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GEOLOGY OF THE NORTHERN CRYSTAL FALLS AREA IRON COUNTY, MICHIGAN

By F. J. Pettijohn

Prepared with the cooperation of the

Geological Survey Division

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CONTENTS

ILLUSTRATIONS

TABLES

GEOLOGY OF THE NORTHERN CRYSTAL FALLS AREA, IRON COUNTY MICHIGAN

INTRODUCTION

The northern Crystal Falls area is located in Iron County, which is in the western part of the northern Peninsula of Michigan (fig. 1). The area is 2 miles wide and $4\frac{1}{2}$ miles long, lying just north of the town of Crystal Falls and bisected by the Paint River. It is north of and continuous with the area shown on Preliminary Map 3-181, Geology of the Crystal Falls-Alpha iron-bearing district, Michigan, issued by the U. S. Geological Survey in 1947.

This study is part of a continuing cooperative project by the U. S. Geological Survey and the Michigan Department of Conservation, Geological Survey Division. The report is one of a series of preliminary reports on the Iron River-Crystal Falls district (Dutton and others, 1945; Dutton, 1949; Good and Pettijohn, 1949; James, Clark, and Smith, 1947; James and Wier, 1948; James and Dutton, 1951; Pettijohn, 1947, 1948).

In addition to the staff members of these two organizations, the writer is indebted to the officials of the mining companies who have kindly permitted access to their records from which the data on the exploratory drilling and mining operations were obtained. In particular he is indebted to the M. A. Hanna Co., the Inland Steel Co., the Jones and Laughlin Ore Co., the Pickands, Mather and Co., and the Republic Steel Corp.

J. R. Balsley, Jr., served as instrument man in the plane-table survey of the outcrops along the Paint River. L. D. Clark assisted in the Superdip survey of the area west of the Bristol mine. The magnetic survey of the Great Western-Hilltop mine area (pl. 7) was made in 1947 by S. E. Good assisted by J. J. Hill. M. W. Leighton added the magnetic data in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 21, T. 43 N., R. 32 W., in 1949. Supplementary readings were made by John Bokman in 1950. The writer is indebted to Dr. J. W. Gruner of the University of Minnesota, for X-ray identification of stilpnomelane.

The geological map (pl. 1) is based on a restudy of all known outcrops and test pits, the available records of exploratory drilling, and detailed magnetic mapping. Most of the magnetic surveying was done with a Hotchkiss Superdip, but the magnetic anomalies of the Great Western and the Hilltop areas were mapped with a Wolfson vertical magnetometer. The anomaly in sec. 17 was mapped previously with a dip needle by the Michigan Geological Survey. Most of the field data were obtained by pace and compass traverses, though the numerous outcrops along the Paint River just below the municipal power dam were mapped with a plane table. The outcrop of iron-formation that forms the apron of the dam was mapped by H. L. James and W. S. White with a plane table at a scale of 10 ft to 1 in.

GENERAL GEOLOGY

Stratigraphy

The bedrock of the district is all of pre-Cambrian age. The rocks fall into four mappable units which occur in east-trending belts and in order of age, from north to south, are greenstones, footwall strata, iron-formation, and hanging-wall strata.

Greenstones

Much of the northern half of the area mapped is underlain by greenstone. Outcrops, however, are most numerous near the Paint River in sec. 17, T. 43 N., R. 32 W.

The greenstones are mainly altered basaltic lavas and associated pyroclastic deposits. They commonly are fine-grained and massive. Less common, but by no means rare, are greenstones marked by ellipsoidal (pillow) structures. Also present are agglomerates and tuffs. They are generally sheared and therefore exhibit a schistose structure. A sheared tuff in the SE$\frac{1}{4}$ sec. 17 is markedly magnetic and is responsible for the strong magnetic anomaly of that area.

Some of the greenstone, such as that near the Fortune Lake mine in sec. 24, T. 43 N., R. 33 W., is coarse-grained. This rock is probably intrusive metagabbro or metadiorite.

The contact of the greenstones with the overlying sediments is nowhere exposed. The boundary probably follows rather closely the limits of the greenstone outcrop area because the greenstone, where present, crops out whereas the softer overlying slates do not. The latter underlie the drift-filled and swampy valley of Briar Hill Creek and its topographic homologue east of the Paint River.

The thickness of the greenstone is unknown, but it is probably several thousand feet.

Footwall strata

Immediately south of and overlying the greenstones is a series of beds, here termed the footwall slates because they are subjacent to the iron-bearing formation. They are almost wholly gray and black slates. So little information about them is available that a subdivision of them into members has not been attempted. The uppermost footwall stratum, however, is a fissile black graphitic and pyritic slate such as is known to underlie the iron-formation

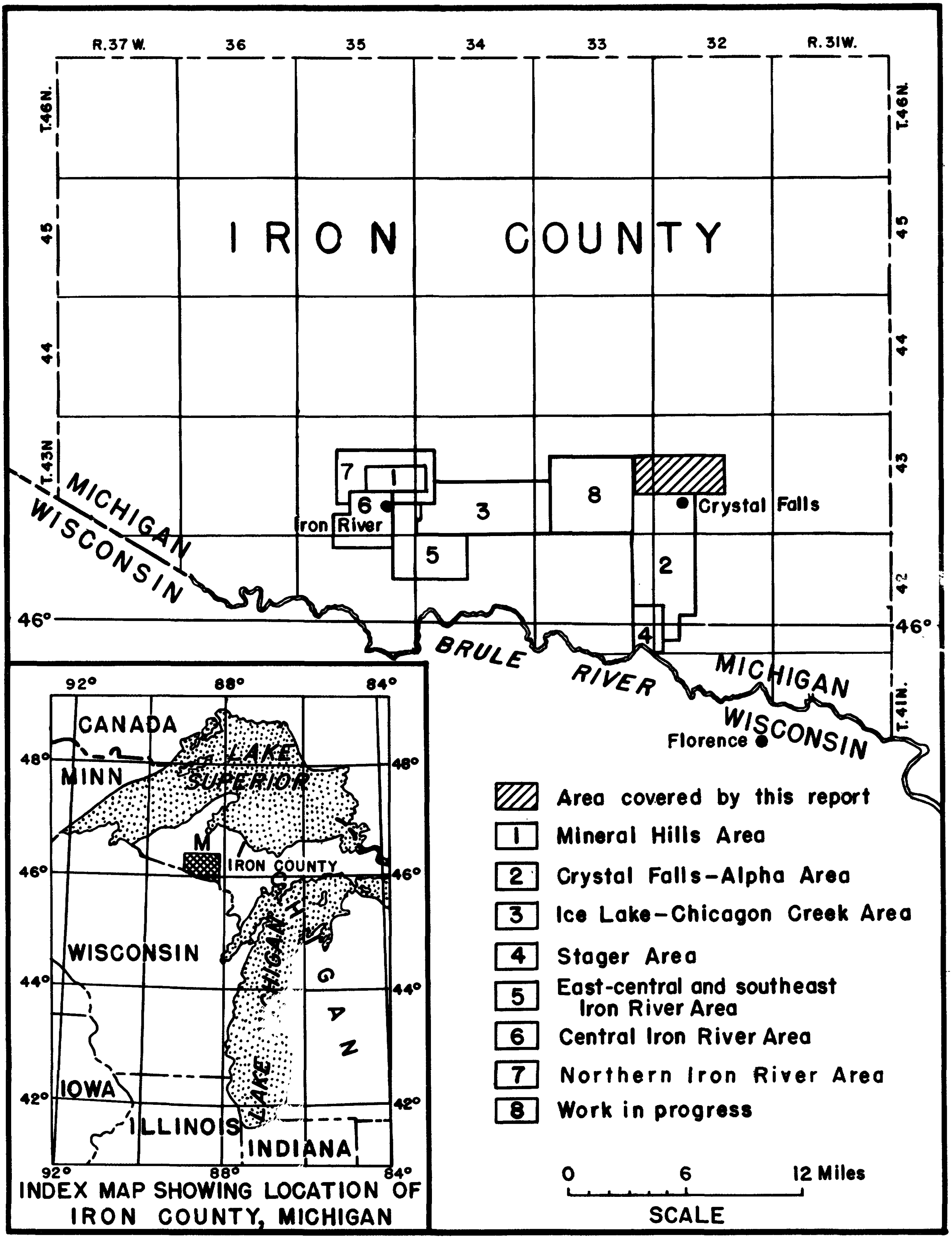

Figure 1. --Index map showing location of the northern Crystal Falls area in Iron County, Mich.

Table 1.--Stratigraphic column of the northern Crystal Falls area

Rock unit	Character of unit	Thickness (feet)
Hanging-wall strata 1/	Graywacke, basal and (or) chert breccia overlain by gray and black slates and graywackes. Lower slates magnetic at the west of Paint River.	500
---Unconformity---		
Iron-formation	Chert and siderite, interbedded; locally oxidized to banded chert and hematite; locally rich in iron silicates.	300-600
Footwall strata	Slates, gray and black, with fissile pyritic slate in upper part.	800-900
---Unconformity(?)---		
Greenstones	A complex of fine-grained, massive, greenish-gray altered lavas, in part ellipsoidal, with a little agglomerate and tuff.	Very great

1/ For detailed subdivision of the hanging-wall strata see table 2.

elsewhere in the Crystal Falls area. Debris from this member appears on most of the mine dumps of this area and was also found in several test pits near the east quarter corner of sec. 21.

The thickness of the footwall strata does not exceed 1,000 ft in the SW$\frac{1}{4}$ sec. 24, T. 43 N., R. 33 W., inasmuch as this is the distance separating the greenstone from the iron-formation at that place. Elsewhere the distance between the iron-formation and the basement greenstone is somewhat greater, but close folding and crumpling may readily account for the wide footwall belt.

The footwall-greenstone contact is presumed to be an unconformity.

Iron-formation

The iron-formation, unlike the footwall slates, is exposed in many places, mainly along the north-facing slopes south of Briar Hill Creek, near the dam on the Paint River, and on the north and north-west sides of the hill on which the Crystal Falls and Hilltop mines are located. Except where oxidized, it always has the same outcrop characteristics. It consists of alternating 1- to 2-inch layers of laminated to slaty gray siderite and equally thin layers of dense black chert. Steeply plunging drag folds are very numerous. No secondary cleavage is present though some of the carbonate layers contain a chloritelike mineral, and locally these chlorite-rich layers form an appreciable part of the rock.

Fresh exposures, which have the appearance just described, are rare. Weathering commonly converts the siderite to limonite. The chert beds weather white or gray and become sugary and somewhat friable.

Locally, as in the vicinity of the ore bodies, the iron-formation is thoroughly oxidized. The carbonates are changed to hematite (or to some extent to limonite) whereas the chert assumes a light-colored paraffinlike appearance.

The limits of the iron-formation shown on the map (pl. 1) are not everywhere determined with the same degree of certainty. In general the hanging-wall contact is rather accurately mapped from numerous drill holes, test pits, and outcrops. The footwall contact, on the other hand, is poorly controlled. It lies mainly in swampy or low ground, and its position is largely hypothetical. In discussing this contact it has been assumed that the graphitic black footwall slate encountered in drilling is infolded with the iron-formation in the same manner as are the hanging-wall strata and that there is no major inter-bedded black slate in the iron-formation itself. This may not be a wholly valid assumption.

The thickness of the iron-formation is very difficult to ascertain. It cannot exceed 600 ft in the western part of the district. The great variations in width of the outcrop belt are readily explained by close and repeated folding.

Hanging-wall strata

The hanging-wall strata are exceptionally well exposed along the course of the Paint River just south of the municipal power dam, in the SE$\frac{1}{4}$ sec. 20, T. 43 N., R. 32 W. Detailed mapping of these exposures has made possible a subdivision of the hanging-wall strata into members. These are described in detail in this report on page 6.

The lowest member of the hanging-wall sequence is in some places a coarse chert breccia whereas in others it is a massive graywacke. The breccia facies, where best shown, is a massive erosion-resistant rock composed of large and small, angular slablike pieces of chert in a graywacke matrix. The graywacke facies is a massive structureless rock that, under the hand lens, is seen to consist of many large rounded quartz grains together with a few particles of chert set in a dark-gray to black matrix. The maximum thickness of this member is 75 ft. It may decrease to a few inches in some places.

Overlying the basal breccia-graywacke bed is a series of slatelike rocks that in places contain enough magnetite to produce a very marked magnetic anomaly. The magnetic bed itself is about 50-60 ft thick. It is separated from the breccia-graywacke member by a few feet of nonmagnetic waxy green slates. The magnetic stratum is a hard, flinty slate, rich in magnetite, overlain by more massive, blocky dark-green stilpnomelane-rich strata, which are interbedded with white to gray chertlike porcellanites.

Conformably above the magnetic slate and associated rocks is a thick series of clay slates of a gray color. These slates are interlaminated with siltstones, and higher in the section they are interbedded with coarse massive graywackes.

Igneous rocks

A few microcline-bearing quartz veins, from 1 to 8 in. wide, cut the hanging-wall slates along the Paint River. A large dike of much-altered basic rock--probably originally a gabbro--is exposed at the east end of the Paint River-Lamont caved area. Drilling in the old Ravenna mine area disclosed a greenstone intrusive that may be a similar rock body.

Structure

The strata of the area have been steeply upturned. They crop out in long, narrow belts, which in this part of the district have an east-northeast trend. They form a broadly monoclinal sequence with oldest beds at the north and youngest at the south. Upon this structure has been superimposed a series of east-plunging minor folds, the axial planes of which trend west-northwest. As a result the boundaries of the formations are highly crenulated; therefore, in horizontal section, they have a pronounced zigzag course. Moreover, the strike of the beds within each east-trending belt is generally to the northwest.

Most of the secondary folds plunge southeastward at a low angle, but locally the direction of plunge is reversed. These closely spaced second-order folds (100 to 200 ft apart) locally produce a great expansion in the width of the outcrop belts, especially in that of the iron-formation.

The sequence of beds from older at the north to younger at the south, the southeast plunge of most of the secondary folds, and the apparent termination of the Paint River greenstone belt near the center of T. 43 N., R. 32 W., all suggest that the strata of the northern Crystal Falls area form the south flank of a major east-plunging anticline. Slates were encountered in drilling in the NE$\frac{1}{4}$ sec. 16 and the NW$\frac{1}{4}$ sec. 15, T. 43 N., R. 32 W. The greenstone would be presumed, therefore, to constitute the core of the anticlinal structure.

On the other hand, outcrops of ellipsoidal greenstone in sec. 9, T. 43 N., R. 33 W., in the north part of the Paint River greenstone belts, show the tops of the flows to be southward as they are in the Paint River area proper. Outcrops in sec. 36, T. 44 N., R. 34 W., at the very north edge of the greenstone, also seem to have the same orientation. Therefore the Paint River greenstone does not appear to have an anticlinal structure; thus the slates that lie north of the greenstone are either older than the volcanic rocks or are in fault contact with the greenstone.

Despite the easterly plunge of many of the secondary folds, it seems probable that the strata of the northern Crystal Falls area form the nearly intact north limb of a large complexly faulted syncline that widens and plunges southwestward. The strata of the southern Crystal Falls area (Pettijohn, 1947) form the south limb of this structure.

The north limb has been traced from Iron River eastward into the northern Crystal Falls area. The southern limb is traceable northward and eastward from the Brule River, south of Stager, to the Odgers mine in sec. 30, T. 43 N., R. 32 W. Eastward from the Odgers mine this limb appears to be severed by two or more oblique faults with large strike displacements. The continuity of the iron-formation is interrupted; and distribution, in the absence of outcrops or adequate exploration, can only be inferred. The best guide to the structure is the pattern of the magnetic anomalies produced by the ironstone magnetic slate of the lower hanging-wall strata. The probable structural relationship between the strata of the northern and southern Crystal Falls areas is shown on the structure map, plate 8. Structural details, especially of the apical area in sec. 21, are given elsewhere in this report.

THE PAINT RIVER OUTCROP AREA

(SE$\frac{1}{4}$ sec. 20, T. 43 N., R. 32 W.)

Introduction

The outcrops along the Paint River, between the Crystal Falls municipal power plant and Michigan State Route 69, are some of the most informative in the Iron River-Crystal Falls district. The best exposure of the iron-bearing formation in the county is that below the power dam (pl. 3). In the next half mile downstream the strata overlying the iron-formation are exposed in rocky bluffs and knobs. The sequence of beds, the hanging-wall strata, is better shown here than elsewhere. The standard section established from these outcrops is applicable to much of the Iron River-Crystal Falls district.

Chert breccias, found to mark a significant unconformity in this district, are best exposed in the Paint River outcrop area; and here also is the only known outcropping of the contact between the breccia and the iron-formation.

The magnetic slate--a significant marker bed--is well displayed here. Because of the abundance of outcrops, it is possible to see most clearly the relation between magnetic anomalies produced by the slates and the structure and lithology of the bedrock.

It was deemed desirable, therefore, to make a detailed study of the outcrops along the Paint River and to present the results of this study in full. Accordingly, the area was mapped in 1943 with a plane table and telescopic alidade on a scale of 200 ft to 1 in. The most informative part of the area so mapped is shown on plate 2.

Topography

The Paint River outcrop area is characterized by a group of rocky knobs and bluffs adjacent to the Paint River. The rocky area begins at the municipal power dam and extends downstream to the crossing of Route M-69. Although the relief is only 150 ft, the area close to the river is very rough. On the west side of the river, between the stream and the railroad, is a small-scale scabland characterized by isolated rock knobs, rock-rimmed basins, and abandoned river channels. Largest of the isolated rock hills is that on the south line of sec. 20. This hill, more than 40 ft high, is separated from the higher ground farther west by a channel about 200 ft wide and 1,000 ft long.

This complex of knobs, basins, and channels was probably produced by river action at a time when the volume of water was much larger than it now is. A glacial melt-water river, which was superimposed on the bedrock of this area, scoured out the network of channels and isolated knobs. Upon disappearance of the glacial ice the flow was greatly diminished, and many channels were abandoned.

Stratigraphy

The strata exposed along the Paint River are all pre-Cambrian in age. The sequence and essential features are summarized in table 2.

Iron-formation

The iron-formation is the most extensive formation within the confines of the mapped area. It apparently underlies the northern half of the area--namely the $N\frac{1}{2}SE\frac{1}{4}$ sec. 20, T. 43 N., R. 32 W. It is best exposed along the river, especially so just below the dam. Excellent exposures also occur in the abandoned railway cuts near the east quarter corner of sec. 20.

The unoxidized iron-formation consists principally of thin layers of dense black chert and light-gray to greenish-gray siderite. The beds are $\frac{1}{2}$ to 3 or 4 in. thick and almost everywhere are crumpled or contorted. The chert is dense, black, and possesses a marked conchoidal fracture. Upon weathering the chert becomes granular and white. The carbonate is commonly thinly laminated. The laminations appear to be due to varying proportions of a greenish chloritic material--probably stilpnomelane. The latter forms layers that range from paper thin to a quarter or half inch in thickness. The more thinly laminated carbonate has a parting parallel to the bedding and is commonly described as "slaty carbonate." The thicker carbonate beds tend to be blocky, owing to absence of well-defined cleavage and to close-set jointing. Fresh carbonate is difficult to secure except in deep artificial cuts or in freshly scoured outcrops along the river. Both the slaty and the blocky carbonate weather very easily. The latter oxidizes to limonite, which forms a brownish-black crust or veneer that effectively armors the unaltered interior. Oxidation penetrates so deeply along bedding planes and along the numerous close-spaced joints that one can collect only limonite-coated fragments. In a few places oxidation has not penetrated to the core of a joint block. In such cases, the limonite forms a "box-work." The core of the unaltered "boxes" is fresh carbonate, which is separated from the hard limonite shell by a thin mustard-yellow zone.

The more severely weathered outcrops of iron-formation disintegrate into a lot of loose pieces of sugary iron-stained chert and many small chiplike fragments of brown to mustard-yellow color. These remind one of an accumulation of flaky pieces of pine bark.

In places the alteration of the iron-formation is very different from that described above. The chert becomes bleached and paraffinlike in appearance. The carbonate alters to an earthy or compact red hematite (or more rarely to a dense submetallic yellow-brown limonite). This type of alteration is apparently only found in association with the ores; and, unlike that described above, it extends to great depths. The altered iron-formation, consisting of alternate layers of red hematite and white chert, resembles salt pork.

The original iron-formation apparently consists of about equal parts of siderite and chert. A chip sample taken across the face of the outcrop below the municipal power dam showed the following composition (J. G. Fairchild, analyst):

SiO_2	31.84
Al_2O_3	2.09
Fe_2O_3	14.83
FeO 1/	20.59
MgO	3.80
CaO	1.49
Na_2O	----
K_2O	----
H_2O 2/	1.80
TiO_2	0.12
CO_2	19.40
P_2O_5	0.83
SO_3	None
S	0.33
MnO	2.35
	99.47

1/ Calculated from remaining CO_2 equivalent. A direct determination is not possible. Any MnO_2 is disregarded.

2/ Includes organic material.

Table 2.--Detailed stratigraphy along Paint River

No.	Member	Description	Thickness (feet)
8	Graywacke	Clay slates, interbedded with thick layers of massive black graywacke.	50+
7	Gray slate	Slates, sericitic, fissile, thinly laminated light- and dark-gray.	200-300
6	Stilpnomelane mudstones	Mudstones with rude irregular fracture and porcellanite interbeds. Mudstones, greenish-black, weathering to olive drab, with blackened submetallic tarnish on surface and along fractures. Highly refractive folia visible under hand lens. Porcellanites in hard, compact beds 2 to 14 in. thick; exceedingly tough. Armored with dense, hard black limonite shell. Unaltered core of cream-colored to gray laminated flintlike rock. Without cleavage; fracture conchoidal. Harder than knife; effervesces in hot HCl. Gray porcellanite is magnetic. Thin pyrite layers common below porcellanite layers.	35
5	Magnetic slate	Slate, flinty, very hard, with pronounced platy cleavage parallel to bedding; thinly laminated. Weathers to iron-gray color. Highly magnetic. Some thin porcellanite seams near top.	40
4	Green slate	Slate, gray, fissile, thinly laminated. Weathers brownish-green and yellow. Oxidizes near ore to soft pink and yellow slate. Nonmagnetic.	20
3	Graywacke	Compact, massive rock. Fresh rock is black with conspicuous vitreous quartz sand grains. Numerous small flecks of detrital chert. Locally with imperfect schistosity. Weathers brown. Grades down into, is interbedded with, or grades laterally into chert breccia.	0-70
2	Chert breccias	Complementary to graywacke member. Ranges from very coarse breccia with large chert slabs, with subordinate matrix, to very fine breccia with small pieces of angular chert scattered throughout a dominant graywacke matrix containing large glassy quartz grains. Massive.	0-70
1	Iron-formation	Well-bedded formation consisting of equal parts of laminated gray siderite in layers $\frac{1}{2}$ to 2 in. thick, and dense black chert beds of similar thickness. On outcrop, chert weathers to semifriable white sugary beds; siderite oxidizes to brown to mustard-yellow limonite. Commonly much crumpled. Some "chlorite"-rich seams interbedded with carbonate. Oxidizes to red hematite with white chert ("salt pork") or to dense limonite and chert.	----
	Total (hanging-wall strata only)		415-515+

The CO_2 content corresponds to about 51 percent siderite. This agrees very well with the visual impression that the unoxidized formation consists of about equal parts chert and siderite. Moreover, the iron content of the formation is about 25 percent, which is surprisingly near the average for the unaltered iron-formations of the Lake Superior region (Van Hise and Leith, 1911, p. 462).

The iron-formation is the most universally drag-folded formation in the district. It is difficult to find an outcrop of any appreciable size that does not show some irregularity of strike, and many are so crumpled that strike and dip values for mapping purposes are not readily obtained. The folding is most intricate and is mainly of the concentric type. The broad concentric arcs pass into sharp chevron folds along the axial plane. The plunge is nearly everywhere high--commonly over 50°; in some places it is vertical. The drag folds seem to plunge in random manner though, on the whole, they show an easterly plunge.

The internal structures characterisitic of the iron-formation are exceptionally well shown by the large outcrop below the municipal power dam. The detailed structures of this outcrop have been mapped on a scale of 10 ft to 1 in. by W. S. White and H. L. James (pl. 3). The principal element of the structure in this outcrop is a complex drag fold that plunges westward at about 70°. A notable feature of this fold is its complexity to the east compared with its extremely simple form at the west edge of the outcrop. Minor folding along northward-plunging axes is also evident but is subordinate in importance. Many faults are clearly defined in the outcrop, but the displacement along them is small. The faults commonly branch, one branch passing into a bedding-plane slip and the other maintaining the fault line.

The relations between the iron-formation and the subjacent beds are nowhere shown in this area. On the west side of the Paint River, between the power house and the road bridge southeast of it, are some much-sheared graphitic slates of uncertain age. These rocks may be the same as the graphitic slates known to occur in the footwall elsewhere in the district. If so, they are the only exposed strata older than the iron-formation.

The contact with the overlying beds is well displayed on the east side of the Paint River about 600 or 700 ft downstream from the road bridge. The relations observed here are described in the next section.

Breccia-graywacke bed

Overlying the iron-formation and prominently exposed along the Paint River are chert breccias and associated graywackes. This unit consists of two distinct facies, namely, chert breccia and massive graywacke. Either of these facies may occur alone, or be interbedded with the other, or grade into the other.

The breccia facies is a massive erosion-resistant unit, which, in its thicker parts, crops out as prominent bare knobs or ridges. Typically it consists of a jumble of chert slabs. The fragments are tabular and range from 1 or 2 in. to 20 or 30 in. in length and from $\frac{1}{2}$ to 2 in. in thickness. In the coarser breccias the chert fragments average from 3 to 6 in. in length. The tabular fragments are arranged in subparallel fashion, and it is probable that this is the way in which they were deposited. In general they are angular; only rarely do they exhibit any rounding. The matrix is a dark-brown, somewhat oxidized material of uncertain character. Elsewhere, drill core shows it to be mainly graywacke. Locally the breccia is heavily sheared. It then exhibits a very rude irregular cleavage. The chert fragments tend to assume a rough rodlike form that is elongate parallel to the plunge of other structural features.

The chert breccias grade into graywacke. Several transitional types of rock can be seen in the field. One consists of many small, tabular chert fragments--as much as 1 or 2 in. long and $\frac{1}{4}$ to $\frac{1}{2}$ in. thick--sprinkled liberally throughout a graywacke matrix. Matrix and fragments may occur in equal proportions, though commonly the rock is chiefly graywacke with widely scattered fragments of chert. In general the flat fragments are subparallel.

In other outcrops beds of coarse chert breccia, 5 to 10 ft thick, alternate with graywacke containing little or no chert. In at least one place coarse breccia seems to grade upward into breccia with small fragments, which in turn grades upward into graywacke with few or no chert fragments.

The graywacke itself is a massive, structureless sediment devoid of bedding. It is black on fresh exposure; the weathered surface is a light brownish gray. The unsheared outcrops are massive, with widely spaced joints. No bedding-plane fissility can be detected. The rock therefore breaks out into large angular blocks. Some exposures, however, are so sheared that the rock has a rude nearly vertical parting analogous to the slaty cleavage of the finer-grained rocks. Nearly all the graywacke exposed will reveal under close scrutiny a few very small and widely scattered particles of chert. In a few places a single large slab of chert appears in the middle of a massive graywacke.

Locally the graywacke has some interbedded slate and even a little interbedded bluish-gray chert. The chert occurs in layers 2 to 6 in. thick.

The breccia-graywacke bed is not very thick. In places it apparently is only 10 or 15 ft thick and may be even less. The maximum thickness is probably not more than 50 or 75 ft. The apparently greater thickness in some places is probably due to twofold or even threefold repetition of the bed.

The contact with the underlying iron-formation is very sharp. It is exceptionally well displayed in the cliff on the east bluff of the Paint River about 600 ft below the road bridge. The breccia here is very coarse and the lower few feet consist of very large and little disturbed slabs of chert. Though the rock superficially resembles the iron-formation on which it rests, there is little doubt as to the position of the contact. The basal phase grades upward into normal coarse chert breccia. In other places the lowest bed appears to be normal graywacke.

Little or no breccia is present at the contact with the iron-formation.

The breccias are mentioned but briefly in several older reports. Clements (1899, p. 166) says:

"Near Crystal Falls on both banks of the river, between the wagon and railroad bridges, there is exposed a conglomeratic phase of graywacke. Several bands of these coarse conglomeratic graywackes are interlaminated with bands of fine-grained graywacke and chert. A well-developed reibungsbreccia is also associated with these. I do not consider this conglomeratic graywacke anything more than a purely local and very slight unconformity."

It is now apparent that there is only one breccia, that it is of sedimentary origin, and that it marks a widespread and significant unconformity. From the relations shown along the Paint River and described above, it is also apparent that the chert breccia and the graywacke are but the two "end-members" of a sedimentary unit. The breccia-graywacke bed is a distinct mappable unit. The close stratigraphic and geographic association supports the view that the formation is an original sedimentary layer. The interbedding of the two facies, the gradation from one to the other, and the observation that an increase in abundance of graywacke matrix is accompanied by a decrease in size of the chert fragments all support this view. A reibungsbreccia or friction breccia would normally be produced by sharp folding of thin interbedded materials of unlike competency. The chert breccias are associated with graywackes and grade into them. No gradation of breccia into an unbroken interbedding of chert and graywacke was found. Even the iron-formation with its thin, sharply folded chert bands is, in the main, unbrecciated. In short, the evidence that the chert breccias are sedimentary rather than tectonic is overwhelming and conclusive.

The breccia is therefore a basal deposit; it is a basal rubble derived from the underlying iron-formation. The chert rubble is analogous to the basal conglomerates that are commonly found as the initial deposit of a marine transgression. A similar deposit is, in fact, well-exposed in several places in Dickinson County where the Cambrian sandstones rest on the Vulcan iron formation. Tongues of breccia are interbedded and grade into sandstone. The mingling of locally derived coarse angular chert with fine far-traveled well-rounded sand is a commonplace feature.

Observations elsewhere in Iron County have confirmed the conclusions drawn from the study of the Paint River outcrops. The chert breccias and associated graywackes are widespread and form an important marker bed. The unconformity on which they rest is therefore widespread. It is possible that locally the relief on this surface was great enough to cut through the whole thickness of the iron-formation. The importance of this possibility in exploration for iron ore is obvious.

Green slates

The lower slates which rest on the graywacke-chert breccia unit are not well exposed, and for some time their importance was overlooked. Some of the better exposures are those in the small syncline west of the Paint River and about 500-600 ft south of the road bridge. The slates have a waxy greenish-yellow appearance in outcrop. They are delicately laminated, fissile, and unlike the overlying beds, they are nonmagnetic. It is not likely that they exceed 20 ft in thickness.

Magnetic slate

The magnetic slate proper is a very hard fissile, flinty slate best exposed in the north-facing bluff that lies west of the Paint River and east of the railroad track, in about the middle of the SW$\frac{1}{4}$SE$\frac{1}{4}$ sec. 20. The rock is very hard and platy. A good bedding-plane parting yields flat sharp-edged pieces. The rock is thinly laminated, iron-gray in color, and contains much magnetite, which is visible to the naked eye. The rock is highly magnetic and is responsible for the principal magnetic anomaly of the Iron River-Crystal Falls district. The slaty facies is about 40 ft thick. In the upper part of this magnetic slate are porcellanic seams as much as 2 to 3 in. in thickness. The upper part of the slate is not so platy and seems to have a greenish cast. This facies is probably transitional to the next overlying beds.

Stilpnomelane mudstones

Overlying the magnetic slates are interbedded greenish mudstones and porcellanites. The porcellanite occurs in beds 2 to 14 in. thick. It is a very dense rock; it is exceedingly hard to break with a hammer. In outcrop it is marked by a heavy, dense black limonitic crust. Beneath this crust is a hard, chertlike greenish-gray to creamy white porcellanite. Though delicately laminated, the fracture is strictly conchoidal. The flakes produced by breaking are razor sharp. The rock is too hard to be scratched by a knife, but it effervesces nonetheless in hot HCl. The gray laminated varieties are magnetic. The hard limonitic crust is separated from the unaltered porcellanite by a thin soft yellowish ochre.

An analysis, by B. Brunn, of a similar 12-inch porcellanite bed near the Dunn mine (outcrop 900 ft west of the center of sec. 1, T. 42 N., R. 33 W.) follows:

SiO_2	43.43
Al_2O_3 1/	11.25
Fe_2O_3	0.18
FeO	21.00
MgO	1.39
CaO	0.70
Na_2O	1.21
K_2O	3.99
H_2O, total	0.50
CO_2	15.76
C	0.08
	99.49

1/ Includes MnO, TiO_2 and P_2O_5.

As can be seen from the analysis, the porcellanite contains about 35 percent siderite.

Associated with the porcellanites are rocks to which the term "mudstone" may be applied. They are marked by their blackened appearance in outcrop; they commonly show a submetallic tarnish that is somewhat iridescent. The fresh surface is olive drab; the powder is khaki brown. The mudstones in the Paint River area have a rude, irregular schistosity. They break into irregular flakes upon hammering. Under the hand lens the fresh surface sparkles, owing to minute scales of a highly refractive mineral. According to a written communication from J. W. Gruner, X-ray analysis of a green mudstone with blocky fracture, somewhat less altered than the Paint River material, showed quartz, chlorite, and stilpnomelane. It seems probable that the refractive, micaceous silicate of this rock is an iron-silicate, either stilpnomelane or a closely related species. In some places these greenish mudstones are notably magnetic.

The composition of the blocky green mudstone examined by J. W. Gruner is given below:

Analysis of stilpnomelane mudstone 1/

[J. G. Fairchild, analyst]

SiO_2	52.85
Al_2O_3	8.71
Fe_2O_3 2/	24.03
FeO	----
MgO	2.87
CaO	0.10
Na_2O	1.48
K_2O	1.89
H_2O 3/	5.56
TiO_2	0.60
CO_2	0.20
P_2O_5	0.78
SO_3	----
S 4/	0.03
MnO	1.10
	100.20

1/ Road cut, SE¼NW¼ sec. 12, T. 42 N., R. 33 W.
2/ Direct determination not possible because of organic matter.
3/ Includes organic material.
4/ Total sulfur.

The porcellanite seams within the stilpnomelane mudstone member are commonly underlain by a thin (1/8 to 1/2 in.) bed of pyrite. This relationship has elsewhere proved useful in determining the order of superposition. A rough estimate in the Paint River section shows that the porcellanite forms from one-tenth to one-fifth of the total thickness of this member. The mudstone bed itself is probably about 35 ft thick.

Gray slates

The mudstone is overlain by thinly laminated dark-gray clay slate and lighter-gray siltstone. The alternating laminations are 1/8 to 1 in. in thickness. The rock is fissile and splits without difficulty into large thin sheets. Fresh material is readily obtained.

The slaty cleavage is commonly, though not everywhere, parallel to the bedding. The cleavage surface has a sheen--almost silky in places, and in the right illumination it shows faint striations. These are probably due to near-microscopic crinkling.

A chemical analysis of this rock shows it to be a normal slate in most respects though it has a considerably higher than normal iron content.

Analysis of gray slate 1/

[Robert H. Nanz, Jr., analyst]

SiO_2	54.59
TiO_2	1.58
Al_2O_3	11.62
Fe_2O_3	3.05
FeO	16.09
MnO	0.10
MgO	3.38
CaO	0.25
Na_2O	----
K_2O	1.70
P_2O_5	0.13
H_2O+	6.34
H_2O-	0.21
CO_2	0.83
C	0.70
SO_3	----
	100.58

1/ C&NW railroad cut north of Crystal Falls, SW¼SE¼ sec. 20, T. 43 N., R. 32 W.

Owing to close folding it is difficult to estimate the thickness of the gray slates. They are probably not more than 200 ft thick and may not exceed 100 ft.

Upper graywackes

The highest bed exposed in the Paint River section is chiefly graywacke. Exposures of this bed occur west of the river in the northeast part of sec. 29. The rock exposed is a badly sheared graywacke which resembles rather closely the graywacke associated with the chert breccias. No breccia was found in association with these graywackes, however, and their association with the gray slates and their position in the section makes it probable that they are superimposed on the gray slates and are therefore the youngest exposed strata in the mapped area. The exposed thickness is probably not more than 100 ft.

The total thickness of the hanging-wall strata exposed in the Paint River section cannot be much more than 500 ft and may not exceed 350 ft.

Intrusive igneous rocks

Within the mapped area (pl. 2) two types of crosscutting intrusives were found. These were pegmatitic quartz veins and metagabbro.

Pegmatitic quartz veins

The veins are all rather small; most of them are but 1 to 2 in. wide, though one or two are 12 to 18 in. thick. They are flat-lying or nearly so and everywhere appear to fill tension cracks in "pencil" or "split-wood" slates. The best examples are the five or six rather large flat veins exposed on the east bank of the Paint River in lot 5. These are predominantly white quartz with subordinate (10-20 percent) salmon-pink microcline. They are, therefore, essentially feldspathic quartz veins rather than true dikes. These veins tend to pinch out laterally. At best they are traceable for only a few yards. In some of the small veins the quartz is columnar with the columns normal to the vein walls.

Metagabbro

A dikelike body of basic rock about 50 or 60 ft thick is exposed in the caved area of the Paint River mine and in a nearby test pit. The rock has been thoroughly altered. It is now a soft gray rock that breaks into large irregular blocks. Although the original minerals are wholly altered, the original texture is rather well retained. The rock was apparently a coarse-textured rock of gabbroic character.

The dike at the Paint River mine is evidently the same one referred to by Wadsworth (1893) and also mentioned by Clements (1899, p. 183). According to Clements the Lake Superior survey notes that ***"the strata of the ore formation***is cut by an eruptive dike which runs about northwest and southeast. This dike hades to the west and forms with the hanging-wall slates of the ore formation a trough pitching to the west at a very steep angle. In this trough is situated the ore body upon which the Paint River and Monitor mines are working."

Structure

The structure of the Paint River outcrop area is characterized by a series of close folds. Between the road bridge and the south line of sec. 20 are four anticlines and four synclines. Inasmuch as the distance involved is a little more than 2,000 ft, it is evident that the average distance from the crest of one anticline to the trough of the adjacent syncline is about 250 ft.

In the area south of the road bridge the minor drag folds, the minute crinkling in the slates ("striations" on cleavage surfaces), and the rodlike elongation of the fragments in the chert breccias all plunge to the east. Though these minor features seem to show a rather steep plunge, 25° - 75°, it is apparent from the map that the over-all plunge must be rather small and that in some places it is westward.

All the slates have a prominent slaty cleavage, which is apparently parallel to the axial planes of the folds. As is usual in slates of this type, the cleavage is nearly parallel to the bedding everywhere except in the apical portions of the folds. In the latter areas the cleavage and bedding are nearly perpendicular to each other, and this relationship causes the rock to break up into "pencils" or larger fragments that resemble split wood. Quartz-filled tension fractures normal to the pencils are common in these places.

There is little good evidence of faulting in the Paint River area. Near the southeast corner of sec. 20, however, there are abrupt changes in strike and some pyritized schists, which suggest the presence of faults. The most convincing evidence of faulting is southeastward in the adjacent part of sec. 28 where the strike of the strata changes abnormally. The prevailing strike in the Paint River outcrop area is about N. 70° W. Along the Paint River the strike becomes N. 30° W., locally due north and even N. 45° E. It is highly probable that this "drag" is related to one or more major faults with large strike slips. The deflection of the strike near the faulted zone indicates an eastward movement of the north wall and a westward shift of the south wall. The faulting may be a westward continuation of that known to occur just north of the Hope mine in the N½ sec. 27, T. 43 N., R. 32 W., where the strata are deformed in a similar manner adjacent to the fault. A fault may lie between the footwall-like material in the three test pits some 1,050 ft west and 400 ft south of the northeast corner of sec. 29. These test pits lie only 50 to 100 ft from outcrops of the upper graywackes. Faulting is apparently responsible also for the eastward bend and termination of the altered granite dike found on the west side of the Paint River in the NW¼NW¼ sec. 28, T. 43 N., R. 32 W. (see pl. 8).

Magnetic anomalies

Two very pronounced magnetic anomalies characterize the Paint River outcrop area and adjacent parts of secs. 20 and 21 (pl. 4). The principal anomaly extends entirely across the S½S½ sec. 20. A related anomaly lies north of the Paint River, mainly in the SE¼SE¼ sec. 20 and the SW¼SW¼ sec. 21.

These anomalies were mapped in 1946 by the author with a Hotchkiss Superdip. The Superdip was oriented in a vertical plane normal to the magnetic meridian. The angle between the gravitational and magnetic arms (sigma) was set at 2°. The average of the first down swing, the first back swing doubled, and the second down swing was computed. The readings thus obtained were corrected for temperature and for diurnal changes. The differences between the temperature- and base-corrected readings and the mean value of a local base station were then plotted on a map and contoured (pl. 4). The stations occupied were spaced 100 ft apart on north-south lines 200 ft apart. Points were located by pacing from stakes set at 200-foot intervals along an east-west base line. Errors of position probably do not exceed 50 ft.

As used, the Superdip measures departures of the vertical intensity of the earth's magnetic field from a normal value. For the lower readings each scale division was found to correspond to about 35 gammas. Inasmuch as a simple linear relation between the gamma values and scale divisions does not hold for the higher readings, the total magnetic relief of the area is not known. It is probably well above 5,000 gammas.

One of the most obvious features of the magnetic map is the parallelism of the isoanomaly contours and the strike of the rocks. This is especially true of the anomaly south and west of the Paint River. The general trend of the magnetic contours is about N. 70°-80° W., which is about the average strike of the beds west of the river.

Comparison of the overlapping parts of plates 2 and 4 will show that the anomaly is clearly related to the magnetic slate and associated magnetic stilpnomelane mudstones and porcellanites. The combined thickness of these beds, however, is only about 75 ft. Where the anomaly is located over the vertical magnetic strata it is about 100 ft wide. This relationship is best shown on the west side of the Paint River near the west edge of the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 20.

In the area farther west, especially in the SE$\frac{1}{4}$ SW$\frac{1}{4}$ sec. 20, the anomaly is very broad. It is about 1,200-1,300 ft wide. Nearly any traverse across this area will show several magnetic crests--usually three. The great width and the appearance of several crests suggest either that there are several magnetic beds or that one magnetic bed has been repeated by folding or faulting.

Repetition by folding is almost certainly the correct explanation of the wide anomaly. This interpretation is consistent with the close-folded nature of the structure disclosed by detailed mapping of the breccia-graywacke bed along the river. Furthermore, outcrops along the river reveal only one magnetic bed. The over-all pattern of the anomaly west of the Paint River (pl. 4) is that of a bed involved in close, eastward-plunging folds (see pl. 5). In fact, many years of field work have shown that the cardinal principle in interpretation of the magnetic anomalies of most of the folded Huronian rocks is that the magnetic anomalies are to be read in the same way one reads a geologic map. The anomalies are centered over the concealed (or exposed) bedrock "outcrop" of the stratum responsible for the anomaly.

The magnetic anomaly north and east of the river is more complex and less easy to interpret. The long, somewhat "spotty" anomaly that extends eastward from the river along the north edge of the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 20 is closely related to the complex syncline involving hanging-wall strata shown on plate 2. Apparently this structure is deeper in some places than others; so these deeper, spoonlike structures contain magnetic slate over which the anomaly reaches a higher value than elsewhere. The broad, double-crested magnetic high in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 21 is related to two southeast-plunging anticlines involving the magnetic slate.

Areas markedly lower in magnetic intensity are present just north of the higher positive anomalies. These "negative" areas that lie north of the "highs" are characteristic features not only of this area but of other places in the vicinity of Crystal Falls. Also noteworthy is the larger irregular negative area that lies just off the "ends" of the east-plunging folds of magnetic slate in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 20. In the southeast part of sec. 20, on the other hand, where the magnetic slate is carried down beneath younger strata, the magnetic anomaly continues as a weaker positive feature. The presence of a magnetically negative area at the turn of a plunging syncline and a magnetically positive area over the nose of a plunging anticline are diagnostic features of anomalies produced by folded beds.

Although the iron-formation is known to continue eastward for some distance, there is no magnetic anomaly associated with the overlying slates. It is not clear why this is so. In part the oxidation of the slates may have destroyed the magnetite that is responsible for their magnetic character.

GREAT WESTERN-HILLTOP AREA

General statement

The bedrock geology of the Great Western mine area (pl. 6), chiefly the S$\frac{1}{2}$ sec. 21, T. 43 N., R. 32 W., and the Hilltop mine area, the W$\frac{1}{2}$W$\frac{1}{2}$ sec. 22 of the same township, is poorly known, mainly because of an extensive and thick drift cover. Outcrops are confined to the Crystal Falls golf course in the SW$\frac{1}{4}$ of sec. 21 and the hill in secs. 21 and 22 on which the Crystal Falls and Hilltop mines are located. Bedrock is apparently so near the surface of most of this hill that it was reached in many old test pits. On the other hand, in the area near Runkle Lake and the Crystal Falls airport and in the north half of sec. 21, the drift is very thick. It is 200 ft thick beneath much of the airport and exceeds 250 ft just north of Runkle Lake.

Stratigraphy

The stratigraphic sequence in the Great Western-Hilltop area is practically the same as that elsewhere in the northern Crystal Falls area. The lower footwall slates, exposed in numerous test pits and a few outcrops in the Crystal Falls mine area, are silky or glossy phyllites or slates with a minor quantity of graywacke. These are dark gray where unoxidized, red or yellow or "bleached" where oxidized. Oxidation seems rather widespread in the NW$\frac{1}{4}$ sec. 22. The upper footwall slates are graphitic. This member of the footwall sequence was reached in test pits near the east quarter corner of sec. 21. As seen on the dumps it is a very black sooty rock. Locally it has been so sheared that the fragments are polished and slickensided. Superficially the debris from the test pits resembles slaty anthracite coal. It soils ones fingers and readily marks paper. A little chert is associated with the graphitic slate.

The iron-formation is best exposed in the caved areas of the Crystal Falls and Hilltop mines where it is thoroughly altered and consists of alternating layers of red hematite and white chert. Oxidized iron-formation also occurs in the caved area of the Fairbanks mine in the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 21. Unoxidized iron-formation was, however, found in test pits just south of the east quarter corner of sec. 21 and in the old railroad cuts northwest of the Crystal Falls mine. A single outcrop occurs near the north line of the NW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 21. Where exposed, the formation closely resembles that found elsewhere in the Crystal Falls area. An unusual facies was encountered in one of the drill holes in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 21. The iron-formation, in appearance somewhat like the Negaunee iron-formation of the Marquette district, consists of jaspery chert bands alternating with thin layers of hard blue hematite and an iron silicate. The core is decidedly magnetic. This phase is apparently responsible for the notable magnetic anomaly in this "forty" and probably also the cause of the anomaly in the east part of the SE$\frac{1}{4}$NE$\frac{1}{4}$ sec. 21. Oxidation and leaching of this member may have produced the hard limonitic bands found in the Victoria exploration and in the drilling in the $SW\frac{1}{4}NW\frac{1}{4}$ sec. 21.

The hanging-wall beds are exposed only in the $SW\frac{1}{4}$ sec. 21. A little chert breccia and graywacke are found in the $NW\frac{1}{4}$ of this quarter section. A number of small outcrops of gray slate are found in the golf course in the $SW\frac{1}{4}$ of the same quarter section. Black slate is poorly exposed near the road south of the Great Western mine. Somewhat graphitic slates were found south of the iron-formation in the Great Western workings; some slate was reached in drilling in the center of the $SE\frac{1}{4}$ sec. 21 and also near the west margin of this same quarter section. These are probably all hanging-wall slates. Except in the golf-course area, the hanging-wall strata are not notably magnetic.

Structure

As shown on plate 6, iron-bearing formation is present in drill holes and test pits near the west quarter corner of sec. 21, in the Great Western mine, and in drilling near the center of the $SE\frac{1}{4}$ sec. 21; it crops out in ledges and is found in test pits in the vicinity of the Crystal Falls and Hilltop mines and in test pits at the Victoria exploration.

How these various occurrences of iron-formation are connected is not self-evident. It now seems probable that most are a part of a single uninterrupted bed. This formation has been traced from Iron River to Crystal Falls. A similar stratum has been followed, without gaps, from the Brule River northward to Crystal Falls (Pettijohn, 1947). These two converging belts of iron-formation are presumed to join in the vicinity of Crystal Falls and to mark the "apex" of a great triangular basin of Huronian rocks, the other apices of which lie at Iron River, Mich., and at Florence, Wis. By this interpretation, the iron-formation of the northern Crystal Falls area and that of the area south of Crystal Falls mark the two limbs of a large southwest-plunging syncline. The apex of this structure lies in the Crystal Falls mine area.

Inspection of plate 6 will show that there is some evidence to support this concept. The footwall contact itself outlines the structure. Although a narrow belt of black graphitic footwall slate is present in a narrow anticlinal infold near the west quarter corner of sec. 21, the main footwall contact is located in relation to drilling just south of the center of the $NW\frac{1}{4}$ sec. 21. It probably extends northeastward to the Hilltop mine where it may be seen in the mine pit. From this point it runs southward, between numerous outcrops and test pits, in a slightly irregular manner, to the east quarter corner of sec. 21 where there are several test pits in black graphitic slate. The location of the contact beyond this point is less clear, but the line probably continues its southward course to the southeast corner of the section. The iron-formation in the Victoria exploration probably occurs in an isolated downfold surrounded by footwall slates.

The extraordinary width of the outcrop belt of the iron-formation is most striking. From a width of about 600 or 700 ft near the south line of sec. 24, T. 43 N., R. 33 W. (pl. 1), the outcrop area of the formation has widened until it exceeds 2,000 ft along the north-south center line of sec. 21. The divergence of the hanging-wall and footwall contacts is most marked in the Great Western area. As a result of this divergence, the iron-formation underlies a large roughly triangular area between the west quarter corner of sec. 21, the Hilltop mine area, and the southeast corner of sec. 21 near the west end of Runkle Lake. This triangular region has an area of about 250 acres, or a little less than half a square mile.

That this triangle is the apex area of a large syncline is further shown by the strike and dips of the beds involved. Near the west quarter corner of sec. 21 the strike is nearly east with a low south dip. In the Crystal Falls and Hilltop mines area, near one corner of the triangle, the strike changes from slightly northeast along the old railroad grades northwest of the Crystal Falls mine, to southeast at the mine itself, to southwest just east of the mine. The dips are relatively low, being about 60° - 70° to the south or west. A general change in strike is also shown by the outcrops in the $SW\frac{1}{4}SW\frac{1}{4}$ sec. 21. Near the north line of this "forty" the beds trend nearly east but in the southeastern part they are more nearly north. The structure is also outlined in part by the magnetic contours, which generally follow the strike. They are northeast by east in the northern part of the section, nearly due north just east of the Crystal Falls mine, and almost southwest near the east quarter corner of sec. 21 and in the adjoining parts of sec. 22.

Important evidence bearing on the structure is obtained from the maps of the Crystal Falls mine. The workings show a progressive southwestward displacement of the ore body from the caved ground in the eastern part of the $SE\frac{1}{4}NE\frac{1}{4}$ sec. 21 to the southwest part of the "forty". The plunge is about 60° SW. The shaft was inclined in the same direction. Minor drag folds confirm the southwest plunge of the structure.

Magnetic anomalies

Magnetic data shown on the map (pl. 6) were secured with a Wolfson vertical magnetometer. The magnetic values represent departures, in gammas, of the vertical intensity of the earth's magnetic field from that of a local base station.

It is apparent from inspection of the map that the observed anomalies are all relatively small. The total magnetic relief is only about 350 gammas. It is also evident that there is no sharply defined anomaly associated with any marker bed as occurs in the Paint River outcrop area. Instead, the isoanomaly contours are widely spaced and wander in an irregular way over much of the area.

In general, however, it is clear that there is a magnetic gradient from southwest to northeast. Moreover, the contours in the $S\frac{1}{2}$ sec. 21 have a general west-northwest trend, which is the prevailing trend of both the magnetic contours and the beds in the $S\frac{1}{2}$ sec. 20. It is probable, therefore, that the prevailing strike in the $S\frac{1}{2}$ sec. 21 is also west-northwest. Near the east quarter corner of the same section, however, the contours have a general northeasterly trend. In the area around the Crystal Falls mine, the trend is north or even northwestward. The trend of the anomaly contours throughout the area is usually consistent with the observed strike of the underlying beds.

The strongest anomalies seem to be centered over the iron-formation; the lowest values appear to be related to the footwall slates. There are so many apparent exceptions to these observations that it is unwise to draw conclusions concerning the nature of the bedrock from these relationships alone. The strongest local anomaly is that found in the SW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 21 which, as noted elsewhere, is related to a magnetic silicate phase of the iron-formation. An anomaly of like magnitude occurs in the Crystal Falls mine area where outcrops show the underlying rock to be iron-formation. Some of the low values over areas designated iron-formation may be related to thorough oxidation of that formation and destruction of its magnetite content. Again, it would be unwise to conclude that a low value over the iron-formation is a certain indication of oxidation and perhaps ore. It might only mean that an unsuspected body of footwall slate had been infolded with the formation.

RAVENNA-BRISTOL AREA

General statement

The Ravenna-Bristol area (pl. 7) includes the S$\frac{1}{2}$ sec. 19 and the N$\frac{1}{2}$N$\frac{1}{2}$ sec. 30, T. 43 N., R. 32 W., and the S$\frac{1}{2}$SE$\frac{1}{4}$ sec. 24, T. 43 N., R. 33 W. In general, the bedrock of this area is poorly exposed, and therefore the geology of much of it is known only from mining and exploratory drilling. Where such exploration is lacking, very little is known about the geology.

Stratigraphy

Insofar as can be determined from the available data, the stratigraphic sequence in this area is similar to that elsewhere in the northern Crystal Falls area. The footwall slates are overlain by iron-formation which, in turn, is overlain by the hanging-wall strata that consist mainly of slates with some interbedded graywackes.

The footwall slates are nowhere exposed. They apparently underlie the low ground traversed by Briar Hill Creek. As encountered in drilling, they are black, graphitic, and pyritic.

The iron-formation is exposed in the caved area of the Bristol mine. It also crops out on the northwest side of Briar Hill just southwest of the Bristol mine. The best outcrops, along the old railroad grades, are the usual unoxidized formation consisting of crumpled thin-bedded siderite and chert. Two small outcrops of iron-formation occur in the SW$\frac{1}{4}$SW$\frac{1}{4}$ sec. 19, just south of the Ravenna-Prickett mine.

Outcrops of the hanging-wall strata are the most numerous. They are widely scattered throughout the mapped area but are most abundant near the south line of the NW$\frac{1}{4}$NW$\frac{1}{4}$ sec. 30. The hanging-wall strata consist chiefly of gray and black slates. Also present are both coarse- and fine-grained graywackes. The slates all have a well-marked slaty cleavage which, over most of this area, cuts the bedding at a high angle.

Structure

Very little is known about the structure of the Ravenna-Bristol area. The formations have a general east strike, and they decrease in age from north to south. The iron-formation apparently extends from the west edge of the mapped area where it was observed in a test pit, through the Ravenna-Prickett and the Ravenna mines, to the Bristol mine.

The iron-formation is involved in close folding at the Bristol mine and is probably faulted in the old Ravenna property. The principal fold at the Bristol is an anticline of graphitic footwall slate, which extends across the Ravenna property north of the no. 1 shaft and goes at least as far eastward as the no. 1 shaft of the Bristol mine. A downfold of the iron-formation lies north of this anticline.

On the 250-foot level of the Ravenna mine, the strike of the beds is southwest, practically parallel to the drift between the main workings and the no. 1 shaft. In the main workings the strike is about N. 50° W. and parallel to the magnetic high that lies south of the mine. The discordance in strike northeast of the ore body with that in the area of the ore body and south of it suggests a fault, which would separate the two areas of unlike strike.

The hanging-wall contact has been followed by drilling westward from the Ravenna to the "forty" south of the Ravenna-Prickett shaft. It is located again on the west line of the SE$\frac{1}{4}$SE$\frac{1}{4}$ sec. 24, T. 43 N., R. 33 W., where it passes between a test pit in iron-formation and an outcrop of hanging-wall graywacke. It has apparently been displaced northward along a fault. The probable position of the fault has been shown on the map (pl. 7).

Two large faults are presumed to cross the southern part of the mapped area. Each is traceable from adjoining areas into the Ravenna-Bristol area, but within the vicinity itself there is no evidence of these two faults. The location of these faults is so uncertain that they have not been shown on the map.

Magnetic anomalies

The magnetic anomalies in the Ravenna-Bristol area were mapped with a Hotchkiss Superdip. The instrument was set to swing in the plane of the magnetic meridian. The angle between the gravitational and the magnetic arms was set at $10\frac{1}{2}^{\circ}$ ("sigma" $3\frac{1}{2}^{\circ}$). The first down swing, the first back swing doubled, and the second down swing were averaged. The average values were corrected for temperature and diurnal variations. The differences between the corrected values and that of a local base station were plotted and contoured (see pl. 7). Stations were placed 100 ft apart on north-south lines 200 ft apart. The stations were located by pace and compass traverses from established points on the south line of sec. 19. Errors of position are probably not more than 50 ft. On the average, each scale division is approximately 40 gammas.

As can be seen from the map (pl. 7), magnetic anomalies are weak and ill-defined over most of the area. In general, the magnetic readings over the hanging-wall strata are higher than those over iron-formation, so there is a slight but distinct drop in values as one goes from hanging wall to iron-formation.

A fairly strong anomaly is associated with the lower hanging-wall strata at the west edge of the mapped area, especially in the SE¼SE¼ sec. 24, and at the east edge of the mapped area, in the SW¼SW¼ sec. 20. In addition to these better-defined anomalies, there are several weaker local anomalies related to the lowest hanging-wall beds. The largest of these lies south of the old Ravenna workings; it has a northwest trend. There is no evidence in this area to show what bed is responsible for these basal hanging-wall anomalies, but the strong anomaly near the east edge of the mapped area is traceable farther eastward to the Paint River where it is found to be due to the magnetic slate member of the hanging-wall succession. The other anomalies therefore are presumed to be due to the same bed.

Locally the iron-formation is responsible for an anomaly. A small but distinct anomaly is associated with an iron-formation outcrop south of the Ravenna-Prickett mine. But as noted above, readings over the iron-formation are, in general, two to three scale divisions lower than those over hanging-wall beds.

GEOLOGIC HISTORY AND CORRELATION

Greenstones

The geologic history of the area begins with the lava floods that produced the thick section of greenstones. The lavas were probably mainly basaltic. Many of them may have been subaqueous inasmuch as they show pillow (ellipsoidal) structures. The lava outpourings were interrupted locally by the explosive volcanism responsible for deposition of tuffaceous materials. The volcanic products, both flows and pyroclastics, were predominantly basic; acidic products are very rare.

The age of the greenstone is not certainly known. Greenstones, lithologically indistinguishable from those in the Paint River area, occur in the Marquette area and in the Mansfield area in Iron County. The former are pre-Huronian; the latter have been considered Middle Huronian. The greenstones of the Paint River area are similar to the Quinnesec greenstone and the greenstones of the Pentoga and Mastodon areas. The age of these rocks is also uncertain. The Quinnesec greenstone, for example, were assigned to the pre-Huronian or Archean (Bayley, 1904); later they were considered to be Upper Huronian (Van Hise and Leith, 1911, p. 344). All that is certain is that the greenstones of the Paint River area are the oldest rocks in the northern Crystal Falls area.

The greenstones are presumably overlain unconformably by the footwall slates. This relationship cannot be established either from this area or from adjacent areas. The contact between the footwall slates and the greenstones can be seen, however, in a road outcrop south of Alpha, in the SW¼NW¼ sec. 19, T. 42 N., R. 32 W. There is neither conglomerate nor sandy material at the base of the slates.

Footwall strata

The footwall slates were apparently deposited in a relatively deep, quiet body of water inasmuch as they are generally fine muds. During the later stages of deposition of the footwall slates the bottom waters were poorly ventilated. The graphitic nature of these beds and their pyritic content indicate an absence of oxygen. The carbon is almost certainly degraded organic matter. Because of its close association with the carbon, the sulfur is also probably of organic origin. It may have been produced by bacterial reduction of sulfates or by decomposition of sulfur-bearing organic matter. In any case the H_2S that was present reacted with available iron to produce iron sulfide, which was probably reorganized into pyrite after deposition.

Iron-formation

The iron-formation was also deposited under anaerobic conditions inasmuch as siderite is highly unstable in the presence of oxygen. Apparently conditions were favorable for the rhythmic precipitation of silica and ferrous carbonate. It is not clear just what these conditions were. Several hypotheses have been advanced to explain the deposition of iron-formation (Leith and others, 1935, pp. 21-23). These will not be reviewed here.

The iron-formation has been correlated by Van Hise and Leith (1911, p. 597) with the Ironwood and Vulcan formations of the Gogebic and Menominee districts, respectively. All were considered to be Upper Huronian. More recently the Ironwood and the Vulcan have been regarded as Middle Huronian whereas the iron-bearing formation at Crystal Falls was thought to be Upper Huronian and equivalent to the Bijiki iron-bearing member of the Michigamme slates of the Marquette district (Leith and others, 1935, p. 13). Although most students of the problem concur in this view, there are some who consider the iron-formation and associated slates to be Middle Huronian (Snelgrove and others, 1944, table 3).

Hanging-wall strata

The hanging-wall beds record the renewal of deposition after a notable interruption. The large volumn of detrital chert in the basal breccia implies the reduction, by weathering, of a significant thickness of iron-formation. The cherty residue was swept up by the advancing sea and mingled with an influx of quartz sand. The source of the sand is unknown, but it cannot have been produced by erosion of either the iron-formation or the beds underlying it in most of this area. The sand contains so little feldspar that it probably was produced by erosion of earlier sandy sediments. Possible sources are the Sturgeon quartzite and the sandy phases of the Randville dolomite.

After the initial influx of material and reworking of the residual mantle, the waters deepened and very fine-grained clastics and chemical precipitates were laid down. The materials precipitated were the iron silicates (now chlorite and stilpnomelane), siderite, chert(?), and pyrite of the stilpnomelane mudstones, porcellanites, and magnetic slates. This iron-rich group of sediments, some of them 75 ft thick, is in fact an "iron-formation." Although nowhere altered to ore, the average iron content must be about 20 percent. For the most part the iron is in the form of an iron silicate. Possibly the iron, like the chert in the underlying breccias, was derived by the erosion of the productive iron-formation. The deposit would then be a second-cycle deposit.

The higher hanging-wall beds record an increasing influx of clastic material, both fine- and coarse-grained.

The hanging-wall beds, like the iron-formation and the strata beneath, are generally called Michigamme slate and considered Upper Huronian. This assignment was made on the supposition that this group of beds was a conformable sequence. If, as seems to be the case, they are divided by an important unconformity, the relative ages need to be reconsidered. If the unconformity is that which elsewhere overlies the productive iron-formation and separates it from overlying Upper Huronian, then only the strata above the unconformity are Upper Huronian. The basal breccias and graywackes would then be the equivalent of the conglomerates and quartzites of the Goodrich quartzite of the Marquette district or the so-called Pabst conglomerate of the Gogebic district. The magnetic "slate" and associated iron-bearing beds might be the equivalent of the Bijiki iron-bearing member of the Michigamme slate in the Marquette district.

IRON ORES AND ORE POSSIBILITIES

General statement

In the northern Crystal Falls area, nine mines have at some time shipped iron ore (table 3). Three of them have each shipped over one million tons. Only one of the mines is active at the present time--the Bristol which was reopened in 1949 and is now producing ore.

The ores shipped from this area were mainly soft red to brown, non-Bessemer hematites, carrying about 53-55 percent iron (dry weight) and characterized by high phosphorous content (0.40-0.80 percent). Some of the ores were notably manganiferous. Small shipments of manganate grade ore running about 4.0 percent (dry weight) manganese were made from the Bristol mine.

Though the bulk of the ore shipped was hematite, some hard limonite is found on the dumps of the Victoria property and some is also known from drilling in the SW¼NW¼ sec. 21.

As can be inferred from the production figures, most of the ore bodies mined were rather small--less than one million tons. The larger production figures for some of the mines, such as the Bristol, were secured by mining of several ore bodies on the same property. As can be seen from the maps, the mine workings tend to be elongated parallel to the strike of the beds. As elsewhere in the Crystal Falls area, the ore bodies tend to plunge with the prevailing structure. None of the ore bodies were mined to great depths although, in the Bristol, development work extended to a depth of 1,525 ft.

One notable feature of the area, especially in the eastern part, is the location of the ore bodies near the hanging-wall contact of the iron-formation. Possibly the upper part of the iron-formation is more readily converted to ore; in any case, the ore mined at the Lincoln and Great Western mines was near the hanging-wall contact.

The concordance in strike and plunge of the ore bodies with that of the host rock suggests structural control of these ore deposits, but details of the relations of ore to structure are not available from present information. The ore is presumed to lie in structural troughs. At the Bristol it is said to lie in several closely spaced downfolds. Intrusives occur in the Paint River and Ravenna mines. In the former, the intrusive dike is said to form (with the beds) the trough in which the ore was formed.

Iron ore exploration

Evidence is clear that the ores have been formed by alteration of the iron-formation. The siderite has been oxidized to hematite (or limonite) and the chert removed by solution or replaced by iron oxide. The nature of the solutions responsible for the oxidation and leaching, and the mechanisms proposed to explain the processes, have been summarized elsewhere (Leith and others, 1935, pp. 23-26) and need not be reviewed here.

The first principle governing exploration for ore is that the ores will be confined to the iron-bearing formation; therefore, accurate delineation of the boundaries of that formation is a prerequisite to the search for ore. The ore bodies in much of the Iron River-Crystal Falls district lie in plunging troughs--principally synclinal folds. Such structures would seem to be the areas most promising for exploration. However, some ore bodies seem to have no obvious relation to structure; so no part of the iron-formation can be excluded as nonproductive until adequately tested by drilling.

Ore-bearing areas are extensively oxidized. Such oxidation commonly extends some distance beyond the ore itself and may involve the hanging-wall strata as well. Even the footwall beds may be oxidized. The presence of yellow and red slates, graywackes, or thoroughly oxidized iron-formation ("salt pork") is, therefore, a favorable indication.

Lesser guides to ore include coincidence of iron-formation and low ground, weakness of magnetic readings over oxidized areas, and float. None of these are very reliable. For the most part the iron-bearing strata do underlie low ground, though both the Crystal Falls and Hilltop mines are located on a conspicuous hill. The magnetic readings in this area are all low. It is difficult if not impossible, in the absence of other criteria, to discriminate between areas of low magnetic readings due to

Table 3.--Ore shipments from nine mines, northern Crystal Falls area 1/

Mine	Dates of shipment	Total shipment
Bristol-Youngstown (Claire)	1892-93; 1899-1934 2/	2/ 8,614,235
Crystal Falls	1890; 1895-1909; 1911-13	1,744,015
Great Western	1882-84; 1886-93; 1896; 1898-1913; 1915-19; 1922; 1925.	2,296,739
Hilltop	1899-1901; 1906; 1914-19	98,202
Lamont (Monitor)	1889-94; 1899-1900; 1902-7; 1910	558,524
Lincoln	1891-93; 1899-1907; 1909	241,627
Paint River (Fairbanks)	1882-92; 1900; 1902-7; 1913	382,078
Ravenna (old)	1912-17	296,421
Ravenna-Prickett (new)	1940-43	338,806

1/ Largely compiled from Lake Superior Iron Ores, 1938, Lake Superior Iron Ore Association.

2/ Does not include shipments made in 1950 or later.

oxidation and those due to other causes. Float must be used with great caution in a region such as this which has been glaciated. Fragments of oxidized iron-formation or ore mingled with any foreign debris are likely to have traveled many miles from their source.

Iron ore possibilities

There are a number of unexplored places within the northern Crystal Falls area. The most promising is the apical part of the Crystal Falls syncline in sec. 21, T. 43 N., R. 32 W. Several 40-acre tracts are practically unexplored. Most of this area seems to be thoroughly oxidized and complexly folded, so almost any place in sec. 21 shown as iron-formation on the map (pl. 1) is potentially ore-bearing. The most promising places are those having very weak or no magnetic anomalies.

Parts of sec. 20 are inadequately explored. The most promising area for iron ore is near the center of the section, north of the small syncline of chert breccia. There has been no exploration north of this synclinal axis to the writer's knowledge.

In view of the interpretation of the structure as presented on plates 1 and 8, there can be no northeast extension of the iron-formation beyond the Victoria exploration. Numerous test pits in secs. 15 and 22 and drilling in sec. 22 have failed to find iron-formation. However, there must be a southward or southwestward connection between the iron-formation near the west end of Runkle Lake and that at the Kimball and the Odgers mines. As shown on plate 8, the structure between these places is much complicated by the intrusive stock of sec. 28 and by major faults. A simple unbroken connection is therefore not to be expected. It is highly probable that the iron-formation is faulted at the Odgers mine and displaced southeastward about 1 mile to the Kimball mine. If this interpretation is correct, it would be futile to search for iron-formation between these two places.

The structural relations in the area between the Kimball mine and Runkle Lake are less clear, and the interpretation shown on the structure map is quite uncertain. If the strong magnetic anomalies in the southwest part of sec. 28 are due to the magnetic slate of the hanging wall, and if the slates that crop out along the Paint River in this section are footwall beds, the iron-formation should lie between them. The low ground and lower slopes along the west side of the Paint River have been extensively test-pitted without much success (May exploration). Most pits reached soft slates, mainly oxidized to yellow and red colors. A few are in graphitic slate, a little hematite, and some chert. It is certain that if there is iron-formation in this area it is very thin and not likely to be productive. The exploration, however was about half a mile east of the magnetic line found in the southwest part of this section. Possibly, therefore, the exploration found only slates far down in the footwall section, well below the productive iron-formation of this district. The iron-formation elsewhere in this district is several hundred feet thick and follows rather closely the magnetic anomaly of the lower hanging-wall slate. The logical areas to explore would have been the W½SE¼ sec. 28 and the NE$\frac{1}{4}$ sec. 29. These areas lie northeast of the magnetic lines and somewhat down slope from them. The writer knows of no exploration or excavations that reached bedrock in these areas. It is possible, of course, that the limb of iron-formation here postulated is faulted out as it is between the Odgers and Kimball mines.

Inasmuch as the iron-formation at the Victoria exploration seems to be in a small isolated basin, it is possible, though not very probable, that similar outliers exist. Exploration to date has not located such outlying structures except the Victoria. Because of its small size and isolation the Victoria structure is probably relatively shallow.

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UNITED STATES DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

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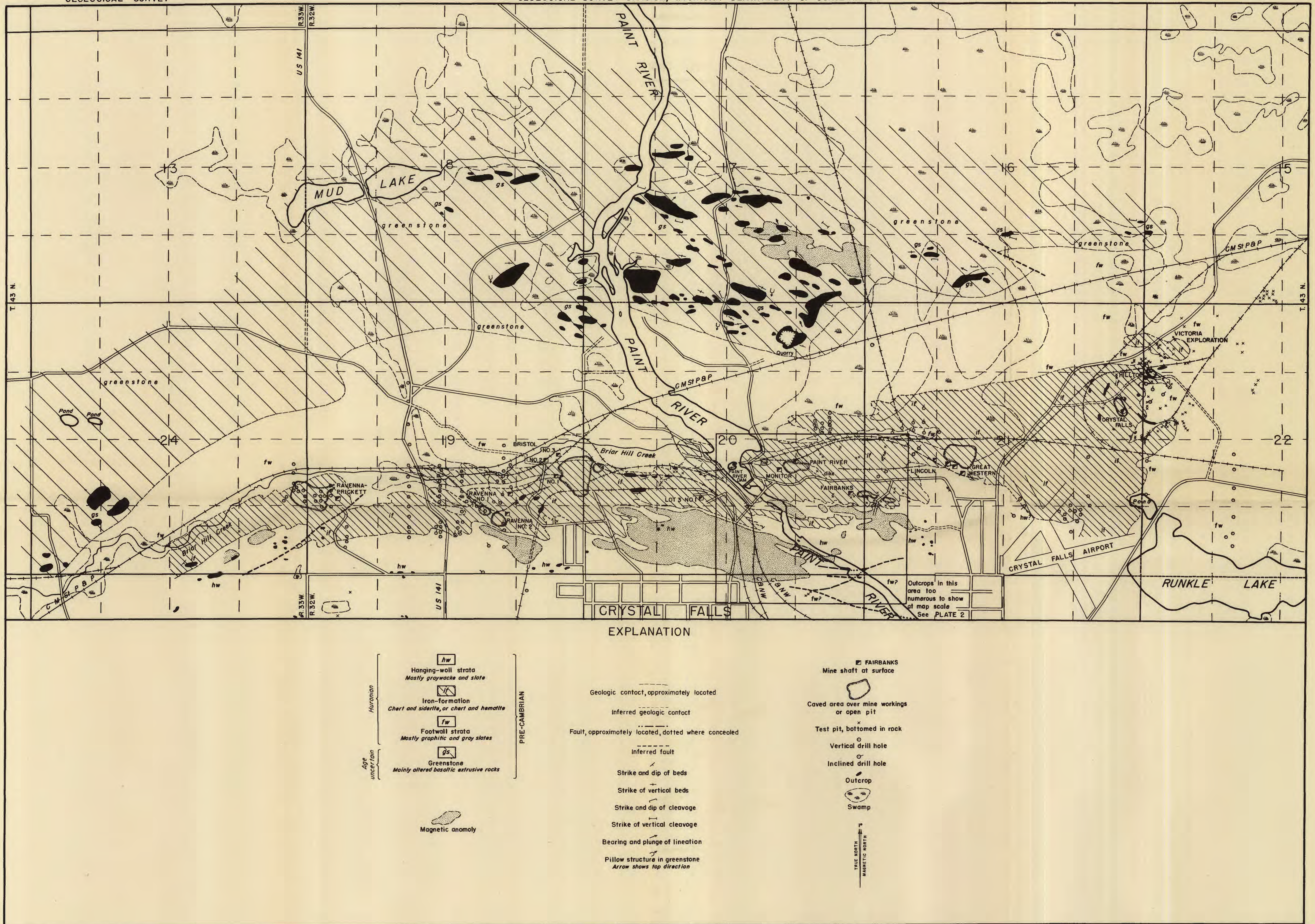
GEOLOGICAL SURVEY DIVISION, MICHIGAN DEPARTMENT OF CONSERVATION

CIRCULAR 153 PLATE 1



Base modified from Crystal Falls and Fortune Lakes quadrangles

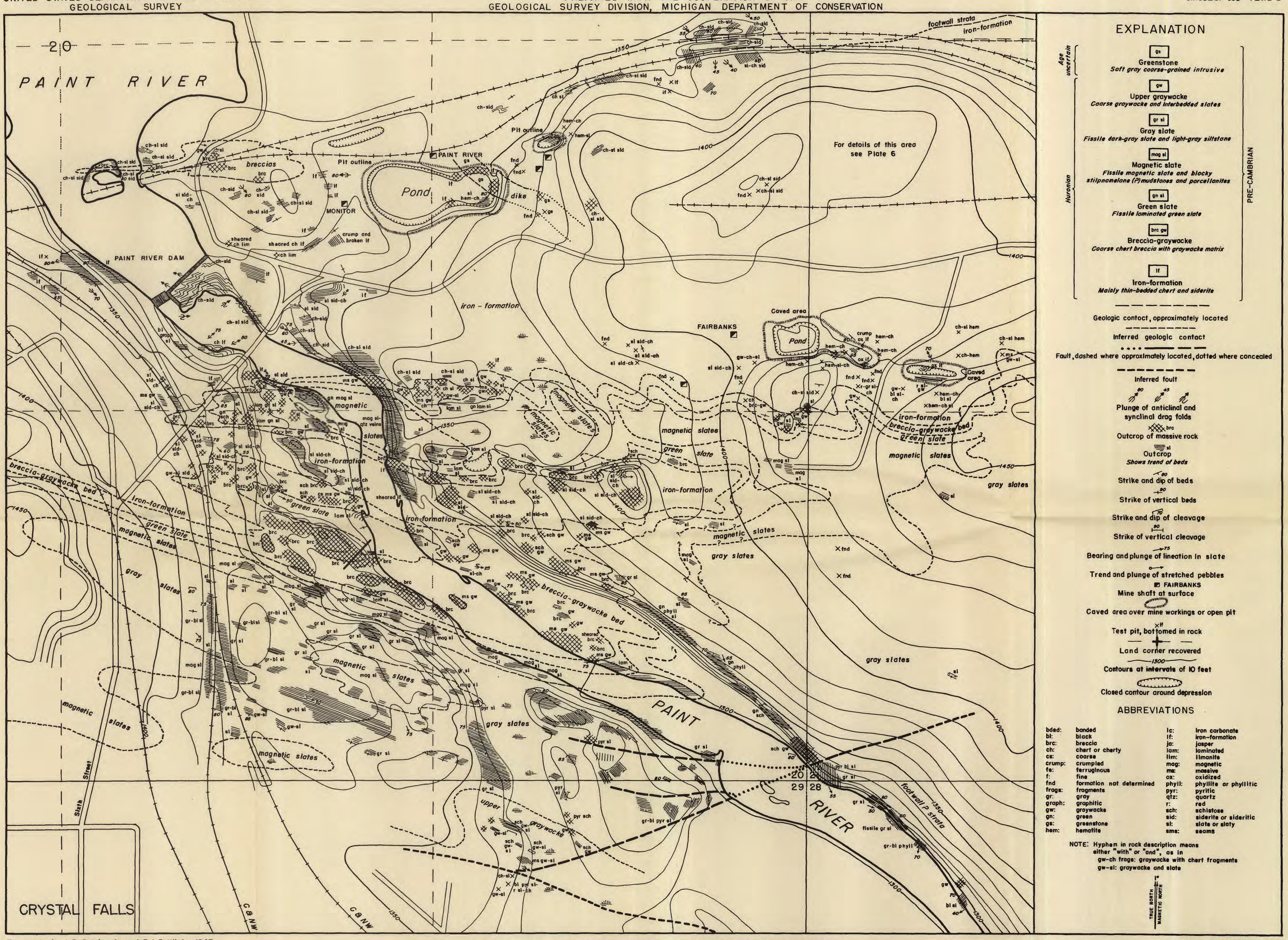
Geology by F. J. Pettijohn, 1943-1948

GEOLOGY OF THE NORTHERN CRYSTAL FALLS AREA

IRON COUNTY, MICHIGAN

0 ½ 1 Mile

PREPARED WITH THE COOPERATION OF THE
GEOLOGICAL SURVEY DIVISION, MICHIGAN DEPARTMENT OF CONSERVATION



Topography by J. R. Balsley, Jr., and F. J. Pettijohn, 1943

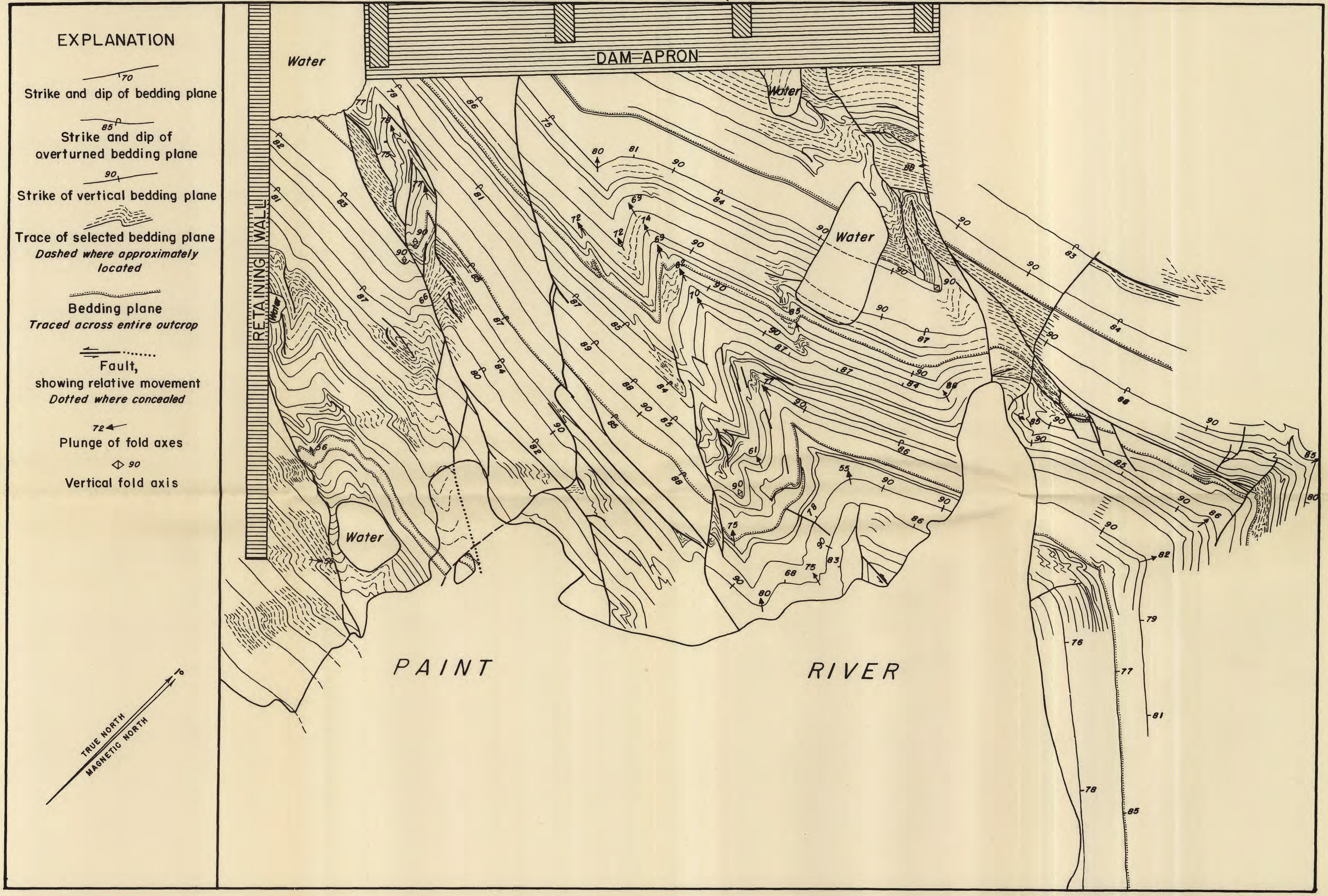
Geology by F. J. Pettijohn, 1943

THE PAINT RIVER OUTCROP AREA

SE 1/4 SEC. 20, T.43N., R.32W.

IRON COUNTY, MICHIGAN

250 0 250 500 750 Feet

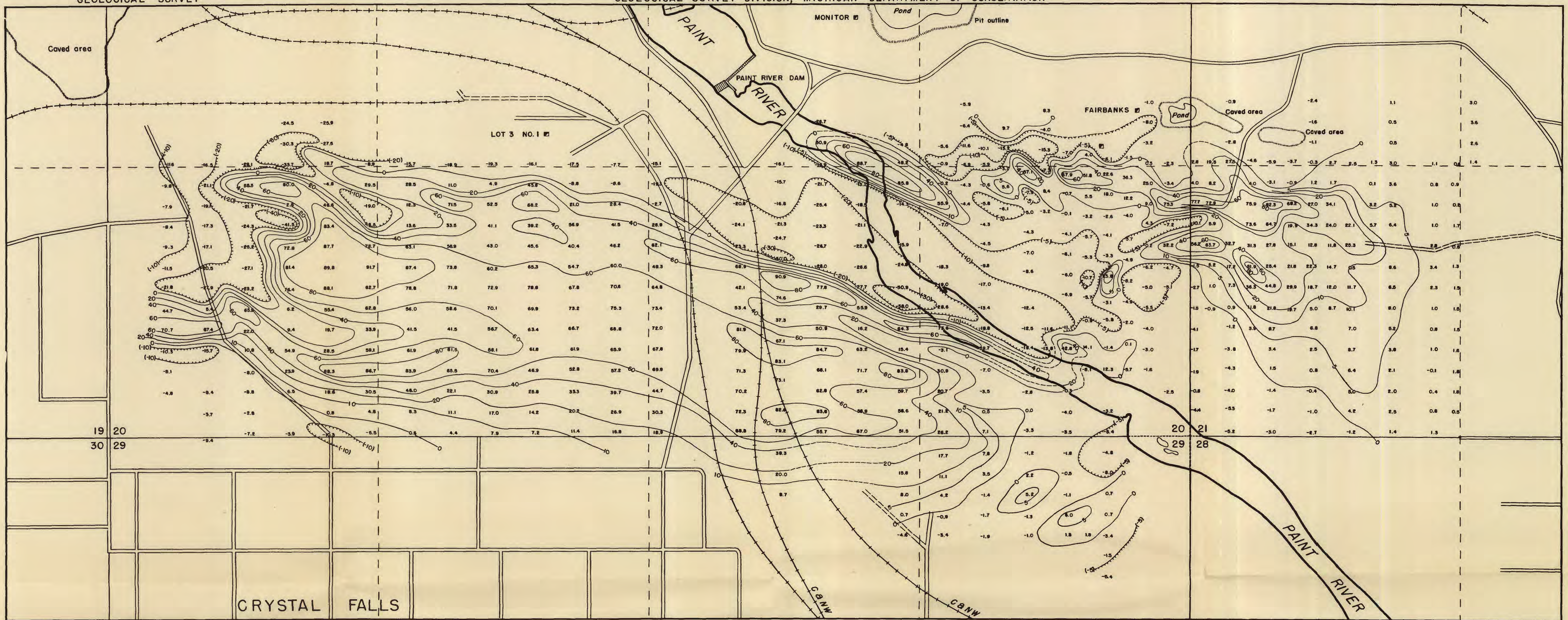


Surveyed by H. L. James and W. S. White, 1948

STRUCTURAL MAP OF IRON-FORMATION OUTCROP AT PAINT RIVER DAM

NW 1/4, SE 1/4 SEC. 20, T.43N., R.32W.
IRON COUNTY, MICHIGAN

10 0 10 20 30 Feet



EXPLANATION

72.3
Magnetic determination
Surveyed with Superdip oriented normal to magnetic meridian; sigma 2°. Value in scale divisions above or below local base station.

20
Isoanomaly contour
Interval 5, 10, or 20 scale divisions

(-10)
Closed contour around magnetic depression

FAIRBANKS
Mine shaft at surface

Caved area over mine working or open pit

TRUE NORTH
MAGNETIC NORTH

MAGNETIC SURVEY

S1/2 of S1/2 SEC. 20, T.43N., R.32W.
SW1/4 of SW1/4 SEC. 21, T.43N., R.32W.
IRON COUNTY, MICHIGAN

400 0 400 800 1200 Feet

Surveyed by F. J. Pettijohn, 1946

UNITED STATES DEPARTMENT OF THE INTERIOR
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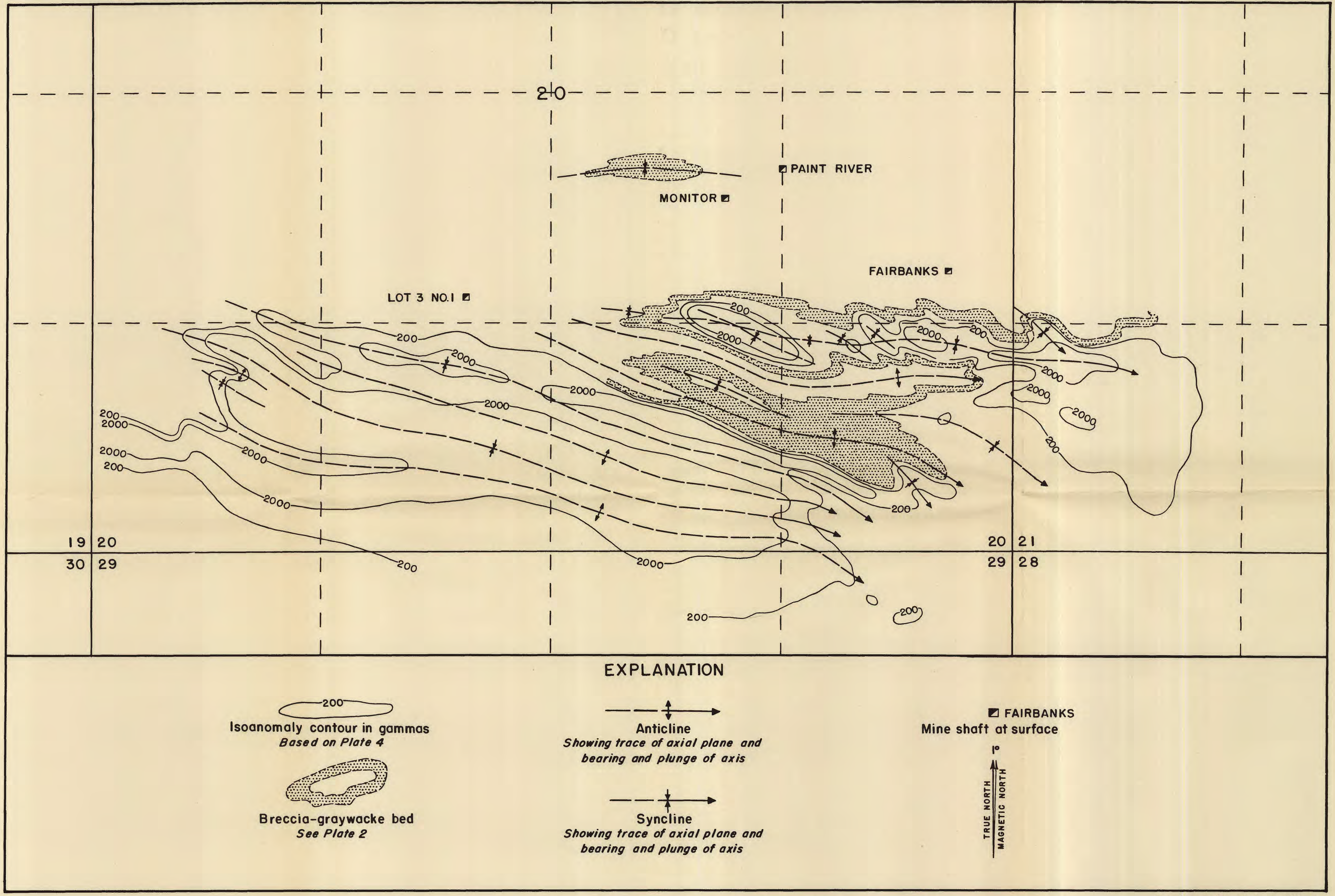
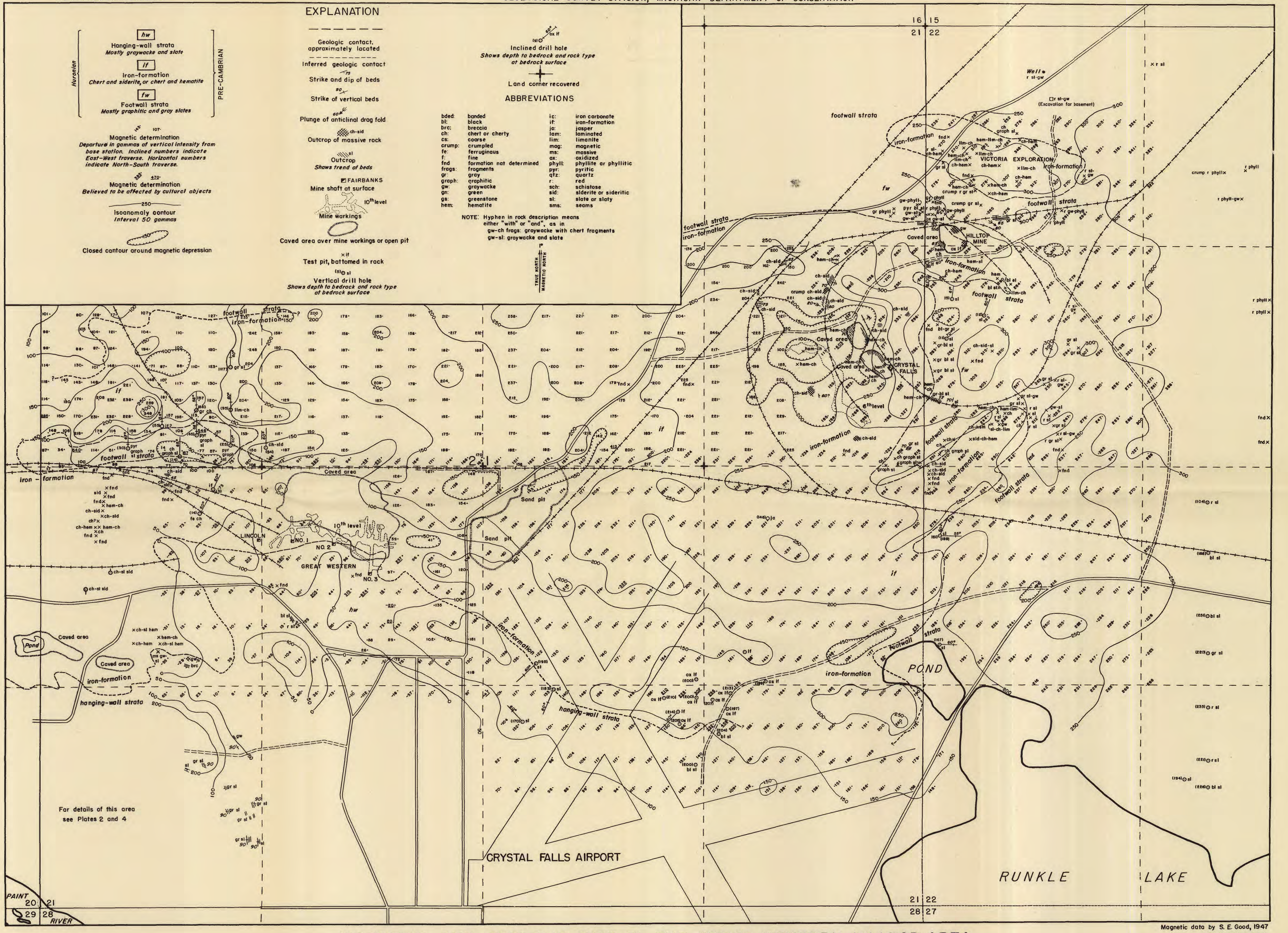
CIRCULAR 153 PLATE 5



STRUCTURAL INTERPRETATION OF MAGNETIC ANOMALY
S1/2 SEC. 20, T.43N., R.32W.
IRON COUNTY, MICHIGAN

500 0 500 1000 1500 Feet

Geology by F. J. Pettijohn,
1943 and 1946



MAGNETIC AND GEOLOGIC DATA IN THE GREAT WESTERN-HILLTOP AREA

S1/2 SEC. 21, T.43N., R.32W.
W1/2 of W1/2 SEC. 22, T.43N., R.32W.
IRON COUNTY, MICHIGAN

400 0 400 800 1200 Feet

Magnetic data by S. E. Good, 1947
M. W. Leighton, 1949
John Bokman, 1950
Geology by F. J. Pettijohn, 1948-1949

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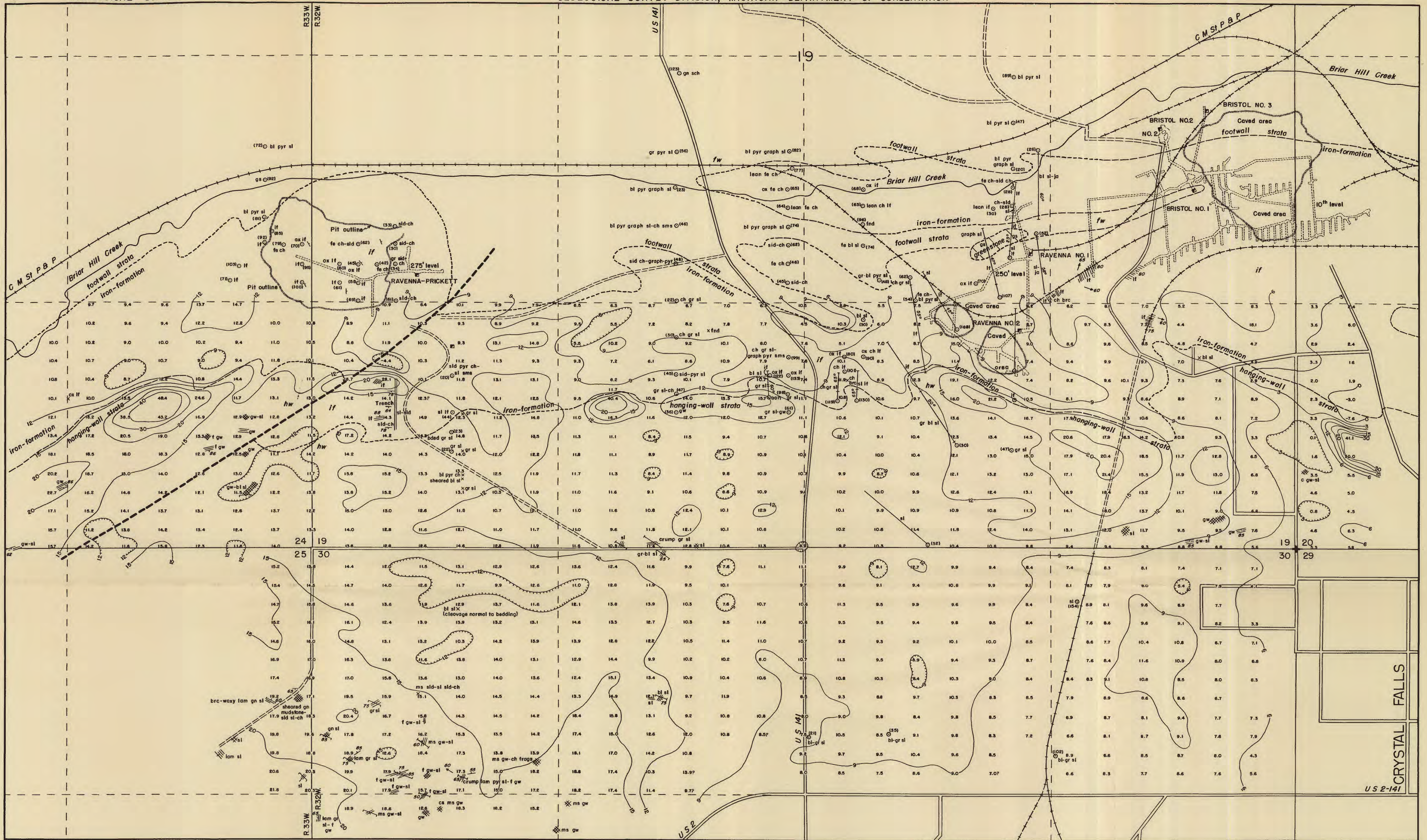


EXPLANATION

PRE-CAMBRIAN

Age uncertain

Greenstone
Mainly altered basaltic intrusive rocks

Huronian

hw — Hanging-wall strata
Mostly graywacke and slate

if — Iron-formation
Chert and siderite, or chert and hematite

fw — Footwall strata
Mostly graphitic and gray slates

19.5
Magnetic determination
Superdip readings in scale divisions above base station. Sigma $3\frac{1}{2}°$ parallel to meridian

Isoanomaly contour
Drawn on 0, 3, 6, 9, 12, 15, 20, 30, and 40 scale divisions

Closed contour around magnetic depression

Geologic contact
Dashed where approximately located or inferred

Inferred fault

Bearing and plunge of drag fold

Outcrop of massive rock

Outcrop
Shows trend of beds

Strike and dip of beds

Strike of vertical beds

Strike and dip of cleavage

Strike of vertical cleavage

FAIRBANKS
Mine shaft at surface

250' level
Mine workings

Caved area over mine workings or open pit

× gr sl
Test pit, bottomed in rock

(35) ○ gr sl
Vertical drill hole
Shows depth to bedrock and rock type at bedrock surface

(21) 15° if
Inclined drill hole
Shows depth to bedrock and rock type at bedrock surface

Section corner recovered

NOTE: Attitude of bedding in Ravenna-Prickett Mine from map by C. F. Park, Jr., and J. R. Balsley, Jr.

ABBREVIATIONS

bded:	banded	ic:	iron carbonate
bl:	black	if:	iron-formation
brc:	breccia	ja:	jasper
ch:	chert or cherty	lam:	laminated
cs:	coarse	lim:	limonite
crump:	crumpled	mag:	magnetic
fe:	ferruginous	ms:	massive
f:	fine	ox:	oxidized
fnd:	formation not determined	phyll:	phyllite or phyllitic
frags:	fragments	pyr:	pyritic
gr:	gray	qtz:	quartz
graph:	graphitic	r:	red
gw:	graywacke	sch:	schistose
gn:	green	sid:	siderite or sideritic
gs:	greenstone	sl:	slate or slaty
hem:	hematite	sms:	seams

NOTE: Hyphen in rock description means either "with" or "and", as in
gw-ch frags: graywacke with chert fragments
gw-sl: graywacke and slate

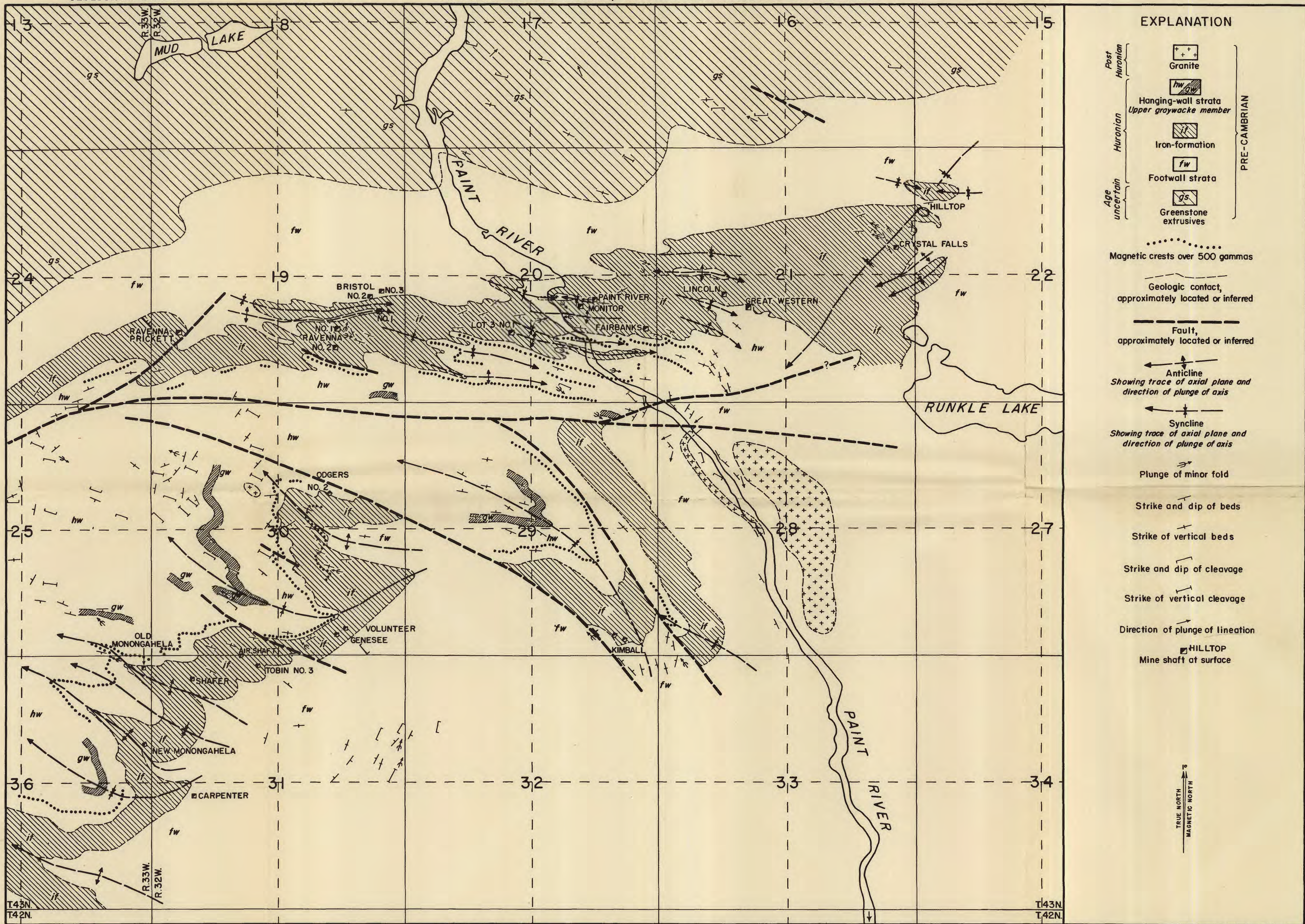
1°
TRUE NORTH
MAGNETIC NORTH

Geology by F. J. Pettijohn and L. D. Clark, 1944

MAGNETIC AND GEOLOGIC DATA IN THE RAVENNA-BRISTOL AREA

SECS. 19, 20, 29, 30, T.43N., R.32W.
SECS. 24, 25, T.43N., R.33W.
IRON COUNTY, MICHIGAN

400 0 400 800 1200 Feet



Geology by F. J. Pettijohn, 1943-1950

STRUCTURE MAP OF CRYSTAL FALLS AREA

IRON COUNTY, MICHIGAN

1000 0 1000 2000 3000 Feet