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ANOMALOUS STRUCTURES OF THE BARABOO BASIN

BY

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ANOMALOUS STRUCTURES OF THE BARABOO BASIN

LOCATION AND SIZE OF THE BARABOO BASIN

The Baraboo synclinal basin of southern Wisconsin is located in Sauk and Columbia Counties, Wis., along the $43^{\circ}28'N$ Parallel, and between the $89^{\circ}30'W$ and $90^{\circ}00'W$ meridians.

The basin, which varies from two to ten miles in width, is formed by two roughly parallel quartzite ridges which extend approximately twenty eight miles west-southwest from the town of Portage. They converge at both ends of the area to give the basin a canoe, or spoon, shape. The town of Baraboo is situated in the geographic center of the 225 square mile area.

For further information concerning the general location and geography of the area, refer to the index map of the area on Plate I, (Page 2) and the larger scale geologic map of Plate II, (Page 3).

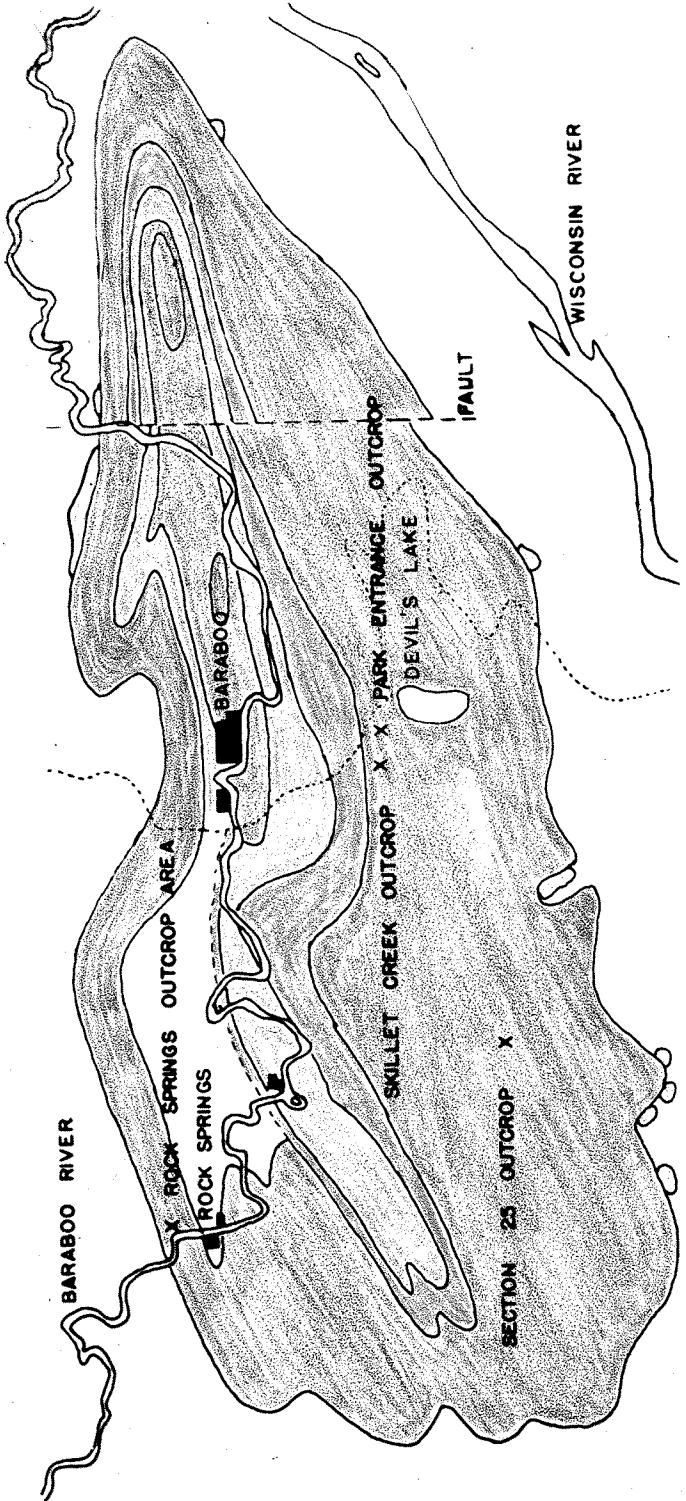
GENERAL GEOGRAPHY AND PHYSIOGRAPHY OF THE AREA

North, south, and east of the quartzite ranges, the area is relatively low with level farmland in drift filled valleys. However, west of the basin, the land is somewhat more broken and hilly, due to the erosion resistant Lower Magnesium limestone which underlies the area.

The southern quartzite ridge (The South Range) forms the most outstanding topographic feature of the area, for, due to its flatter dips, it is less vulnerable to erosion than the steeply dipping quartzite of the Northern Range. Thus the South Range is broader, and has greater relief than does its northern counterpart. The South Range reaches an altitude of 1620 feet, and stands from 300 to 800 feet above the surrounding farmland. The crest, which varies







INDEX MAP OF THE BARABOO SYNCLINE



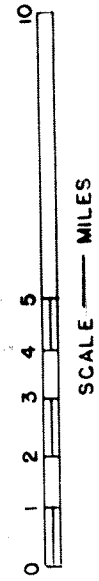


PRE - CAMBRIAN GEOLOGY

BY
 ANDREW LEITH
 (1935)

-  ROWLEY CREEK SLATE
-  DAKE QUARTZITE
-  FREEDOM FORMATION
-  SEELEY SLATE
-  BARABOO QTZ.
-  PRE - C IGNEOUS

.....
 MORaine



from 1 to 5 miles in width, is a gently rolling highland plain, with a series of flat or dome shaped bluffs suggestive of one or more peneplainations. Inasmuch as the quartzite of the South Range dips flatly to the north, the slopes to the interior valley are gentle compared to the southern slopes overlooking the surrounding plain.

The North Range does not exceed 2 miles in width or 600 feet in relief; nor is its crest as flat as that of the South Range. It has been cut by streams at the Upper and Lower Narrows of the Baraboo River, and at the Narrows Creek gorge. The southern ridge is broken only by the gorge at Devil's Lake.

The Baraboo River, which carries drainage waters from the area, enters the basin via the Upper Narrows, just north of the village of Rock Springs, Wis. Once within the basin, it turns to the east, roughly paralleling the northern ridge for approximately twenty miles before leaving the area through the Lower Narrows, six miles northeast of Baraboo. The Baraboo joins the Wisconsin River a few miles south of the town of Portage. The valley drained by the river and its tributaries varies between 800 and 900 feet above sea level, and like the land outside of the basin, consists of gently rolling farm and woodland.

Devil's Lake, the only lake in the region, is situated in a deep gorge in the southern ridge, about six miles south of Baraboo. It has long been a tourist attraction because of its scenic qualities, but students of geology have also been drawn here by the excellent rock exposures.

The chief industry of the area is agriculture, and rich farmland abounds in and around the basin, with the exception of the forested quartzite ridges. Although not strictly a "Baraboo industry",

the Badger Ordinance Works, located immediately to the south of the basin along U. S. Route 12, exerts a considerable influence upon the economy of Baraboo and the surrounding region, for several thousand people are employed at this plant.

The basin is easily accesible by major highways and paved secondary roads, and is served by the Chicago and Northwestern Railroad.

Fenneman (6) considers the Baraboo area to be divided by the physiographic boundary between the Driftless area and the Great Lakes Section.

PREVIOUS WORK ON THE AREA

The Baraboo basin has been of geologic interest ever since 1856, when Dr. J. G. Percival (21) expressed the opinion that the quartzite was actually a metamorphosed facies of the Potsdam sandstone. Later, in 1862, Dr. James Hall (9) placed the age of the quartzite as Archean. Dr. R. D. Irving discovered the Cambrian-Pre-Cambrian unconformity in 1872, and later, in 1877, published (with some apprehension) a paper which expressed the opinion that the two quartzite ridges were, in reality, one vast limb of a major anticline situated to the south of the area. C. R. Van Hise (30), in 1893, substantiated these findings in a paper dealing with the secondary structures of both ranges. In 1882, professor T. C. Chamberlain reported the possibility of iron ore bodies in the basin, but, it was not until 1900 that they were discovered by W. G. LaRue.

The most comprehensive report of the basin was made by S. Weidman, in 1904 (34). He presented the first widely accepted theory dealing with the structural geology of the area when he postulated that the region was a complex synclinorium, with a reversal of pitch resulting in the spoon shaped outcrop pattern. Much of the general

geology of this paper has been taken from Mr. Weidman's report.

Van Hise and Leith studied the area between 1909 and 1910; and published two papers (31 & 32) which dealt with the basin in a general manner. Later, Leith drew many illustrations for his textbook on structural geology from the area (15). Since 1935, when A. Leith summarized the region for the Kansas Geological Society (13), numerous Master's Theses dealing with the structural features of the basin have been written, but only one of these papers mentions several outcrops bearing drag folds and shears that are reverse to those secondary structures which would be expected if they are to be ascribed to a synclinal deformation of the area.

A STATEMENT OF PROBLEMS AND OBJECT OF THIS PAPER

The secondary anomalous structures were shown to me by Dr. S. A. Tyler, during the fall of 1954. Two crops, on the South Range; one by Skillet Creek, and a second near Devil's Lake, bear drag folds which indicate differential motion reverse to that which would be anticipated in the structural setting of the crops. The two exposures also show thin zones of underthrust shears which cannot be accounted for by normal differential motion.

A third anomalous secondary structure was observed near Rock Springs, Wis., in the massive quartzite of a large quarry along the Baraboo River. Here, in the fracture cleavage zones of the quartzite, two sets of contradictory fracture cleavage were noted: one normal set, resulting from differential movement between beds formed during the folding of the syncline; the other set opposing the normal cleavage. The object of this thesis is to explain the mechanics of these anomalous secondary structures.

ACKNOWLEDGMENTS

I would like to thank Dr. S. A. Tyler for suggesting this problem, and for his friendly guidance, consultation, and criticism of the work. I should also like to thank my fellow graduate students, who gave so freely of their time and knowledge: and my wife Roberta F. Adair, who assisted frequently in the field, and never ceased to encourage me.

METHODS OF STUDY

During the fall of 1955, and the winter and spring of 1956, three outstanding exposures showing anomalous structures were mapped in detail by Brunton and tape survey. Particular attention was given to dips, strikes, axial plane orientations, plunge, and other structural phenomena. Oriented samples were taken, and sketches made, in order that laboratory study could be continued during inclement weather. The compilation of the map and laboratory data resulted in the arguments and ideas to follow.

STRATIGRAPHY OF THE BARABOO BASIN

Plate III (Page 8) is a summarized stratigraphic column of the formations in the area.

The oldest (Archean) rocks of the region consist of rhyolite, granite, and diorite, with the rhyolite being the predominant rock type.

THE RHYOLITE

The most extensive area of rhyolite is located at the Lower Narrows of the Baraboo River. It is a hard, pink, porphyritic rock, composed of grains of feldspar and translucent quartz in a fine-grained groundmass. The rhyolite which occurs in close proximity to the overlying quartzite, has been sheared locally into a sericitic

THE STRATIGRAPHIC SECTION OF THE BARABOO REGION
(AFTER WANEMACHER)

	PLEISTOCENE	GLACIAL DRIFT & LAKE DEPOSITS	QUATERNARY
	MIDDLE ORDOVICIAN	BLACK RIVER DOLOMITE	ORDOVICIAN
		ST. PETER SANDSTONE	
	LOWER ORDOVICIAN	ONEOTA DOLOMITE	
		MADISON SANDSTONE	
		TREMPELEAU FORMATION	
		FRANCONIA SANDSTONE	CAMBRIAN
		DRESBACH SANDSTONE	
	UPPER BARABOO SERIES	GRANITE INTRUSIVES	
ALGONKIAN (HURONIAN)		ROWLEY CREEK SLATE	
		DAKE QUARTZITE	
	LOWER BARABOO SERIES	FREEDOM FORMATION	PRE - CAMBRIAN
		SEELEY SLATE	
		BARABOO QUARTZITE	
ARCHEAN		RHYOLITE, DIORITE	

schist.

THE DIORITE

Two small crops of diorite, locally known as granite, are situated near the town of Denzer, Wis. It is a medium-grained, massive, reddish material, consisting of feldspar, hornblende, and quartz, with accessory biotite, apatite, and iron oxides.

THE GRANITE

There is one crop of granite along the main branch of Otter Creek, on the southern side of the South Range. It is a gray to reddish, medium-grained rock, consisting of feldspar, quartz, and small percentages of ferromagnesium mineral.

The granite has been interpreted as intrusive into the overlying quartzite by Dr. R. M. Gates (7). Thus, it would seem that not all of the underlying volcanic rocks of the Baraboo area are of Archean age.

THE RELATIONSHIP BETWEEN THE IGNEOUS ROCKS AND THE BARABOO QUARTZITE

The mutual relationship of the three igneous rock types cannot be ascertained, due to the lack of exposures. However, it can be shown that some of the igneous rocks antedate the overlying quartzite, for fragments of similar, if not the same granites and rhyolites, have been reported in the basal conglomerate of the quartzite.

THE BARABOO QUARTZITE

Inasmuch as the Baraboo quartzite forms the surrounding ridges, and underlies the floor of the basin, it is the most common rock type in the area. The formation can be divided into two facies: the quartzite, and a basal conglomerate that unconformably overlies the Archean igneous rocks.

The phenoclasts of the conglomerate consist of rounded and

angular fragments of rhyolite, but elsewhere, pebbles of white vein quartz, black slate, and pink chert are abundant. The matrix consists of water worn quartz grains, and stratified fine-grained sediments.

The quartzite is a clean, well sorted, water deposited rock. It is generally massive, but there are some thin beds measured in fractions of an inch. The erosion resistant, hard, vitreous, pink to purple quartzite generally shows well developed bedding planes. However, due to a very deceptive color banding, and abundant cross bedding, the true bedding may occasionally be concealed, confused, or misinterpreted. Ripplemarks are not scarce in the quartzite, but here again, care must be exercised, for pseudo-ripplemarks do occur on some weathered surfaces.

There is some disagreement as to the thickness of the formation, for it may be faulted. Fault displacement cannot be recognized because the quartzite contains no marker horizons, so that measured sections may include fault repetition of some beds. Nevertheless, most writers seem to agree to a thickness between 2,500 and 3,500 feet. Except for the basal conglomerate, occasional conglomeritic horizons, and some slaty beds, the formation is remarkably free of all impurities.

Microscopically, the quartzite is composed of rounded to sub-angular quartz grains cemented by secondary interstitial quartz. Many of the original grains have been enlarged; their previous shapes being outlined by a thin film of impurities (chiefly finely divided hematite) which retained its position on the original grain in spite of the later overgrowth. See microphotograph # 1 (Page 17).

The individual quartz grains frequently show undulatory extinction and deformation lamellae, which Riley (25) has studied and found to be unrelated to the synclinal folding.

The quartzite becomes increasingly slaty in its upper horizons, and is gradational with the overlying Seeley slate. As we will see later, the interbedded quartzite and incompetent slate present optimum conditions for the occurrence of such secondary evidences of dynamic deformation as fracture cleavage, drag folds, and boudinage structures.

THE SEELEY SLATE

The Seeley slate does not crop out in the area, so that all information concerning it has been derived from drill cores. It is, in general, a soft, gray, uniform, fine-grained, slaty rock. Alternating bands, varying in texture and color, represent the original stratification of the slate, but generally, a cleavage which cuts the bedding diagonally, forms the outstanding characteristic of the rock.

The thickness of the formation is believed to be between 100 and 500 feet.

THE FREEDOM DOLOMITE

The Freedom dolomite is gradational, and conformably overlies the Seeley slate. Although it does not crop out, considerable information has been collected concerning the dolomite, for its lower horizons carry low grade iron ore which was exploited during World War I.

Essentially, the formation consists of dolomite, or dolomitic marble, interbedded with slate, chert, ferro-dolomite, and manganese.

ferro-dolomite at the base.

THE UPPER BARABOO SERIES

At this position in the stratigraphic section, Leith (13) proposed a break in the Pre-Cambrian deposition because: (1.) the Dake quartzite (a younger formation, to be described later) has a flatter dip than does the Baraboo quartzite to the north of the "Dake" outcrop: (2.) drill log data indicates that the Dake bevels the underlying Freedom dolomite; lying at times over the dolomite's lower members. In addition, Leith suggested that the fragments of the Dake quartzite conglomerate were derived from the underlying Freedom and Baraboo formations.

THE DAKE QUARTZITE

Leith has described two additional Pre-Cambrian formations: the Dake quartzite, and the Rowley Creek slate. The slate is not known to crop out in the Baraboo region, and the quartzite, although believed to crop out, cannot be proven to do so, because of its resemblance to the Baraboo quartzite.

The Dake, which is thought to have a maximum thickness of 214 feet, consists of a sericitic, chloritic quartzite. However, much of its thickness consists of a coarse conglomerite, with phenoclasts of Baraboo quartzite and red jasper pebbles from the Freedom dolomite.

THE ROWLEY CREEK SLATE

This formation has been encountered in drill holes in the eastern part of the district, where it has been found to have a thickness varying between 40 and 150 feet.

The gray sericitic slate contains some chlorite and quartz, and must bear some iron, for it has oxidized to a red color along bedding

and cleavage planes.

CORRELATION WITH OTHER PRE-CAMBRIAN AREAS

Due to the great distances between the major areas of the Pre-Cambrian of the Lake Superior region and the Baraboo area, correlation with the other Pre-Cambrian rocks is highly problematical.

However, the Baraboo series greatly resembles the lithology, succession, and structure of some of the known Middle Huronian rocks of the Lake Superior region. Leith (13) was content to classify the Baraboo Series as Algonkian, and it is not my purpose to correlate the section further.

THE PALEOZOIC FORMATIONS

Inasmuch as this report does not concern the Paleozoic rocks of the region, I shall only summarize their characteristics.

They are generally flat lying, massive, clean quartz sandstones, with some interbedded horizons of shale, conglomerate, siltstone, dolomite and greensand. The maximum thickness of the Paleozoic rocks in the interior valley is probably somewhere between 400 and 600 feet.

For details of the Paleozoic rocks in the area, the reader is directed to a Ph. D. thesis by J. M. Wanemacher (33).

THE PLEISTOCENE

It is possible that the Illinoian ice sheet covered the eastern end of the Baraboo region, but no positive evidence exists. However, ice from the Green Bay lobe of the Wisconsin stage of glaciation did enter the area from the east, stopping midway through the basin. The terminal moraine lies just west of the town of Baraboo. The ice sheet covered the quartzite bluffs as well as the interior valley, and resulted in a glacial lake in the western half of the basin.

For details concerning the glacial geology of the district, G. H. Smith's "Physiography of the Baraboo Range of Wisconsin" (28) is recommended.

REGIONAL STRUCTURE

Since Weidman's paper, the Baraboo area has been accepted as a synclinal trough with a reversal of plunge resulting in the spoon shaped basin of quartzite. More recent studies, dealing with the secondary structures of the area have substantiated Weidman's general theory.

The southern limb of the syncline, although somewhat crenulate, strikes generally N75°E and dips flatly to the north. The northern limb is steeply inclined, with dips varying both north and south of verticality. The basin strikes approximately E-W. The geology of the east and west ends of the basin is more complex than that of the longer dimensions of the valley, but dips are generally toward the interior of the trough. Thus, there seems little reason to doubt that Weidman's original conclusions concerning the overall structure are incorrect.

To date, folding has been assumed to dominate the structural picture of the basin, mainly because the complete lack of marker horizons makes recognition of fault displacement difficult.

DESCRIPTIONS OF THE PERTINENT EXPOSURES

THE SKILLET CREEK EXPOSURE

The first, and most outstanding crop considered is a vertical exposure about 200 feet long, and from 1 to 20 feet high. It is located on the South Range, 4,000 feet east of the intersection of U. S. Route

12 and State Highway 159; 1,000 feet south of highway 159, on the eastern bank of Skillet Creek. (T. 11 N., R. 6 E., SW $\frac{1}{4}$, SE $\frac{1}{4}$, NW $\frac{1}{4}$, Section 14).

Like the exposure at the entrance to Devil's Lake, to be described later, this crop bears drag folds and shears that cannot be explained by normal differential movement.

Differential movement involving incompetent beds sandwiched between competent beds often results in drag folds, with axial planes which dip away from the major anticline. (See Plate IV, Part A. page 53). Thus, it can be seen that the axial plane of a normal drag fold situated on the northern limb of an east-west trending anticline should dip northward, and strike parallel to the major fold.

The Skillet Creek, and Park Entrance crops are located on such a north limb, but only a few drag folds with north dipping axial planes can be found. Instead, the predominant dip is to the southeast, whereas axial plane strikes, although varying, are predominately northeasterly. These folds are therefore considered to be reverse and abnormal drag folds, for they do not fit the regional pattern for normal secondary drag folds.

The rock of the exposure varies from pink to gray, and consists of Baraboo quartzite and interbedded quartz schist, overlain by a few feet of a more slaty rock type. Stratigraphically, it represents the gradational contact of the upper portion of the Baraboo quartzite and the Seeley slate, although massive quartzite occurs above and below the exposure. The true thickness of the interbedded rock between the two zones of confining quartzite was calculated to be approximately 25 feet.

I have divided the exposure into four zones, or units, in order to facilitate discussion of the rock and its behavior during deformation.

Plate V (Folded Enclosure # 1) is a vertical projection of the crop. It shows the limit of the zones, and the location of the various features to be discussed.

Locations of phenomena under consideration will be given as follows: "21' x 3'". The "21'" corresponds to the horizontal distances on Plate V, and the "3'", the vertical elevation above the "21'" mark.

THE MASSIVE QUARTZITE ZONE

The first unit to be considered is that rock underlying the mapped portion of the exposure on Plate V. It may be seen to consist of typical massive, vitreous, cross-bedded, pink quartzite, with occasional fracture cleavage zones. Photograph # 2 (Page 17) shows fracture cleavage of the massive quartzite zone under discussion. This fracture cleavage dips 60° N, and strikes $N80^{\circ}$ E. The dip and strike of the bedding is $N80^{\circ}$ E and 20° NW. Thus, the relationship of fracture cleavage and bedding verify the theory that a roughly east-west anticline formerly existed to the south of the area.

THE BUCKLED QUARTZITE ZONE

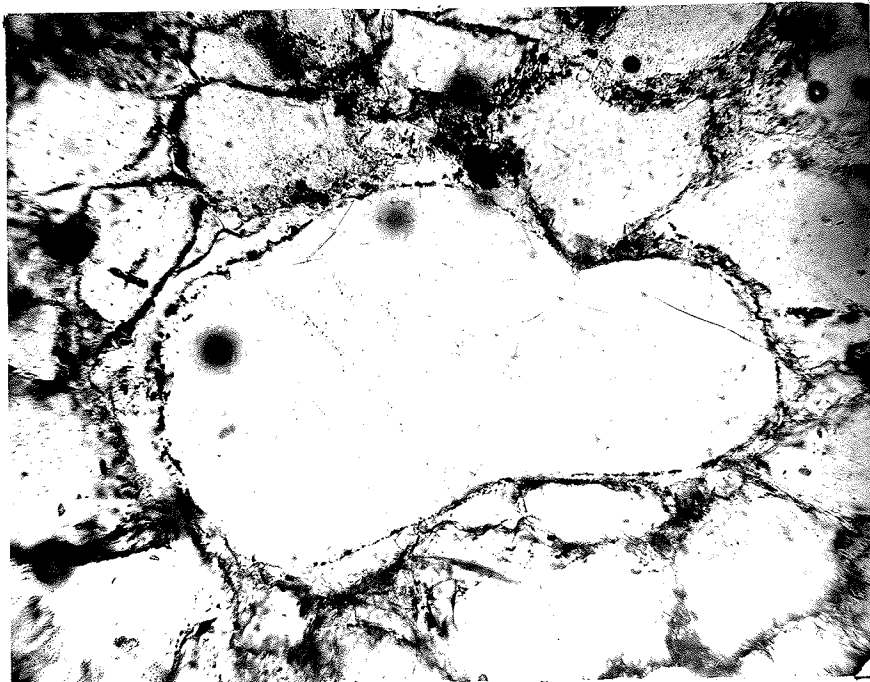
Overlying the massive quartzite zone there are several beds of quartzite varying in thickness between six inches and two and one half feet. These beds extend from location 22' x 0', where the uppermost bed emerges from the soil cover, to location 193' x 0', where it dips from view. Although the quartzite is relatively undeformed, it is not always possible to follow any one bed of the unit over the entire length of the crop because they become schistose

Microphotograph # 1.

A quartz grain showing secondary enlargement. The original grain boundary is marked by a finely divided hematite ring. Magnified 143 times.

Photograph # 2.

Fracture cleavage in the Massive Quartzite Zone of the Skillet Creek Exposure. Cleavage planes strike and dip $N80^{\circ}E, 60^{\circ}NW$. Bedding: strike $N80^{\circ}E$, dip $20^{\circ}NW$. Six inch rule gives scale.



locally.

A typical example may be observed at the offset in the crop at the 100' mark. The two foot bed at location 97' x $2\frac{1}{2}$ ' should over-ly the two foot bed at the 109' x $2\frac{1}{2}$ ' mark, but instead, there exists a mixture of sheared and platy quartzite which must represent the bed at the 97' mark, for faulting could not be detected. A discussion of the origin of these sheared and platy zones will follow in a later section.

Strikes of the quartzite beds in the unit vary somewhat because of local buckling, but the trend is roughly $N70^{\circ}E$. Dips also vary, but are generally to the northwest at, or near, $20^{\circ}N$.

At locations 33' x $3\frac{1}{2}$ ' to 45' x $2\frac{1}{2}$ ', and other scattered spots in the quartzite of this zone, white quartz can be seen to fill sharply defined gash veins. See photograph # 3 (Page 20). The gash veins generally dip between $75^{\circ}S$ and $75^{\circ}N$, and strike between $N60^{\circ}E$ and $N75^{\circ}E$. The strikes indicate that the stresses which resulted in the relative motion between beds had a northwest-southeast trend, thereby relating them to the primary folding of the area.

The quartz of the veins is coarse-grained, shows an allotriomorphic texture under the microscope and contains occasional large grains of platy specularite. The quartz vein quartzite boundary was found to be indistinct, leading to the conclusion that some quartzite had recrystallized. The hematite of the quartzite probably regrouped in these veins to form the large specularite grains previously mentioned.

It is of interest that at location 149' x 4' the gash veins are oriented at right angles to the bedding plane, suggestive of tension

fractures in an extremely competent rock.

Local upwarp between the 57' and 70' marks has caused a minor fault in the uppermost of the two quartzite beds at the 69' x 3' mark. The fault plane strikes $N30^{\circ}E$, dips $43^{\circ}S$. See photograph # 4, (Page 20). Associated shear cleavage suggests that either the hanging wall was thrust over the footwall, or the footwall under the hanging wall.

Fracture cleavage ($N80^{\circ}E$, $40^{\circ}N$) between the two beds indicates that normal differential motion occurred at one time. Probably the beds buckled upward, locally, but still remained sufficiently competent to transmit stress from the northwest. This stress forced the footwall under the hanging wall. It seems improbable that the hanging wall was overthrust to the northwest, because the underlying normal fracture cleavage between the two beds is intact. Should there have been a reverse motion, the existing fracture cleavage, already a plane of weakness and shear, would have been ground to a gouge.

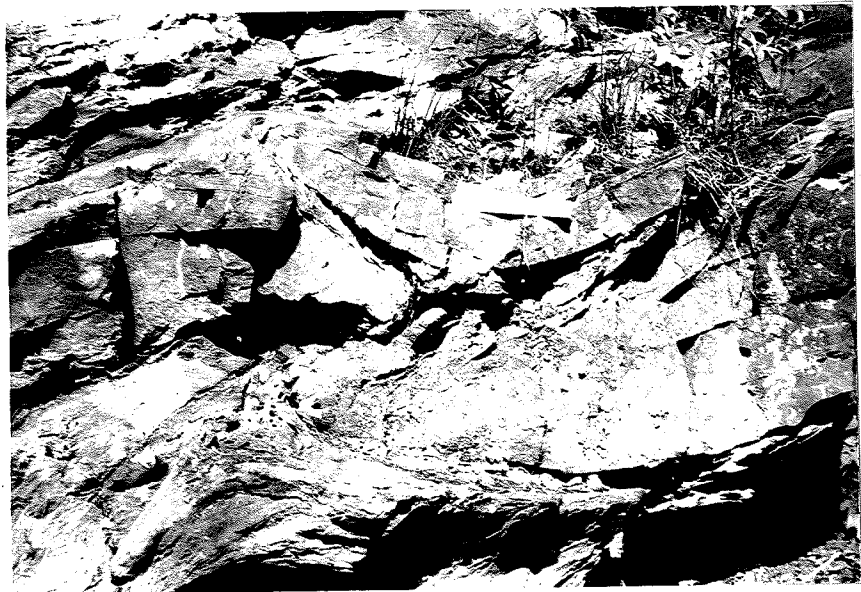
Another interesting feature of the buckled quartzite zone is the "S" shaped fracture cleavage planes developed in the quartzite bed at location 80' x 1'. See photograph # 5, (Page 24). The shears measure about a foot in length, and are rather widely spaced. The peculiar "S" shape of the cleavage planes can be explained by a variation of competence within the bed, causing the fractures to be refracted. Near the edge of the bed, flow cleavage accounts for the smaller angle between the bedding and fracture cleavage planes. The orientation of the cleavage planes indicates that the overlying material moved to the south with relation to the underlying rock. The cleavage planes have an E-W, $60^{\circ}N$ orientation. This phenomena

Photograph # 3

Quartz filled tension fractures at
location 33' x $3\frac{1}{2}$ ', Skillet Creek Outcrop.
Six inch rule gives scale.

Photograph # 4

Underthrust fault at location 69' x
3'; Skillet Creek Exposure. Six inch
rule gives scale.



will be discussed in more detail in a later section of the paper.

At the 119' x 6' - 124' x 10' marks, there is a normal overthrust fault. Here, a mass of quartzite, one foot thick and six feet long has been thrust southward, and over a non-yielding section of the same bed. The dip and strike of the fault plane is N75°E, 78°N.

The remainder of the Buckled Quartzite Zone, between the 148 and 193 foot marks, is not well exposed.

THE QUARTZ SCHIST ZONE

This zone is best developed over and between the 22' x 0' and 100' x 3' marks. It consists of that material overlying the uppermost massive bed of the Buckled Quartzite Zone, and underlying, but including, the discontinuous, buckled, lensatic, fractured and sheared massive quartzite bed traceable from ground level at the 15' mark to a spot seven feet high at the 97' mark. The zone is not well demarcated between and above the 100' x 0' and 200' x 0' marks, but can be considered as that platy quartzite and quartz schist, between (and including) the uppermost and limiting recognizable quartzite bed, and the continuous massive quartzite of the Buckled Quartzite Zone.

The color of the rock varies from the characteristic pink of the massive quartzite beds, to flesh and gray tones in the more schistose material.

Close examination of any weathered schistose area will reveal minute bands of quartzite, standing in relief above thin, less resistant micaceous bands. Evidence of former bedding planes could not be found at the crop, or in thin section, leading me to believe that

(1.) the bedding has been obliterated, or (2.) the schistosity is parallel to the bedding. Inasmuch as the schistosity is generally parallel to the underlying quartzite beds, I favor the later alternative.

It is especially characteristic of this zone that many massive quartzite beds may be traced into quartz schist over relatively short distances. This phenomena is especially prevalent in that area between the 103' and 200' marks, where all stages of transformation from massive beds, through platy quartzite, to quartz schist may be found. In every case, development of the quartz schist seems to be related to normal adjustment of the rock to the primary folding; the conversion starting as normal fracture or flow cleavage.

R. E. Rettger (24) explained the megascopic and microscopic development of fracture cleavage in the quartzite of Devil's Lake, and his explanations and descriptions seem to apply to the quartz schist of this crop. Rettger observed that as differential motion between beds was initiated, flow cleavage, at low angles to the bedding plane, developed along the edge of the bed; gradually working towards the center of the bed as movement progressed. As bedding slip continued, the stresses could not be dissipated at the edges of the beds, and fractures at high angles to the bedding formed. These fractures, although at high angles to the bedding (60°) are guided by the earlier developed flow cleavage planes along the edges of the beds, resulting in "S" shaped fractures. As the rock became more thoroughly fractured into plates, progressively more flow cleavage developed until the final product of the two more or less contemporaneous types of shearing was the conversion of much

of the massive quartzite into quartz schist.

No doubt, most of the quartz schist formed as the result of slippage between adjacent quartzite beds, and fracture cleavage played only a minor roll.

Photograph # 6 (Page 24) shows a few of the stages of transformation of a quartzite bed into a quartz schist due to contemporaneous fracture and flow cleavage.

Evidence of overthrusting is abundant in the quartzite of this unit, but only two of the more outstanding examples will be cited.

Six feet above the 105' mark, a six inch quartzite bed can be seen to be overthrust to the south. See photograph # 7 (Page 25). Accompanying this thrust fault, under the overthrust portion of the bed, a series of shears have developed in the quartz schist. They strike $N20^{\circ}E$, and dip $45^{\circ}NW$. If the theory of the strain ellipsoid were to be applied to this fault, with the axis of easiest relief striking $NW-SE$ and the intermediate axis striking approximately $N20^{\circ}E$, the shears would coincide with the shear planes predicted by the theory.

Another excellent occurrence of overthrusting can be seen at the 163' x 4' mark. See photograph # 8 (Page 25). Here, a series of quartzite beds have been tightly folded, as though preliminary to overthrust faulting. However, the fault failed to develop in three of the thin beds. The result is a tight overthrust fold (overthrust to the south) measuring eighteen inches in height, and illustrating the former flexibility of the rock, for it is remarkably intact in spite of the brittleness of the quartzite. That the beds were competent at the time of folding seems apparent, since quartz filled

Photograph # 5

Massive Baraboo quartzite bed bearing "S" shaped fracture cleavage. Six inch rule gives scale.

Photograph # 6

Hand specimen of quartzite showing "S" shaped fracture cleavage in the massive quartzite: flow cleavage (and quartz schist) near the edge of the bed. Six inch rule gives the scale.



Photograph # 7

Overthrust fault at location 105' x
6'; Skillet Creek Exposure. Six inch rule
gives the scale.

Photograph # 8

Overthrust fold at location 163' x
4'; Skillet Creek Exposure. Six inch rule
gives scale.



tension fractures, at right angles to the bedding, occur on the over-turned limb of the fold.

Shear cleavage along the bedding slip fault immediately over the fold indicates that the southward movement continued along the fault, possibly bringing the folding to an end by dissipating the stresses. The dip and strike of the shear cleavage of this fault is $N70^{\circ}E$ and $38^{\circ}N$.

The axial plane of the fold dips $68^{\circ}NW$; and strikes $N70^{\circ}E$. Thus, the trend of the shear cleavage and the fold agrees with that of the beds; relating this secondary structure to the primary folding.

As suggested previously, the uppermost quartzite bed of this unit has suffered considerable shearing which has resulted in the development of all stages of boudinage and related structures in the bed. The boudins, which vary in size from $4'' \times 13''$ to $13'' \times 18''$, also vary in cross section from lensoid to circular, and are characterized by a tendency to exfoliate, perhaps due to a schistosity which developed parallel to the sides of the boudin. The boudins are the result of differential movement or slip of the slate or quartz schist over the competent quartzite bed; the result being tensional stresses which developed in the competent bed and tended to part it at right angles to the bedding plane. Once the bed was parted into blocks, the incompetent schistose material squeezed into the voids left by the parting. The shear resulting from this void filling process rounded the corners of the quartzite blocks, resulting in their ovoid or lensoid shapes.

Tension fractures, or gash veins, in the buckled quartzite

bed have also been filled with the white quartz, characteristic of the underlying Buckled Quartzite Zone.

Between the 15' x 1' and 51' x 3' marks remnants of the bed, and boudins, may be seen to be completely isolated from each other by areas of quartz schist. However, their pattern of occurrence parallels that of the underlying intact beds; and inasmuch as evidence of faulting could not be found, it must be assumed that the bed in question has been locally sheared beyond recognition.

Many minor reverse drag and chevron type folds were observed in this zone, but only a few normal drag folds could be identified. The axial planes of the normal drag folds dip to the northwest between 20° and 32° . The strike of the axial planes varies between $N55^{\circ}E$ and $N85^{\circ}E$. The folds plunge to the northeast without exception. Both sets of folds (normal and reverse) are equally developed with regards to dimension, for they seldom exceed three inches in crest to trough or wavelength measurement, and smaller folds are more the normal.

The strike of the axial planes of the reverse drag folds varies considerably, with the extremes being $N15^{\circ}E$ and $N80^{\circ}E$: however, the general trend is about $N55^{\circ}E$, which as we shall see later, is the trend of similar folds at the Devil's Lake Exposure. Dips of the reverse fold axial planes also are irregular, but range between 5° and $50^{\circ}SE$. The folds plunge to the northeast; generally flatly.

There seems to be no set pattern of occurrence for the reverse drag folds, as they exist everywhere outside of the major quartzite beds. A number of the more prominent folds have been plotted on Plate V, but it would be impossible to plot all of the folds due to

their large number, minute size, and poor exposure. Photograph # 9 (Page 29) illustrates the general appearance of some of the better developed reverse drag folds. The origin of these folds, which is the major problem involved in this study, will be discussed under a later section of the report.

Accompanying, and gradational with the reverse drag folds of this unit is another type of secondary fold which resembles reverse drag folds superficially. However, upon closer examination, these folds may be seen to be unlike drag folds in that they have chevron type crests and troughs. The chevron fold dimensional range, axial plane and plunge trends are the same as their drag fold associates, and inasmuch as the two fold types are gradational into each other, I consider them to represent the same deformation. In all cases, they seem to indicate reverse differential motion with a north-west-southeast trend. One character of their occurrence seems of note: they occur in the more quartzitic areas of the zone, and, as will be seen later, are less abundant in the overlying, more mica-ceous slate.

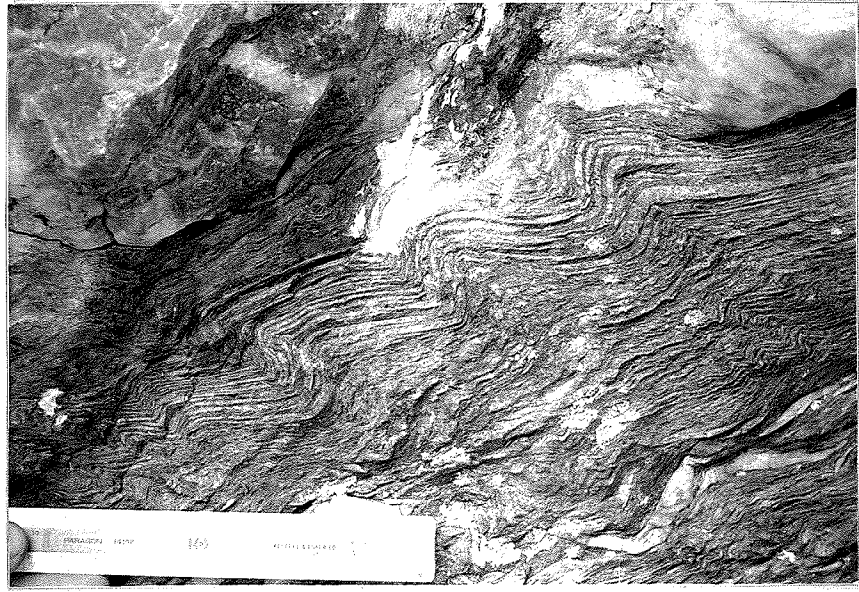
Associated with the chevron folds are minute shear planes which cut through some of the folded areas. The shears tend to be guided by the flanks of the folds, which suggests a genetic association between the two secondary structures. The strike of the shears is remarkably parallel to that of the axial planes of the folds. It would appear that the rock folded in chevron fashion, and later sheared when folding could not entirely accommodate the stresses. Photograph # 10 (Page 29) and # 11 (Page 31) illustrate the chevron fold-shear relationship. This theory of fold, shear

Photograph # 9

Reverse drag folds at location 24'A x
3'; Skillet Creek Exposure. Six inch rule
gives scale.

Photograph # 10

Hand specimen showing underthrust
shears, shear folds, and chevron folds.
Six inch rule gives scale.



shear plane relationship is strengthened by the fact that shears die out into chevron folds. (Note Photographs # 10 & 11)

On the other hand, however, shears were noted to offset the schistosity of the rock in such a fashion as to form shear folds strongly resembling the chevron folds mentioned previously. These shear folds may also be seen on photographs # 10 & 11. To further complicate the problem, shears, independent of folds were also observed; particularly in thin bands of schist sandwiched between more competent quartzite. The offset lineation of these shears can be considered as shear cleavage along a fault, and a study of the phenomena revealed that in every case, the footwall moved to the east or southeast with relation to the hanging wall. The problem of which came first, the shears or the folds, seems to call for a compromise, inasmuch as shears occur without folds, and folds occur without shears. Most probably, the two features are contemporaneous, and related to the same origin.

The dip and strike recordings of the shear planes vary between $N10^{\circ}W$ and $N55^{\circ}E$, with constantly flat dips to the east and southeast. Upon weathered surfaces, these shears produce a distinct south dipping lineation in the rock. See photograph # 12 (Page 31). The removal of the sheared material along the flanks of a series of chevron folds by erosion, causes the unsheared crests and troughs to stand in relief. In other cases, the shear affects the entire flank of a series of folds, whereas the opposing flank remains intact.

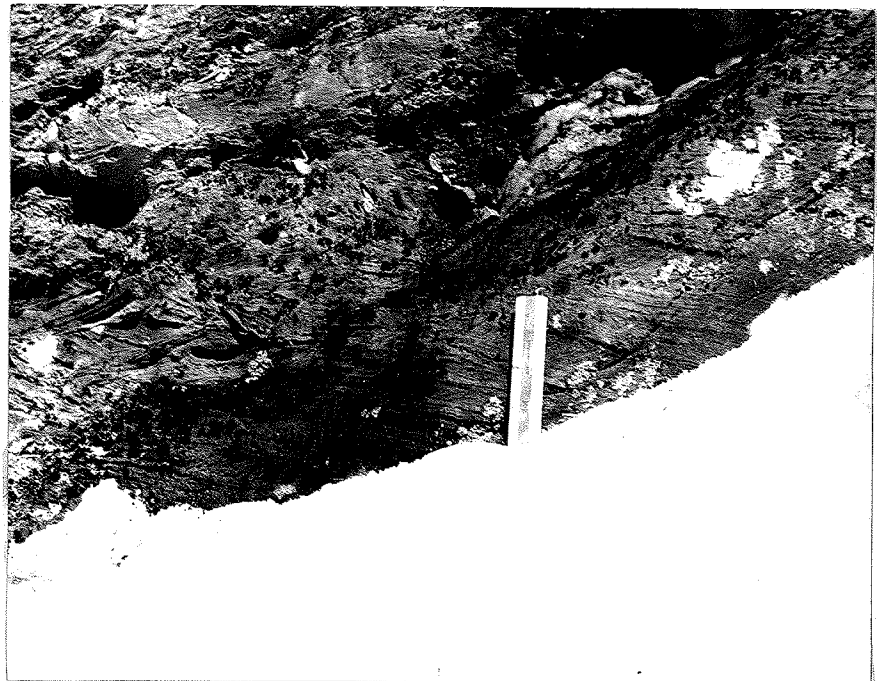
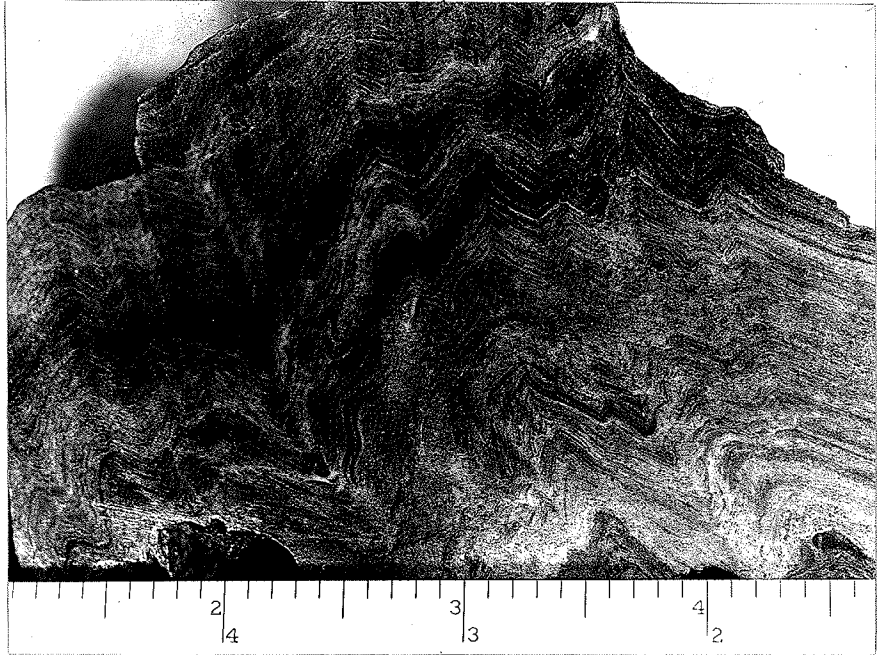
Although the shear planes are best developed where the lineation is distinct, they may be observed over the entire outcrop in the more

Photograph # 11

Hand specimen showing underthrust
shears, shear folds, and chevron folds.
Six inch rule gives the scale.

Photograph # 12

South dipping lineation produced by
erosional removal of sheared flanks of re-
verse folds. Six inch rule gives the scale.



schistose material, thereby indicating that they are not local phenomena.

The interpretation of these shears will be presented in a later section of this paper.

THE SLATY ZONE

The uppermost unit of the Skillet Creek Exposure consists of a schistose micaceous rock which bears numerous reverse drag folds, but no normal drag folds. The unit is continuous over the length of the exposure, and is easily located, for it rests upon the uppermost quartzite bed of the sheared and platy quartzite zone, and extends upward to the soil cover over the crop. It contains no measurable quartzite beds, although thin stringers of quartzite may be seen upon close examination. In fresh hand specimen, the gray to buff, fine-grained, talcy feeling rock exhibits a poorly developed undulatory cleavage which either coincides with the bedding, or has completely destroyed it. When held in good light, small grains of quartz and hematite can be identified, but no other minerals were recognized megascopically.

In thin section, the slate consists of minute grains of quartz and fine-grained sericite. Lesser amounts of other micaceous mineral are no doubt present, but could not be identified. In most areas of the thin sections, the micas have a parallel to sub-parallel orientation with the sinuous and folded planes of schistosity. However, occasionally the micas are oriented at angles to minute shear planes much as shear cleavage is oriented along larger scale shear planes. Large platy grains of hematite also occur in parallel orientation with the micas.

Included in the schist are numerous stringers and lenses of fine-grained quartzite which are generally folded and contorted with the schist. See microphotograph # 13 (Page 34). Within the stringers, the quartz grains may be seen to be somewhat elongate in the direction of schistosity, suggesting secondary growth parallel to that direction. Sericite and flakes of hematite also occur within the stringers, in well developed parallel orientation.

Inclusions of white quartz, apparently of the same age and character as the quartz of the tension fractures of the lower units may be seen megascopically in the slate. The quartz takes the form of lenses, often parallel to the schistosity (See photograph # 14, Page 34), but at times is evidently rotated at angles to it. The result is an apparent daming of the slate behind the rotated lenses, as though flowage of the schist had occurred. See photograph # 15, (Page 35).

Other occurrences of white quartz take the shapes of drag folds, (See photograph # 16, Page 35) and suggest replacement, or filling of dilatent areas produced by folding. In many instances. the drag fold forms also appear to have been rotated after their formation, for their present position does not coincide with the planes of schistosity, or other drag folds. The quartz drag folds must be considered as being contemporaneous with the reverse drag folding of the schist, for although they take the form of folds, the fact that some have been rotated indicates that movement within the schist continued after their formation.

In thin section, the quartz drag folds appear to be composed of coarse allotriomorphic quartz grains which formed by recrystallization

Microphotograph # 13

Stringer of folded fine-grained quartzite. Slaty Zone, Skillet Creek Exposure. Magnification is 18x.

Photograph # 14

White quartz lenses in parallel orientation with the schistosity. Slaty Zone of the Skillet Creek Exposure. Six inch rule gives the scale.

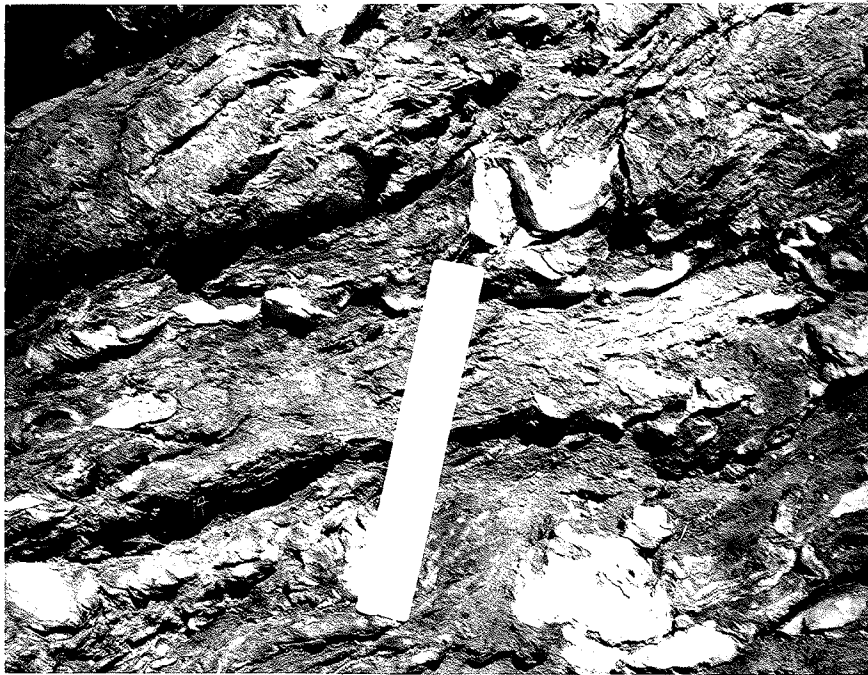


Photograph # 15

Rotated lense of white quartz, with
apparent daming of the schist behind it.
Slaty Zone of the Skillet Creek Exposure.
Six inch rule gives the scale.

Photograph # 16

White quartz in the form of a drag
fold. Slaty Zone of the Skillet Creek
Exposure. Six inch rule gives the scale.



of the fine quartz grains of the previously mentioned thin stringers of drag folded quartzite. See microphotograph # 17, (Page 37).

Further indication of recrystallization, or replacement of the quartzite stringers can be seen in microphotograph # 18, (Page 37) where the quartz-slate contact has a cusp and carries texture. Other such contacts are sharp, leading me to believe some stringers were dislocated after they recrystallized.

The case of the quartzite lenses may be somewhat different, because no direct replacement criteria were observed. However, the lenses do contain stringers of mica, suggesting a replacement of material in a dilatent zone along a shear plane. Quartz lenses are not uncommon along shear planes, and, in fact, a few may be seen in the quartzite units of this exposure. It seems reasonable to infer that the lenses of slate have similar origins, but that many have been rotated out of position by subsequent adjustment in the slate.

As in the quartz schist of the underlying unit, differential weathering has resulted in a lineation caused by shear planes guided by the flanks of chevron folds. Like their lower counterparts, these shear planes tend to die out into chevron folds, and indicate that the footwall has underthrust the hanging wall. As stated previously, measurements taken on the shear planes of both zones indicate that they dip flatly to the east or southeast, and strike $N10^{\circ}W$ to $N55^{\circ}E$.

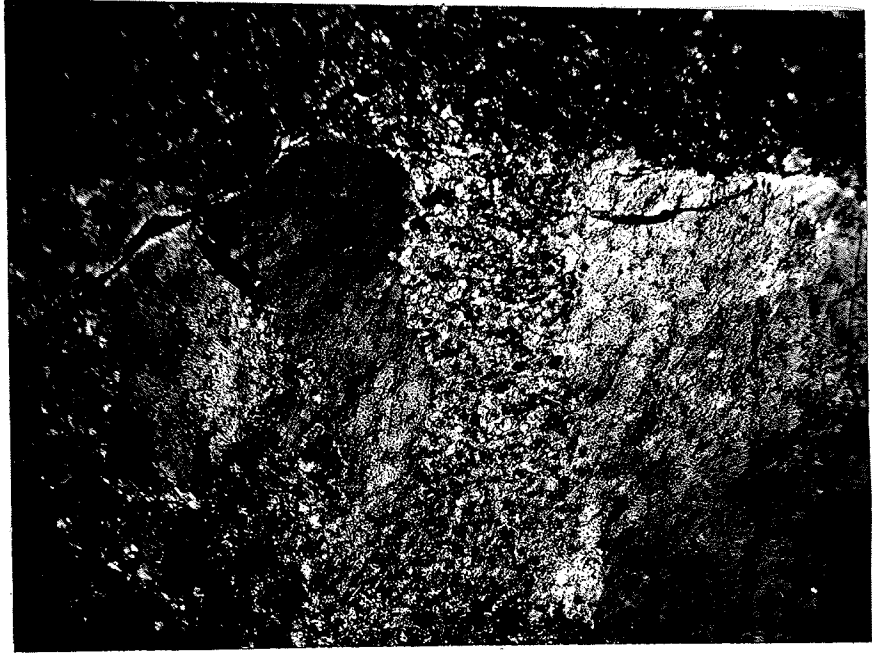
Although the lineation produced by the weathering of these shears does not occur over the entire length of the unit, incipient shear planes can be found almost continuously along the exposure.

Microphotograph # 17

White, optically uniform quartz replacing fine-grained quartzite of a minute quartzite stringer. Slaty Zone of the Skillet Creek Exposure 47 X.

Microphotograph # 18

Cusp and caries contact of white quartz lense and slate. Slaty Zone of the Skillet Creek Exposure. 53 X.



Inasmuch as they go hand in hand, it could be expected that chevron and shear folds would occur with the shear zones; and this is the case, although chevron folds are less abundant in the slaty horizon. The folds vary in size from less than an inch to four inches along the wavelength dimension.

Reverse drag folds and minute crenulations are the outstanding feature of this micaceous zone; probably because of its higher mica content as compared to that of the underlying quartz schist. Thus, it would seem that the slate tended to flow, rather than shear, in response to the forces acting upon the unit. The drag fold axial plane orientations are the same as those of the quartz schist zone, in that they strike generally $N55^{\circ}E$, and dip to the southeast. No normal secondary structures could be found in the Slaty Zone, which, as we shall see later, is highly significant. A ten foot face of the massive quartzite which stratigraphically overlies the mapped area occurs approximately 300 feet to the north, down the dip slope from the exposure. This rock is massive, cross bedded devoid of fracture cleavage and homogeneous. Dip and strike recording ($N55^{\circ}E$, $18^{\circ}NW$,) indicate conformity with the underlying quartzite.

The actual thickness of the quartzite overlying the Skillet Creek horizon can not be determined due to overburden and cover by the Cambrian Dresbach sandstone, but it is known to be at least 150 feet thick.

THE PARK ENTRANCE EXPOSURE

A second, less revealing crop, which bears anomalous drag folds and shears may be found on the western slope of the valley leading

to the northern end of Devil's Lake. (T. 11 N., R. 6 E., SE $\frac{1}{4}$, SE $\frac{1}{4}$, NE $\frac{1}{4}$, Section 14). The exposure may be reached by pacing 420 feet (S60°E) from the entrance gate of Devil's Lake State Park, along the road leading to the park area at the north end of the lake: then, 166 feet S10°W from the 420' mark. Although there is a considerable length of crop scattered about on the hillside, I have mapped only that portion of the exposure that bears the reverse structures under consideration. The mapped area is about 85 feet long (Trend N20°E), and does not exceed 10 feet in height. The northern end of the crop is 44 feet above the level of the previously mentioned road.

As in the case of the Skillet Creek Exposure, massive quartzite occurs both above and below the zone, so that the horizon of relatively incompetent rock is sandwiched between competent beds of quartzite. The total thickness of the horizon under consideration was calculated to be approximately 12 feet. A scale drawing of the vertical section may be found on Plate VI, (Folded enclosure # 2). Locations mentioned in the description of the exposure will be given as in the previous crop discussion. Three outstanding rock types occur at the exposure: thus, I have divided the crop into three units.

THE MASSIVE QUARTZITE ZONE

The rock underlying the crop was not mapped, but is known to consist of massive flesh to pink colored cross-bedded quartzite which is highly jointed. The rock is very uniform, and some difficulty was encountered in finding fracture cleavage zones to verify the existence of a major anticline to the south of the crop. Very thin fracture cleavage zones were found, however, and the cleavage planes were noted to strike N88°E, and to dip 65°N, thereby indi-

cating that normal differential motion has occurred in the underlying quartzite. The bedding plane dip and strike is $N75^{\circ}E, 20^{\circ}NW$.

THE BUCKLED QUARTZITE ZONE

This unit may be considered as the material underlying the quartzite bed which extends from the 0' x 1' location to the 76' x $5\frac{1}{2}$ ' mark. The unit compares with the Buckled Quartzite Zone of the Skillet Creek Exposure, in that it consists of bedded quartzite intermixed with slate and quartz schist.

The color of the unit is generally pink, due to the predominance of quartzite, but flesh tones occur in the quartz schist, whereas the intermixed slate tends to gray or black.

Because of the buckled nature of the quartzite beds of the unit, dip and strike recordings taken along the crop vary considerably ($N25^{\circ}E$ to $N75^{\circ}E$), with the average trend about $N46^{\circ}E$; all dips are to the northwest. The beds are generally continuous, and range in thickness between six inches and a foot. Thus, they are relatively competent in comparison with the interbedded quartz schist. In addition to buckling, the quartzite beds have been subjected to differential shear which has resulted in numerous partially to completely developed boudinage structures. ($16' \times 4\frac{1}{2}'$, $23' \times 4'$, $26' \times 3'$, $40' \times 3\frac{1}{2}'$) See photograph # 19 (Page 42). In many cases, white vein quartz may be observed in the tension cracks between boudins, whereas, other cracks contain slate that has flowed into them.

Another outstanding feature of the quartzite of the unit may be found at location 70' x 6', where a large normal drag fold occurs in a one foot thick quartzite bed. See photograph # 20 (Page 42). The fold measures six feet from crest to trough, and has an axial

plane which strikes $N58^{\circ}E$, and dips $81^{\circ}NW$. Thus, the fold agrees with the overall structural picture of the South Range.

The micaceous rock of the unit bears numerous minute secondary structures which are similar to those of the Skillet Creek Exposure. However, outside of the previously mentioned normal drag fold in the quartzite, only two other normal drags could be identified in the less competent quartz schist. Both of these folds had northeasterly axial plane strikes, and dips to the northwest.

A number of reverse drag folds, none of which exceeded three inches from crest to trough, or wavelength dimension, were noted in this zone. The axial plane strikes vary from $N25^{\circ}E$ to $N80^{\circ}E$, but the average trend is $N56^{\circ}E$, which agrees remarkably well with the general trend of the folds of the Skillet Creek Exposure. The axial planes dip to the southeast, whereas plunges are flat and to the northwest.

Although incipient shears may be seen in all the micaceous material of the unit, they are developed sufficiently for measurement in only one location. ($31' \times 2\frac{1}{2}'$) Here, they have a strike of $N55^{\circ}E$: dip of $11^{\circ}SE$. As in the previous cases, the shears are associated with minute buckle or chevron folds, and essentially take the position of the axial planes of the folds.

The development of reverse drag folds and shears in this zone was impaired somewhat because of the predominance of massive quartzite beds which confined the interstratified schist in such a manner that the vertical space required for drag folds was not available. Similarly, large areas of underthrust shears were prohibited.

THE SLATY ZONE

Photograph # 19

Boudinage structure at the Park Entrance
Exposure. Geologic pick gives scale.

Photograph # 20

Large drag fold in the Buckled Quart-
zite Zone of the Park Entrance Exposure.
Geologic pick gives the scale.



Overlying the uppermost quartzite bed of the Buckled Quartzite Zone is one to six feet of a slaty rock type which contains no measurable quartzite beds. The rock, which is gray, micaceous, and extremely crenulated, also bears lenses and drag fold forms of white quartz, similar to those of the Skillet Creek Exposure. The unit contains no normal drag folds, although numerous reverse drag folds were observed. The average axial plane trend is $N56^{\circ}E$, whereas the dips are to the southeast. None of these folds exceeds three inches in dimension.

Two additional areas of measurable underthrust shear planes were located in this unit, although there are incipient shears over its entire length. The two zones have strikes of $N75^{\circ}E$ and E-W; dips are $20^{\circ}SE$ and $9^{\circ}SE$ respectively.

As previously mentioned, the slaty unit at the Park Entrance Exposure contains inclusions of lense shaped white quartz from one to three inches in length. These lenses occur both parallel to, and at angles with, the schistosity, suggesting rotation after formation. Drag folded quartz forms were also observed in various orientation with regards to the schistosity.

Stratigraphically overlying the crop, and down a dip slope from it, there is a face of massive quartzite approximately 20 feet in thickness. This quartzite, although highly jointed, does not contain fracture cleavage zones. The dip and strike is $N85^{\circ}E, 25^{\circ}NW$, suggesting conformity with the underlying rock.

In summary, it seems apparent that this crop contains all the structures and characteristics of the Skillet Creek Exposure and that in every case the dips, strikes, underthrust shears, and axial

plane orientations of both normal and reverse drag folds agree with those of the Skillet Creek Exposure.

THE SECTION 25 EXPOSURE

A third area of reverse structures, approximately six miles southwest of the Skillet Creek and Park Entrances Exposures (T. 11N., R. 5 E., NE $\frac{1}{4}$, SE $\frac{1}{4}$, SW $\frac{1}{4}$, Section 25) was referred to in the Master's Thesis of C. J. Leith (16). The area was visited, and found to bear folds and crenulations similar to those discussed previously.

The crop, which is located in a wooded pasture, consists of approximately 200 yards of scattered exposures of interbedded quartz schist and massive quartzite. The quartzite is the typical medium-grained, pink, cross-bedded rock described previously, but the quartz schist is more coarsely banded than the schist at the Skillet Creek or Park Entrance Exposures. In many cases, it still retains the pink color of the quartzite, and seems to be more of a sheared quartzite than a quartz schist.

The folds in the schist differ from true drag folds in that they are open crenulations, more suggestive of slight buckling along shear planes than closed drag folds. These crenulations occur in the thickly banded quartz schist, and are rather large structures. (4" to 6" in wavelength, and 1" to 2" in amplitude)

In the more thinly-banded schist, however, chevron and shear folds similar to those previously discussed were observed. These folds often reach five inches in wavelength, and two to three inches in amplitude; making them considerably larger than the chevron and shear folds of the crops to the east. The fold axial plane strikes

range from $N30^{\circ}W$ to $N40^{\circ}E$; the axial planes dip to the east or southeast at, or near, 40° . A number of reverse shear planes were observed at this location. They strike $N40^{\circ}E$, and dip $50^{\circ}S$. The strike of the massive quartzite beds varies from $N28^{\circ}E$ to $N60^{\circ}E$, suggesting that some local buckling has occurred in the area, although overburden prevents actual observation. Dips were found to be 20° to $40^{\circ}NW$.

In summary, it seems sufficient to say that this area consists of interbedded quartzite and quartz schist, which is somewhat more competent than that of the two other crops previously discussed. The chevron and shear folds, as well as the reverse shear planes of the outcrop compare favorably with their counterparts in the crops east of this location. There is no reason to believe that the three areas have not suffered similar deformation.

A REVIEW OF CRITICAL STRUCTURAL EVIDENCE

Perhaps it would be best to review the general trends of the secondary structures of the Skillet Creek and Park Entrance Exposures before entering into a discussion of the origin of the reverse drag folds and underthrust shears. Strike frequency diagrams for some of the phenomena may be found on Plate VII (Page 51).

NORMAL STRUCTURES

The bedding of the massive quartzite underlying the Skillet Creek & Park Entrance Exposures has a general $N70^{\circ}E$ to E-W trend, whereas dips are to the northwest at 20° to 30° .

Included in the massive quartzite of both locations are zones of fracture cleavage which strike $N80^{\circ}E$, and dip between 45° and $65^{\circ}NW$,

thereby indicating a major E-W anticlinal structure to the south. Inasmuch as it will be significant in the arguments to follow, it seems best to mention that these zones bear only one set of cleavage planes, and are free of fault gouge, or other evidence of a second deformation.

Normal drag folds, found only in the Quartz Schist Zones, are considered as additional evidence of the former existence of a major E-W anticline to the south, for the axial planes dip to the north or northwest, whereas the axial plane strikes vary between $N50^{\circ}E$ and E-W. A frequency diagram of these strikes may be found on Plate VII (Page 51).

Gash veins in the more competent quartzite beds are considered to be normal structures. Inasmuch as gash veins result from tensional stretching within a quartzite bed due to differential motion between that bed and adjacent beds, it follows that the gash veins form at right angles to the direction of tensional stress. Thus, the trend of the gash veins ($N55^{\circ}E$ to $N80^{\circ}E$) indicates that the tensional stress had a north to northwest azimuth, which agrees with the general structural picture of the area.

REVERSE STRUCTURES

Although the reverse secondary structures of the Skillet Creek and Park Entrance Exposures are on a smaller scale than many of the normal structures, they are found everywhere outside of the massive quartzite beds, and their great number cannot be overlooked.

The reverse drag and chevron folds are considered together inasmuch as they are gradational into each other. The axial planes of these folds dip southeastward at all angles between 5° and 60° ,

and vary in strike between $N15^{\circ}E$ to $N80^{\circ}E$, with the greatest concentration between $N45^{\circ}E$ and $N70^{\circ}E$. Frequency diagrams of the strikes of these folds may be found on Plate VII (Page 51).

The second group of reverse structures which cannot be accounted for by normal differential motion is the underthrust shear planes discussed in the micaceous zones of both crops. The measured shear planes reveal a range in strike between $N35^{\circ}W$ to E-W, with apparent concentration around the north azimuth. See Plate VII for the frequency diagrams of the strikes of these structures. In most cases, the shears seem directly related to chevron folds although shears were noted without accompanying folds. They have a common tendency to dip flatly to the east or southeast. The cleavage accompanying the shears indicates that the foot wall was thrust to the east or southeast with relation to the hanging wall.

THE RELATIONSHIP OF SHEARS, CHEVRON, AND REVERSE DRAG FOLDS

Because of their association with chevron and shear folds, and the broad agreement of axial plane and shear plane strikes, it must be concluded that the underthrust shears and chevron folds have a common origin. In addition, the chevron and reverse drag fold forms are intergradational; thus, it seems probable that all three reverse structures (reverse drag folds, chevron folds, and underthrust shears) are genetically related.

The immediate objection to the proposed interrelationship of the three reverse structures is the wide range of their trends. At first glance, the strikes of the shear planes, (which as suggested previously assume the position of the axial planes of reverse chevron or shear folds), seem incompatible with the strikes of the measured axial planes.

To make further objection to the proposed interrelation and common origin of all reverse secondary structures, the broad range of the axial plane strikes of the reverse drag folds appears to be too great to be ascribed to a single deformation. Certainly, these ranges do not represent the best criteria to base a theory of interrelationship upon, for in the ideal case, all the reverse and normal drag fold axial plane strikes should assume one definite trend. The normal drag folds, thus, should have axial plane strikes which are parallel to the east-west trend of the former anticline to the south of the area.

Similarly, the reverse drag folds should reveal one limited trend, if they are to be ascribed to a single origin. However, this is not the case with the reverse drag folds of the South Range, for the axial plane range of the folds measured varies from $N15^{\circ}E$ to $N80^{\circ}E$, with isolated occurrences of N-S and $N30^{\circ}W$.

The theory of a single deformation which would account for the shear planes is even more problematical, for the shear plane strike range is between $N15^{\circ}W$ to E-W; with one isolated strike of $N35^{\circ}W$. (Associated with the outstanding folds mentioned above). It would seem impossible to ascribe this broad range of strikes to a single deformation.

One would assume that the strikes of the various secondary structures should have more uniform trends, if they are to be considered as evidence of one deformation. Thus, the normal drag folds should have a common trend if they are to represent normal differential motion of the beds toward the crest of an anticline. Likewise, the axial plane strikes of the reverse drag and chevron folds should agree

with the strikes of the associated shear planes, if they too have a common origin.

In seeking uniformity of the trends of the reverse folds and shear planes, we have been assuming that the rock in which they occur is homogeneous, and that the direction of the stresses which formed the secondary structures had one precise azimuth. This is not the case, however, for the reverse secondary structures of the Skillet Creek and Park Entrance Exposures occur in a micaceous schist which is heterogeneous in that scattered irregularly throughout it, there are boudins, plates, blebs, and stringers of quartzite and quartz. The presence of these units of varying size and degree of competence would be expected to exert innumerable minor stress-strain effects on the enclosing incompetent micaceous material, in response to a major stress acting upon the entire rock unit.

Geologic deformation does not occur rapidly, nor as the result of one set of stresses. Instead, deformation is considered to be a pulsational phenomena, with stress directions varying about a general azimuth.

When a pulsating and variable stress source is considered, coupled with a heterogeneous assemblage of competent-incompetent rocks, it becomes obvious that secondary structures cannot be expected to assume identical orientations over the entire heterogeneous rock assemblage.

The underthrust shears appear to be related to the shear folds, for in photographs # 10 and 11, the two structures occur together. Shear folds die out into chevron folds in the same photographs thereby relating these two fold types. Areas of recorded associated reverse chevron and shear folds and underthrust shears occur at locations

7' A x 2', 54' x 1', 41' x $3\frac{1}{2}$ ' of the Skillet Creek Exposure, and 6' x $3\frac{1}{2}$ ', and 30' x 3' of the Park Entrance Exposure. Even the most extreme "deviation" from the trend of shear plane strike (N35°W) is associated with reverse drag folds, with axial plane strikes of N30°W. (Location 41' x $3\frac{1}{2}$ ' of the Skillet Creek outcrop). However, the majority of strikes of both shears and reverse drag fold axial planes are in the northeastern quadrant. It is unfortunate that more observations could not be recorded from folds directly associated with shear zones, but in most cases, the folds were not sufficiently exposed or developed to warrant measurement.

Chevron and reverse drag folds can not be separated using their axial plane strikes as criteria. Both types strike to the northeast, and dip to the southeast. Thus, it must be assumed that the two fold types are genetically related. Inasmuch as the underthrust shears are related to reverse chevron folds which, in turn grade into reverse drag folds, it seems logical to assume the general north-northeast trend and east to southeast dips of the shears and axial planes represent a common origin for all of the reverse secondary structures of the South Range.

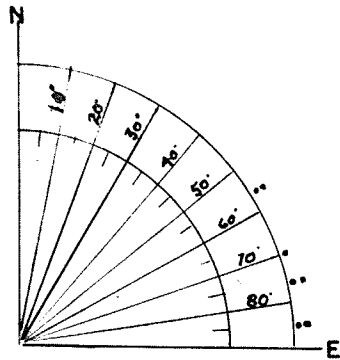
THEORIES OF REVERSE DRAG FOLD FORMATION

THE SOUTH LIMB OF AN OVERTURNED FOLD TO THE NORTH OF THE AREA

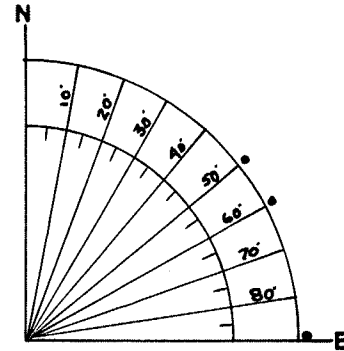
Perhaps the first explanation of reverse drag folds that comes to mind is that they are actually normal folds on the overturned limb of a major anticline. If this is the case at the Skillet Creek and Park Entrance Exposures, we would be assuming the crops to represent the

STRIKE FREQUENCY DIAGRAMS: AXIAL PLANES OF NORMAL DRAG FOLDS

SKILLET CREEK OUTCROP

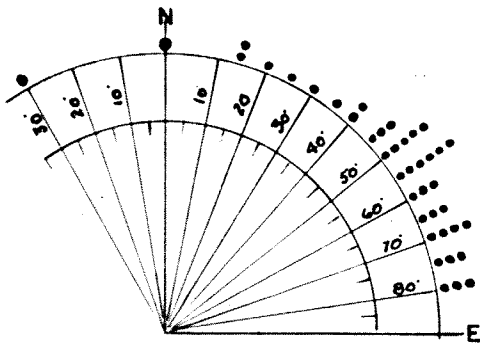


PARK ENTRANCE OUTCROP

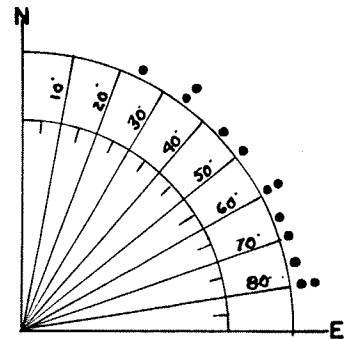


STRIKE FREQUENCY DIAGRAMS: AXIAL PLANES OF REVERSE DRAG FOLDS

SKILLET CREEK OUTCROP

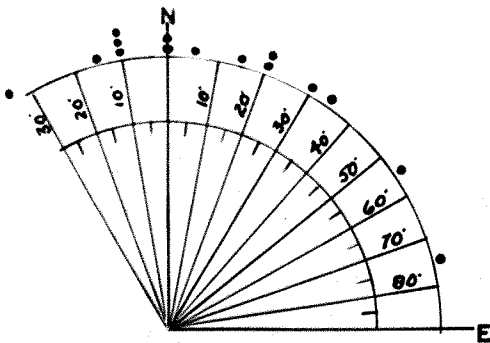


PARK ENTRANCE OUTCROP

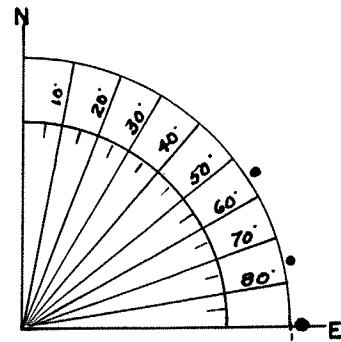


STRIKE FREQUENCY DIAGRAMS: SHEAR PLANES

SKILLET CREEK OUTCROP



PARK ENTRANCE OUTCROP



southern limb of an overturned anticline to the north, as illustrated on Plate IV, Part B (Page 53).

This explanation does not seem plausible, however, inasmuch as the structure of the South Range has been studied in detail without observation of overturned beds, or any structures which would indicate deformation sufficiently intense to produce overturned folds. Observation of truncated cross-bedding in the quartzite beds of the South Range indicates that the beds are not overturned.

Secondly, the thickness of the quartzite formation would prevent tight folding by virtue of its inherent strength.

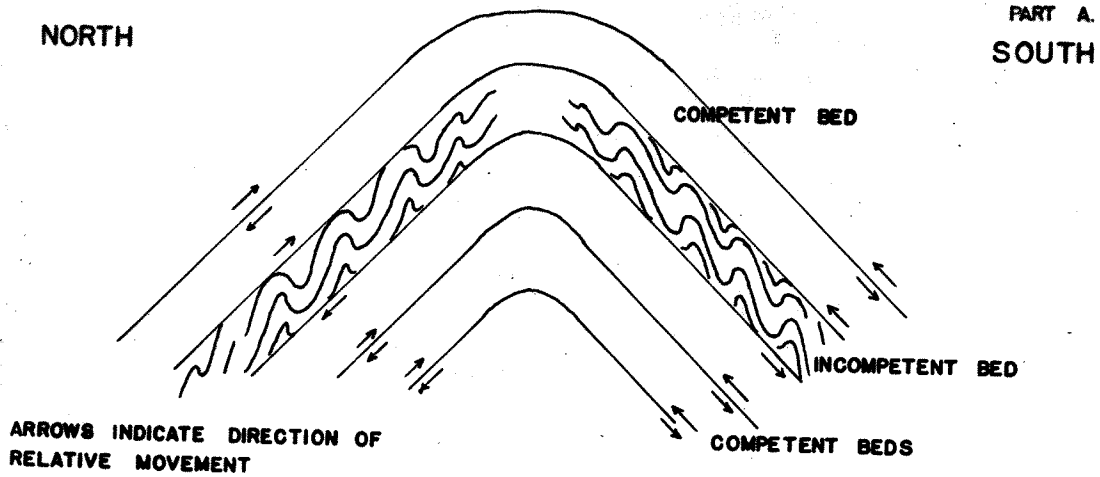
Lastly, should we accept the overturned fold theory, we would eliminate all the present reverse drag folds by considering them to be normal and overturned; but what of the present normal drag folds? These normal folds would be reverse folds on the proposed overturned anticline, and our problem would be no less complicated.

FLOWAGE FOLDING

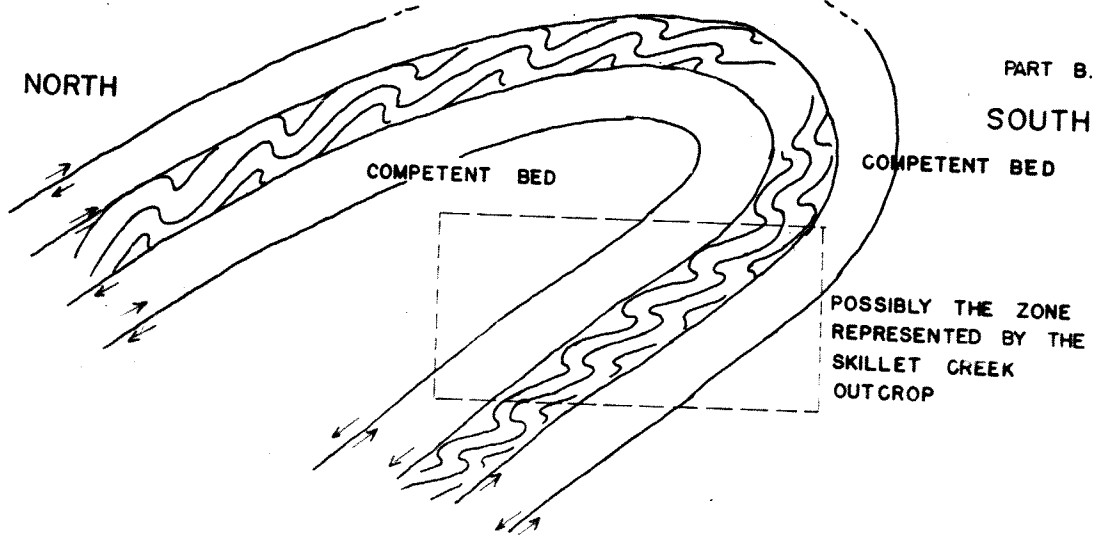
In 1931, G. W. Bain (1.) described the flowage of deeply buried marbles. According to his diagrams, the bedding planes of the marble beds which had flowed formed cross sections that resemble those of reverse drag folds. The axial planes of the flowage folds would be generally parallel to the major anticline upon which they are situated, thereby completing the resemblance of flowage folds to the reverse drag folds of the South Range, (See Plate VIII, Page 59). The micaceous composition of the rocks under consideration would also add support to this theory.

Flowage of the quartz schist at the areas under consideration

DIAGRAMMATIC CROSS SECTION: RELATION OF DRAG FOLDS
TO A LARGER FOLD



DIAGRAMMATIC CROSS SECTION: NORMAL DRAG FOLDS
OVERTURNED TO RESEMBLE REVERSE DRAG FOLDS



could well account for the widespread occurrence of reverse drag folds, and the general lack of normal structures in the Quartz Schist and Slaty Zones. It could also account for the boudins, general foliation, and the rotation of the quartz inclusions in the slate. Thus, the affirmative case for flowage folding seems quite strong. However, according to Bain, flowage folds resemble tar moving away from the crown of a road on a warm day, (See Plate VIII, Page 59). A close examination of such tar flowage folds will reveal that they plunge in both directions parallel to the crown. The reverse folds of the South Range plunge to the northeast almost without exception, thereby destroying the seemingly close resemblance of the reverse folds to flowage folds.

Secondly, Bain's flowage folds all tend to have long thinned limbs and thickened troughs. The drag folds of the South Range show no such variation along their cross section.

Lastly, according to Bain, the more competent beds are drag faulted and swelled to the shape of the flowage folds in the incompetent material beneath them. Although the exposures under consideration are on a much smaller scale than those described by Bain, no minor drag faulting in the plane of schistosity (and folding) was observed.

In conclusion, it seems unlikely that the reverse folds under consideration were the result of flowage, although flowage may have occurred in the schist.

REVERSE DRAG FOLDS RELATED TO A RELAXATION OF MAJOR FOLDS

A third explanation of the reverse structures might be found in a relaxation of the major anticline following the primary folding.

This relaxation could conceivably cause differential motion reverse to the original movement between adjacent beds which, in turn, would result in drag folds with axial planes dipping to the south, and with strikes generally parallel to those of the major structure. Such an origin for the reverse folds of the South Range could account for the widespread occurrence of the reverse folds, the presence of underthrust shears, and the disoriented white quartz lenses. Upon close examination of the theory, however, we are faced with a number of problems and objections to it.

Firstly, if reverse differential motion produced by the proposed relaxation of the major anticline resulted in reverse drag folds in the Slaty Zones, could we not expect these zones to have suffered normal drag folding during the primary folding? It would seem likely. Yet, not one normal drag fold was observed in either of the Slaty Zones, and it seems unlikely that earlier normal folds could have been completely eradicated by the subsequent reverse movement.

A second, and equally damaging piece of evidence against the theory may be found in the fracture cleavage horizons between the massive quartzite beds. The fracture cleavage, which generally strikes $N80^{\circ}E$, and dips 45° to $65^{\circ}NW$ is clearly related to the regional structure.

Assuming the anticline relaxed after its formation, and that the reverse adjustment was accomplished by the upper beds slipping differentially toward the syncline, it seems logical to expect the reverse motion to occur along the original fracture cleavage planes, for were not these horizons already zones of weakness in the quartzite? Reverse motion would be expected to result in a second, and opposing,

set of fracture cleavage planes, or at least, the destruction of the primary fracture cleavage and the formation of a slippage gouge. No gouge or reverse fracture cleavage could be located in the fracture cleavage zones of the South Range. Because of these two bits of missing evidence, it seems best to dismiss this theory of origin for the anomalous secondary structures.

REVERSE DRAGS FORMED BY WEDGING

In 1925, R. T. Chamberlain (3) expressed the opinion that under compressional stresses, a wedge shaped section of the earth's crust might be upthrust, the apex of the wedge pointing downward. Thus, the compressional stresses would be dissipated by the resulting shortening of the earth's crust. The upthrusting of the wedge would result in two opposing sets of shears, or drag folds, at the boundary of the upthrust segment and the surrounding crust. An idealized cross section of this phenomena is pictured on Plate VIII, Part B (Page 59).

Evidence of upward buckling and thrusting is abundant at both the Skillet Creek & Park Entrance Exposures. Assuming an east-west wedge on the northern limb of the major anticlinal structure, oriented at right angles to the compressional stresses, we could expect two sets of drag folds (or shears) with axial planes striking normal to the direction of the major stresses, and parallel to the major structure. The two sets of drag folds (or shears) would have opposing dips: one set dipping northward, and the other to the south. The folds with southward dipping axial planes (those to the left on Plate VIII, Part B) would thus fit the characteristics of the reverse drag folds under consideration. However, several bits of evidence, taken

mainly from the Skillet Creek Exposure, do not agree with this theory.

The theory calls for two sets of opposing folds or shears such as the observed normal and reverse secondary structures at the Skillet Creek and Park Entrance Exposures. However, as previously stated, very few normal drag folds were observed, and none were located in the Slaty Zone, although reverse drag and chevron folds are abundant. Where are the two sets of opposing structures?

It is possible that such overthrust evidence as that at locations 105' x 7' and 164' x 4' represents the north dipping set of shears predicted by the theory, but why should this set of shears be represented by relatively large scaled structures whereas the second and opposing set is represented by minute reverse drag folds? It would seem more logical that both sets of structures resulting from the wedging would be more equally represented in both quartzite and schist.

It could be argued that the large overthrust faults represent closer proximity to the southern wedge boundary, thus secondary structures resulting from the shear along the southern boundary might be expected to be better developed than the secondary evidence of the northern wedge boundary. However, if this is the case, why do normal drag folds not predominate over the reverse variety? Then too, reverse drag folds (representatives of the northernmost "wedge slippage plane") may be found to the south of the overthrust faults (representatives of the southern slippage plane). There seems to be no way to account for this unless we postulate overlapping wedges.

Another argument against the wedge theory may be found in the local distribution of the overthrust structures, whereas the reverse drag and chevron folds are widely and equally distributed, with no

apparent relation to the overthrust structures. No evidence of major upward wedging could be found, or has been reported in the underlying massive quartzite, indicating that the upward buckling and overthrusting of the Skillet Creek rocks is a local feature, common only to mixed competent-incompetent horizons.

According to Chamberlain, the folds and shears tend to die out away from the actual zone of slippage. (See Plate VIII, Part B, Page 59). Yet as mentioned previously, the reverse folds at Skillet Creek not only abound over the length of the outcrop, but also tend to be of constant size at most locations along the exposure. If the local buckling had caused the folds, then, could we not expect to find a systematic increase (or decrease) in fold dimension and degree of development when tracing the beds in one direction or another? It would seem so.

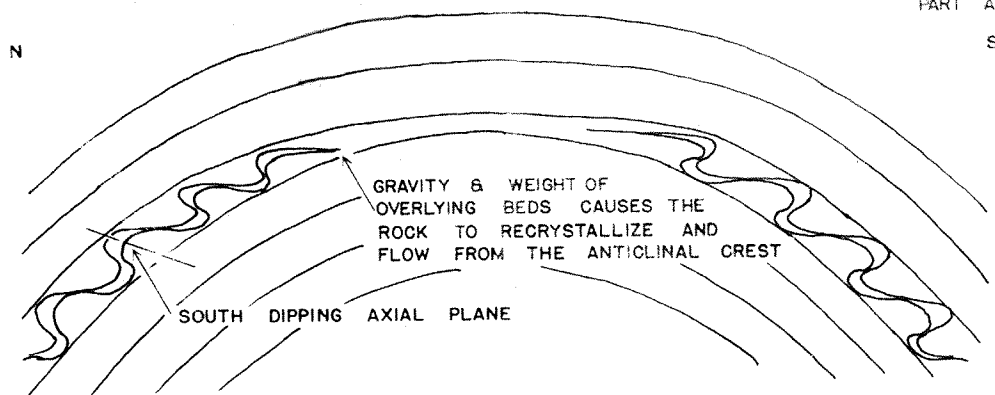
Because of these arguments against the wedge theory of drag fold formation, it seems best to abandon the idea, and seek another which might better apply to the evidence.

REVERSE DRAG FOLDS AS A RESULT OF A SECOND DEFORMATION

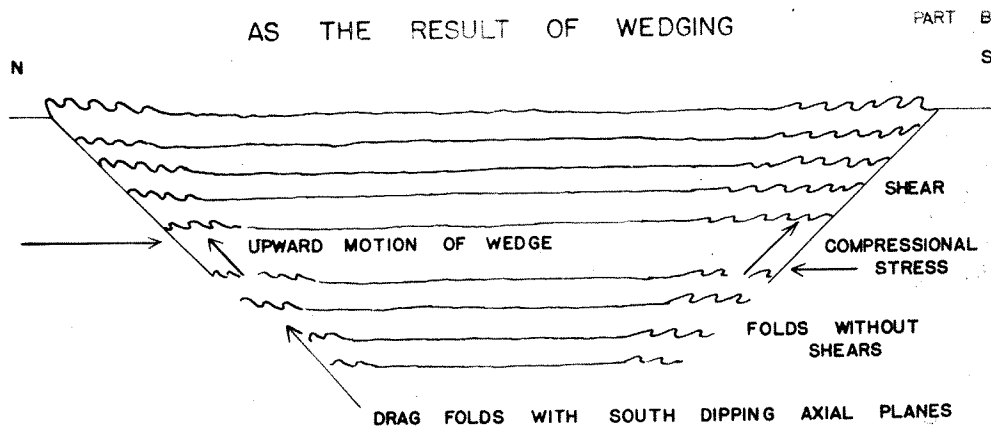
A fifth possible explanation of the reverse secondary structures of the South Range might be found in a second deformation of the area. Certainly, with rocks as old as the Baraboo Series, a number of periods of deformation could be expected, and, in fact, several writers have in the past found evidence of two or more disturbances in the region.

At first glance, it would seem rather simple to explain away the problem of the reverse structures by postulating a second deformation, and assigning the structures to it. However, the trend of the reverse drag fold axial plane strikes would require that the second deformation

DIAGRAMMATIC CROSS SECTION: FLOWAGE FOLDS WHICH RESEMBLE
REVERSE DRAG FOLDS



DIAGRAMMATIC CROSS SECTION: REVERSE DRAG FOLDS
AS THE RESULT OF WEDGING



AFTER T. C. CHAMBERLAIN

be parallel to the primary structures, for both normal and reverse structures have generally parallel trends. In addition to this, the axial planes of the reverse folds dip to the southeast; thus, the indicated differential motion would require the upper beds of a series of beds to move north or northwest to the synclinal trough.

With the trend of the second deformation striking as the primary folding, and with differential motion to the northwest, our second deformation is in reality nothing but a reversal of the primary folding. Inasmuch as this hypothesis has already been considered (and eliminated) under the discussion of relaxation of the major folds, it seems needless to pursue it further.

REVERSE DIFFERENTIAL MOTION AS A RESULT OF FAULTS OR FOLDS

IN THE QUARTZITE BEDS OVERLYING THE HORIZONS UNDER CONSIDERATION

The schistose material of the Park Entrance and Skillet Creek Exposures may be considered as being sandwiched between two confining horizons of massive competent quartzite, for the greatest part of the Baraboo formation underlies the two crops, whereas a lesser thickness is known to overly them.

The south dipping axial planes of the reverse drag folds indicate that the beds underlying the two horizons moved to the south or southeast on the flank of the anticline upon which the exposures are situated. The normal fracture cleavage of the massive rock verifies this movement. But what of the overlying beds at these exposures? The south dipping axial planes indicate that the overlying beds moved northwest with relation to the previously mentioned underlying beds. The differential motion suggested by the micaceous horizons could be

formed by the normal movement of the underlying beds while the overlying beds remained stationary, or lagged behind while riding south and crestward on the main mass of the underlying quartzite. An immediate objection to this theory is that a thrust fault or fold must be postulated in the upper quartzite, if it is to be stripped of its otherwise normal ability to transmit stress from the north or northwest. See Plate IX, (Page 64). However, such a fault or fold is not as improbable as it might seem.

The thickness of the quartzite overlying the Skillet Creek and Park Entrance Exposures cannot be great, because the crops are known to represent the transitional zone between the Baraboo quartzite and the Seeley slate. (The actual thickness of the upper quartzite could not be determined because of concealing overburden). The upper quartzite is in turn overlain by the incompetent Seeley slate, and the shaly Freedom dolomite: neither of which could be considered as a competent or confining formation.

By the proposed fault in the quartzite beds overlying the mapped horizons, we could account for the reverse differential motion necessary to produce drag folds with south dipping axial planes. The strikes of the axial planes would be more or less parallel to the major anticline to the south of the two areas under consideration.

The differential motion indicated by the micaceous exposures could also be accounted for if the quartzite beds overlying the mapped horizons buckled and folded instead of being overthrust as previously suggested. As a bed (or beds) of the upper quartzite folded, the same bed (or beds) immediately south of the fold would stop moving to the crest of the anticline because the compressive stresses from the north-

west would be dissipated by the formation of the minor fold. Throughout the buckling of the upper quartzite, the quartzite underlying the mapped exposures would continue to move south and crestward due to differential movement toward the anticlinal crest. The effect would be an underthrusting of the upper quartzite and the micaceous horizons which would produce drag folds with south dipping axial planes in the micaceous rock sandwiched between the two zones of quartzite. South dipping shear planes would also result from the reverse differential motion produced by minor folding of the upper quartzite horizons.

The micaceous rocks deformed plastically, resulting in folds with smooth rounded crests and troughs, whereas the more quartzose schist buckled and folded into chevron folds with angular crests and troughs.

In still other cases, the reverse differential motion produced underthrust shears in the material which did not deform plastically. If the theory of the strain ellipsoid were to be applied to the ideal occurrence of the shears, with the axis of greatest strain in a NW-SE orientation, and the intermediate strain axis generally parallel to the strike of the quartzite (NE-SW), the shear planes would assume the south dipping position of the shears predicted by the ellipse. However, as stated previously, inhomogeneity of the rocks under consideration resulted in a broad range of strike azimuths for the shear planes.

The origin of the few normal drag folds in the Quartz Schist Zones of the crops can be explained quite readily when we consider that normal folds do not occur in the overlying slate. It is apparent

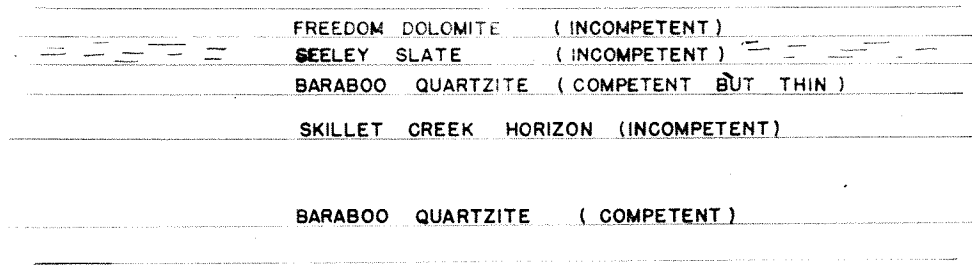
that the quartz schist contains interbedded quartzite beds and lenses that at one time were relatively continuous and competent. During the initial folding, these beds, behaving as struts moved southward and to the crest of the anticline, resulting in normal differential motion and drag folds in the material below them. At a later stage, however, the competent struts buckled or fractured so that they no longer transmitted stresses from the northwest: the result was a cessation of normal drag folding in the schistose material below the struts. With the competent quartzite struts either sheared or buckled, the quartz schist zone was also subjected to the same reverse differential motion as the overlying slate, and reverse drag folds formed in it as well as the slate. Thus, the "underthrusting" of the massive quartzite underlying the two crops could account for the normal structures of the massive quartzite as well as the reverse structures of both micaceous units.

When the three areas of reverse structures are plotted on a regional map, they assume positions along a $N65^{\circ}E$ line; roughly parallel to the trend of the South Range. The question which comes to mind is, "are the three areas the result of one major fault or fold?"

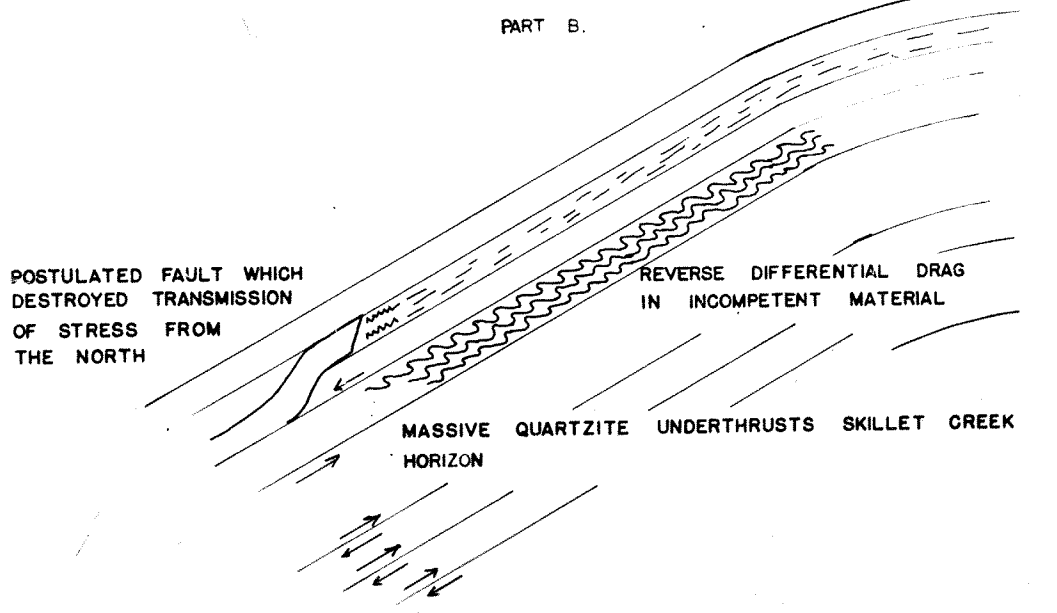
Until further work is done on the areas between the Skillet Creek and Section 25 crops, I would be most reluctant to postulate a major fault which transgresses the six miles between the two areas. No topographic expression of such a fault is evident, and because of the relatively small thickness of quartzite thought to overly the Skillet Creek and Park Entrance crops, minor local faulting or folding would seem more likely than a single major fault or fold.

DIAGRAMMATIC CROSS SECTION: REVERSE DRAG FOLDS
PRODUCED BY REVERSE DIFFERENTIAL MOTION INITIATED
BY FAULTING OF OVERLYING COMPETENT BEDS

NORTH AREA PRIOR TO FOLDING PART A.
SOUTH



NORTH AREA AFTER FOLDING SOUTH



ANOMALOUS CLEAVAGE ZONES OF THE UPPER NARROWS

The third major locality bearing anomalous secondary structures may be found in the abandoned Wisconsin Granite Quarry located in the gorge (Commonly known as the Upper Narrows) north of Rock Springs, Wis. (T. 12N., R. 5 N. along the south line of the NW $\frac{1}{4}$ of section 28. Refer to the general map of Plate II, Page 3).

In the east end of the quarry, (See Station # 1. of the map included on Plate XV, Page 99) a sequence of massive quartzite beds measuring eight and one half feet thick occurs between two thin quartz schist "fracture cleavage" zones. The orientation of the cleavage planes within these zones indicates that the intervening sequence of quartzite beds slipped downward with relation to adjacent quartzite beds. Photograph # 21 (Page 70) shows the crop under consideration.

The quartzite is a medium-grained, purple gray, cross-bedded rock, generally similar to the quartzite of the South Range. The beds strike N75°E, and dip 83°S. The cleavage planes of the "fracture cleavage" zone on the south side of the down faulted block strike N75°E, and dip 80°N, whereas the cleavage planes of the northern zone strike N75°E, and dip 55°S.

A survey of other fracture cleavage zones in the quarry revealed that many thin zones of both north and south dipping cleavage occur in the area.

It is apparent that only the southernmost zone of the sets of "fracture cleavage" at station # 1, can be related to normal differential motion resulting from the synclinal folding of the Baraboo area, for the cleavage planes of this zone (Strike N75°E, dip 80°N) indicate that the uppermost, or southern members of the series of

quartzite beds moved toward the crest of the anticline to the north of the crop, with respect to underlying beds. The problem, then, is to explain the origin of the northernmost anomalous "fracture cleavage" of the exposure at station # 1. (Cleavage planes $N75^{\circ}E$, dip $55^{\circ}S$). The problem was approached by mapping the bedding, joint systems, fracture cleavage, and other structural phenomena of the quartzite beds in quarries on both sides of the Upper Narrows Gorge. The structural data has been incorporated on the transparent overlay of Plate XV, (Page 99).

A GENERAL DESCRIPTION OF THE GEOLOGIC SETTING

Stratigraphically, the crops of the Upper Narrows Gorge consist of the lower members of the Baraboo quartzite, although the basal conglomerate was not observed. The exposures are located on the southern flank of the anticlinal structure situated to the north of the Baraboo syncline.

The quartzite of the Upper Narrows varies in color from deep purplish red to pink and flesh tones. The rock is a brittle, medium to fine-grained clastic and contains some coarser conglomeritic horizons. The beds of the gorge are not overturned; they strike generally $N75^{\circ}E$, and dip between $79^{\circ}S$ and verticality.

The thin quartz schist "fracture cleavage" zones between the massive quartzite beds vary in color from shades of pinkish purple to gray, and, in most cases have a talcy feel. Minute quartz grains, and small flakes of hematite were identified in the material, but no other minerals could be recognized megascopically. No doubt sericite and other micaceous minerals are present in the schist.

THE NORMAL FRACTURE CLEAVAGE ZONES

In the structural setting of the exposure in the Upper Narrows, differential movement of upper quartzite beds north and crestward with relation to underlying strata, should result in fracture cleavage planes which dip to the north and strike parallel to the major structures upon which they occur. Such fracture cleavage planes were observed in the nearly vertical quartz schist zones at Stations 1, 3, 8, 13, 28, 37, and 50. The cleavage planes of the zones have an average strike of $N75^{\circ}E$, which is the general trend of the massive quartzite beds. The dip of the normal fracture cleavage planes varies between $52^{\circ}N$ and $80^{\circ}N$, with the average dip being about $70^{\circ}N$. Normal fracture cleavage zones are abundant throughout the general area.

The orientation of fracture cleavage planes has been used successfully to interpret geologic structures, for it may be assumed that fracture cleavage planes on the flank of a major fold are parallel to the dip and strike of the axial planes of the fold. Inasmuch as the $N75^{\circ}E$ strike of the fracture cleavage planes observed in the Wisconsin Granite Quarry is the same as the general strike of the quartzite beds, the application of fracture cleavage plane orientation to the major fold north of the Upper Narrows might lead one to the conclusion that the anticlinal structure is isoclinal, and overturned slightly to the south. However, since the intersection of cleavage and bedding in this area is nearly horizontal the strike relationship may be considered regional.

C. K. Leith used the wide zone of North dipping cleavage of Van Hise Rock (Station 28) as a classic example of fracture cleavage, and its application to structural interpretation, (15). The dip of

this cleavage is approximately 60°N , whereas the fracture cleavage in the Wisconsin Granite Quarry dips more steeply to the north, (Average dip; 70°N).

The apparent discrepancy between the dip of the cleavage at Van Hise Rock and that in the quarry may be explained by the fact that the width of the fracture cleavage zones in the quarry is considerably thinner than that of the cleavage zone at Van Hise Rock. The fracture cleavage planes of a thin cleavage zone might be expected to be rotated, by continued differential motions after the fracture had occurred. The cleavage plates of a broader fracture cleavage zone would not suffer such rotation if exposed to the same differential motion. Instead, the cleavage plate of a thick cleavage zone would be dragged into steep dipping orientations (approximating the steeper dips of the thin cleavage zones) near the slippage surface, but the major part of the cleavage plate would not be rotated. Thus, the result of the continued differential motion along the bedding contact of a competent quartzite bed and a relatively thick incompetent bed would be fracture cleavage planes with "S" shaped cross sections.

THE ANOMALOUS CLEAVAGE ZONES

Thin anomalous cleavage zones were observed between the massive quartzite beds at Stations 1, 2, 4, 8, and 13. The cleavage planes range in strike between $\text{N}72^{\circ}\text{E}$ and $\text{N}83^{\circ}\text{E}$, and dip between 35°S and 82°S . The fact that the cleavage planes have strikes which parallel the massive quartzite beds indicates that the beds have slipped directly up, or down, the dip. If the anomalous cleavage zones are fracture cleavage zones, the fact that the cleavage planes dip to the

south would require that the southern, and uppermost, of the series of beds, moved to the south. (Toward the trough of the Baraboo syncline). Thus, they would indicate differential motion reverse to that which would be anticipated in the structural setting of the exposures.

On close examination, incipient anomalous south dipping cleavage planes occur in many of the normal fracture cleavage zones. Weathered fragments from some of the apparently normal fracture cleavage zones have diamond shaped cross sections at right angles to the strike of the cleavage planes. The shape of the fragments is due to weathering along the opposing surfaces of both normal and anomalous cleavage planes. Thus, it appears that reverse differential motion resulting in the anomalous south dipping cleavage planes did not take place equally between all the massive quartzite beds, and in some cases, did not take place at all.

The anomalous cleavage planes are believed to have cut and offset the normal fracture cleavage planes, thereby indicating that the anomalous cleavage planes and zones are later than their normal, north dipping, counterparts.

BEDDING SLIP FAULTS

In addition to the thin zones of anomalous cleavage, several major bedding slip faults were observed in the abandoned quarry on the eastern side of the Upper Narrows Gorge. (Stations 4, 23, 24, 47, and 50). These fault zones, which vary in width from one to four feet, dip and strike as the adjacent quartzite beds, and in some cases bear the previously discussed diamond shaped cross sectional pattern at right angles to the cleavage planes in the weathered schist;

Photograph # 21

The exposure at Station 1., showing
the thick "downfaulted block of beds"
bordered by thin "fracture cleavage" zones.

The geologic pick gives the scale.

Photograph # 22

The narrow steep walled gully formed by
erosion of fault gouge along a bedding slip
fault at Station # 23.

Geologic pick gives the scale.



indicating that both normal and reverse differential motion has occurred along the bedding fault plane. At Stations 23, 24, 47, and 50, the fault plane is outstanding in that the shear cleavage or fault gouge has been eroded from between the massive quartzite beds adjacent to the fault plane, leaving a small steep walled gully to mark the fault zone. See photograph # 22, (Page 70).

The fault zones can be interpreted as former slaty, or quartz schist horizons, which have been eroded to form the steep walled gullies between massive beds of quartzite. However, I feel the zones represent major bedding slip faults because: (1.) million structures occur along the quartzite walls of the zones, and; (2.) other quartz schist fracture cleavage zones have not disintegrated under similar exposure to weathering and erosion.

It is puzzling, and perhaps significant, that no anomalous south dipping cleavage planes or bedding slip fault zones were found in the quarries of the western side of the Upper Narrows Gorge. However, it is probable that these bedding slip phenomena occur on the valley's western slopes, but are covered by overburden. If the fault zones are traced southwest along strike, the western extensions should crop out on the hill immediately west of Van Hise Rock, (Station # 28). This hill, although dotted with large quartzite exposures, does not afford the continuous outcrop so accessible in the quarry on the eastern side of the Baraboo River. Thus, the fault zones may be concealed by overburden on the western side of the Upper Narrows Gorge.

THE TENSION BRECCIA ZONES

On the eastern side of the Upper Narrows Gorge, extending from

Station 22 to Station 25, much of the quartzite exposed along the eastern side of the railroad tracks is broken and brecciated in a very unusual manner. A similar breccia zone may be found between Stations 54 and 56 on the western side of the Upper Narrows Gorge.

The breccia consists of angular fragments of purple to pink quartzite cemented by coarsely crystalline white vein quartz. In many cases, the quartz completely surrounds the angular quartzite pieces. The fragments vary in size between two foot square blocks to minute pieces of quartz measuring less than $\frac{1}{4}$ inches. In all cases, angularity of the brecciated fragments is outstanding. See photograph 23, (Page 74).

The breccia zone of the western valley wall is currently exposed in a working quarry, (Station 40) and here, vugs in the white quartz cement were noted. The vugs are lined with euhedrally developed clear quartz crystals, intermixed with dickite.

Although the breccia zones are mapped as large areas, the most intense brecciation is very local. It occurs at Station 40, on the western wall of the valley, and 100 feet southwest of Station 22 on the eastern side of the Baraboo River. Both zones grade rapidly into unbrecciated rock. The brecciation is apparently controlled by joint faces, for at Station 54, minor brecciation occurs along a joint face which strikes $N35^{\circ}E$, and dips $5^{\circ}NW$. At Station 55, brecciation is more strongly developed along another joint surface which strikes $E-W$, and dips $35^{\circ}N$. Slight fault displacement along these joints is apparent. Immediately south of Station 55, intense brecciation obliterates all trace of bedding and joints, but no evidence of crushing, abrasion, or a fault plane could be found. Instead, the

angular quartzite fragments appear to have been broken as fragments of open stoped ore, then cemented with white quartz, without motion or rotation of the pieces. The individual fragments may be matched together, much as the pieces of a jig saw puzzle. See photograph 24, (Page 74).

It is of interest that the zone of maximum brecciation of the western valley slope does not coincide with the zone of maximum brecciation of the eastern side of the Upper Narrows. See the transparent overlay of Plate XV, (Page 99). If these two areas of intense brecciation represent one zone which is cut by the Upper Narrows Gorge, that zone (1.) either cuts across the strike of the quartzite beds, or (2.) has been offset approximately 300 feet along a north-south line.

Interpretation of the breccia zones is problematical, for the angularity of the quartzite fragments, the presence of vugs, and the general lack of fault motion, rotation, and crushing, suggests a tensional disturbance. If the area has been thrust faulted or sheared the breccia fragments should show indication of crushing, rounding, and abrasion.

A number of possible explanations may be considered for the breccia zones. Their apparent E-W trend could represent a major tensional fault parallel to the strike of the beds, for a similar breccia zone may be found in the Narrows Creek Gorge 1.7 miles to the west (along strike) from the Upper Narrows exposures. Thus, it is possible that the breccia of the Upper Narrows and the Narrows Creek Gorge represent one continuous fault, and that the 300 foot offset in the Upper Narrows Gorge is due to a second N-S fault within

Photograph # 23

Angular breccia from the eastern
breccia zone near Station 22.

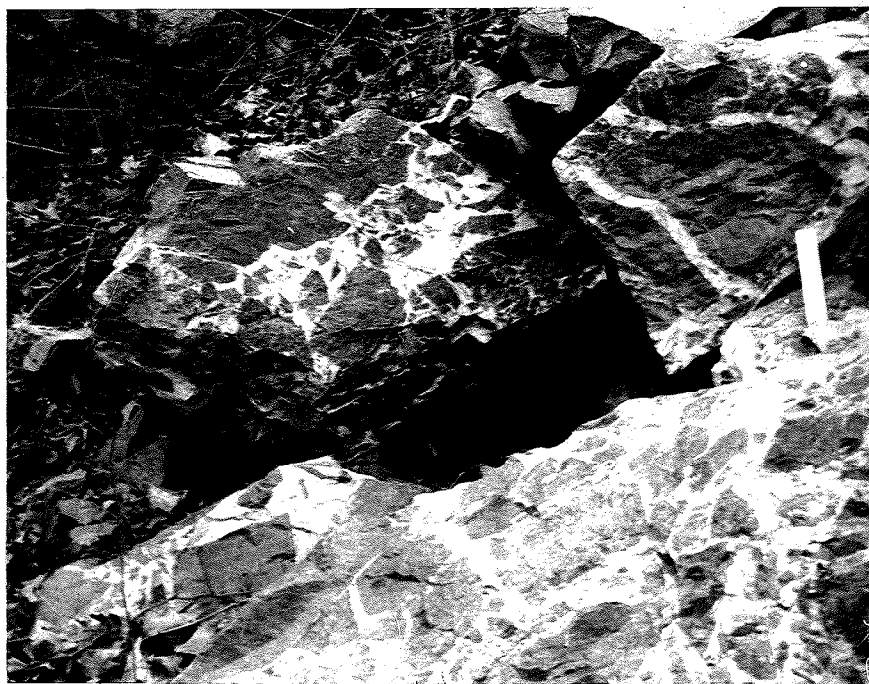
Note the angularity of the fragments

The six inch rule gives the scale.

Photograph # 24

Angular breccia from the eastern
breccia zone, near Station 22. Note the
lack of crushing, and the "jig-saw puzzle"
relationship of the fragments.

The six inch rule gives the scale.



the valley. The nature of the fault resulting in the tension breccia is unknown, but it seems reasonable to assume that it involved a N-S expansion of the quartzite of the North Range. The fact that the quartzite is brecciated indicates a volume increase of approximately 33% in the zone of brecciation; thus, a N-S expansion must be called upon to accommodate the increased volume of the breccia zones.

The breccia zones could also represent E-W trending offshoots of a large fault or breccia zone concealed under the present valley floor. A N-S fault through the Lower Narrows, 14.5 miles to the east of the Upper Narrows Gorge, has been established by drill hole data, and it seems reasonable to assume that the Upper Narrows Gorge could represent a similar N-S fault.

JOINT SYSTEMS

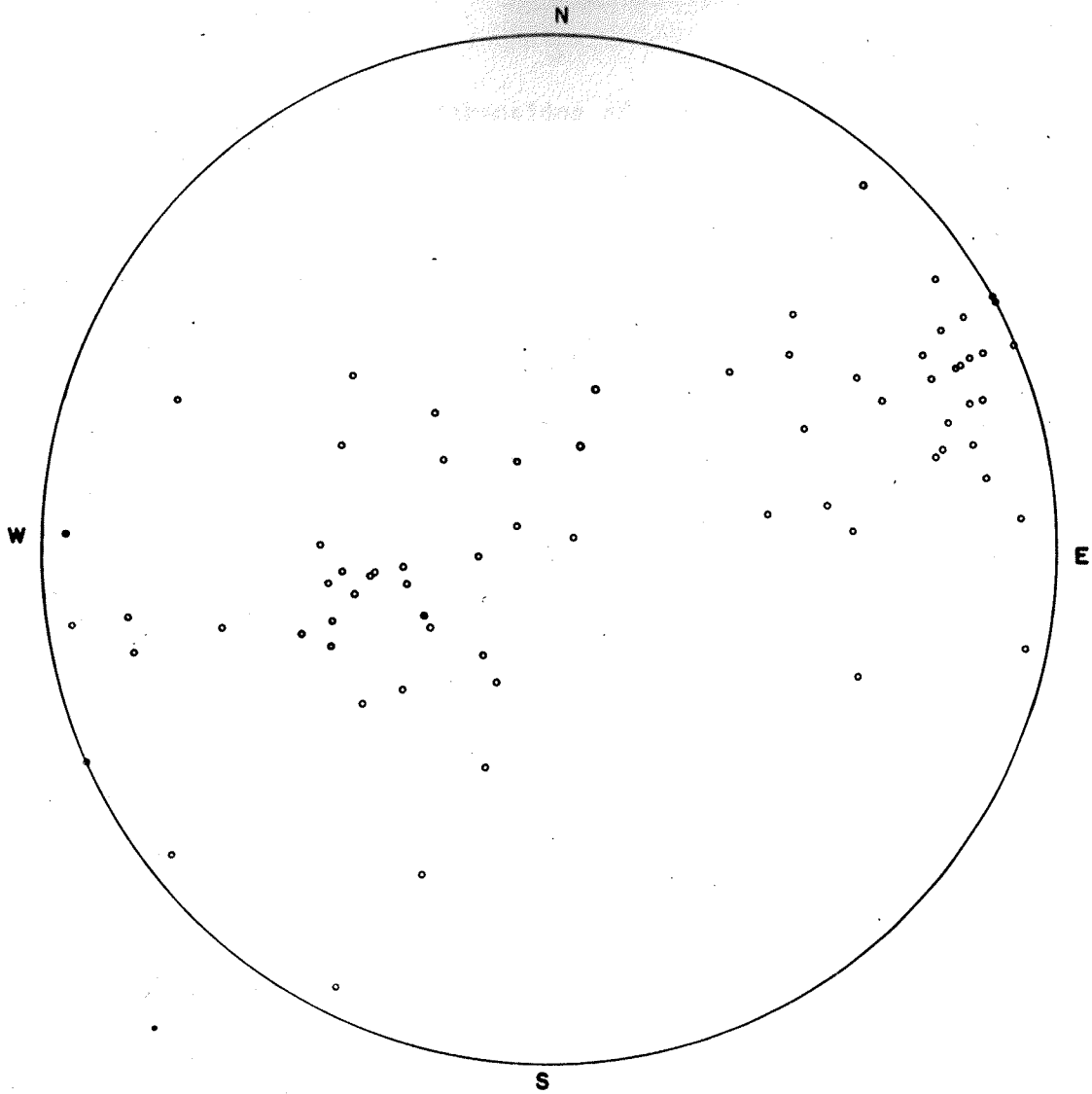
The massive quartzite of the area bears numerous joint sets and independent joints which were recorded, and are shown diagrammatically on the point diagram of Plate X, (Page 76). The strike of these joints is concentrated between N30°W and N10°W, with only a few deviations from this strike range.

The majority of the joints can be classified into one of the five following joint sets. The joint sets are:

Joint set # 1.	Strike N-S to N25°W.	Dip 25°W to 45°W
Joint set # 2.	Strike N-S to N25°W.	Dip 45°E to 90°
Joint set # 3.	Strike N-S to N25°W.	Dip 45°W to 90°
Joint set # 4.	Strike N25°W to N50°W.	Dip 25°W to 45°W
Joint set # 5.	Strike N25°W to N50°W.	Dip 45°E to 90°

It is of note that on those joint planes of joint set # 1., situated on the eastern side of the Upper Narrows Gorge, slickensides occur on a white quartz film which is characteristic of many joint surfaces of the area, (regardless of their orientation).

POINT DIAGRAM — JOINT PLANES OF
THE UPPER NARROWS
67 MEASUREMENTS - UPPER HEMISPHERE ONLY



Joints bearing slickensides occur at Stations 5, 6, 10, 20, 22, 23, and 51,. The slickensides always strike as the quartzite beds adjacent to the joint surfaces, indicating that the slickensides were caused by a movement which was parallel to the strike of the massive quartzite beds.

In addition to the slickensides of joint set # 1., additional evidence of displacement along joint planes may be found associated with other joint sets of the area. An excellent example of this displacement occurs at Station 49, where white quartz filled gash veins along a joint surface indicate that the hanging wall of the joint (or more correctly shear joint) has slipped downward, and to the east along the joint plane. This shear joint (strike N25°W; dip 66°E) belongs to the #2. joint set. Other evidences of minor fault displacement along joint surfaces were discussed previously under the subject of the tensional breccia zone near Station # 55.

Related to the # 1. and # 2. joint sets are numerous areas of tensional faults which are generally arranged in an echelon pattern; the trend of which is parallel to the joint surfaces. See photograph 25, (Page 78). The cross sections of these tension faults is lense shaped, whereas they appear to be planar in longitudinal section. The faults strike between N10°W and N30°W, and dip between 65°E and 85°E. Photograph 25, (Page 78) shows the trend of the en echelon pattern of the faults to dip approximately 60°E, which is roughly parallel to a joint plane on the same crop which dips 66°E, and strikes N30°E. The strike of the tensional faults is N20°W. Thus, the tension faults appear to be related to the # 2. joint set. The gash veins at Station 49 also occur along the east dipping surface

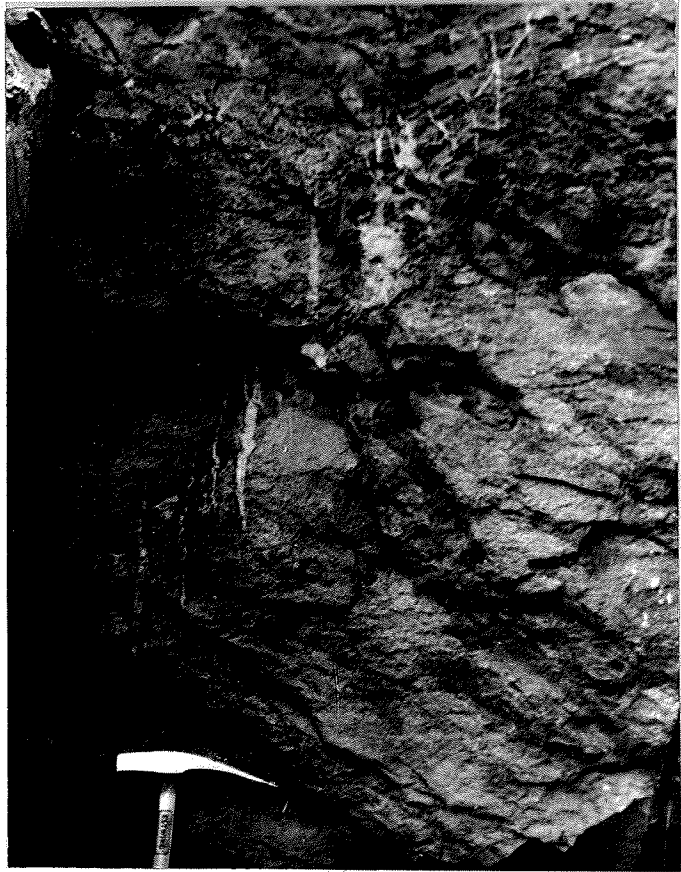
Photograph # 25

White quartz filled en echelon tension faults which parallel the surface of joint set # 2., at Van Hise Rock, (Station 28).

The geologic pick gives the scale.

... joint set, suggesting ...

... on the ...



... joint set ...

... on the ...

... joint set ...

... on the ...

... joint set ...

... on the ...

of a member of the # 2. joint set, suggesting that general slip down the dip of all # 2. joint set members has occurred.

Similar en echelon tension faults occur on the eastern side of the Upper Narrows Gorge. (Stations 1, 7, and 15). Like their western counterparts, these faults roughly parallel the trend of joint surfaces. (The # 1. set). all normal fracture cleavage

Thus, two joint sets with parallel strikes and opposing dips show evidence of displacement along their dips. It is of special interest that the two joint systems occur on opposite sides of the Upper Narrows Gorge, and that the projections of their surfaces intersect under the valley.

POSSIBLE ORIGINS OF THE ANOMALOUS CLEAVAGE ZONES

FORMATION OF ANOMALOUS CLEAVAGE ZONES DUE TO RELAXATION OF THE MAJOR FOLDS

It would be possible to account for the reverse differential motion indicated by the anomalous south dipping "fracture cleavage" zones by assuming that the major anticline, upon which the zones are located, relaxed at some time after it was formed. See Plate XI, (Page 81).

By such a theory, we could not only account for the anomalous cleavage zones formed during the relaxation of the anticline, but also the north dipping fracture cleavage which formed between massive quartzite beds during the initial folding. The theory would also account for the parallel strikes of both the normal fracture cleavage planes and anomalous cleavage planes, for the reverse differential

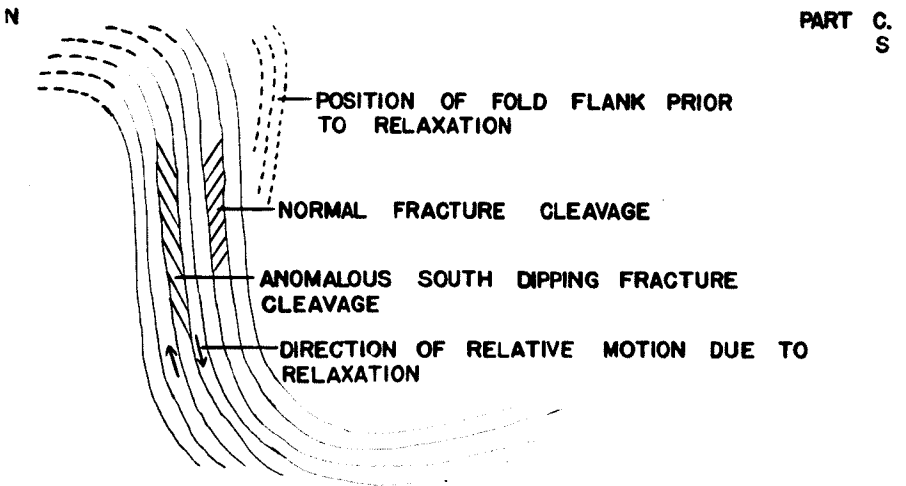
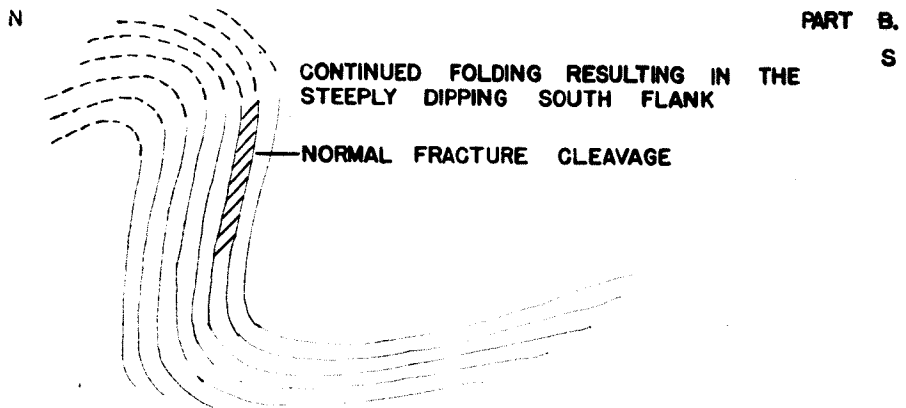
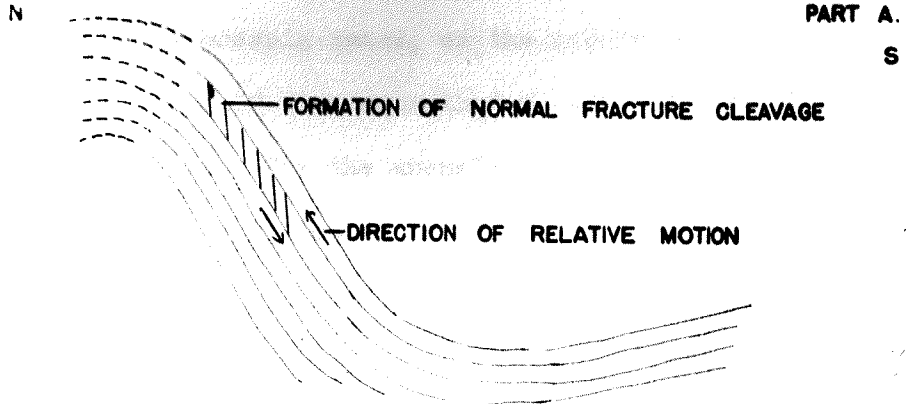
motion resulting from the relaxation of the anticline would be opposite, but parallel to, the initial normal differential motion.

Incipient reverse cleavage planes, indicative of relaxation and reverse differential motion, are widespread among many of the normal fracture cleavage zones, although they are by no means universal. It could be argued that all normal fracture cleavage zones should also bear reverse fracture cleavage, for if normal differential motion occurred along these planes during normal folding, why should reverse differential motion not occur along them as a result of the relaxation of the anticline. This argument might be countered by postulating that because of excessive friction between some beds, reverse motion did not take place between all of the quartzite strata. Thus, certain normal fracture cleavage zones could conceivably remain intact.

Another objection to the theory of relaxation of the major anticline may be found in the four major bedding slip faults at Stations 23, 24, 47, and 50. These fault zones are too wide, and bear more fault gouge and mullion structure than differential motion related to anticlinal relaxation should produce. However, the fault zones could be accounted for by some deformation other than that which produced the thin anomalous cleavage zones, but inasmuch as the cleavage zones and bedding slip faults are of the same dip, strike, and general bedding slip character, it would only serve to complicate the problem by postulating two or more parallel deformations.

A third objection to the theory may be encountered when we postulate a relaxation of a sizable fold in the Baraboo quartzite, for it is an exceptionally brittle rock, seemingly incapable of elastic rebound.

DIAGRAMMATIC CROSS SECTION: ANOMALOUS CLEAVAGE ZONES DUE TO RELAXATION OF THE MAJOR FOLD



Relaxation of the major anticline could not account for the northeast trending Upper Narrows Gorge which cuts across the major structural trend of the quartzite; nor does the theory explain the E-W trending tension breccia zones, or the general N-S en echelon tension faults. Thus, if we assume that a relaxation of the major anticline is responsible for the anomalous cleavage zones, a second deformation must be postulated to account for these structures of a tensional nature.

FORMATION OF ANOMALOUS CLEAVAGE ZONES

BY BEDDING SLIP FAULTS: THE BEDS SLIPPING DOWNWARD

INTO A FAULT FORMED VOID

A second explanation of the reverse cleavage zones might be found in the sequence of events diagrammatically shown on Plate XII, (Page 84).

Part A. of the plate illustrates the initial anticlinal folding of the quartzite beds of the North Range. During the folding, differential motion between adjacent beds in a series of quartzite strata would account for the normal fracture cleavage zones observed in the abandoned Wisconsin Granite Quarry.

Part B. of the plate suggests that as folding became more severe, the brittle quartzite beds formed tensional joints at, or near the trough of the syncline. Continued compression from the north of the area might tilt the beds of the south flank of the anticline to near verticality, thereby resulting in a hinge fault at the site of the former tension joints.

The void formed by the opening of the hinge fault would not be

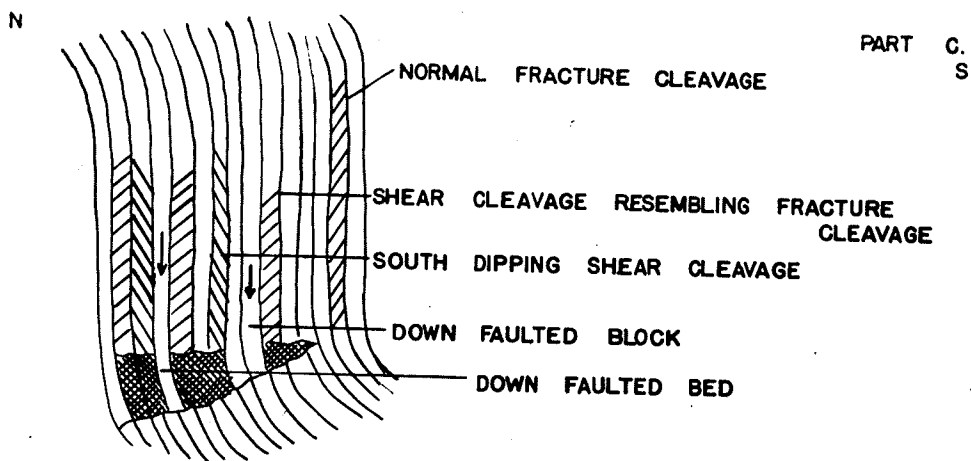
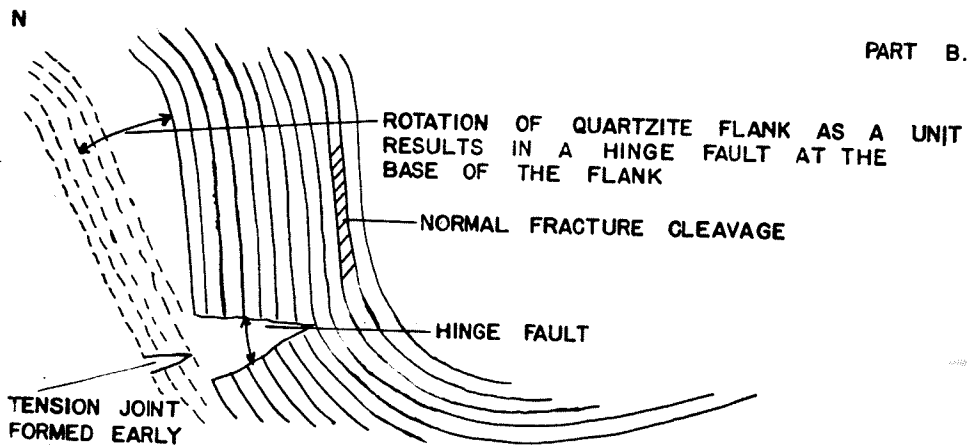
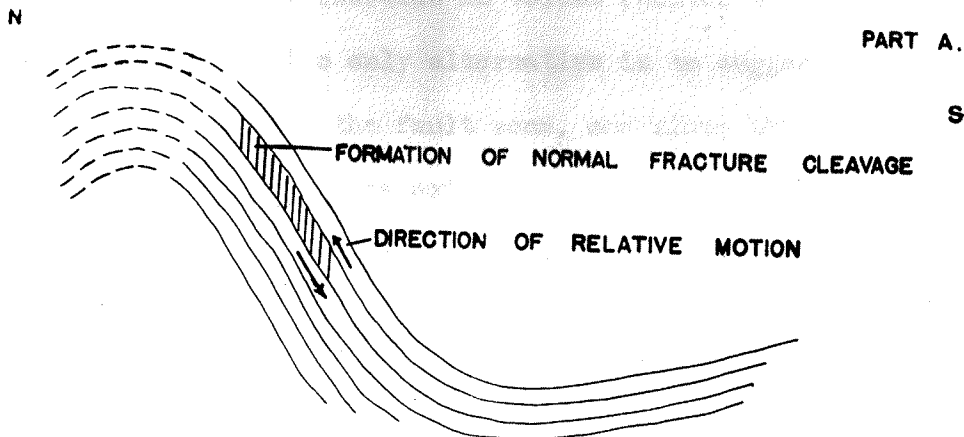
expected to remain open, and Part C of Plate XII indicates that the quartzite beds overlying the fault void would slip downward into it, producing south dipping bedding slip fault shear cleavage on the northern side of down faulted beds, and north dipping shear cleavage (similar to normal fracture cleavage) on the southern sides of down faulted quartzite beds.

It is not necessary to assume that the fault void formed completely before the overlying beds slipped into it, for it is possible that as the limb of the fold was tilted to near verticality, the beds over the void slipped downward into it. By such a means we could eliminate the necessity of postulating a stable void at considerable depth.

The downward slip of the beds into the void would not be expected to occur equally between all quartzite beds: thus, a series or block of beds might drop as a unit, resulting in zones of south dipping shear cleavage on the northern bedding slip surface of the unit, whereas other undisturbed bedding plane contacts of the block of beds would not bear shear cleavage. By postulating downward slip in blocks of beds, we could account for the normal fracture cleavage zones intermixed with anomalous cleavage zones of the Wisconsin Granite Quarry. The southern bedding slip surfaces of such a series of faulted beds would bear shear cleavage that could not be distinguished from normal fracture cleavage because the cleavage planes would strike as the normal fracture cleavage planes do, and dips of both types of cleavage would be to the north.

It could be argued that breccia would develop in the tensional fault required by this theory of origin for the anomalous cleavage

DIAGRAMMATIC CROSS SECTION ANOMALOUS CLEAVAGE ZONES DUE TO BEDDING SLIP INTO A FORMED VOID



zones. Thus, the fault formed void might be completely filled with breccia, thereby preventing the downward slip of the overlying beds into the void. The 33% increase in volume related to brecciation cannot be denied, and the only alternative is to suggest that the quartzite beds overlying the fault zone, and along the fault surfaces did not fracture to any large extent.

The result of a hinge fault with accompanying slippage of the overlying beds into the fault formed void could account for the mixed zones of both normal fracture cleavage, and anomalous south dipping cleavage. The wedge shaped void, with the widest displacement of the quartzite to the north, and least to the south, might also account for the frequency of large bedding slip faults in the north end of the valley, and apparent lack of such fault zones in the southern section of the gorge, for the northern beds would be expected to slip further into the widest part of the void.

However, this theory cannot explain the northeast trending Upper Narrows Gorge, the E-W striking tension breccia zones, or the N-S striking en echelon tension faults. Thus, these structures would have to be assigned to a later deformation.

FORMATION OF ANOMALOUS CLEAVAGE ZONES DUE TO SLUMP

OF THE QUARTZITE BEDS INTO A MAGMA CHAMBER

The differential motion required for the formation of anomalous south dipping cleavage zones between massive quartzite beds could be explained by irregular downward slip of the massive quartzite beds into a magma chamber at depth. A low pressure area under the quartzite of the north end of the Upper Narrows Gorge, and perhaps the entire

valley, could remove the support of some of the quartzite beds, and induce them to slip downward into the chamber; singly, or in blocks of beds. The irregular slip of the beds and blocks past each other would result in south dipping shear cleavage along the bedding slip faces on the north side of the down faulted units. This shear cleavage would resemble "reverse fracture cleavage", and would correspond to the anomalous cleavage zones of the Wisconsin Granite Quarry. North dipping shear cleavage would develop on the southern bedding slip face of the down faulted blocks, and this cleavage would be indistinguishable from normal fracture cleavage found between quartzite beds where fault displacement had not occurred.

Thus, a magma chamber could account for the south dipping anomalous cleavage zones as well as the larger bedding slip fault zones in the abandoned Wisconsin Granite Quarry.

Tensional stresses which might be instituted by the intrusion of a magma into the region under the Upper Narrows Gorge could also account for the N-S tensional faults which roughly parallel that valley. In fact, the entire river valley could be the result of a graben structure caused by upward bulging, or doming, produced by a large scale intrusive at depth.

The slickensided joint surfaces of joint set # 1., and the en echelon tension fault zones parallel to the joint planes of joint set # 2. seem to indicate that tensional stresses have been active roughly normal to the trend of valley. Certainly, it is possible that upward doming produced by large scale intrusion could result in the roughly N-S tensional structures.

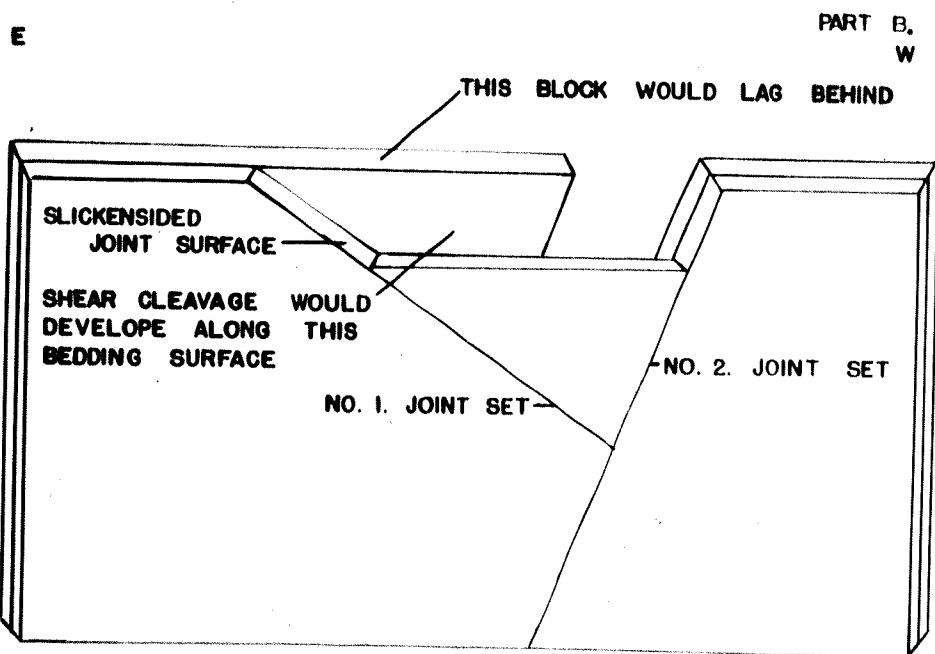
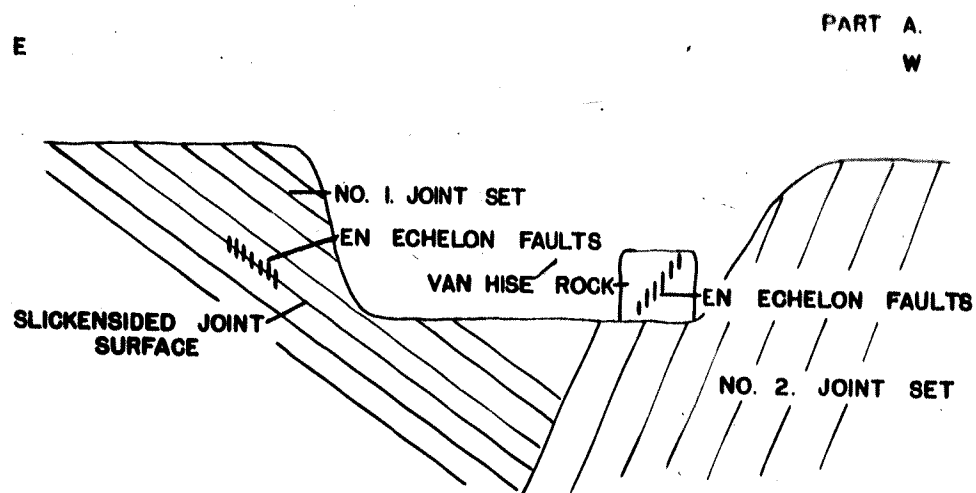
Thus, it is apparent that roughly E-W tensional stress has been active in the area, and that quartzite beds on the eastern valley wall have slipped downward and to the west, parallel to the strike of the quartzite beds in the abandoned Wisconsin Granite Quarry. No similar eastward dipping slickensides were observed on the west bank of the river; however, tension faults parallel to the # 2. Joint set suggest a movement of the quartzite beds downward and to the east. The results of the E-W tensional stresses, coupled with the two opposing joint sets is diagrammatically illustrated on Plate XIII, Part B, (Page 89).

The irregular westward slip of the quartzite of the east wall of the valley toward the graben valley could conceivably result in south dipping shear cleavage between two adjacent beds; the southernmost of which slipped toward the graben while the other remained stationary, or lagged behind. As in previous cases, the slippage of beds would be irregular in that some would slip as a unit or block while others would move singly. South dipping shear cleavage, as well as north dipping shear cleavage would also result on the north and south sides (respectively) of the down faulted beds as described in the discussion of other theories of origin for the anomalous cleavage zones.

The presence of a roughly N-S graben under the present Upper Narrows Gorge could account for the south dipping cleavage planes between certain beds, or blocks of quartzite. It could also account for the larger bedding slip fault zones, the N-S trending lense shaped en echelon tension fault zones, the slickensided joint planes, and the valley itself.

DIAGRAMMATIC LONGITUDINAL SECTION: ANOMALOUS CLEAVAGE ZONES DUE TO A GRABEN STRUCTURE

LOOKING SOUTH



However, there is a serious argument against this theory or origin of the south dipping anomalous cleavage zones, for the cleavage planes of the anomalous cleavage zones strike generally $N75^{\circ}E$, parallel to the strike of the normal cleavage. Both cleavages strike parallel to the strike of the quartzite beds, thereby indicating that differential motion in both cases was in a vertical direction, with no slip component to the east or west. If the south dipping cleavage planes are the result of a downward and westward motion of the quartzite beds, the strike of the shear cleavage planes on the northern slippage plane of a down faulted quartzite bed or block of beds would be to the north of west. The strike of the shear cleavage of the southern slippage face of a down faulted block would be more to the north of east than the existing cleavage plane strikes.

There seems to be no way to coordinate the $N75^{\circ}E$ strike of the south dipping anomalous cleavage with the downward and westward differential motion of some beds as required by this theory of westward slip into a graben.

Thus, if a graben does exist under the Upper Narrows Gorge, it must have developed independent of the deformation that resulted in the south dipping cleavage planes of the anomalous cleavage zone.

FORMATION OF ANOMALOUS CLEAVAGE ZONES BY SLUMPING

OF BEDS INTO VOIDS RESULTING FROM TENSIONAL

STRETCHING OF BEDS ON THE FLANK OF AN ANTICLINE

Another explanation of the anomalous south dipping cleavage zones might be found in the sequence of events diagrammatically shown on Plate XIV, (Page 92). As shown on Part A. of the plate, anticlinal

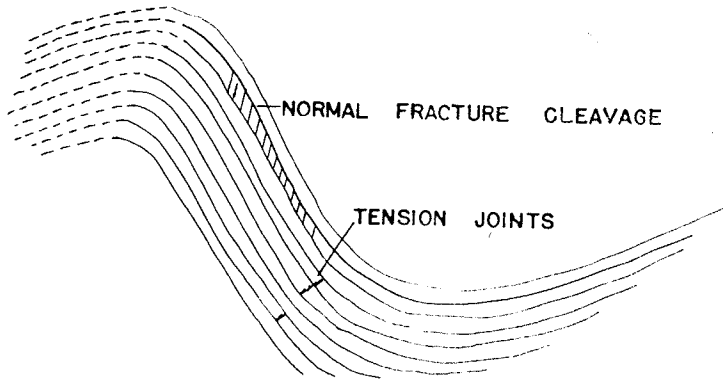
folding of the North Range would result in normal north dipping fracture cleavage zones when the quartzite beds reached a vertical, or near vertical position. However, as folding proceeded, the quartzite strata on the flanks of the anticline would be subjected to tensional stress resulting from the stretching of the beds over the crest and trough of the respective anticline and syncline. Stretching of the brittle quartzite might ultimately result in tension fractures in some quartzite beds (or series of beds) as shown in Part A. of Plate XIV, (Page 92). Continued folding would cause separation of the fractured faces as the bed or blocks of beds were drawn crestward on the anticline. The enlarging void resulting from the tension fracture might conceivably remain open, inasmuch as it would be walled by competent brittle quartzite beds.

At a later stage in the folding, the previously parted quartzite beds that had moved crestward might again fracture due to tensional stresses resulting from gravitational pull. The parted beds or blocks of beds would then slide down dip into the original tension formed void. The differential motion between the beds that slipped and those that did not would result in south dipping bedding slip shear cleavage along the northern slippage surface of the down faulted bed or block of beds, and north dipping shear cleavage along the southern slippage plane. The north dipping shear cleavage would be indistinguishable from normal fracture cleavage formed during the anticlinal folding of the region. Therefore the three types of cleavage; normal fracture cleavage, and north and south dipping bedding slip shear cleavage, would result from this sequence of events.

This explanation could thus account for the anomalous cleavage

DIAGRAMMATIC CROSS SECTION: ANOMALOUS CLEAVAGE ZONES BY BEDDING SLIP INTO VOIDS FORMED BY STRETCHING OF BEDS ON AN ANTICLINAL FLANK

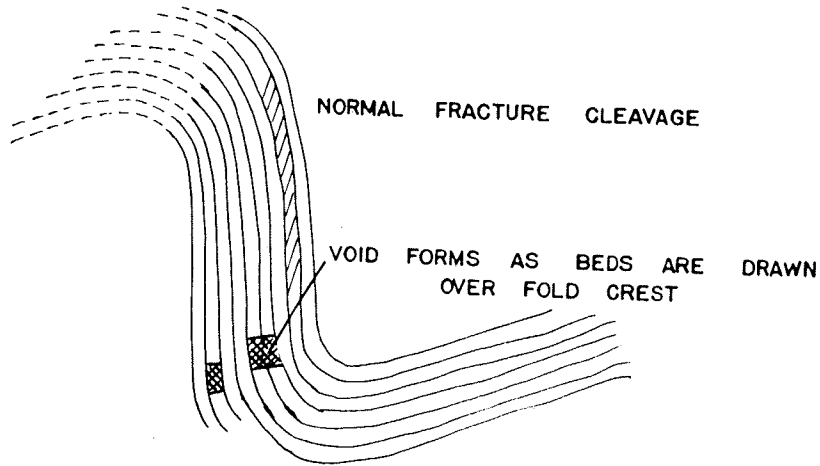
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PART A.

S

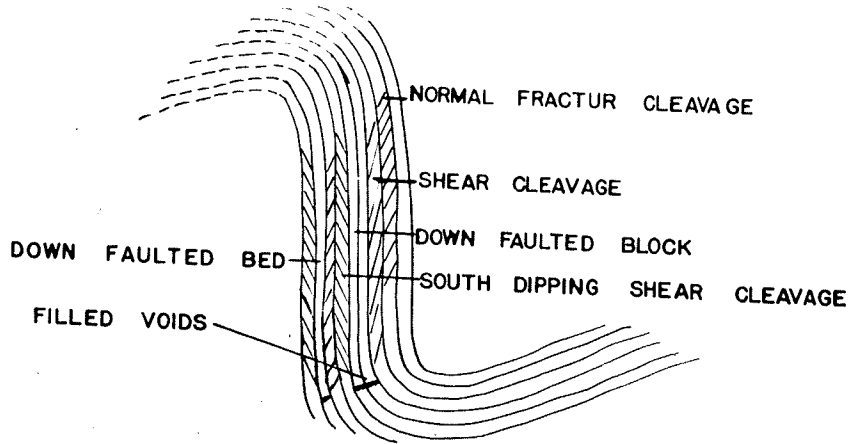
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PART B

S

N



PART C.

S

zones between quartzite beds, and the larger bedding slip faults. However, it does not explain the E-W tensional breccia zones, the N-S en echelon tension faults, or the Upper Narrows Gorge. Thus, we must postulate a second and tensional origin for these structures; most probably a theory involving a N-S graben valley under the present valley floor.

REVERSE DIFFERENTIAL MOTION AS A RESULT OF FAULTS OR FOLDS

IN THE BEDS TO THE SOUTH OF THE WISCONSIN GRANITE QUARRY

It is possible that the differential motion indicated by the south dipping cleavage planes of the anomalous cleavage zones in the Wisconsin Granite Quarry resulted from an upward movement of the beds to the north of the quarry, with relation to the beds south of the quarry.

It will be recalled that possibly the reverse drag folds and anomalous shears of the South Range resulted from faulting or folding in the quartzite beds overlying the mapped micaceous horizons, while the underlying quartzite beds moved south and crestward on the rising anticline to the south of the exposures.

If the quartzite beds north of the Wisconsin Granite Quarry moved north and crestward on the anticline to the north of the area, while the beds to the south of the quarry remained stationary, or lagged behind on the rising anticlinal flank, the resulting differential motion between beds of a series of beds could result in south dipping fracture cleavage in incompetent material situated between two quartzite beds. The strike of the cleavage planes would be parallel to the major structures, as are the strikes of the cleavage planes of the zones in the quarry. However, as in the case of the reverse drag

folds of the South Range, in order to prevent the beds to the south of the quarry from moving north and crestward on the anticlinal flank with relation to underlying beds, a fault must be postulated to dissipate the compressional stresses normally transmitted by the beds.

The greatest objection to postulating minor faults or folds in the quartzite south of the quarry is the fact that the anomalous cleavage zones occur near the base of the Baraboo formation. Thus, they are overlain by a vast thickness of massive quartzite which would be most resistant to the local overthrust faulting or minor folding, for the great thickness of massive quartzite would not allow the vertical (or horizontal) volume increase which must accompany overthrust faulting or folding. For this reason, it seems improbable that the cleavage zones are the result of an underthrusting of the beds to the south of the quarry by the beds to the north of the quarry.

It is possible that the bedding slip fault zones in the quarry represent major faults related to underthrusting of the beds to the north of the quarry, and that the faults are not associated with the folding of the area. Thus, a post folding upthrust of the beds north of the quarry (or a downward movement of those beds south of the quarry) may be responsible for the differential motion indicated by the south dipping cleavage planes of the anomalous cleavage zones.

Instead of being concentrated along a single fault plane, the fault motion could have taken place along a number of bedding planes, with considerable slip along some surfaces and little motion along others. This explanation could thus account for both bedding slip fault zones, and the anomalous cleavage zones in the abandoned quarry.

SUMMARY STATEMENT

Anticlinal folding produces differential motion between beds of a series of beds situated on the fold flank, for as folding proceeds, the upper beds of the series move toward the crest of the anticline with respect to underlying beds of the series. Differential motion between beds may result in the development of drag folds and fracture cleavage in incompetent beds. In the ideal case, the axial planes of the drag fold dip away from the crest of the anticline at angles which are greater than the dip of the beds adjacent to the drag folded horizon. The strike of the axial planes would be parallel to the axial plane of the anticline to which the drag folds are related. Fracture cleavage also results from differential motion involving an incompetent horizon situated between two competent beds. Normally, fracture cleavage planes dip away from the crest of the anticline, and strike parallel to the trend of the anticline.

However, at the Skillet Creek and Park Entrance Exposures of the South Range, drag folds occur with axial planes which dip toward the anticlinal structure to the south of the two exposures. The drag fold axial plane strikes vary considerably, but are generally parallel to the trend of the southern anticline. Thus, the drag folds indicate differential motion reverse to that which would be anticipated in the structural setting of the two mapped exposures. Anomalous south dipping underthrust shear zones are associated with the reverse drag folds.

South dipping fracture cleavage planes were observed in the anomalous cleavage zones between massive quartzite beds of the

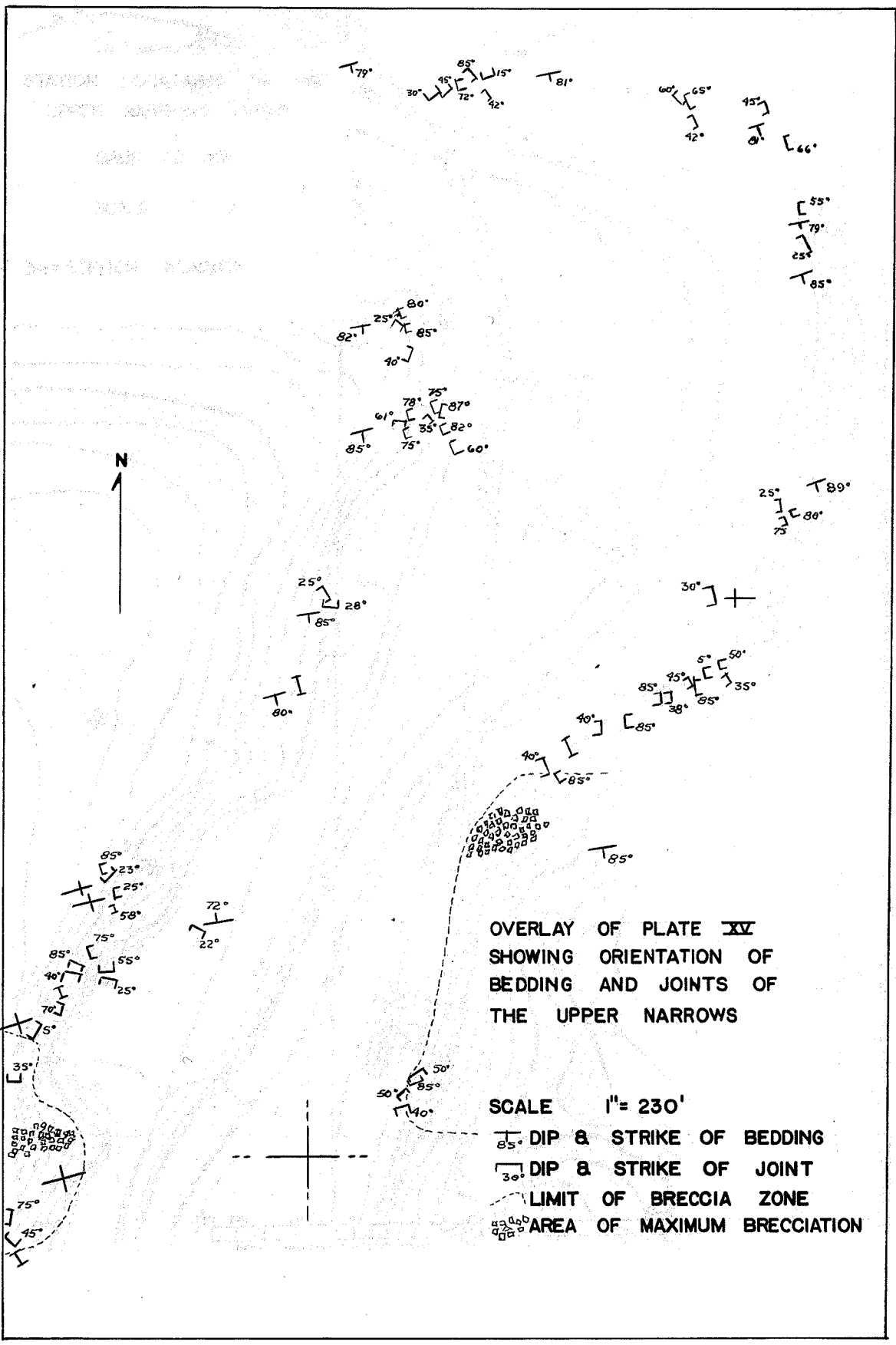
Wisconsin Granite Quarry on the North Range. These fracture cleavage planes indicate differential motion which is contradictory to the anticipated differential motion in such a structural situation, for an anticlinal structure exists to the north of the quarry, and inasmuch as upper beds should move to the crest of that anticline, the resulting fracture cleavage should dip to the north, and strike parallel to the associated anticline. Although the cleavage planes in the anomalous cleavage zones strike parallel to the trend of the major structure, they dip to the south.

CONCLUSIONS

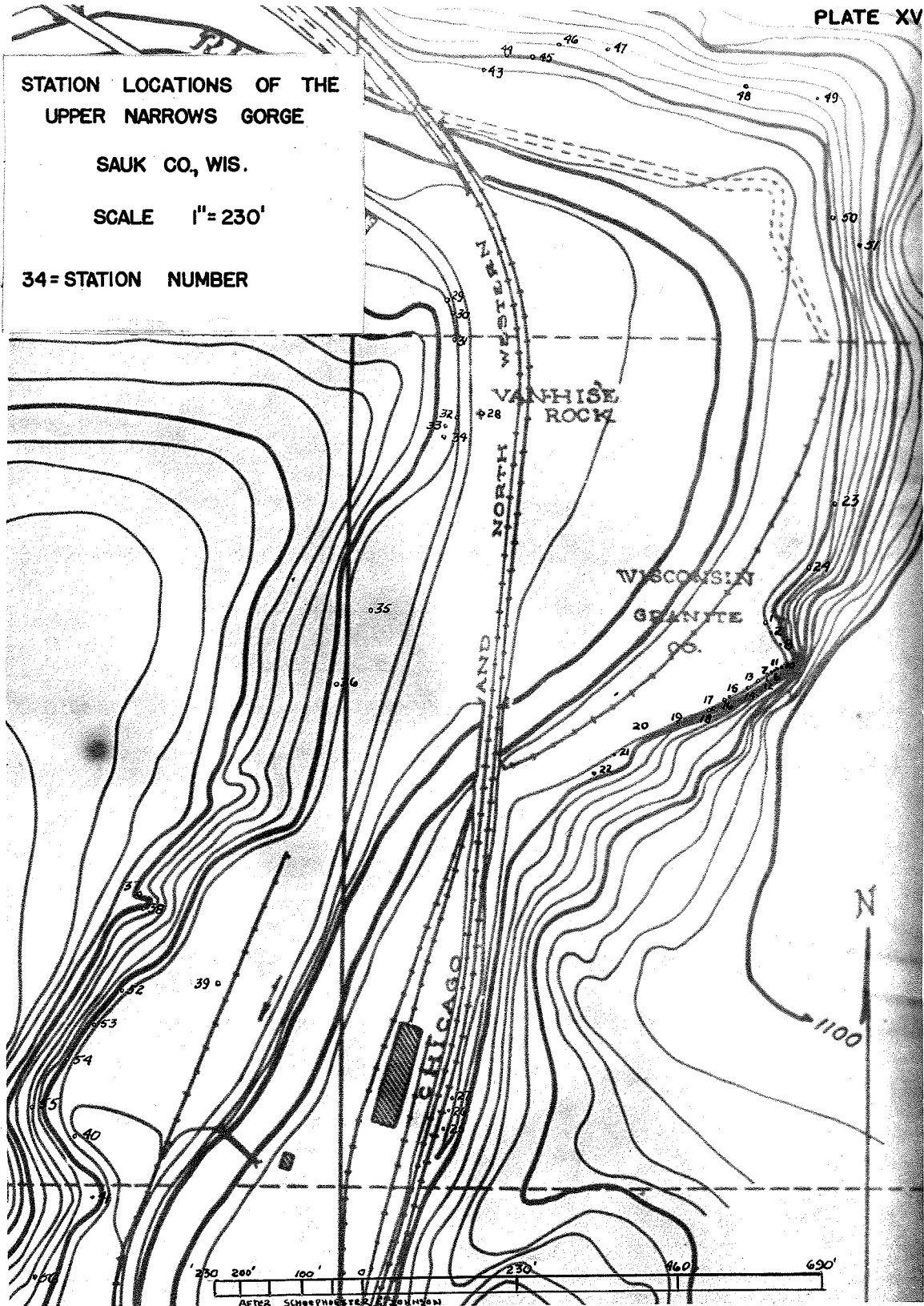
The reverse drag folds of the South Range may be the result of: (1.) normal drag folds on an overturned limb of a large fold; (2.) flowage folding within the micaceous horizons; (3.) reverse differential motion initiated by a relaxation of the major anticline; (4.) an upthrust wedge of rock caused by compressional stresses, and resulting in shears and drag fold near the contacts of the wedge and the beds not involved in the wedging; (5.) a second deformation; (6.) south and crestward motion of the quartzite beds underlying the micaceous horizons due to anticlinal folding, while the overlying beds buckled or faulted in such a manner that they did not move southward. The latter theory seems to be the most plausible explanation of the reverse drag fold and anomalous shear formation, for it takes into account the absence of normal drag folds in the Slaty Zones of the Skillet Creek and Park Entrance Exposures.

The south dipping cleavage planes of the anomalous cleavage zones in the Upper Narrows Gorge may be the result of; (1.) differential motion produced by a relaxation of the major fold; (2.) down-

ward slip of beds and blocks of beds into a fault formed void; (3.) slump of beds and blocks of beds into a magma chamber at depth; (4.) bedding slip of beds and blocks of beds into a graben under the present Upper Narrows Gorge; (5.) downward slip of beds and blocks of beds into voids formed by the stretching of beds over the crest of the northern anticline; (6.) underthrusting of the beds to the south of the Wisconsin Granite Quarry by the beds north of the quarry, due to either the formation of the anticline north of the quarry, or post fold faulting along the bedding slip fault zones in the quarry. The most reasonable interpretation of the evidence supports the theory that the anomalous cleavage zones are the result of bedding faults which are more recent than the folding of the region.



STATION LOCATIONS OF THE
 UPPER NARROWS GORGE
 SAUK CO., WIS.
 SCALE 1" = 230'
 34 = STATION NUMBER



AFTER SCHEPHERDSTER (1920) (LINDSEY)

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Approved... *SA. Tyler*