CURRENT EVALUATION OF THE CAMBRIAN-KEWEENAWAN BOUNDARY[1]

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In the Lake Superior region the youngest of pre-Cambrian sequences is the Keweenawan system, 30,000 to 60,000 feet thick; of this system the youngest unit which appears universally recognized as undoubtedly Algonkian is the 12,600 foot Freda sandstone of the Upper Keweenawan Oronto group.

South of the Lake Superior region in the Upper Mississippi Valley, the oldest of recognized Paleozoic sequences is the Upper Cambrian, Croixan Series; of this, the oldest unit universally conceded to be Paleozoic in age is the Mt. Simon sandstone member[2] of the Dresbach formation.

In a kind of no-mans-land of controversy between the obviously Keweenawan units and obviously Croixan units is a group of redbed sandstones and shales ranging up to 2600 feet in thickness, to which Thwaites (1912) applied the term Bayfield group. It now seems highly probable, especially as the result of the heavy mineral studies by Tyler and Thiel (1940), that the Wisconsin Bayfield is represented in Minnesota by similar sediments, there referred to as Red Clastics, Fond du Lac, or Hinckley, and in Michigan by the Jacobsville sandstone. It is the age relations of these units, then, that come into question. The term Bayfield, when used below, is employed as embracing all of them.

Broader regional relations.—The problem fundamentally is whether the Bayfield group is structurally, stratigraphically, and in time more closely associated (1) with the Keweenawan, Oronto group, (2) the Cambrian, Croixan series, or (3) independent of either.

The distribution of strata belonging to the Oronto group, as indicated in figure 1, is confined to the inner portion of the Lake Superior Basin. The distribution of Bayfield strata areally is much more extensive and not necessarily related to the distribution of the Oronto group. The two groups occur together only in the Lake Superior region, and it is this writer's opinion that the occurrence is coincidental. The two sequences occur together *in the same outcrop* at only two localities (Thwaites, 1912): on the south fork of Fish Creek, near Ashland Junction, Bayfield County, and on Middle River in eastern Douglas County, both in Wisconsin. In both instances they occur in the drag zone along the Douglas thrust fault, and/or its eastern extension (fig. 8).

The basal contact of the older, Oronto group is in all cases with the immediately preceding Middle Keweenawan eruptives. The upper contact of the Oronto group is known only from the two localities cited and probably also from deep wells at Ashland, Wisconsin (Thwaites, 1912, p. 65), and Stillwater, Minnesota (Hall et al., 1911; Thwaites, 1931, etc.).

At the two outcrops conformability has been claimed, but since the

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[2] The Illinois Geological Survey regards the Mt. Simon as a separate formation rather than a member of the Dresbach formation.

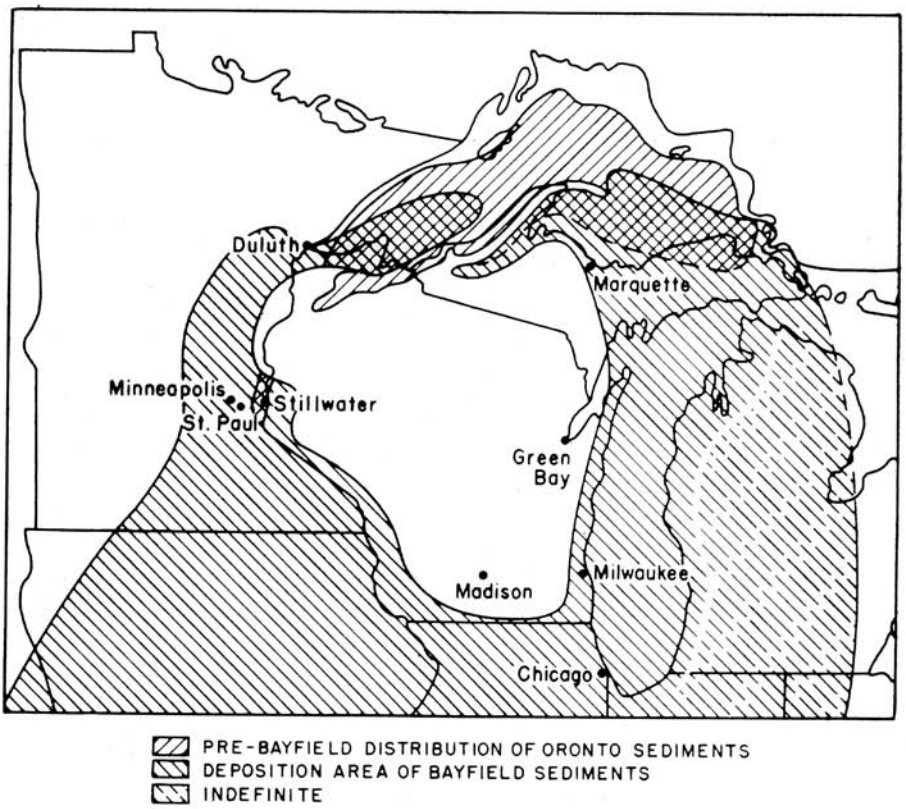

FIG. 1.—Regional Distribution of Oronto and Bayfield Sediments.

strata stand nearly vertical, this appearance of conformability can be misleading, as pointed out by Van Hise and Leith (1911) in connection with Keweenawan-Huronian relations under similar conditions. Furthermore, in the area of the two outcrops and the Ashland well, the attitude of the Oronto beds, lying as they did in the center of the broad Lake Superior syncline, should have been nearly horizontal at the time the Bayfield sediments were deposited on them. Such concordance of strata does not necessarily imply close age relations.

Furthermore, when we consider the regional relations of the Bayfield group, we find that, whereas in a very limited area it is in basal contact with the Oronto sandstone, over a far greater extent it rests nonconformably and in a relatively horizontal attitude on a basement complex of pre-Keweenawan gneisses, schists, and slates, cut by acid and basic plutonics and dike rocks of both Keweenawan and pre-Keweenawan age. The upper contact of the Bayfield, on the other hand, is everywhere with the white sandstone of the Mt. Simon member of the Dresbach formation and the Dresbach and Bayfield maintain conformable relations over all the Upper Mississippi Valley[3] and Upper Great Lakes regions. The dif-

[3] In Illinois no basis has been found for separating the Bayfield and Mt. Simon sandstones, and the Illinois Geological Survey classifies all the sandstone between the pre-Cambrian crystallines and the Eau Claire formation as the Mt. Simon formation of Upper Cambrian age (Templeton, 1950).

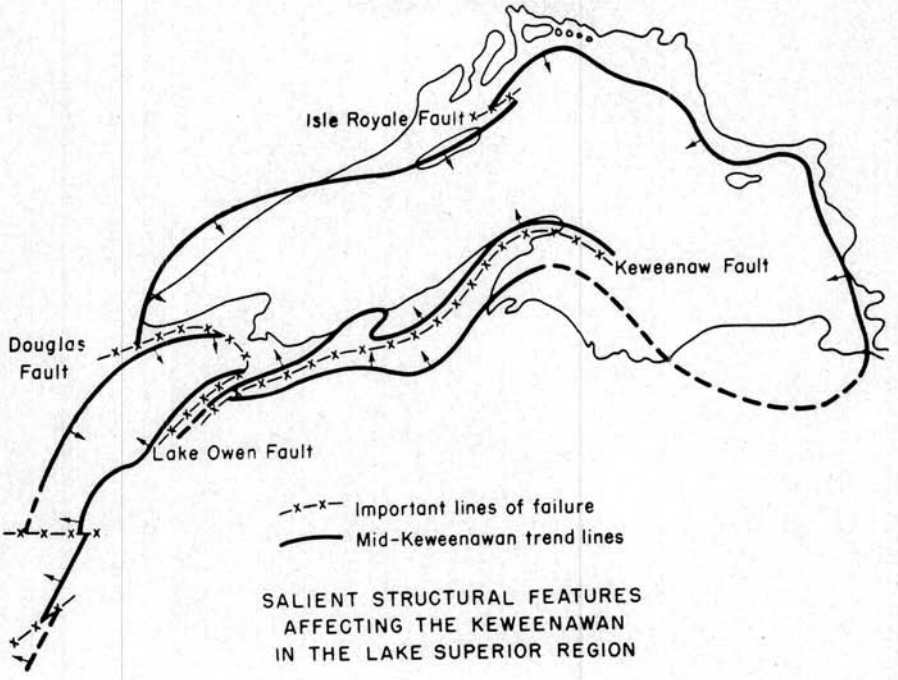

FIG. 2.—Salient Structural Features Affecting the Keweenawan in the Lake Superior Region.

ficulties indicated by Schwartz (1936, pp. 24-25) and others in drawing Red Clastic and Hinckley and Mt. Simon boundaries in the subsurface suggest a high probability that the three units are gradational as well as conformable.

These broad and simple relations might seem to leave no doubt that the age relations of the Bayfield group are with the Cambrian but for the troublesome intervention of seemingly local phenomena, some of which at first glance appear to preclude a Cambrian age. A reassessment of these seeming anomalies is the primary objective of this paper.

ANOMALIES OPPOSING CAMBRIAN ASSIGNMENT OF BAYFIELD

Pre-Cambrian faults.—Those favoring a pre-Cambrian age for the Bayfield stress the fact that in Wisconsin, Minnesota, and Michigan, the Bayfield along with the Oronto is cut by great thrust faults which moved parallel to the dip of the fault plane. They interpret these movements as a part of the orogeny which closed the Algonkian.

That the Bayfield and Oronto are jointly cut by extensive faulting along the Douglas Fault in Wisconsin cannot be denied (see Thwaites, 1912). However, the requirements

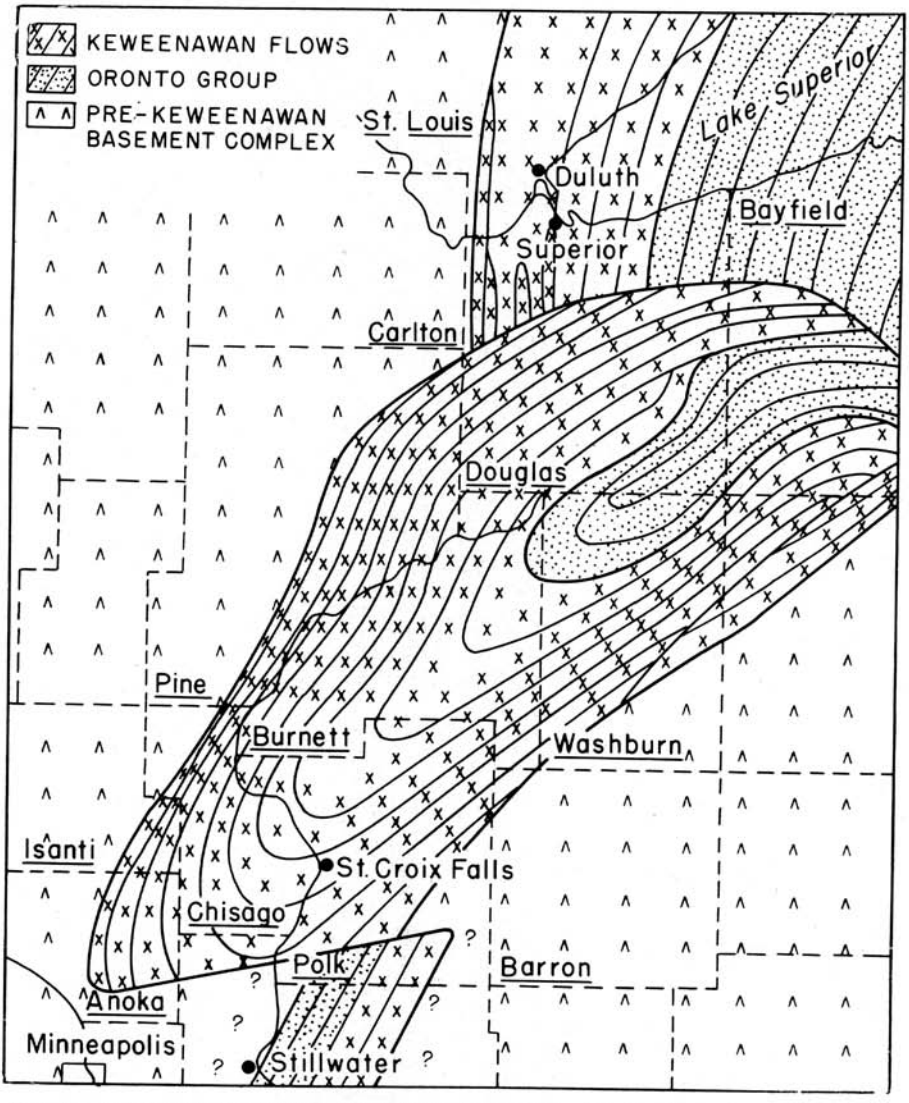

FIG. 3.—Pre-Bayfield Bedrock Surface in West Part of Lake Superior Region.

to account for the type of late pre-Cambrian movements which sheared and disrupted the Lake Superior syncline are, not movements parallel to the dip of the fault plane, but extensive horizontal displacements, north of east, measurable in miles along the Douglas thrust, with only a moderate degree of vertical component. The accompanying map (fig. 2) shows that this latter type of movement must have taken place, and that a thrust block, bounded laterally by the Douglas and Lake Owen faults, respectively, did so move in pre-Bayfield time. However, the present attitude of the Bayfield beds along the fault (and of the

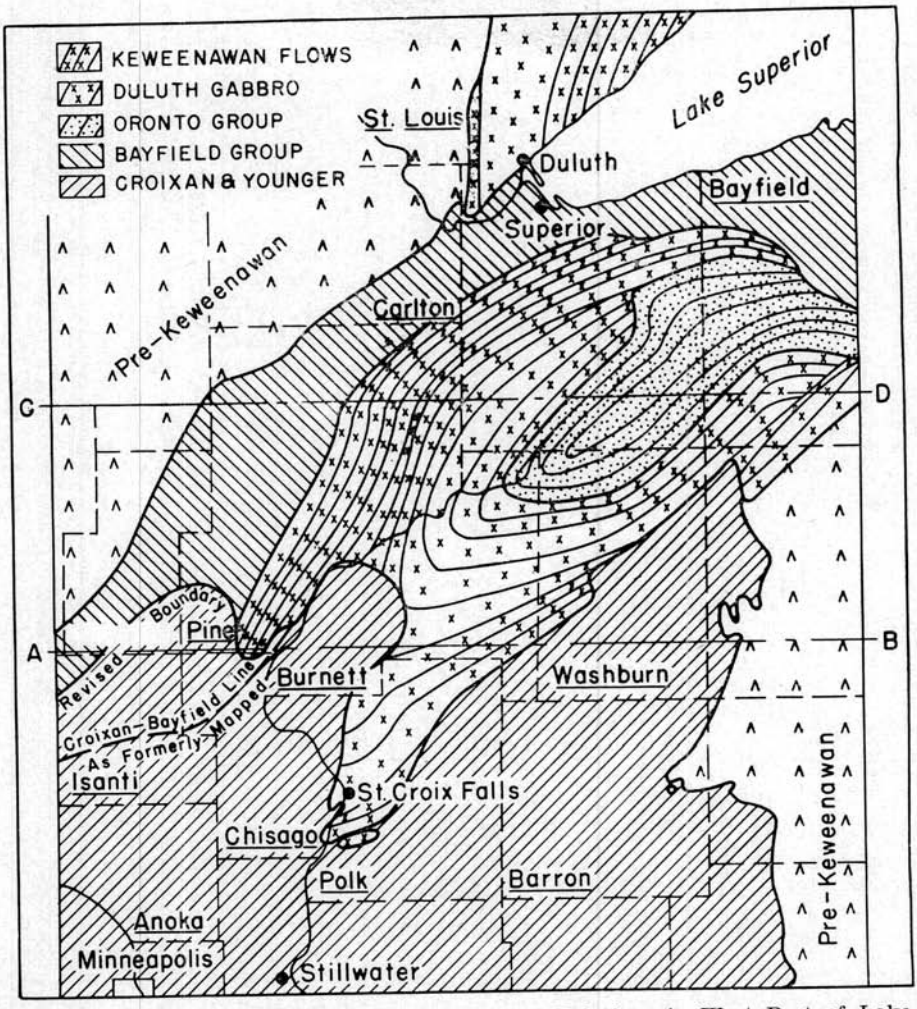

FIG. 4.—Croixan (Bayfield)-Keweenawan Areal Relations in West Part of Lake Superior Region.

Oronto beds dragged up along with them) indicates an extensive thrust movement parallel to the dip of the fault plane with a vertical component of close to 3000 feet of displacement.

That there have been two movements, one pre-Bayfield and one post-Bayfield, seems clear from both regional and local considerations.

In Wisconsin, no evidence is at hand that will permit the dating of the second (post-Bayfield) movement along the old thrust plane. Like the Douglas fault, the Keweenaw fault in Michigan appears to have been pre-Bayfield in origin with postulated secondary movement that, on the downthrust southeastern side, visibly cuts only Jacobsville (Bayfield) beds. But at Limestone Mountain, only a few miles southeast, an isolated outlier of Ordovician, Silurian, and possibly Devonian beds

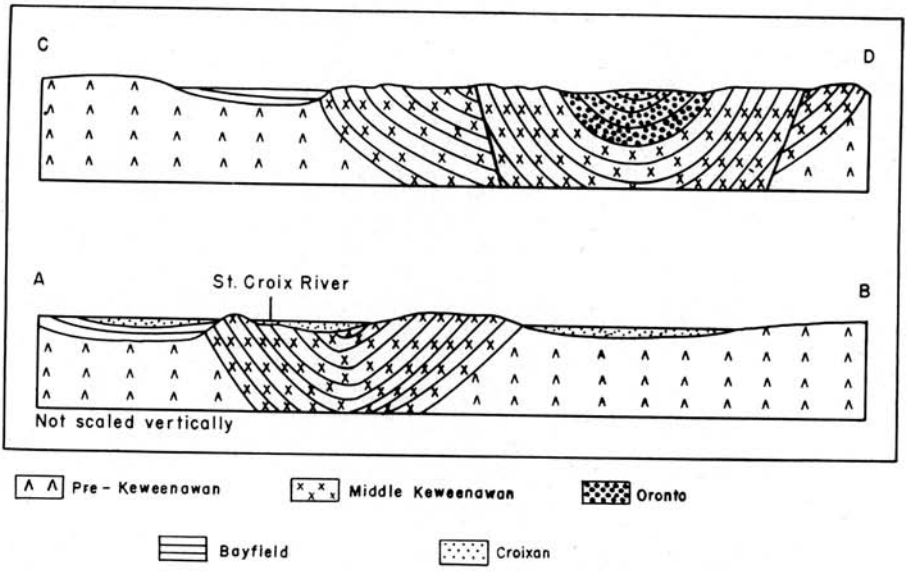

FIG. 5.—Cross Sections Along Lines A-B and C-D of Figure 4.

(Case and Robinson, 1915; Thwaites, 1943) is profoundly shattered by structural movements that can most logically be assumed to be simultaneous with the second period of movement along the Douglas and Keweenaw fault planes.

Douglas fault in Minnesota.—In Minnesota, the structural evidence is less clear and the seeming anomalies more numerous. It has been rather generally assumed that the Douglas fault swings southerly soon after entering Minnesota and continues until lost under glacial drift and/or Paleozoic cover. Unfortunately, the trap-sandstone contact, clearly shown by numerous exposures to be a fault in Wisconsin, is not exposed in Minnesota. Indirect evidence supporting a fault relationship between Bayfield-type sandstone and Keweenawan extrusives seems less than conclusive to the writer. This evidence revolves around two localities, Kettle River and Pine City.

On Kettle River, both Irving (1883, pp. 244-246, figs. 8 and 9, pl. 14) and Upham (1888, pl. 55) describe, map, and illustrate the Hinckley-trap contact in a manner to indicate a nonconformity and a sedimentational contact of horizontal sandstone on steeply dipping lavas. But C. W. Hall (1901, pp. 324-325) states: "Along the entire distance of the contact, the attitude of the sandstone is that of a greatly disturbed formation; it is broken in places in blocks, some of them of huge dimensions lying in many different directions. They have every appearance of being shattered by profound crustal movements." Here is obviously an area calling for further detailed study.

At the Pine City locality, very steeply eastward-dipping lavas outcrop in Snake River at the outlet of Cross Lake, whereas a well drilled scarcely a mile to the west encountered no lava and terminated at a depth of 700 feet in red sandstone. This relationship, plotted on a twen-

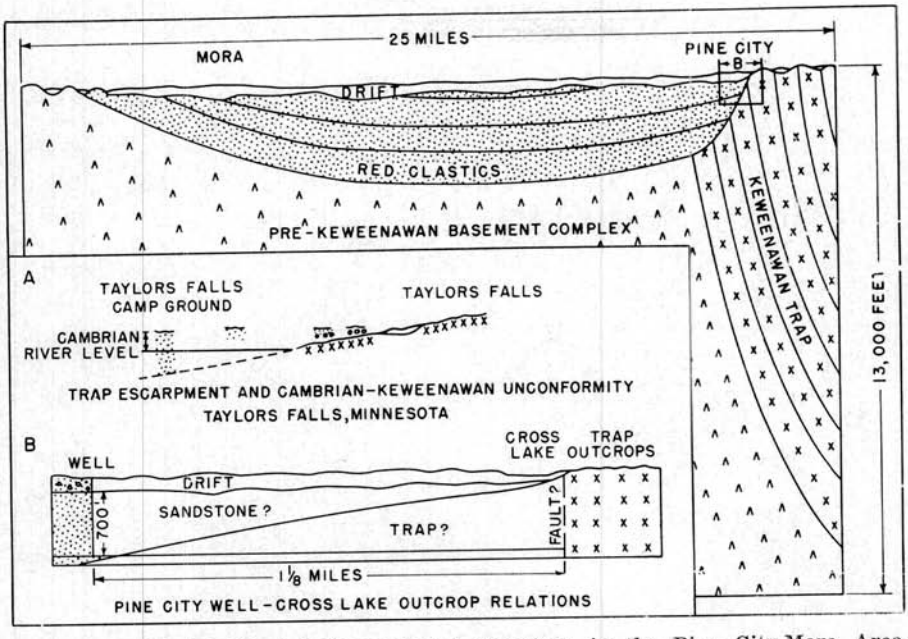

FIG. 6.—Postulated Bayfield-Keweenawan Relations in the Pine City-Mora Area.
a. Actual Pre-Croixan Erosian Surface Profile at Taylors Falls, Minn.
b. Postulated Pre-Bayfield Erosion Surface Profile in Pine City Area, on Scale 1:1.

ty-to-one exaggeration by Thiel (1947, p. 194) gives thus a relief that seems to demand a fault postulate. However, the same relationship plotted on a one-to-one scale by the writer (fig. 6b) compares very closely with the slope of the trap-sandstone contact exposed at Taylors Falls, Minnesota (fig. 6a), a place where the sedimentational nature of the contact is demonstrable and the Cambrian age of the sandstone unquestioned.

Gravity-meter evidence.—G. I. Welch (1941) published the result of a gravity-meter traverse across the lava-sandstone contact a short distance south of the Pine City well. The observed anomaly he interprets as indicative of a fault of about 11,000 foot displacement.

Actually Welch's data do not constitute proof of the existence of a fault at this place. According to his interpretation, which assumes (1) that there is a fault and (2) that the upthrown side of the fault is all trap and the downthrown side is sandstone on trap, then the anomaly shows that 11,000 feet of sandstone is present on the downthrown side of the postulated fault.

If, on the other hand, there be postulated a situation as illustrated in figure 6, the recorded gravity anomaly reflects quite different conditions which do not necessarily involve faulting. Let us assume the sandstone sequence to be approximately 2000 feet thick, normal for the Hinckley-Red Clastic succession. Let us further assume that to the east the sandstone abuts the Keweenawan lava along a steep pre-Bayfield erosional slope similar to the pre-Croixan erosional slope at St.

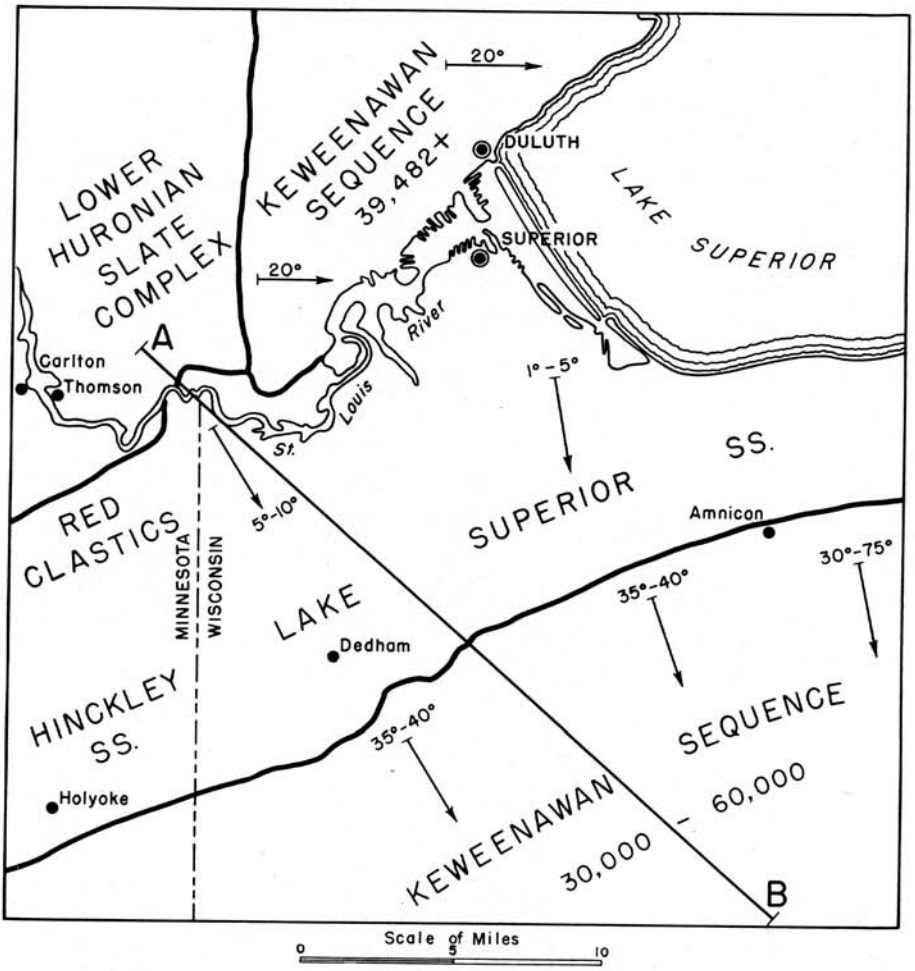

FIG. 7.—Dip-strike Relations of Keweenawan Sequence and Bayfield Equivalents at West End of Lake Superior.

Croix Falls. Finally, concealed beneath the sandstone is a steeply dipping contact between the highly inclined lavas to the east which represent the west limb of the Lake Superior syncline and the pre-Keweenawan complex of granites, gneisses, schists, slates, etc., to the west. The gravity anomaly may thus be a consequence of a line between a western belt of sandstone on various crystallines of lesser density than diabase and an eastern belt of dense diabase extrusives. The steep westerly sloping contact between lava and sandstone and the steep easterly sloping contact between lava and basement complex might well combine to resolve a sharp line of gravitational anomaly. This is not to say that faulting of limited extent may not incidentally be associated with this zone.

Tilting of Bayfield strata.—The facts that the Red Clastics in Minnesota dip at angles up to 10° and the

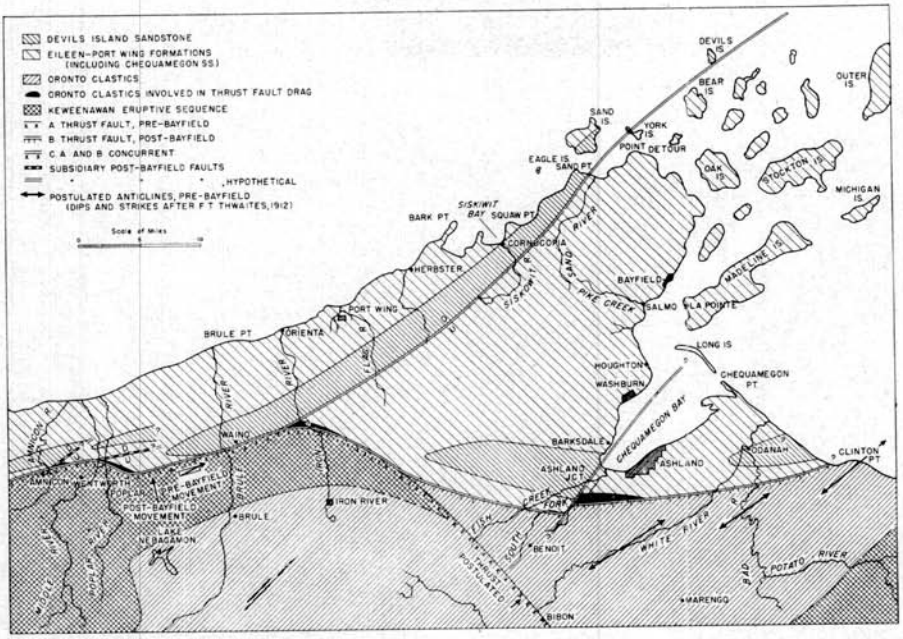

FIG. 8.—Postulated Pre- and Post-Bayfield Fault Patterns in the Bayfield Type Area.

overlying Hinckley sandstone dips commonly from 1°-2°, whereas the St. Croixan beds to south and east are essentially flat-lying, have been cited (Atwater and Clement, 1935) as evidence for the pre-Cambrian age of the Hinckley-Red Clastics (fig. 7). The increase in dip downward in the sequence may be a reflection of initial dip of the basal beds close to the contact with the basement complex; but the writer interprets it to be a consequence mainly of regional uplift of the country lying to the northwest and north of the Hinckley-Red Clastic belt of outcrop (figs. 3, 4, and 5).

That such a regional rise did take place is suggested by the contrast between Bayfield relations in southern Minnesota and in east central Minnesota. In the former area, the Bayfield equivalents in the subsurface are flat-lying, uniform in thickness over a wide area, and conformably overlapped westward by the Dresbach against the granite basement (Hall et al., 1911, pl. V; Couser, C. W., 1935). In the latter area, on the other hand, observable dips are present in sandstones of Bayfield age, outliers occur well beyond the main outcrop belt, and the strata, along with the overlying Croixan beds, have been truncated by erosion (figs. 5, 6, and 7).

Light mineral data. — Atwater (1935, p. 318) considered that the Hinckley sandstone could be distinguished from the Mt. Simon (Croixan) on the basis of secondary enlargement of quartz grains in the latter formation. However, secondary enlargement of quartz has been noted in some Croixan sandstones as well.

Association with diabase.—Hall et al. (1911, p. 48) cite the association

of diabase with red sandstones in a well at Stillwater, Minnesota, as evidence for the Keweenawan age for the Red Clastics of the Minnesota subsurface. Yet of ten Minnesota wells which passed through the redbeds and into pre-Cambrian crystallines (Hall et al., 1911), only this one encountered diabase. Of the remainder, one penetrated quartzite, one "crystalline rock," and seven granite. Except for the Stillwater well, the greatest thicknesses of Hinckley-Red Clastic strata reported in the Minnesota subsurface are at Minneapolis (1200 feet) (Schwartz, 1936, p. 222) and at Mankato (over 1289 feet) (Hall et al., 1911, p. 141). In the Stillwater well, over 2000 feet of redbeds are reported to have been penetrated, above nearly 500 feet of diabase (Hall et al., 1911, p. 366; Thwaites, 1931, pp. 740-742, fig. 3; Stauffer et al., 1935, p. 638). The Stillwater locality is evidently the one place in Minnesota where drilling has encountered Red Clastics underlain by Keweenawan Oronto sandstone, as indicated by the excessive local thickness of the redbeds and association with Middle Keweenawan diabase. This area is in line with the axis of the Lake Superior syncline, and Keweenawan rocks are here to be expected (figs. 1 and 2).

This interpretation removes a serious anomaly from Meinzer's map (Hall et al., 1911, pl. III) showing the elevation of the "pre-Cambrian": that is, the crystalline floor beneath the sediments in Minnesota. In regarding all redbeds as one unit, (pre-Cambrian in age but mapped with the Paleozoic), Meinzer (Hall et al., 1911, pl. III) is forced to contour a deep 2000-foot hole at Stillwater. The writer's reinterpretation of the composite nature of the redbed section here eliminates this peculiar anomaly.

Ordovician-Jacobsville unconformity.—In the Upper Peninsula of Michigan, another seeming anomaly presents itself at the isolated outlier, Limestone Mountain. Here Middle Ordovician Platteville strata lie in concordant dip not far above layers of Jacobsville sandstone with a short concealed belt intervening (Case and Robinson, 1915; Thwaites, 1943). This extensive unconformity has been interpreted to lie between pre-Cambrian and Paleozoic, to indicate the nondeposition of Cambrian and Lower Ordovician rocks in this region, and thus to establish the pre-Cambrian age of the Jacobsville.

However, an examination of relationships in the eastern part of the Upper Peninsula and southward along the west shore of Lake Michigan reveals that the time of erosion was not between the Bayfield and the Croixan, but between Middle and Lower Ordovician (Thwaites, 1923, 1927, 1934, 1943). Truncation of the pre-Chazyan beds cuts progressively deeper as one goes westward from the upper end of Lake Michigan, and also as one goes northward. The extreme case of depth of pre-Middle Ordovician erosion in Wisconsin-Michigan is at Limestone Mountain where Mohawkian strata rest on the Bayfield.

Lack of Chequamegon equivalent in Minnesota.—The problem of the correlation of Thwaites' Chequamegon formation constitutes another seeming anomaly. To recapitulate, Thwaites (1912) divided the Wisconsin Bayfield group into three formations in descending order as follows:

Chequamegon sandstone	1000 feet
Devils Island sandstone	300 feet
Orienta sandstone	3000 feet
Total	4300 feet

Tyler and Thiel (1940) have shown that the Red Clastics of Minnesota correlate with the Orienta sandstone and the Hinckley correlates with the Devils Island sandstone. But, on top of the Hinckley in Minnesota rests the white Mt. Simon sandstone of Croxian age and upon the Devils Island rests the pre-Croixan, redbed Chequamegon sandstone.

Writers accepting the Wisconsin Bayfield succession at face value (see Thiel, 1940, p. 1516) have regarded this as evidence of a pre-Mt. Simon unconformity involving the loss in Minnesota of 1000 feet of strata. Yet, an abundance of deep well data from that state also seems to indicate that Hinckley-Mt. Simon relations there are clearly gradational.

A critical examination of the evidence on which Thwaites (1912) established his Chequamegon formation reveals a probable resolution of this paradox, namely that Thwaites' Chequamegon brownstone formation is none other than the Port Wing brownstone member of the Orienta formation, repeated by faulting (fig. 8). The contact of the Chequamegon formation with the supposedly underlying Devils Island formation is reported by Thwaites only from the type locality, Devils Island. The beds here that he considers to be Chequamegon, he assigns to the "basal Chequamegon" and describes (1912, p. 38) as follows:

> At the south end of Devils Island, which is entirely surrounded by a rock cliff, the light-colored basal layers of the Chequamegon sandstone are seen. These are interbedded layers similar to the main body of underlying Devils Island sandstone, so that no very sharp line of demarkation can be seen.

The writer suggests that these layers are a part of the Devils Island formation rather than the Chequamegon brownstone and that a fault contact lies off-shore to the south and there separates the Devils Island from the brownstone that forms the southern islands of the Apostle group. Thwaites' detailed description (1912, pp. 34-35) of the "Quarry" or "Brownstone Beds" of the Chequamegon on the mainland is essentially identical with that of the "Port Wing Brownstone" of the Orienta, while the upper or "Washburn Beds," especially those from the well of the Barksdale Powder Works, are described in much the same terms as his "upper member" of the Orienta formation.

Reinterpretations by the writer reduce the total thickness of the Bayfield group from Thwaites' figure of 4300 feet down to a maximum of 2600 feet, mainly through the dropping of the Chequamegon formation. This gives a figure more in accord with the average regional thickness of the subsurface Bayfield.

The Bayfield and the pre-Cambrian peneplain.—There remains one more point of issue which is in the nature of an argument rather than an anomaly. Proponents of a Keweenawan age assignment for the Bayfield stress the fact that the structural elements that affected it and related sandstones were truncated by the pre-Cambrian peneplain. The writer maintains that beyond the areas of Paleozoic cover, there is

no means of determining the age of the present bedrock surface on the crystallines. It may be close to the pre-Cambrian erosion surface, but may be of later origin or origins. Within the Lake Superior region itself, there is evidence not only of pre-Middle Ordovician, but also of pre-Cretaceous and post-Cretaceous, erosion surfaces (Van Hise and Leith, 1911, p. 178, p. 616, p. 625).

The Silurian beds at Limestone Mountain lie below the postulated pre-Cambrian peneplain surface, as do the Jacobsville and Bayfield strata. There is reason to believe that Silurian strata may formerly have extended widely in the Lake Superior Basin and over much if not all of the Wisconsin Arch, and that the Devonian clearly extended over the latter at least in part. It is not plausible to infer that the erosion which removed these thousands of cubic miles of rock stopped completely when the pre-Cambrian bedrock surface was reached.

Supporting the idea that the original pre-Cambrian erosion surface developed before, not after, the deposition of the Bayfield group is Tyler's (1940, p. 1481) conclusion that the Bayfield sediments differ from those of the Oronto group in such a way as to indicate a marked difference in time and a partial difference in source. Tyler states as follows:

> The quartzose character of the Bayfield indicates that these sediments were subjected to more mature weathering than those of the Oronto group, and that the Bayfield group may have been derived from previously existing sediments. The most likely sedimentary source for the Bayfield would be the older Oronto series. Their derivation from this source, however, would necessitate almost complete elimination of feldspar, epidote, and garnet of the Oronto sediments and a large decrease in the quantity of ilmenite. It seems more likely that the Bayfield sediments were derived from the Keweenawan sediments or acidic igneous rocks which did not contain large amounts of epidote or ilmenite and that the region from which the garnet was derived during Oronto time had ceased to contribute sediments to this basin of deposition during Bayfield time.

It seems to the writer that Tyler's evidence does not necessarily indicate a bedrock source low in epidote and ilmenite. Rather it seems to indicate a cycle of deposition independent of and much later than that of the Oronto sedimentation. The latter derived its material from fresh bedrock whereas the Bayfield material seems to have been derived from a mature erosion surface on which the epidote and much of the feldspar was eliminated, and a substantial portion of the ilmenite was altered to leucoxene.

Factors Opposing Keweenawan Age Assignment of Bayfield

Study of the broad field relations has inclined the writer to the opinion that the Bayfield group and its equivalents are more closely related to the Croixan than to the Keweenawan. The present paper has been devoted largely to a review and reduction of the "strong points" which appear to resist a Cambrian assignment for the group. Although a full discussion of the case against a Keweenawan age assignment is not within the scope of this paper, it is appropriate to state that, in the opinion of the writer, the sum of the evidence opposing such an assignment is insuperable. In brief, the following are items of cardinal import to this effect.

1. In places Bayfield equivalents demonstrably rest on pre-Keweenawan strata, as in east-central Minnesota, the Michigan Upper Peninsula, at the east end of Lake

Superior in Ontario, and almost universally in the subsurface; those who would assign a Keweenawan age to the Bayfield must account for the absence by unconformable overlap of from 30,000 to 60,000 feet of pre-Bayfield Keweenawan section. The fact that the 30,000-60,000 feet of earlier strata is so generally missing, with only the "terminal" 2,000-3,000 feet of strata present, fosters the suspicion that we are dealing with two independent sequences.

Whether this absence of 90 to 95 percent of the Keweenawan section at these places be explained as a result of unconformable overlap (Thwaites, 1912; Atwater, 1935, etc.), of faulting (Schwartz, 1949, etc.), or of deposition in postulated grabens (Thwaites, 1943), the minimum local relief involved in any case exceeds the altitude of Mt. Everest (29,002 feet).

The accommodation of the latter concepts becomes most difficult at the west end of Lake Superior. Here, to assign a Keweenawan age to the Fond du Lac, where it rests on the Lower Huronian Thomson Slate complex, it is necessary to account for the disappearance of roughly 55,000 feet of strata (over 10 miles thick) in a narrow gap 10 miles wide, between the North Shore Keweenawan sequence and the South Shore Keweenawan sequence. Either a 55,000 foot mountain ten miles wide, a fault with a 55,000 foot vertical displacement, or pre-Keweenawan grabens 55,000 feet deep must be postulated here to maintain conformability of the Bayfield with the Keweenawan.

If it be necessary to mention additional adverse factors to the Keweenawan age assignment of the Bayfield, there are the following:

2. If, as has been generally credited (Schwartz, 1949, p. 33), the diabasic and basaltic dikes cutting the Huronian complex west of the Hinckley-Red Clastic belt in east-central Minnesota are the dike-roots of eroded Middle Keweenawan flows, then neither the postulate of unconformable overlap nor that of pre-Keweenawan grabens can be maintained; and to maintain the simple fault hypothesis, it is necessary to postulate the removal by erosion of strata considerably in excess of 55,000 feet, west of the fault.

3. Cases where essentially flat-lying strata of Bayfield age surround or lie up-dip from inclined Middle Keweenawan extrusive strata have never been satisfactorily accommodated within a Keweenawan age hypothesis for the Bayfield. Among such cases is Silver Mountain, reported by Irving (1883, p. 202), which is composed of diabase, dipping northwestward 30°, and apparently surrounded by horizontal Jacobsville sandstone. Another which has not been described in detail, is mapped in the Batchawana Bay area of Ontario (Van Hise and Leith, 1911, pl. I).

4. The evidence of the heavy minerals, as reported by Tyler and Thiel (1940), indicates that outstanding differences exist between the suites of the pre-Bayfield and the Bayfield sands. In general the Bayfield suites are more closely comparable with those prevailing in the Mt. Simon and Galesville members of the Croixan Dresbach formation, than with the Keweenawan, and unlike the latter, imply a mature erosion surface at the source.

Interpretation of Bayfield Environment

The writer suggests that the Bayfield sediments are continental de-

posits of Middle and quite possibly also of Early Cambrian age laid down in structural basins formed at or after the close of the Algonkian. The basins in the Lake Superior region were narrow and a consequence of down-faulting along one side, whereas those in southeast Minnesota, in the Lake Michigan region and southward, seem to have been the result of gentle downwarping. Deposition appears at first to have been largely fluviatile (Thwaites, personal communication), passing with increased regional subsidence probably through lacustrine and estuarine conditions (Hinckley and Mt. Simon) with the eventual arrival of marine waters, bringing the Eau Claire faunas to parts of the region.

REFERENCES

Atwater, G. I., 1935, The Keweenawan-Upper Cambrian unconformity in the upper Mississippi Valley: Kansas Geol. Soc. 9th Ann. Guidebook, pp. 316-9, fig. 214.

Atwater, G. I., and Clement, G. M., 1935, Pre-Cambrian and Cambrian relations in upper Mississippi Valley: Geol. Soc. Am. Bull., vol. 46, no. 11, pp. 1659-1686.

Berkey, C. P., 1897, Geology of the St. Croix Dells: Am. Geologist, vol. 20, no. 6, pp. 345-383.

Case, E. C., and Robinson, W. I., 1915, The geology of Limestone Mountain and Sherman Hill in Houghton Co., Michigan: Michigan Geol. Surv., Pub. 18, pp. 165-181.

Couser, C. W., 1935, in Kansas Geol. Soc., 9th Ann. Guidebook, p. 168, fig. 152.

Hall, C. W., 1901, Keweenawan area of Eastern Minnesota: Geol. Soc. Am., Bull. vol. 12, pp. 313-342.

Hall, C. W., Meinzer, D. E., and Fuller, M. L., 1911, Geology and underground waters of southern Minnesota: U. S. Geol. Surv., Water Supply Paper No. 256.

Irving, R. D., 1883, The copper-bearing rocks of Lake Superior: U. S. Geol. Surv., Mono. 5.

Schwartz, G. M., 1936, The geology of the Minneapolis-St. Paul metropolitan area: Minnesota Geol. Surv., Bull. vol. 27.

———, 1949, The geology of the Duluth metropolitan area: Minnesota Geol. Surv., Bull. no. 33.

Stauffer, C. R., Burch, E. P., and Schwartz, G. M., 1935, A reinterpretation of the Stillwater deep-well records: Jour. Geol. vol. 43, pp. 630-638.

Thiel (1940), see Tyler (1940).

Thiel, G. A., 1947, The geology and underground waters of northeastern Minnesota: Minnesota Geol. Surv., Bull., vol. 32.

Thwaites, F. T., 1912, Sandstones of the Wisconsin coast of Lake Superior: Wisconsin Geol. and Nat. Hist. Surv., Bull. vol. 25.

———, 1923, The Paleozoic rocks found in deep wells in Wisconsin and northern Illinois: Jour. Geol. vol. 31, no. 7, pp. 529-555.

———, 1927, Stratigraphy and geologic structure of northern Illinois with special reference to groundwater supplies: Illinois State Geol. Surv., Rep. of Inv. no. 13.

———, 1931, Buried pre-Cambrian of Wisconsin: Geol. Soc. Am., Bull. vol. 42, pp. 719-750.

———, 1934, Well logs in the northern peninsula of Michigan, showing the Cambrian section: Michigan Acad. Sci. Papers, vol. 19, pp. 413-426.

———, 1943, Stratigraphic work in northern Michigan: Mich. Acad. Sci. Papers, vol. 28, pp. 487-502.

Tyler, S. A., Marsden, R. W., Grout, F. F., Thiel, G. A., 1940, Studies of the Lake Superior pre-Cambrian by accessory-mineral methods: Geol. Soc. Am., Bull. vol. 40, pp. 1429-1537.

Upham, W., 1888, The geology of Pine County in The geology of Minnesota, Vol. II of the Final Report by N. H. Winchell, pp. 629-645, pl. 55.

Van Hise, C. R., and Leith, C. K., 1911, The geology of the Lake Superior region: U.S. Geol. Surv., Mono. 52.

Welch, G. I., 1941, Geophysical study of the Douglas fault, Pine County, Minnesota: Jour. Geol. vol. 19, pp. 408-13.