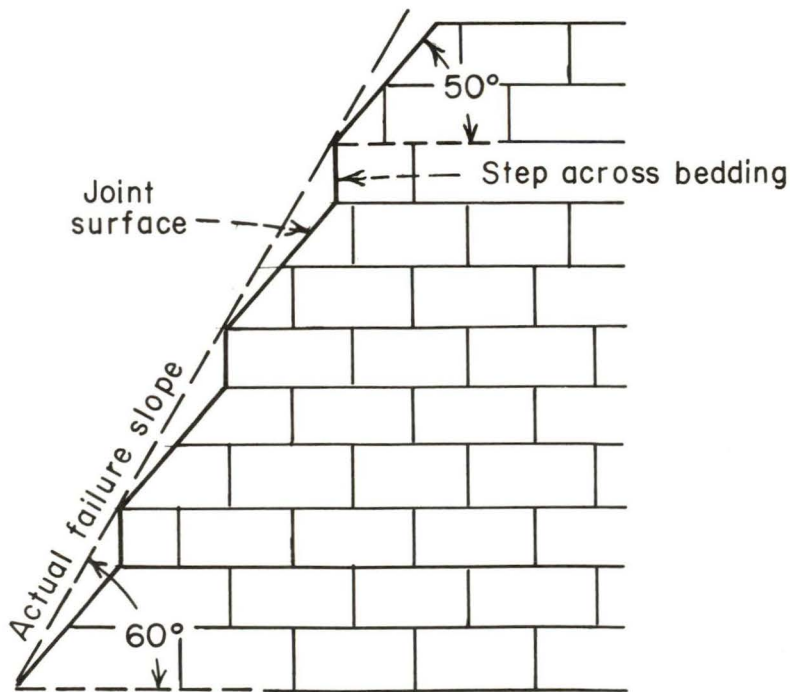


FIGURE 14. - Example of step failure along joint surfaces.

These relationships indicate that a section of the overburden (within the failure area) was outlined by joint sets. Therefore, the natural structural resistance to failure was reduced.

Calculation of the slope angle on the west side of the failure was about 60° east. The angle is slightly larger than the average dip of inclined joint sets in the district, but it is probably due to a steplike failure (fig. 14). This is a reasonable assumption because the inclined joints are not continuous, but zigzag across the bedding.

The east side of the failure had a steeper

slope-- $\sim 79^\circ$ west--and appeared to be overhung. This slope is a result of the northeast limb of the fold containing steeper inclined joint sets and a more steplike fracture system (fig. 9).

Because the east haulage way appeared to be open, on November 20 (appendix C), pillars 15, 16, 19, 22, 35, and 36 were assumed to be still supporting a load. This is interpreted as indicating that the failure slope is probably stable and not overhung.

Lastly, the high-angle inclined joints and vertical fractures transecting pillars will greatly decrease pillar strength. A complete discussion of the effect on pillar strength is contained in the mining dimension analysis section.

Clay Layer Analysis

Underlying the mined-out area and transected by the haulage way along the east wall, is a plastic clay (Spechts Ferry) layer. (See appendix F.) In consideration of the clay composition and thickness, the layer is assumed to have significant compressibility. Therefore, the cutting of the clay layer removed the immediate horizontal confinement and made it possible for confined water to drain and/or plastic flow toward the free face, making it possible for the layer to compress. Because the clay seam was cut along the east side (fig. 5), loss of confinement, alternate wet-dry cycling and drainage--and hence compression--would be more significant, and proceed at a faster rate closer to the free face.

The resulting unequal compression of the clay seam between areas, closer and farther from the free face would result in a reduction of all or part of the active load on supports nearer the free face and would require the supports farther away to assume an additional load. Also, this would increase the amount of the span that adjacent supports must sustain and allow the roof area over compressed pillars to sag. If the increase in load or span is large enough, failure would occur. This is assumed to be what happened to pillars A, B, and C (fig. 4), as they failed in 1961 or 1962, and the clay layer was cut prior to 1961.

Rock Alteration Analysis

The primary effect of rock alteration at the Bautsch mine, whether by hydrothermal fluids or weathering, was a reduction in rock strength. The extent of weathering of the overburden at the mine can be seen in figure 15.

Pillars in the area of failure were mostly dolomitic in composition and probably sanded to some degree. This assumption is based on a random sample collected from pillar 5. The observed incoherency would greatly reduce rock strength.

The thinning of the beds, when the calcite cement was removed, opened fractures across the bedding planes as a result of the volume reduction. Hence, primary rock strength of beds in the overburden and pillars favorable to weathering will be reduced.



FIGURE 15. - Soil profile of weathered in situ rock at north end of Bautsch mine failure.

Bedding Analysis

The bedding and poor cohesion between beds in the overburden reduced the strength of the rock as a unit and allowed sagging, flexural slippage, and fallouts of the back to occur more easily. Lubrication, or pore pressure, created by increased water content also contributed to this instability.

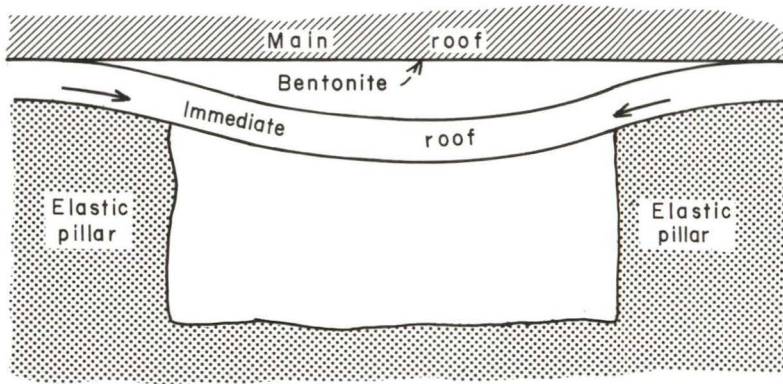


FIGURE 16. - Rotational forces on pillars produced by sagging roof.

Lack of cohesion, or a reduction in cohesion, was a major factor in many of the small roof failures that occurred. For example, when attempts were made to maintain a roof below the bentonite seam in the Galena Dolomite, failures occurred. The poor cohesion across the bentonite and the bedded rock directly below the bentonite gave insufficient resistance to much sagging, fallouts, or flexural slippage. Coupled with suffi-

ciently large spans and/or change in moisture content, the result was the backs caving to the bentonite seam and stopping at the more massive dolomite layer immediately above. The major role this bentonite seam played in controlling the position of the roof can readily be seen in the cross sections of appendix F.

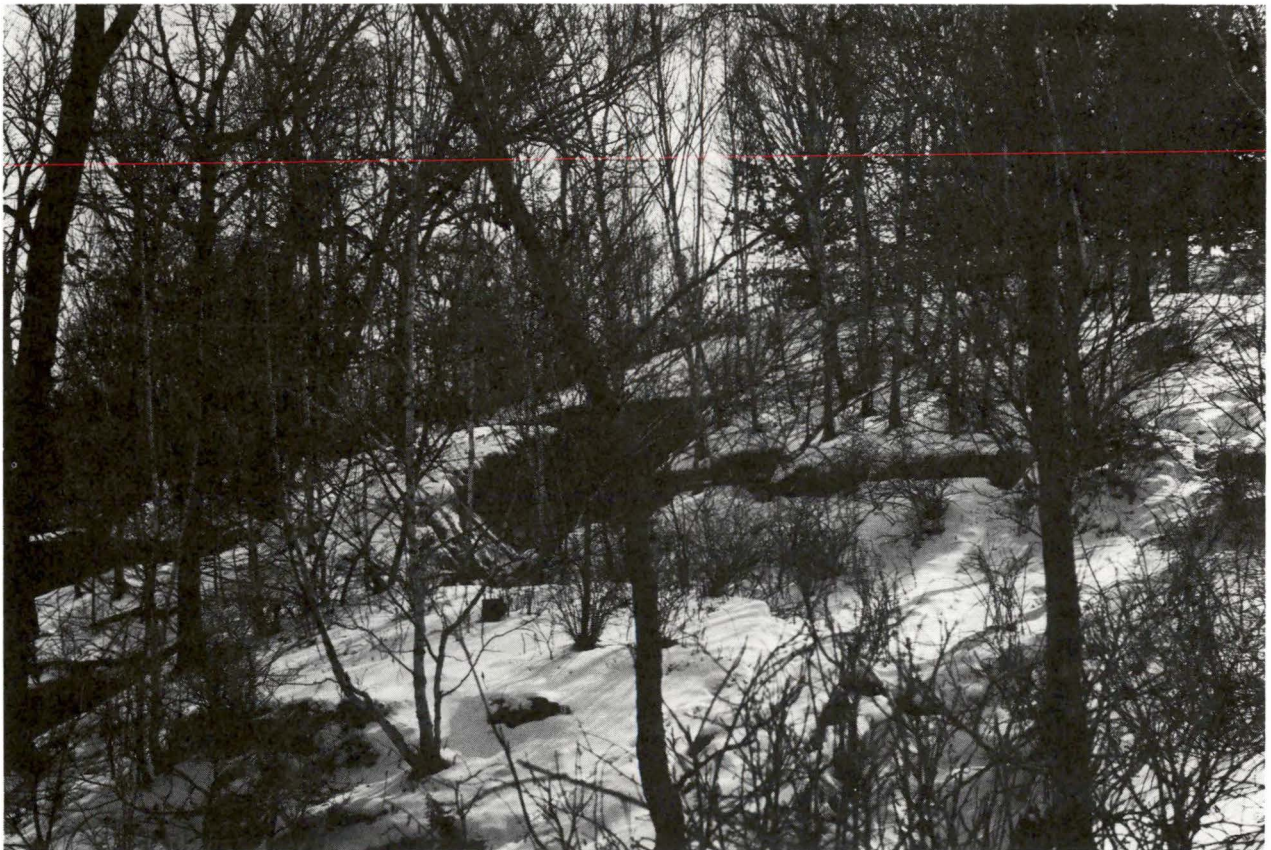


FIGURE 17. - Tensional cracks along southern end of Bautsch mine surface failure.

It is possible that the sagging of the roof on one side of a pillar created rotational forces from a shifting of the center of gravity (fig. 16) in tall pillars and influenced failure. The existence of rotational forces is indicated in at least one instance when pillar D (fig. 4) failed by tipping over intact.

Topography Effect Analysis

Using the analysis of topography effect on stress by Hooker (10), it was calculated that the effect of topography in the area of failure was such that the principal direction of the overburden load was offset at least 7.1° N-NW from vertical (fig. 4). This inclined loading could contribute a moment to the pillars and, in the case of tall pillars, could be significant. Also, because the inclined force is in the general direction of the strike of the inclined joints, it could be expected to increase the shear force along that plane.

Evidence of inclined loading--resulting from the topography effect--consists of tensional cracks (fig. 17) that formed primarily around the southern end of the failure area. At the northern end (fig. 15), however, the failure was more sharp and showed less signs of tensional cracks.

Mining Dimension Analysis

Although the average extraction ratio below the failure in this hard rock mine was only 81 percent, the room-and-pillar dimensions were such that failure was probable. (See table 1.)

The average width of the mining zone in the area of failure was 315 feet (96 meters) and the average thickness of the overburden was 250 feet (78.7 meters). The relationship of the overburden thickness to the mining zone width is such that it affects arching of the overburden load over the mine and dictates whether the pillars carry all or part of the total load.

The importance of this concept can be seen in table 1. In the area of failure, the average ratio of overburden to width of mining zone was 0.794. Computations of the same ratios at the northern and southern limits of the failure were 0.769 and 0.806, respectively. Therefore, for these geologic and mining conditions, a ratio of about 0.806 indicates a critical upper limit for failure.

It would then be reasonable to assume that failure might progress northward until the ratio is closer to the average value of 0.794 or the minimum value of 0.806. However, the effect of the shaft pillar 99 (fig. 4), by shaft 2, may be such that the width of the mining zone should be taken from the middle of the pillar to the west side of the mining zone. If this is done, a new value of the northern limits ratio is approximately 0.8, which agrees closely with the north end. Therefore, if this pillar does not fail and did influence failure's progression, the assumption can be made that failure will not progress farther north and that the critical value for the limit of failure is about 0.806.

TABLE 1. - Representative dimension parameters of the Bautsch mine and failure zone

General study area	Maximum span		Minimum span		Average span		Maximum pillar height		Minimum pillar height		Average pillar height		Average Hp/Wp ¹		Average width of mining zone (A)		Average thickness of overburden (B)		Ratio of A/B	
	Feet	Meters	Feet	Meters	Feet	Meters	Feet	Meters	Feet	Meters	Feet	Meters	Actual	Effective	Feet	Meters	Feet	Meters		
North of failure area.....	² 110	² 33.5	³ 12	³ 3.66	^e ≈45	^e ≈13.72	⁴ 100	⁴ 30.48	⁵ 18	³ 5.49	≈35	≈10.67	≈1.5	ND	200	60.96	160	48.77	0.8	
Northern failure limit.....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	.769
Failure area....	⁶ 126	⁶ 38.4	⁷ 7	⁷ 2.13	⁸ 87	⁸ 26.52	⁸ 134	⁸ 40.84	⁸ 13	⁸ 3.96	96	29.26	2.5	3.0	315	96.01	250	76.2	.794	
Southern failure limit.....	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	NAp	.806
South of failure area.....	⁹ 150	⁹ 45.72	¹⁰ 15	¹⁰ 4.57	≈60	≈18.29	¹¹ 110	¹¹ 33.53	¹² 10	¹² 3.05	≈45	≈13.72	≈1.6	ND	2.75	83.82	400	121.92	1.453	

^e Estimated.

NAp Not applicable.

ND No data.

¹Height-of-pillar-to-width-of-pillar-ratio.

²Section S-S', figure 6.

³Section T-T', figure 6.

⁴Pillar E, figure 4.

⁵26,100 N 39,300 E, figure 6.

⁶Section C-C', figure 4.

⁷Section B-B', figure 4.

⁸Pillar 5, figure 4.

⁹Section P-P', figure 4.

¹⁰Section N-N', figure 4.

¹¹Pillar D, figure 4.

¹²23,790 N 41,320 E, figure 5.

In applying this information to the northern and southern ends of the mine, several important relationships can be seen (table 1 and figs. 4-6). In the southern end of the mine, the average overburden to mining width ratio is 1.453. This is considerably larger than in the failure area. Also, considering the smaller height-of-pillar-to-width-of-pillar ratio (H_p/W_p) in the area, the probability of failure is very remote. In the northern end of the mine, the average overburden-thickness-to-mining-zone-width ratio is 0.800. Although this value is larger than the average value in the failure area, it is less than the limiting condition of 0.806. The northern area would then be expected to have a potential probability of failure. However, H_p/W_p ratio of 1.5 for this area is much less than the ratio in the failure area, which is approximately 2.5. Therefore, the area probably has a smaller safety factor than the southern end of the mine, but has a low probability of failure.

Although there are localized areas in the southern and northern ends of the mining zone, which are less than the critical limit of 0.806, those zones are small and have small H_p/W_p ratios. Therefore, they are considered stable.

Average and effective H_p/W_p ratios in the failure area were 2.5 and 3.0, respectively. Ratios of this size effectively reduced pillar strength by allowing inclined fractures to pass through the pillars and/or reducing pillar stiffness. Laboratory studies have indicated that for model pillars with H_p/W_p ratios greater than two and transected by fractures inclined greater than 30° , rock strength is reduced by a factor of about four (11). Also, as roof failures occurred between pillars, a further decrease in pillar strength would take place as a result of increasing pillar-height-to-width ratios.

The average area of pillars in the failure area, prior to the time that pillars A, B, and C failed, was 1,296 square feet (120 square meters), but the average effective pillar area⁵ would only be 900 square feet (84 square meters) (16). This means that the average pillar load of about 1,700 pounds per square inch (122 kg/cm^2), due to the overburden, would actually be about 2,500 pounds per square inch (176 kg/cm^2). If pillars A, B, and C are removed from the calculations, the average effective load is increased further to 2,675 pounds per square inch (189 kg/cm^2). From the above data, an estimate of the intact compressive strength for the pillars--not considering size effects, alteration, end constraints, or planes of weakness--results in a minimum value of 10,000 pounds per square inch (705 kg/cm^2). End constraint could especially be critical, as the bottom and tops of the pillars at this mine are very nonsymmetrically constrained (figs. 4-6). An analysis of this type is not covered by this report.

From a comparison of table 1 and figure 4, there appears to be a relationship between the average pillar height in the area of failure and pillars that failed; that is, all the pillars that initially failed (A-E) were approximately 96 feet high (29.3 meters) or more. In addition, the final failure involved pillars whose height was between 80 and 110 feet (24.4 to 33.5 meters). In the case of the pillars along the east wall that did not fail, one side was short (~ 20 feet), while the other was higher (~ 90 feet).

⁵The area of a pillar after subtracting the effects of blast damage.

Therefore, their average height was much less than 96 feet (29.3 meters), which may be an additional reason why these pillars did not fail.

In the bedded lithology at the Bautsch mine, some factors that determine a stable roof span are fracture spacing, tightness of fractures, and resistance to roof sag. Furthermore, the last factors are interrelated with the effects from moisture content.

Table 1 shows that large stable spans in the mine were possible in the dewatered state. The long-term stability of these spans are shown where pillars A, B, and C failed, and the spans stood for approximately 10 years. Although spans of this size were stable in the dewatered state, there is evidence that they were not stable with an increase in the overburden's water content. Immediately prior to the final massive failure, a significant increase in the water content of the overburden corresponded to several small roof failures in the area of the large spans (appendix C) at sections U-U' and P-P' of figure 4.

MODE OF FAILURE

Correlation of the geologic conditions and rock mechanic factors, along with the history of events at the mine, made it possible to interpret the sequence of events that led to the final massive failure. The following discussion attempts to explain this sequence and show why failure occurred when and where it did.

From the onset of mining in 1949 until sometime late in the fifties, the size and extent of underground workings were not large enough to result in any massive failures (fig. 3). Most of the mining dimensions were small, and only pilot drifts were in the area that failed. Hence, the roof during this time period was adequately supported, and any adverse external effects, such as those caused by rainfall, were compensated for by a large safety factor.

By the latter half of the fifties, the drifts in the area of failure were completely developed. Blasting of the backs, and pillar robbing had commenced, creating pillars with larger Hp/Wp ratios. The mining width had essentially reached its maximum size, and further mining of the backs was decreasing the ratio of overburden depth to mining width. Precipitation during, and prior, to this time (appendixes A, B, and G) was fairly constant, except for 1951 and 1959. The effect of high precipitation during 1951 was not felt because of the small mining area at that time, while for 1959 any of its adverse effects were small because of its wide distribution. Development of the northern and southern ends of the mine was also taking place, but it is not known to what extent.

At some time prior to 1961, the east haulageway bottom was cut down to facilitate operations in the southern end of the mine. This downcutting transected the Spechts Ferry clay layer along the entire length of the area that failed. Prior to this time, the clay layer was only exposed along the eastern wall, between the two shafts. Further mining in the southern end also transected the clay layer in the area of pillars D and F so that the layer was cut near the base of these pillars (figs. 4-5).

Soon after the clay layer was cut along the haulageway, the mine experienced the first signs of ground trouble. Pillars A, B, and C (fig. 4) failed during 1961 and/or 1962. Although failure of the pillars resulted in large unsupported spans, the roof stabilized above the top of the bentonite layer (appendix F) described in the bedding analysis. This resulted in large flat spans over the area.

The failure of pillars A, B, and C was an end result to the cutting of the clay layer. Cutting of the layer caused a reduction in the load carrying capacity of the east row of pillars, requiring the next row away from the transected clay seam to carry an extra load as explained in the section on clay layer analysis. Mining prior to and after the clay layer was cut had increased the H_p/W_p ratios of the pillars so that their safety factor had been significantly reduced. The added load on the pillars, and inclined overburden loading (topography analysis) reduced safety factors even further. The timing of failure could be determined by the effects of external factors.

Except for 1951 and 1959, which had no adverse effects on stability, precipitation, prior to and including 1960, was normal. However, for 1961 and 1962, the potential for increasing subsurface moisture content was high due to the distribution of precipitation. The effects of moisture were even greater in the area of the massive failure because of its location below a north slope and accompanying low evapotranspiration. The effects of the added recharge decreased the safety factor as described under the hydrological analysis (that is, lubrication and moisture content) thus requiring the supports under the affected area to carry a different load. Therefore, the failure of the first three pillars was a direct result of the increase in load, which resulted from the cutting of the clay layer and the external effects of precipitation.

With the failure of these pillars, the stress concentrations were relieved and the loads redistributed to adjacent areas that could support the added loads. This allowed for a return to stability; but, with a further reduction in the average safety factor of the area. This safety factor was temporarily increased further as a consequence of the low precipitation during 1963 and 1964 and corresponding reduction in the unit weight and lubricating effects on the overburden and pillars.

From the latter part of 1963 until 1968, the mine was closed and allowed to flood. Flooding was not complete, but only to an elevation of 495 feet (151 meters). This meant that only the southern end and the area that failed were actually flooded.

During the time of flooding, pillar D (fig. 4) failed; the mode of failure was by the pillar laying over on its side intact. This mode of failure was possibly due to the combined effect of inclined loading (topography analysis), and offset of the pillar's center of gravity and effect of flooding on the 3-foot-thick (0.91 meters) clay layer in the pillar. Saturation of the clay layer made it more plastic. Being unconfined, in a saturated plastic state, and subjected to rotational forces, resulted in the clay layer compressing more on one side of the pillar than the other. The result was a rotating of

the pillar above the clay layer. Once rotation had commenced, separation from the roof resulted and then it was only a matter of the pillar sliding off along the clay layer. Although the actual date of failure for pillar D is not known, its failure was a response to a decrease in bearing capacity. The saturation of the clay layer, rotational forces and/or an increase in the static load, as a result of high precipitation during 1965, were considered to be the causes of this pillar failure.

Precipitation for 1966 and 1967 was again normal, but for 1968 it was high. However, because precipitation for 1968 was poorly distributed, and the mine was dewatered during the latter half of that year, stability was increased.

During the latter half of 1968, the mine was reopened. The preceding resaturation of the exposed clay layer and the subsequent dewatering again, would result in a cycling effect. Hence, the clay seam could compress even further, pillars, as before, would be able to unload again, and further roof sagging would be possible.

Precipitation during the next three years (1969 to 1971) was low and poorly distributed, leading to temporary stable conditions. Mining activity during this time was in the southern and northern ends, with sporadic activity in the area that failed. Mining dimensions in the southern and northern ends of the mine had almost reached their present size. From the time of dewatering until 1972, pillar robbing and other mining activities were conducted around the periphery of the 1961 and 1962 failures. During the first half of 1972, pillar F and a pillar in between pillars 26 and 35 were removed, along with excavations around pillars 20, 17, and C. These activities further reduced the safety factor in the area by increasing the Hp/Wp ratios and the pillar load (Mine Dimension Analysis). However, with the low rainfall, the critical value of the safety factor was not exceeded.

The last freeze took place by April 25, 1972. Accumulated snowfall was melting 24 hours a day. All further precipitation would be in the form of rain.

At the time of the last freeze, 18.35 inches (46.6 centimeters) of precipitation had been available for infiltration, mostly in the form of accumulated snow. No signs of any instability were reported prior to this time. May to August were characterized by high precipitation, with increased rainfall during the high evapotranspiration months of July and August (appendix A).

By September, the total precipitation had been about 40 inches (101.6 centimeters). This accumulation was already greater than most of the totals for previous years of high precipitation and was close to and/or exceeded other highs, if the effect of their distributions are considered (appendix A). It would then be expected, if precipitation were a factor, that ground troubles could occur soon after this time. This fact was verified when, during September 9-10, 1972, the mine began experiencing ground troubles.

Ground troubles began as sporadic pillar slabbing and small roof falls along the western side of the mine. These events showed that pillars were taking on an added load and that bonding strength between thin slabs in the back was being exceeded. Initial failure activity concurs with previous events (that is, clay layer analysis) showing that the west side would be carrying a larger share of the load, therefore the west side would have a smaller safety factor and show the first signs of postfailure. Also, the initial activity at the northern end of the failure area occurred as a result of a lower time-lag for ground-water recharge through the thinner overburden (figs. 15 and 18) and location near the base of the hill.

No increase in activity was observed from September 15-28, 1972. On the 29th, the first activity in the southern end of the mine occurred. Slabbing from pillar 32 and clay squeezing from the clay layer in pillar 33 showed that the southern part of the failure area was beginning to take on added loading.



FIGURE 18. - View of soil cover over south end of failure.

During the month of September another 7.40 inches (18.8 centimeters) of precipitation fell, bringing the total to over 47 inches (119.4 centimeters). Total precipitation was now close to, or exceeding, any previous year's total, which corresponded to ground trouble.

For the first two weeks in October, there was either no observations of, or increase, in activity. However, on the 14th or 15th of October, the high brow sluffed off above where pillar F was removed (fig. 3). The removal of that pillar had created a large, unsupported span, 150 feet (45.7 meters) where a bentonite layer existed about 20 feet above the original back. Hence, a long, narrow beam of rock was outlined, and with sufficient saturation and span, the brow failed. Activity during the 16th through the 22d of October was mainly in the form of minor slabbing from pillars and small parts of the brow working loose.

There was an increase in activity in the last of October. A large slab fell off of pillar 27 and a section of the brow, weighing over 1,000 tons (over 1,100 metric tons), fell around pillar 20. The failure around pillar 20 occurred as a result of the bentonite layer above the immediate roof. (See cross section 12, west side-appendix F.) The "three legs," across from pillars 14 and 17 (fig. 4), had during this time taken an additional load, as indicated by new fracturing. A large fall of the roof also occurred off the west side of pillar 13 as a result of a fracture zone.

Failure activity up to this time had slightly increased H_p/W_p ratios and decreased effective pillar areas. Consequently, safety factors were decreasing.

During the month of October and before the first freeze, another 4.40 inches (11.2 centimeters) of precipitation fell. Total precipitation was 51.50 inches (130.8 centimeters), exceeding any amount previous to this time.

With the additional rain that occurred in October, activity in November greatly increased. On November 2, 1972, the whole roof span fell in the area of the 1961-1962 failure, between pillars 18 and 29. This event was critical in that it significantly increased adjacent pillar heights and decreased overburden thickness. Activity was almost continuous, with small rocks falling frequently from the vicinity of the incline to south of pillar 29. Failure activity in pillars increased, especially in pillars 13, 30, and 3.

On the sixth of November, a failure occurred along the east wall. This showed for the first time that loading was now affecting the east side.

The brow between pillars 5 and 7 began to work on the eighth as a result of the existence of the bentonite seam over that area, but more important were the signs of failure occurring in pillars 32, 33, and 34. This indicated that additional loading along the east side was increasing as a result of roof movement and the transferring of additional loads to these pillars.

On the ninth of November, pillar 9 failed. It is felt that this was because of its central location, height, and small area. The failure of this

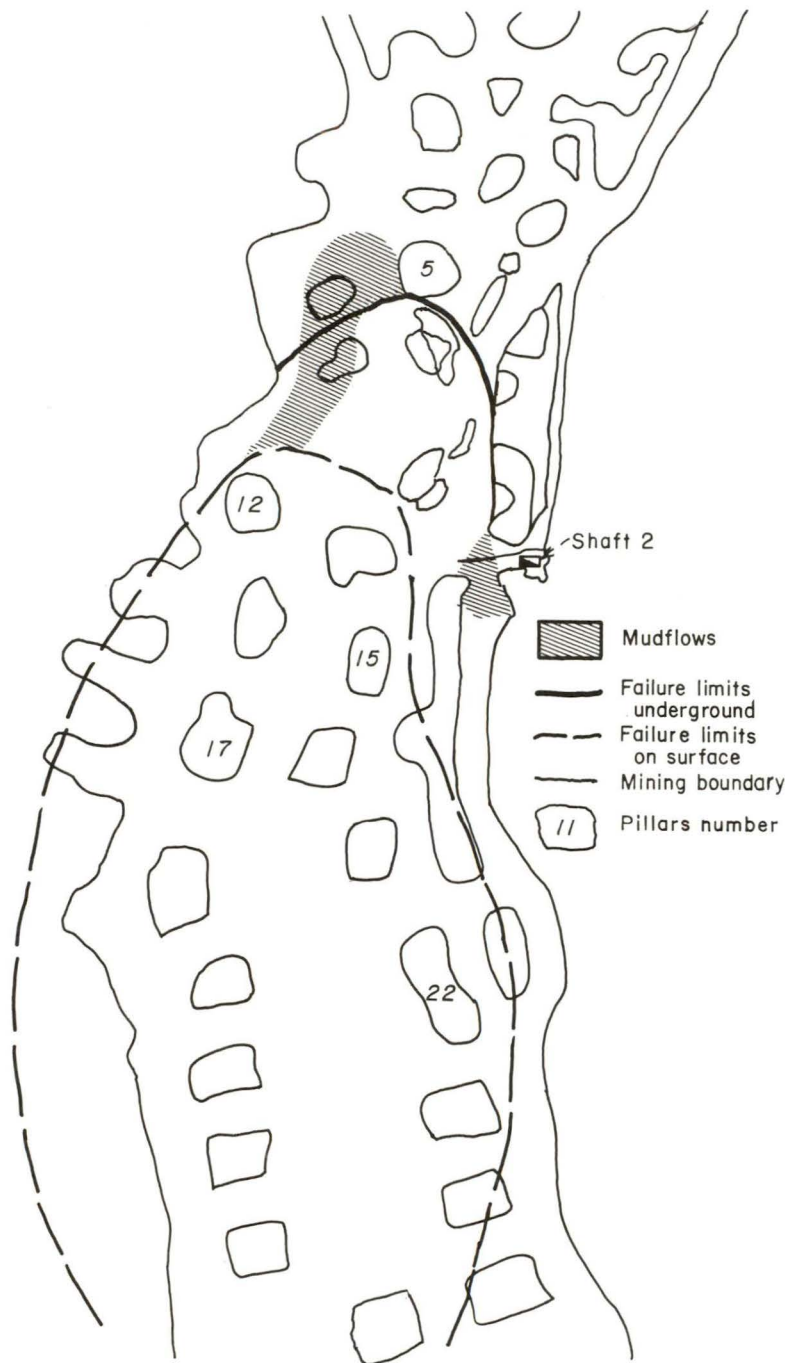


FIGURE 19. - Failure limits and mudflows underground.

periphery of the area of the pillar failures.

Failure occurred rapidly, allowing the overburden to fall nearly intact. The result was a rapid air displacement (air blast) that blew off the heavy steel door for shaft 1. With the occurrence of failure, stresses were relieved and the periphery of the failure area stabilized.

pillar resulted in the transferring of the load to the surrounding pillars. The transferred, additional load resulted in pillars 7 and 8 failing on the 12th. Failure was a result of the added load and the pillars having the largest H_p/W_p ratios in the area of pillar 9.

Failure activity was climaxed when the massive failure occurred on the 15th. The west row of pillars 12, 14, 17, 20, 21, 24, 25, and 26 failed, along with pillars 13, 15, 18, and possibly 19. With the failure of only the west side pillars, the failure surface was skewed toward the west (fig. 4). Large mudflows were associated with the failure underground, attesting to the degree of saturation of the overburden. One flow went all the way north of pillar 5 (fig. 19).

The final failure occurred as a result of pillars failing along the west wall. As each pillar failed, the transferred load would exceed the safety factor of the adjacent pillars. Hence, failure spread outward until the ratio of overburden thickness to mining width was sufficient to stop north-south progression, and a stable failure slope was established to the surface east and west from the

CONCLUSIONS

Analysis of the rock mechanics and mode of failure led to the conclusion that failure at the Bautsch mine was not dependent on any one factor; that is, failure was a result of the interrelationship of many factors.

Determination of the factors important to failure were found to be both external and internal to the mining environment; external factors being such things as earth tremors, precipitation, and evapotranspiration, and internal factors being fractures, mine dimensions, lithology, etc. Internal factors were usually readily apparent, whereas external factors were not. Hence, many external factors were investigated, most of which are not normally considered in classical rock mechanic studies. Internal and external factors determined to be of significant importance were (1) quantity and distribution of precipitation, (2) fractures, (3) plastic clay layer (Spechts Ferry), (4) topography, (5) rock alteration, (6) bedding, and (7) mining zone dimensions.

It was evident from the history, geologic conditions, and mode of failure at the mine that the rock was "talking;" that is, geologic conditions prior to mining (fractures, bed thicknesses, overburden depths, etc.), and occurrences of failures underground prior to 1969 (that is, failure of pillars A, B, C, and D) indicated factors which would and could eventually lead to a massive failure. Underground stability was therefore a matter of preplanning prior to mining, and/or adjusting mining procedures and mine dimensions to concur with the conditions encountered.

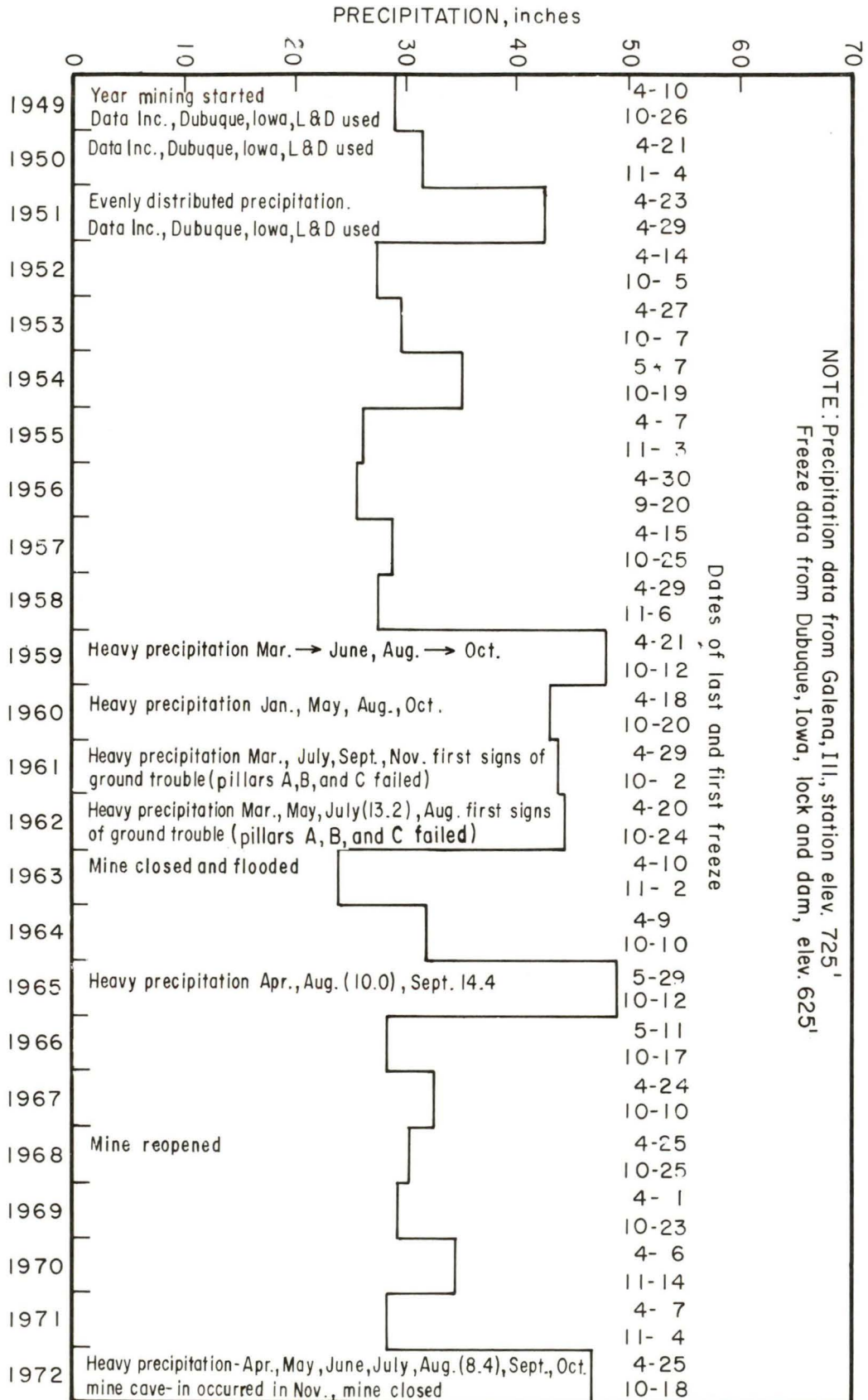
Failure could have been predicted from the conditions encountered without the use of extensive instrumentation. Applications of basic engineering principles to the internal and external factors would have been all that was necessary to predict failure. However, a larger mine engineering staff or consultants than were available would have been necessary to supply the broad expertise and additional employee-hours needed (that is, geological engineering, rock mechanics, soil mechanics, hydrology, etc.). Alternately, failure would in all probability have been delayed by years if there had been no further mining after 1962 in the area that failed.

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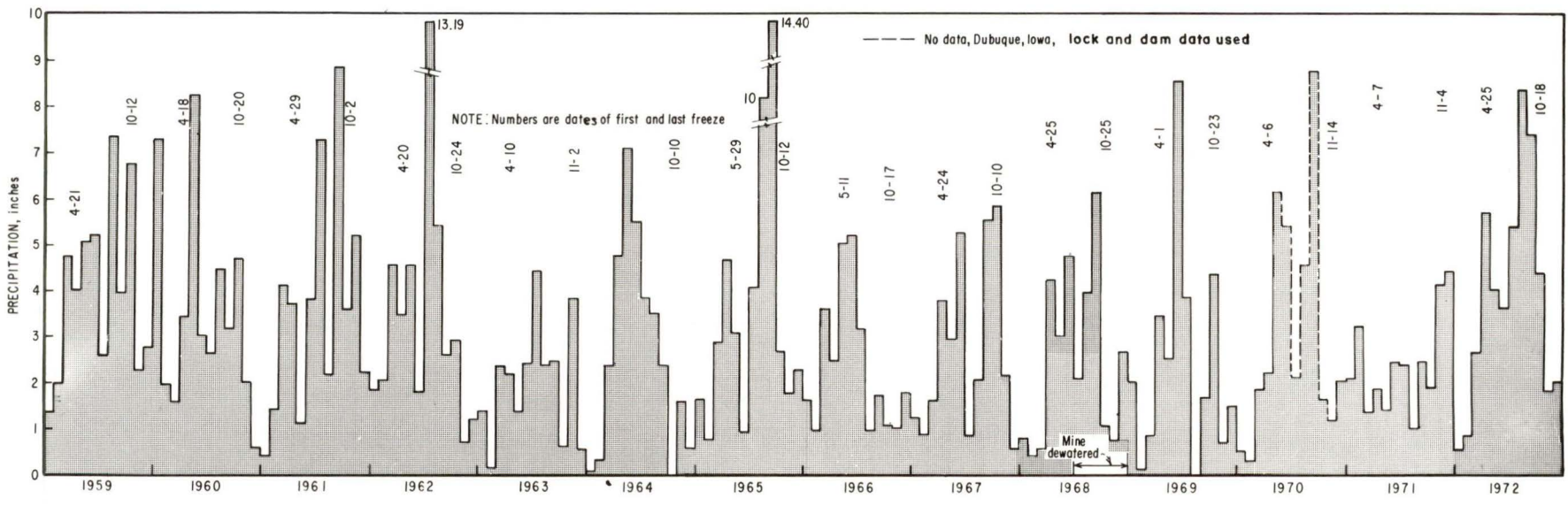
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APPENDIX A.--ANNUAL PRECIPITATION CHART



APPENDIX B.--MONTHLY PRECIPITATION CHART



APPENDIX C.--CONDENSED CHRONOLOGY OF OBSERVED EVENTS PRIOR TO THE 1972
MASSIVE ROCK FAILURE

September 9-10.--A large section fell off the third pillar from the base of the incline (between pillars 8 and 12) on the west side. For pillar numbers see figures 4 and 5.

September 13-14.--During the night, a flat about a foot thick fell from the high back where mucking occurred on the east side. This was followed by a large slab at about 10:30 a.m. on the 14th, falling from the high back on the north end of the old caving area near where mucking from the west side occurred. At the same time, a few small rocks were observed falling from pillar 20 on the west side by the small ramp. Later in the afternoon, a 50-pound rock came off pillar 20.

September 15.--At 12:22:40 a.m., an earth tremore occurred. Madison, Wisconsin reported 4 to 5 on the Richter scale, with the epicenter occurring 50 miles east of Rock Island.

September 29.--Pillar 32 in the south end of the Bautsch started to work. It shed a large piece (approximately 100 tons) first, and then two other smaller pieces later from the north side. Also, the pillar to the north had a slight sign of movement (dribble from clay bed).

October 14-15.--The high brow sluffed off where the pillar from the south end of high ground (area between pillars) was removed (pillar F).

October 19.--Large brow fell near bottom of incline.

October 21.--Rocks heard falling, one in high ground and one near south end of mine.

October 23.--Large fall occurred possibly from large pillar 27 at west side-South.

October 25.--Very large fall of ground of over 1,000 tons occurred about 9:00 p.m., from brow along west side of high ground.

October 27.--The three "legs" along the west wall, across from pillars 14 and 17 were badly fractured with pieces falling off of them.

October 28-29.--New fractures occurred in pillar 40, and a few pieces fell off.

October 30.--At 5 p.m., a large fall of ground occurred off the west side of pillar 13.

November 2.--Some time during the night, a large section fell in the south end. It appeared that the entire area between pillars 18 and 19 fell in. Still pieces falling very frequently in the a.m., all the way from the incline area on the south.

November 4.--Rocks were still falling and had not stopped since the large fall of the 2d. What was heard this morning was apparently in the vicinity of pillar 13. This pillar appeared to be shattered in the middle portion. Also noted was apparently an additional fall.

November 6.--A large section fell off the west side of pillar 30. Another section of oil rock came off the east wall, just south of the south shaft. A small piece along the ramp to the high ground in the south fell, and a slab loosened on pillar 3.

November 8.--A new problem had shown itself: the brow between pillars 5 and 7 started to work very actively. Also, small pieces had been falling from the east sides of pillars 32, 33, and 34.

November 9.--All mining ceased in the south end until things settled down. There was considerable activity on the brows where pillar 9 used to be.

November 10.--Decided to shoot a charge in drill hole, T.S. B-12. This has been done to relieve stresses.

November 12.--Sometime on this day, pillars 7 and 8 came out, possibly even 12. Along with pillars 7 and 8, came a large amount of brow that had been supported by them. Also, a large section of pillar 5. At about 2 p.m., there was still considerable activity that seemed to be mostly around pillar 12 and 13, but one small one came off pillar 3.

November 16.--At approximately 8:00 p.m. on November 15 a tremendous rock fall occurred. The top of the mine fell in to the surface in the south end. We are not too sure of the south boundary of the fall, but it extended south from pillar 5 (daylight around pillar 5).

November 20.--Two employees made their way to shaft 2 along the east side. In shining their lights south, it appeared clear on the road. They did not venture farther south at this time due to the appearance of some of the material along the sides. Later that night when the rounds were shot, a large fall was heard to the south.

November 22.--East side was 100 percent plugged. No further activity.

APPENDIX D.--EFFECT OF SOLUTION THINNING AND WEATHERING ON SPECIFIC FORMATIONS AND MEMBERS

McGregor member.--In mineralized areas, these beds have been leached to a grayish-clayey mass, with an accompanying reduction in thickness.

Quimbys Mill member.--Locally, the mineralizing solutions leached the calcareous elements, increasing the relative brown shale content.

Spechts Ferry member.--In zones of mineralization, the limestones have been almost wholly leached away, leaving only the argillaceous residues and the original shale beds. The shale is blocky in the outcrop, but becomes quite plastic and claylike in the presence of water.

Guttenberg member.--Locally, the mineralizing solutions leached the limestone, leaving a reduced thickness of shale and argillaceous residuum.

Ion member.--The thickness of this member has been reduced by metasomatism.

Galena Formation.--Extremely honeycomb-like weathering throughout the section. Cavernous in Prosser and Stewartville members.

APPENDIX E.--DETAILED LITHOLOGIC COLUMN

	Thickness, feet
Galena Formation	
Noncherty Unit:	
Dubuque Shaly Member-dolomite and dolomite limestone; yellowish gray, finely granular, argillaceous, thin to medium-bedded; thin partings of Colomitic, yellowish-gray shale; lower contact gradational.....	34- 45
Stewartville Massive Member and upper part of Prosser Cherty Member-dolomite; yellowish buff, coarsely granular to crystalline, vuggy, medium to thick-bedded.....	75- 85
Cherty Unit:	
<u>A</u> beds-dolomite; buff to drab, otherwise as above; chert bands common in upper 44 and 50 to 56 feet below top; locally a thin bentonite about 32 feet below top.....	70
<u>B</u> beds-dolomite; as above, except more brownish in color; chert bands are rare.....	15
<u>C</u> beds-dolomite as above; chert bands common, locally called lower chert.....	10
<u>D</u> beds-dolomite as above, except for streaks of greenish-argillaceous material; no chert, locally called lower buff.....	10
Total Galena.....	<u>225</u>
Decorah Formation	
Ion Dolomite Member (gray beds):	
Limestone, light buffish gray, argillaceous, thin-bedded.....	9.4
Limestone, grayish buff, coarsely crystalline, very fossiliferous; 0.1 foot, platy grayish shale at base.....	2.0
Ion Dolomite Member (blue beds):	
Limestone, bluish gray, alternating with grayish buff; thin-bedded in lower 0.5 foot.....	1.2
Limestone, greenish gray, platy.....	.7
Limestone, fossiliferous.....	.7
Limestone, grayish buff and bluish, crystalline, mottled, argillaceous; upper 0.4 feet, very fossiliferous.....	1.4
Limestone, thin-bedded; lower part bluish gray, upper part flesh-colored.....	1.0
Limestone, bluish gray; medium to coarsely crystalline; fossiliferous.....	1.0
Total, Ion.....	<u>17.4+</u>
Guttenberg Limestone Member (oil rock):	
Transition beds: limestone, buffish, medium crystalline, fossiliferous.....	0.9
Limestone, brown, thin-bedded, fine-grained, fossiliferous; band of chert nodules 3.5 feet below top.....	5.0
Limestone, brown, fine-grained, dense, nodular, inter-bedded, brown, platy shale.....	6.3
Total, Guttenberg.....	<u><u>12.2</u></u>

	Thickness, feet
Spechts Ferry Shale Member (clay bed):	
Shale, olive, calcareous, trace orange bentonite(?).....	0.4
Limestone, light-brown to cream; fossil fragments and phosphate nodules.....	.8
Shale, olive; brown and green, mottled, fine-grained argillaceous limestone; brown, platy shale.....	.1
Limestone, light brown, fine-grained, dense nodular.....	1.1
Limestone, light brown, dense nodular, wavy-bedded; parting of tan platy shale at top.....	.1
Limestone and thin platy tan shale.....	0.1- .2
Limestone, greenish-buff, nodular, argillaceous and light-brown interbedded shale.....	.3
Total, Spechts Ferry.....	<u>3.0</u>
Total, Decorah.....	<u><u>32.6+</u></u>

Platteville Formation

Quimbys Mill Member (glass rock):

Limestone, dark purple, fine-grained, dense conchoidal fracture; very wavy upper surface; thin dark brown to black, fossiliferous, platy shale parting at base..... 0.3-0.5

McGregor Limestone Member (Trenton of local usage):

Limestone, light gray, very fine-grained, very dense; conchoidal fracture like "glass rock" above, fairly massive; very fossiliferous; waxy upper surface..... .9

Limestone, as above, but less dense; medium-bedded above to thin-bedded below; fossiliferous; wavy upper surface..... .3

Dolomite, light-olive-drab, finely granular, argillaceous; very thin-bedded; wavy-bedded..... 1.6

Dolomite, as above, but heavy-bedded; calcite near middle..... 3.0

Limestone; thin-bedded yet stands massively as one unit; light greenish-grayish brown, weathering brown; with a few argillaceous streaks; sparingly fossiliferous, but with fossils and fucoids on top surface..... 2.6

Limestone; thin-bedded, as above, but the beds are distinct: wavy beds and shaly partings; argillaceous in upper 0.3 foot, which is very fossiliferous..... 3.4

Limestone, light-buffish-gray: in medium to heavy beds; in places gradational into unit next below..... 3.6

Total Upper McGregor..... 15.8




McGregor Limestone Member (Mifflin beds of Bays, 1938):

Limestone, light-greenish-gray to bluish gray; in massive beds but composed of thin beds which are not separated: much shaly material in wavy bands: fairly fossiliferous, argillaceous: a peculiar mottled light gray and darker gray 0.1 foot zone, 1 foot below top..... 3.9

	Thickness, feet
Limestone, light gray, very fine-grained, very dense, sublithographic; in very thin and wavy beds with thin calcareous shale partings that become thinner below; the shales are light graying blue, mottled very fossiliferous; the unit weathers slightly recessed.....	4.0
Limestone, like next above, but beds are not quite so thin; fossiliferous; shaly zone at base.....	3.6
Limestone, dolomitic, light gray, fine-grained; very slightly argillaceous, very fossiliferous, medium bedded; indistinct argillaceous partings, now wavy; secondary calcite, also limonite, especially in basal 0.6 foot.....	<u>3.6</u>
Total Lower McGregor.....	<u><u>15.1</u></u>

APPENDIX F.--CROSS SECTIONS OF BAUTSCH MINE

LEGEND

	Mining limits
	Lithologic boundary, dashed where inferred
	Fault, dashed where inferred
Ga	Galena Formation
Bl	Ion Member
Oil	Guttenberg Member
Clay	Spechts Ferry Member
Gl	Quimbys Mill Member
McG	McGregor Member

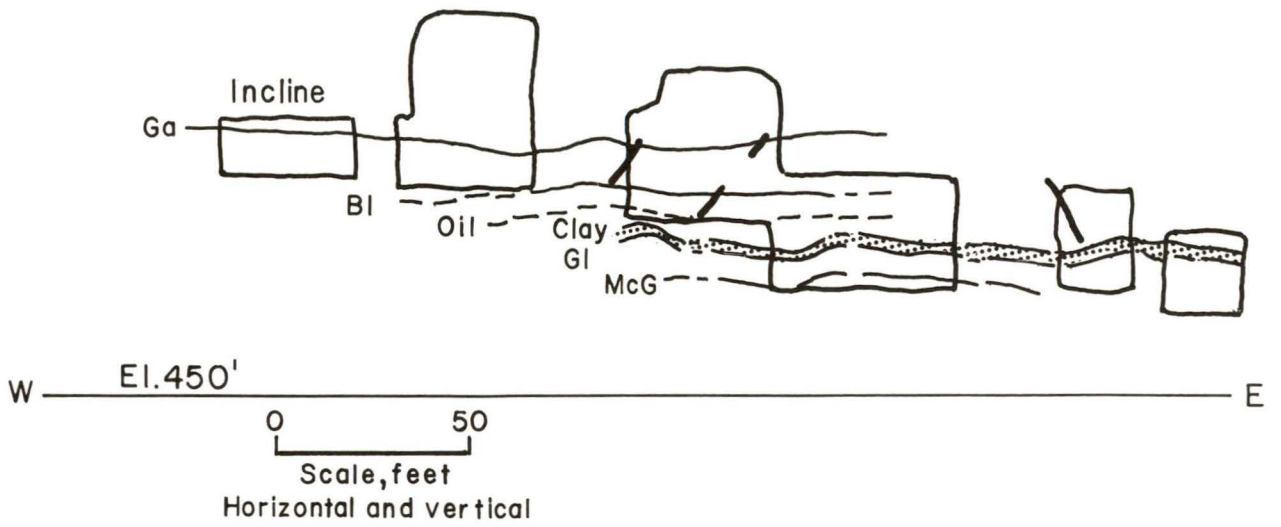


FIGURE F-1. - Bautsch section 1S.

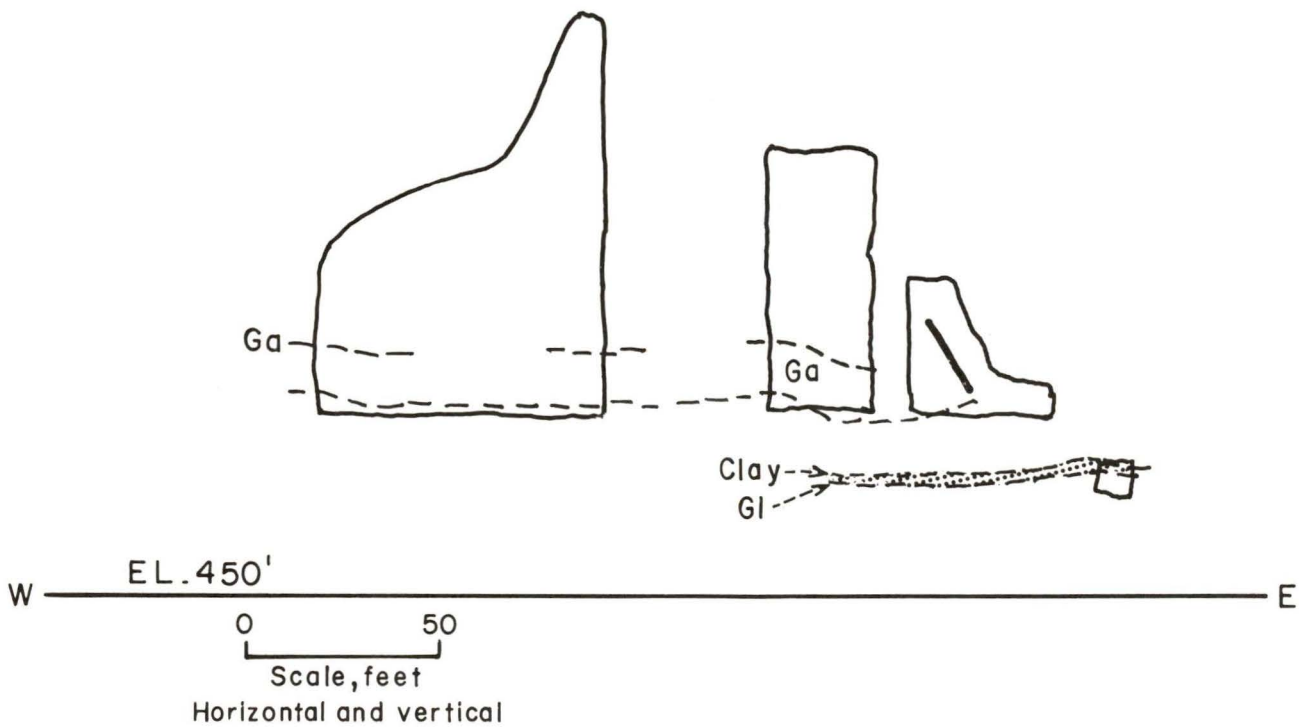


FIGURE F-2. - Bautsch section 3S.

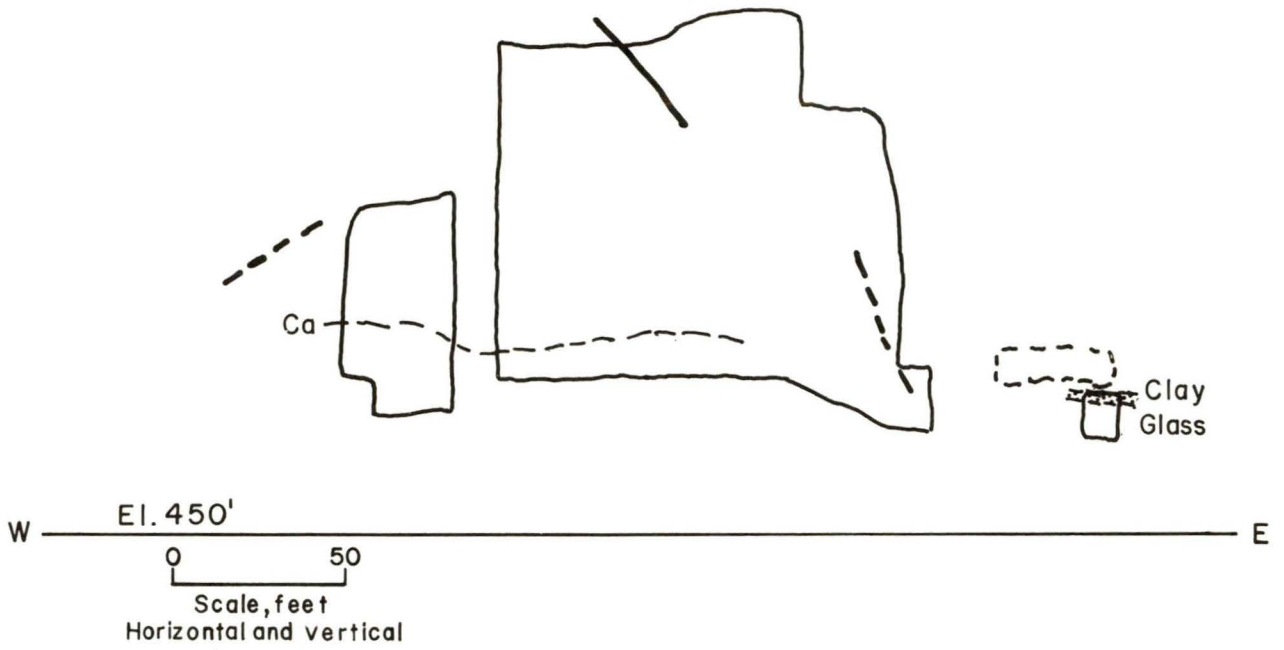


FIGURE F-3. - Bautsch section 5S.

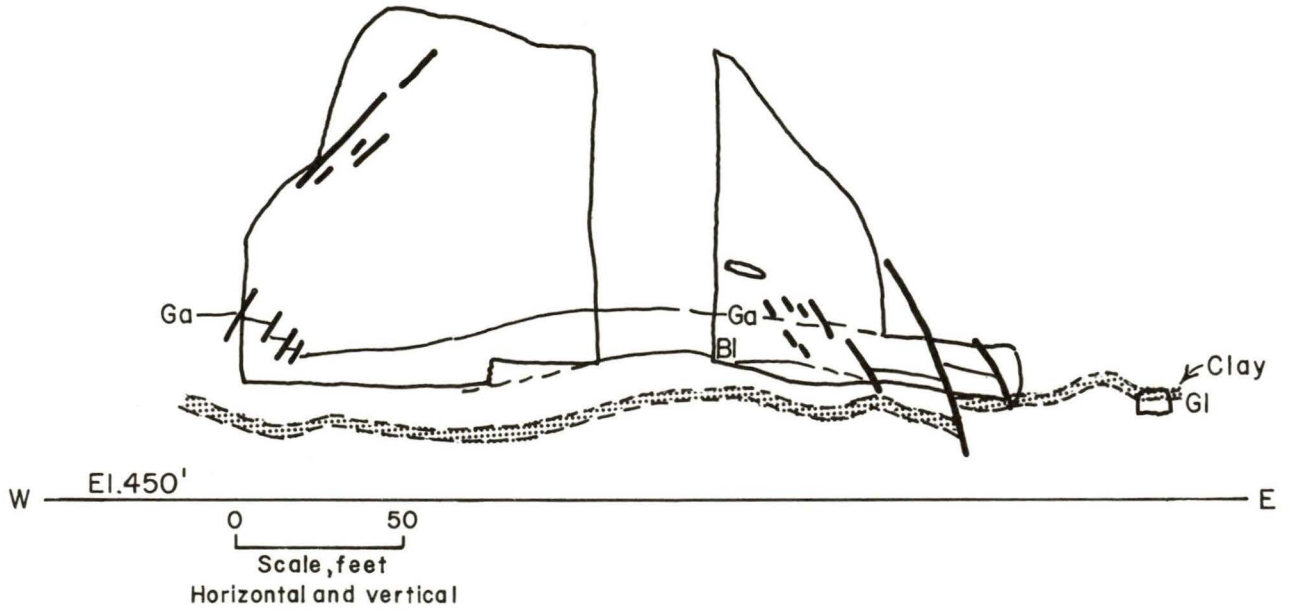


FIGURE F-4. - Bautsch section 7S.

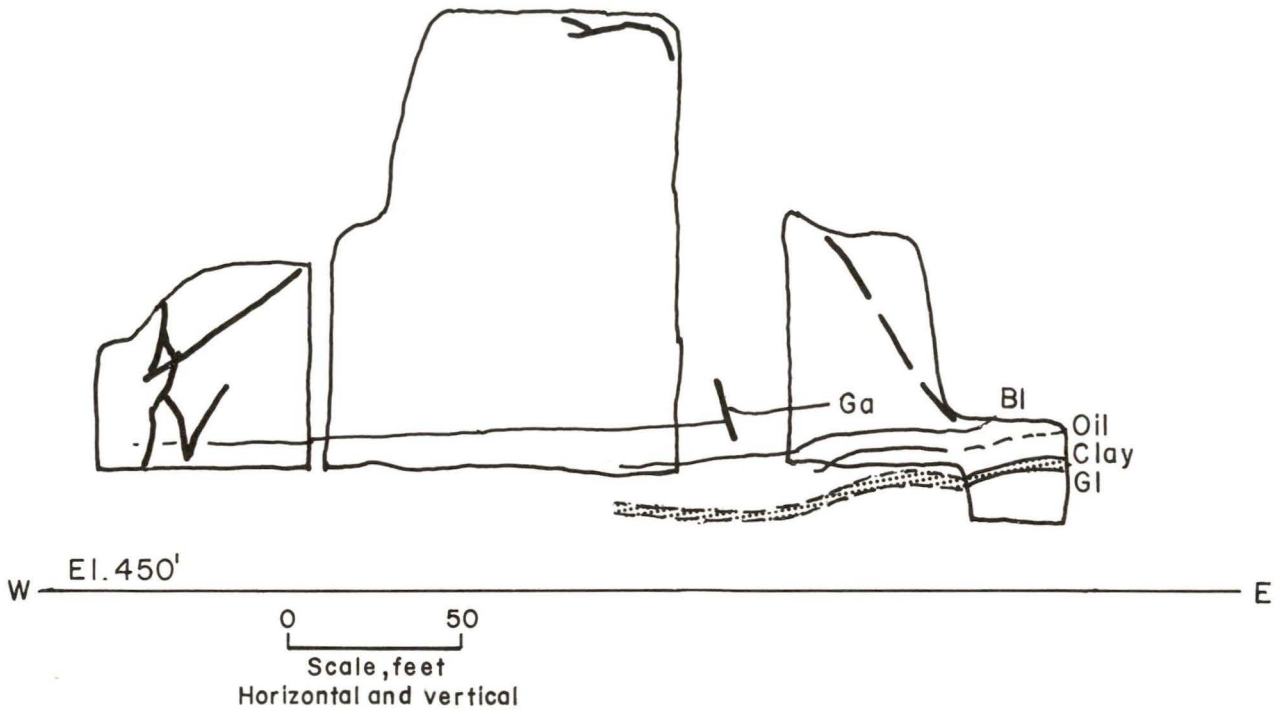


FIGURE F-5. - Batsch section 10S.

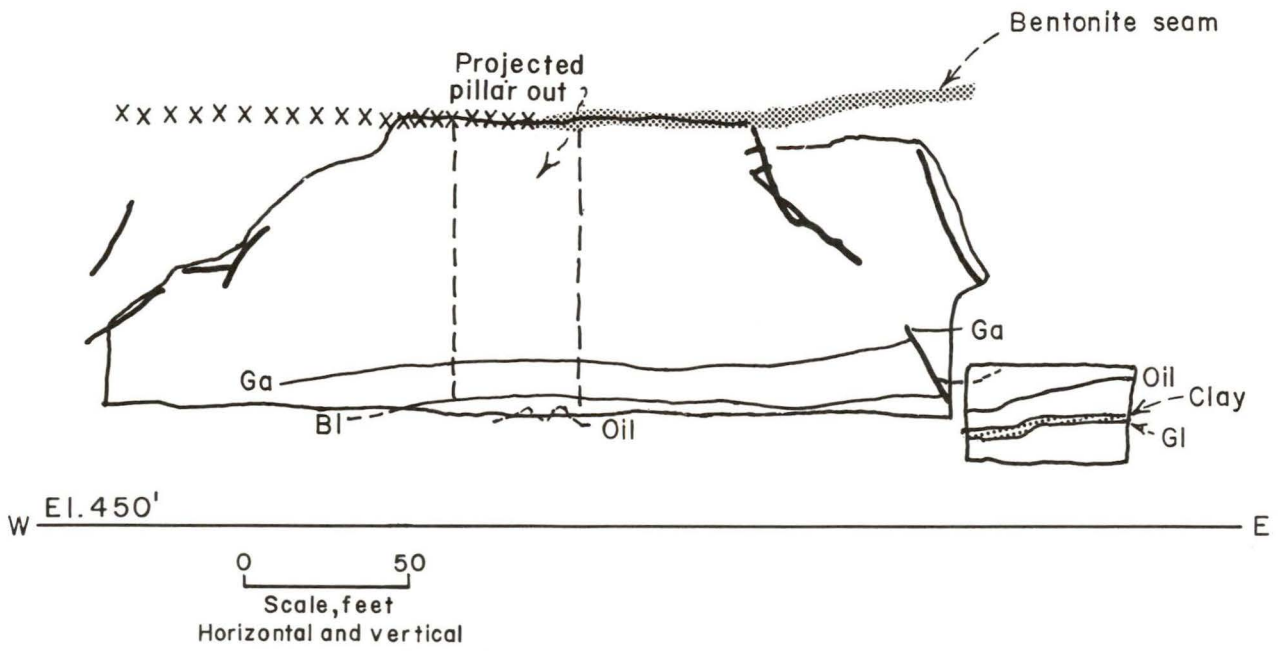


FIGURE F-6. - Batsch section 12S.

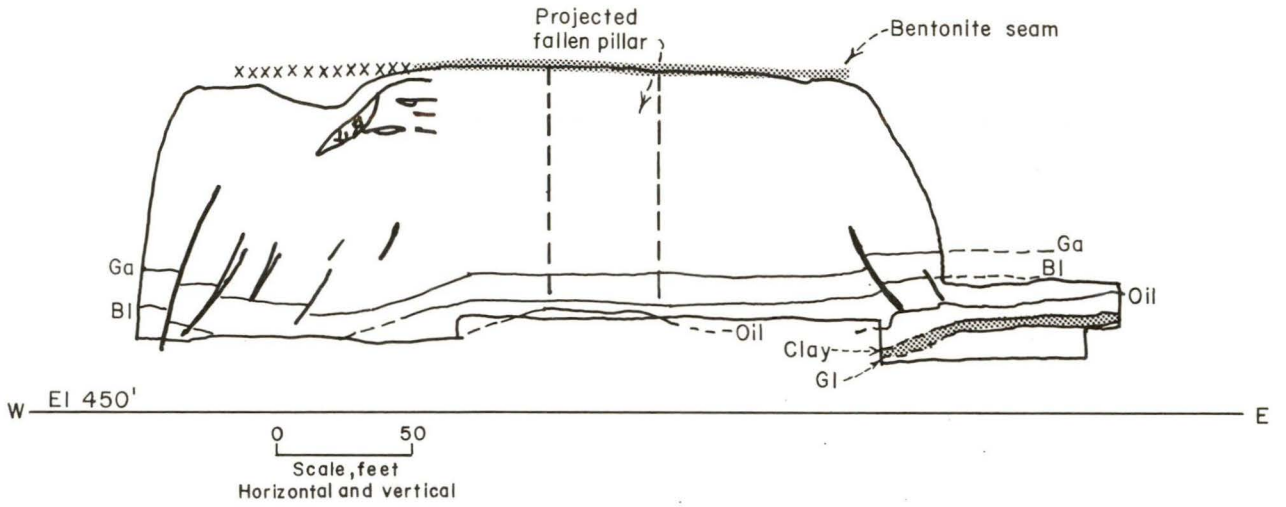


FIGURE F-7. - Batsch section 14S.

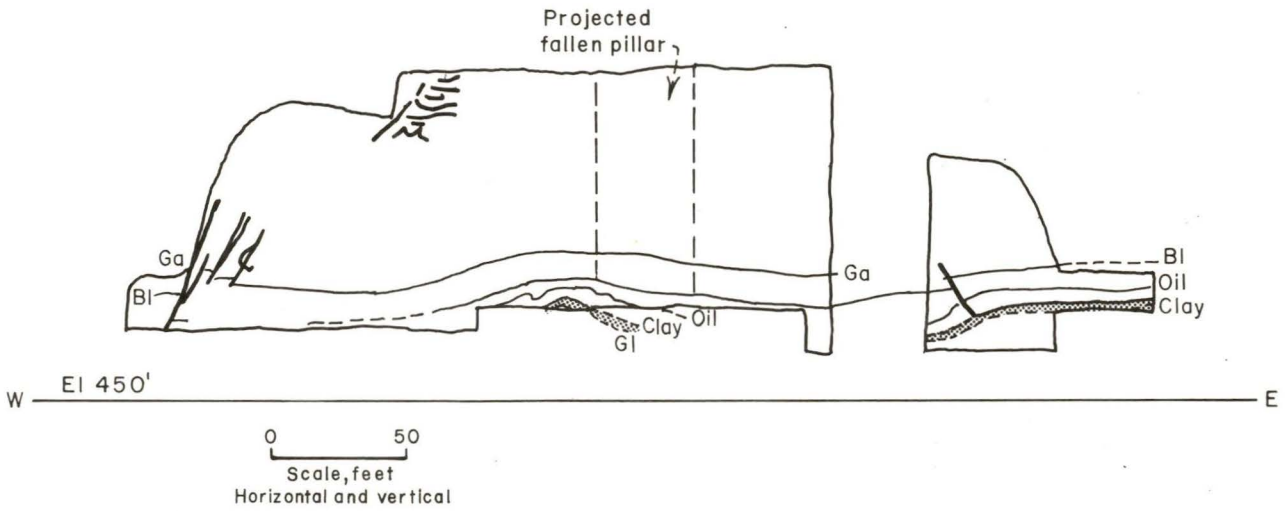


FIGURE F-8. - Batsch section 16S.

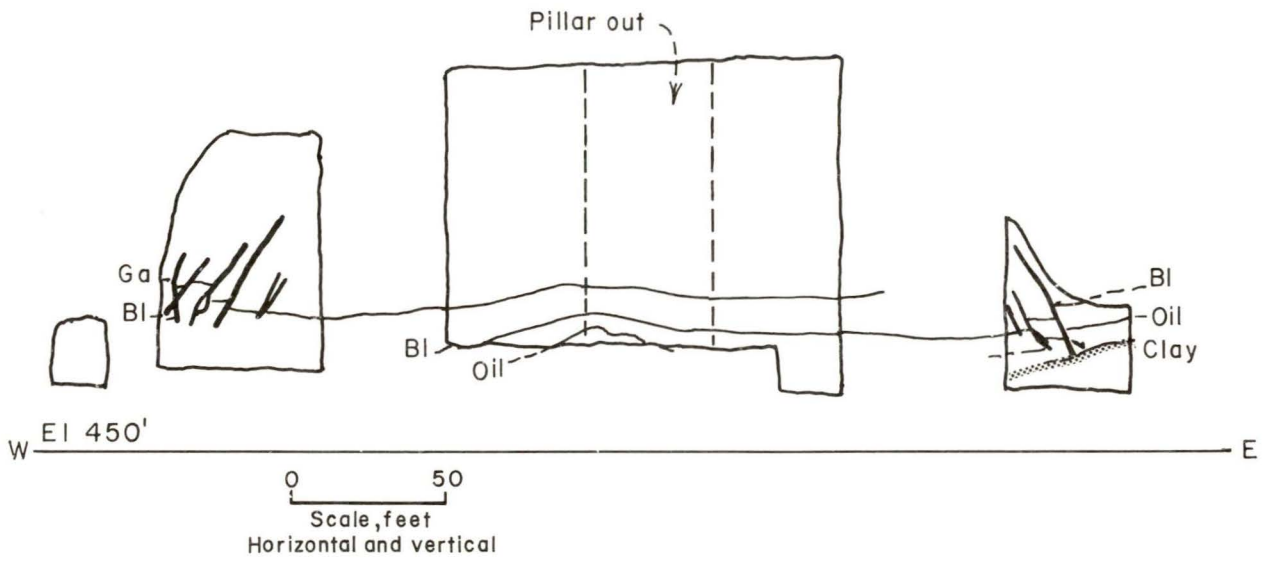


FIGURE F-9. - Batsch section 18S.

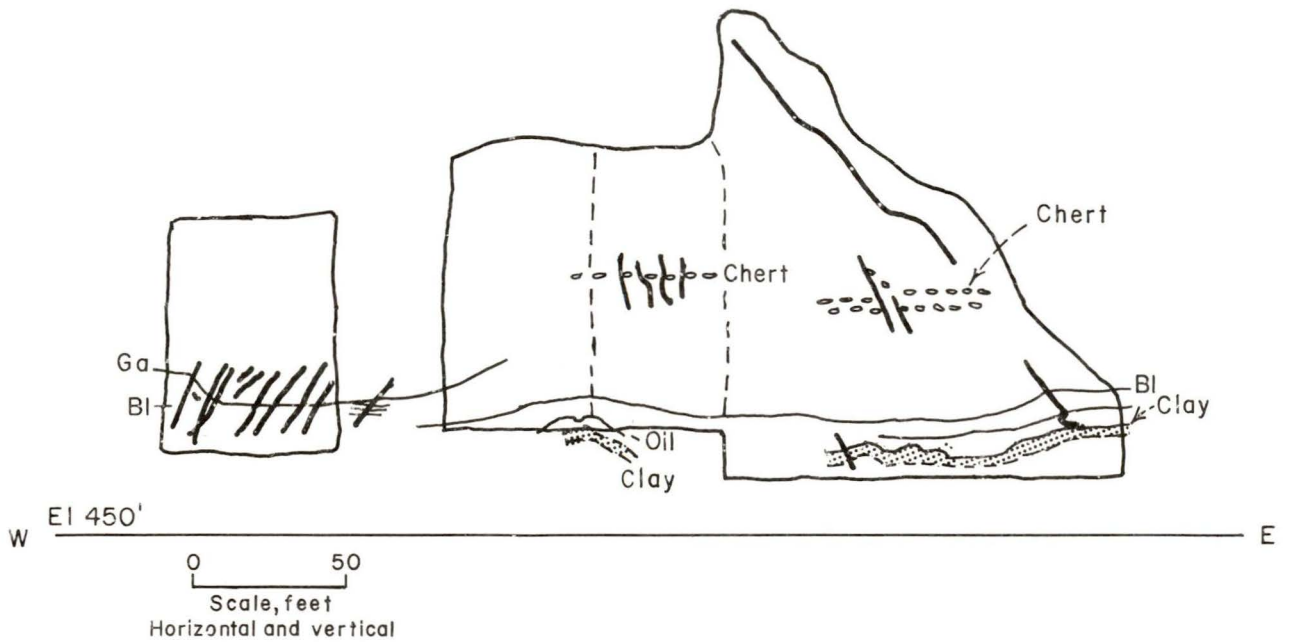


FIGURE F-10. - Batsch section 20S.

APPENDIX G.--ESTIMATE OF PRECIPITATION AVAILABLE FOR RECHARGE¹

1959 - 40.40 inches.

1960 - 51.60 inches.

Remarks: Over 8 inches for month after May freeze. Not all of this would be able to be absorbed by soil. Plus, for the months of June and July rainfall was very low, allowing evapotranspiration to possibly exceed recharge and/or reduce infiltration.

1961 - 35.4 inches.

1962 - 53.3 inches.

Remarks: Over 13 inches in 1 month. Very likely that most of the 13 inches was lost to runoff.

1965 - 44.40 inches.

Remarks: Over 14 inches in 1 month. Very likely that most of that was lost to runoff.

1968 - 35.35 inches.

1972 - 51.50 inches.

¹The amount of precipitation available for recharge for any one year was calculated as that amount between the first freeze from the previous year to the first freeze in the year in question.