V. LOCAL GEOLOGIC ISSUES IMPACTING EXPLORATION

NATURE OF THE NORTHERN BOUNDARY OF THE ST. CROIX HORST

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ABSTRACT
Within the northern Midcontinent Rift System the boundaries of the central horst are defined by major reverse faults: Hastings, Lake Owen, and Keweenaw Faults on the south, and Douglas and Isle Royale Faults on the north. The continuity of the fault system remains a matter of dispute. The connection of the Douglas Fault in northwestern Wisconsin with the Isle Royale Fault, located in north-central Lake Superior, has been variously proposed as an angular unconformity, a conformable sequence, a fold trend, as well as a fault offset or curvilinear continuation of the Douglas Fault. The weight of geologic and geophysical data favors either a fault-offset or curvilinear continuation of the Douglas Fault through Bayfield County, Wisconsin, and offshore under Lake Superior.

DISCUSSION
Thiel (1956) used gravity, geology, and structure of the rock in the Wisconsin-Minnesota area to suggest a horst. He identified the northwest border of this horst with the Douglas Fault. The St. Croix Horst, the central structural segment of the Midcontinent Rift System in Minnesota and Wisconsin, was named by Craddock and others (1963) as an uplifted block of Middle Keweenawan igneous rock, mainly basalt interlayered with thin sandstone beds. Upper Keweenawan conglomerate, sandstone, and shale of the Oronto Group partially mantle this block. This structure has been traced from western Bayfield County, Wisconsin, west and southwest into east-central Minnesota, where it terminates against the northwest-trending sinistral, strike-slip, Belle Plaine Fault (Sloan and Danes, 1962; Morey, 1977; Dickas, 1986).

Where the St. Croix Horst is buried beneath Phanerozoic sedimentary rock in east-central Minnesota, the known and inferred trace of the Douglas Fault is identified by a high gravity gradient (Thiel, 1956; Craddock and others, 1963), by linear aeromagnetic anomalies (King and Zietz, 1971), and by refraction seismic analysis (Mooney and others, 1970). Although the fault plane is not actually exposed here, Farnham (1967) reported basalt and sandstone that are found 8 m apart 6 km east of Hinckley as a good approximation for the location of the Douglas Fault.

Similar fault location criteria are applicable in northwestern Wisconsin. In Wisconsin the Douglas Fault is exposed at only four locations: Black River, poorly exposed in SE1/4, sec. 21, T. 47 N., R. 14 W.; Copper Creek, one distinct exposure in SE1/4, sec. 15, T. 47 N., R. 14 W.; Amnicon River, three good exposures in SE 1/4, sec. 29, T. 48 N., R. 12 W.; and Middle River, three good exposures in NE1/4, sec. 25, T. 48 N., R. 12 W. The best site for determining general fault characteristics is in Amnicon Falls State Park (fig. 1, location A). At the base of the waterfall on the main channel, basalt dipping 40 degrees SE is separated from Keweenawan sandstone by a 2.5-m thick gouge and breccia zone marking the fault plane. Orienta Sandstone dips to the southeast at angles up to vertical adjacent to the fault, but decreases to horizontal within 30 m of the fault gouge. The upper surface of the fault gouge trends N. 85 degrees E., 37 degrees SE. Slickensides indicate that displacement is predominantly dip-slip. Craddock (1972a) estimated throw from 2,500 to 3,500 m.

The Douglas Fault can be traced by gravity data as far east as T. 48 N., R. 8 W.. The extension of this fault further east into Lake Superior is a matter of considerable controversy. A fault continuation is presented in Mudrey and others (1982) and Cannon and Davidson (1982). A sedimentary contact projection is supported on the version by Morey and others (1982). Dutton and Bradley (1970) assumed a neutral point-of-view with their interpretation of a questionable fault extension.

East of T. 48 N., R. 8 W. into the region of Chequamegon Bay, the continuation of the Douglas Fault is complicated by sparse outcrop of sedimentary rock, a complete lack of outcrop of the basalt that is always associated with the upthrown side of this fault in Douglas County, and the presence of a well documented and pronounced (-92 mgal) gravity low centered northwest of Ashland, Wisconsin (fig. 1).

There are five alternatives for fault continuation.

A. The Douglas Fault continues to the east with the strike curving to the southeast around Bayfield County gravity low and then is projected into Lake Superior east and northeast around Isle Royale.

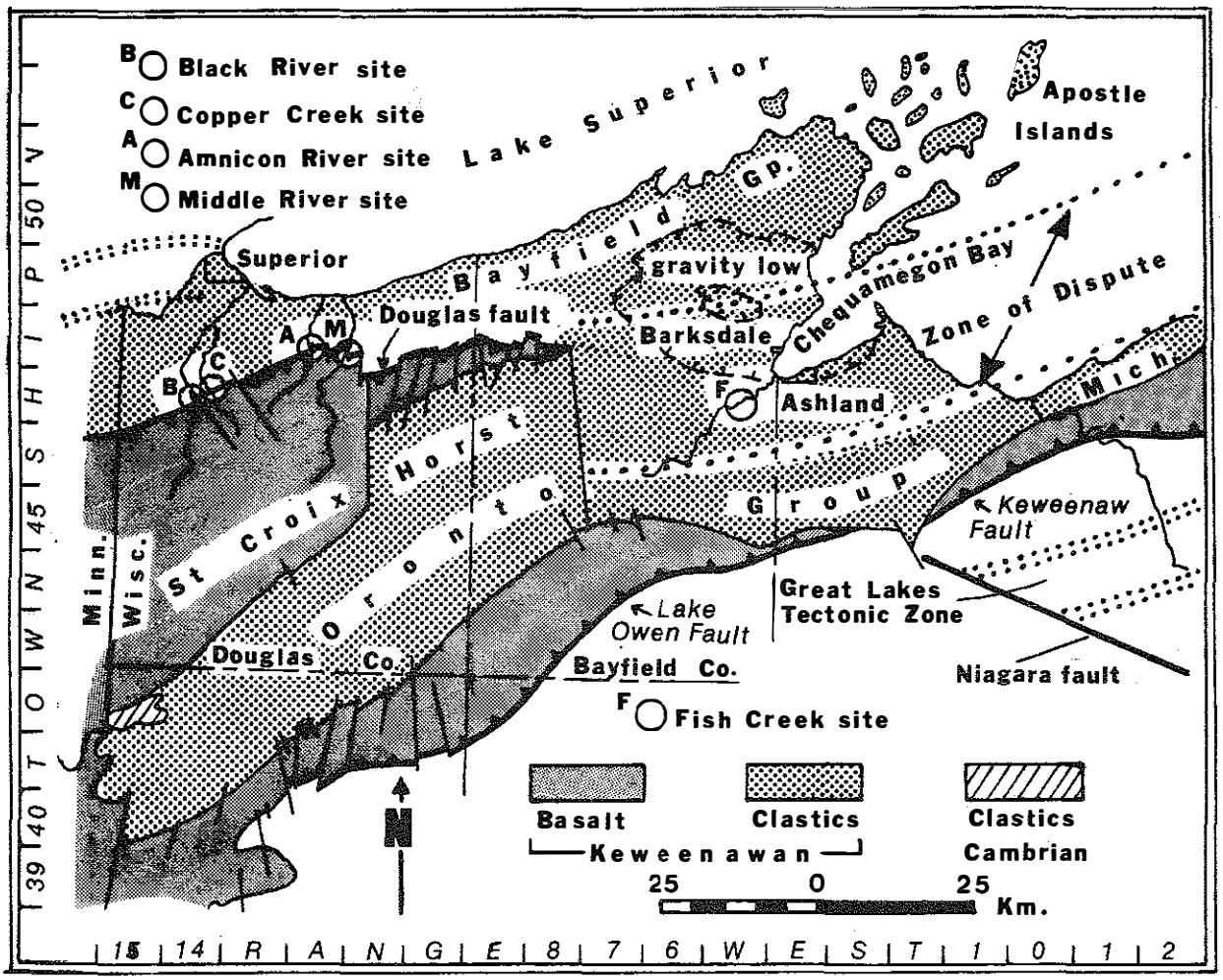

Figure 1. Generalized geologic map of the Midcontinent Rift System in northwestern Wisconsin.

Evidence in support includes:

* The northwest-southeast trending Bouguer gravity gradient marking the abutment of the trend of the St. Croix Horst against the Bayfield County gravity low in T. 48 N, R. 7 W. (Craddock and others, 1970).

* Outcrop of vertically dipping clastic sedimentary rock along the south fork of Fish Creek (fig. 1, location F) in sections 11, 14, and 15, T. 47 N., R. 5 W., Bayfield County (Thwaites, 1912; Tyler and others, 1940; Halls, 1966). To the west in Douglas County the known location of the Douglas Fault is generally marked by structural disturbance of the sedimentary rock adjacent to the fault (Myers, 1971).

* The position of the northeastward-trending zone of Bouguer gravity gradient offshore Lake Superior from southeast of Chequamegon Bay to north of Isle Royale (Hinze and others, 1982; Weber and Goodacre, 1966). This gravity trend appears to be geographically coincident with a "major structural ridge, which may be faulted ... [and] which is best evidenced by magnetics" (Wold and Ostenso, 1966). Further evidence for possible faulting here is shown by a change in magnetic character (Hinze and others, 1982). In the immediate vicinity of this projected sub-lake trace of the Douglas Fault, the geometric pattern of the magnetic data alters from a northerly to an easterly direction.

* Position and characteristic of the Isle Royale thrust fault as mapped by Van Hise and Leith (1911) and White (1966a). Wold and Ostenso (1966) extend the Isle Royale Fault west of Isle Royale. The Isle Royale Fault is considered by Halls and West (1971) to be an extension of the Douglas Fault into north-central Lake Superior.

* Interpretation of Lake Superior seismic refraction profiles (Smith and others, 1966; Hinze and others, 1982; and Luetgert and Meyer, 1982).

In addition, the possibility, but not necessarily the rationale, of this alternative is supported by geologic studies or maps presented by Thwaites (1935), Hamblin (1965); White (1966a, b), Myers (1971), Ocola and Meyer (1973), Watts (1981), Green (1982a), Morey and Green (1982), Morey and Ojakangas (1982), Wold and others (1982), and Van Schmus and Hinze (1985).

B. The Douglas Fault continues its easterly trend but is offset to the southeast by a right-lateral fault and then continues into Lake Superior as in alternative A. This model is really a variation of alternative A, but with the addition of right-lateral offset of the fault trend. Such an offset fault would have a northwest-southeast trend, and be located in central Bayfield County.

Evidence in support includes:

* Geologically and geophysically documented offset is known to cut across or offset the borders of the St. Croix Horst along its entire extent from east central Minnesota to western Bayfield County, Wisconsin (fig. 1) (Myers, 1971; King and Zietz, 1971; Morey and Green, 1982; Morey and Ojakangas, 1982).

* In their accessory-mineral study of the Lake Superior district sedimentary rock, Tyler and others (1940) redefined the stratigraphic nomenclature of Thwaites (1912). Their analysis is partially centered upon structural interpretation of the dipping units exposed on Fish Creek. The writers believed

that either the Douglas thrust or an associated minor fault may have caused the displacement of the Orienta and Freda sandstone at this locality. Within the confinement of outcrop geography, this postulated north-striking minor fault may well have been portrayed with a northwest strike with equal effect. Although the redefined outcrop nomenclature and associated offset might suggest faulting here, difficulty arises by alternative B being left-lateral rather than right-lateral displacement.

* The possibility of a lateral displacement in Bayfield County is further supported by Morey and Sims (1976), Sims and others (1980), and Klasner and others (1985). In each, a part of the discussion relates to the boundary between two Archean crustal tectonic terranes identified in the western Lake Superior region. The boundary separates a Superior province granite-greenstone terrane (2.7 Ga) from an older gneiss terrane (3.5 Ga) to the south. This feature has been named the Great Lakes Tectonic Zone by Sims and others (1980) and is traceable for 1,200 km from Minnesota eastward to Ontario. In northwestern Wisconsin the continuity of this zone is transected by right-lateral displacement associated with the Midcontinent Rift System. The trend of this zone is variously placed as coincidental with the northwest-southeast-oriented high gravity gradient referenced in part 1 of alternative A. In as much as the Douglas Fault and associated cross faults were active during the compressive or latter phase of midcontinent rifting, it is possibly a cross fault developed at this time in eastern Bayfield County along the trend of, or parallel to, this zone of transection. If present, this zone of transection should be confined to Wisconsin and not extended into Minnesota as shown by Morey and Sims (1976). Recently acquired high resolution aeromagnetic data in Minnesota argue against the presence of this zone of transection in Minnesota (Morey, verbal communication, 1985).

* This possible right-lateral cross fault might be related to Keweenawan-aged reactivation of Early Proterozoic or older fault systems mapped within the Penokean fold belt of north-central Wisconsin (Van Schmus and Bickford, 1981). The most logical fault to consider for such reactivation is the Mineral Lake Fault as suggested by Sims and others (1978).

* Such a postulated northwest-southeast striking fault through Bayfield County might be tectonically associated with a Middle Keweenawan ridge, mapped in the same vicinity by White (1966b). White carefully pointed out that this ridge, separating basins of thick from thin basalt deposition, is "strikingly parallel ... to some of the more conspicuous cross faults ... cutting the north limb of the Ashland Syncline." White concluded that these cross faults "seem to mark places where the thickness of lava changes abruptly."

* In developing a rigid-plate tectonic-interaction model for Midcontinent Rift System development, Chase and Gilmer (1973) suggested a transform fault through the Bayfield County area. Green (1983) presented several reservations concerning this alternative, and thus the existence of such a transform fault.

* Synthesis of refraction, gravity, magnetic, outcrop, and borehole data led Farnham (1967) to conclude that the Douglas Fault is offset in strike by a "north-trending cross fault" located in Bayfield County.

C. The Douglas Fault decreases in structural displacement, increases in depth or passes into an anticline to the east. Thwaites (1912) was the first to consider this alternative. He stated (p. 89) that the Douglas Fault "origin is a broken anti-

cline" and considering its extension into Bayfield County (p. 90), "The Douglas fault does not pass through the Apostle Islands, but appears to die out into a fold which in turn becomes gentler and finally flattens out beneath the drift-covered area of the Bayfield ridge." Forty-four years later, Thiel (1956) conducted two local north-south gravity traverses across the projected trace of the Douglas Fault immediately south of Ashland, Wisconsin. The consistent and uniform decrease of gravity from south to north without the usual anomaly associated with faulting in this area suggested to Thiel that should the Douglas Fault be present here in the subsurface the throw is reduced to a point no longer distinguishable by surface gravity. He also considered the possibility of this fault being buried at a great depth as well as the fault phasing structurally into a deeply buried fold.

* Patenaude (1966) conducted aeromagnetic surveys through northwestern Wisconsin and found a progressive decrease in amplitude from R. 9 W. to R. 7 W. Patenaude interpreted the data to suggest a decrease in fault throw eastward. However, after comparing this field data with computed theoretical model magnetic profiles, Patenaude reconsidered this interpretation and suggested that "the anomaly over the fault would be difficult to identify in the observed profiles if the displacement on the fault were less than 500 to 1000 feet at depths in excess of 10,000 feet below the level of observation." Thus, the possibility of the Douglas Fault extending into Bayfield County is preserved.

Patenaude (1966) identified an anticlinal structure, from magnetics. The anticline trends southeastward from T. 47 N., R. 8 W., with the Douglas Fault.

D. The Douglas Fault phases to the east into an angular unconformity separating Oronto Group from Bayfield Group sedimentary rocks. Irving (1883) studied the contact of basalt and sandstone along the Douglas Fault at the four Douglas County sites. Irving concluded that "These disturbances find their explanation, in part, ... in the irregularities of an unconformable contact, ... There seems to be no escape from the conclusion that ... the Douglas County contact line is one of unconformability complicated by faulting."

* In 1969 Hubbard visited the Amnicon River exposure of the Douglas Fault and subsequently decided that the generally accepted, fault-related breccia and gouge zone exposed there was in reality a mudstone containing angular blocks of volcanic clasts (verbal communication, H.A. Hubbard, 1969). He considered this "mudstone" to be in conformable contact with the overlying basalt a "thin, underlying sandstone." In turn he believes the base of the thin sandstone to be in angular unconformable contact with Keweenawan aged clastic sedimentary rock. Hubbard did not consider what he identified as "mudstone" to be the gouge zone caused by Douglas Fault displacement.

Although Myers (1971) believed the Hubbard interpretation of the Amnicon River site was "decidedly unconventional," he retained the concept of an angular unconformity after studying the vertically plunging Freda Formation (Oronto Group) outcrop found along Fish Creek southwest of Ashland, Wisconsin (fig. 1). Contrasting these dips with the essentially horizontal altitude of the Chequamegon Sandstone (Bayfield Group) exposed 7 km to the northeast along the Lake Superior shoreline at Barksdale, Wisconsin, he suggested that this structural discordance could be evidence of an angular unconformity. The sub-

surface trace of this possible unconformity would lie coincidental with the projected extension of the Douglas Fault as presented in alternative A or B.

E. The Douglas Fault passes to the east into a conformable contact separating Oronto Group from Bayfield Group sedimentary rock. Thwaites (1912) interpreted the Fish Creek exposure in Bayfield County and stated that "there is [here] a conformable gradation from quartz sandstone of the general type of the Bayfield group downward into red shales and arkose sandstone or conglomerate of the same general type as the main body of the Oronto group ... it is believed ... that the Bayfield and Oronto groups are conformable." Of course, this conformable contact concept is directly related to the question of whether or not this outcrop displays rock associated with both the Oronto and Bayfield Groups. Thwaites harbored no doubts regarding the lowermost strata being of Oronto lithologic character, and stated that "correlation of the upper quartzose beds with the Bayfield Group is much less definite."

Two recent dissertations have included the Fish Creek outcrop section in their discussion, but they are mixed in their interpretation. Hite (1968) accepted the conclusion of Thwaites (1912) by stating, "close examination of the South Fork of Fish Creek (section) ... strongly suggests a conformable contact between the Freda Sandstone and the Bayfield Group." Myers (1971) addressed the question of formational conformability along Fish Creek. His detailed description of this outcrop indicates that he believes these strata belong in their entirety to the Freda Formation of the Oronto Group.

Since Thwaites (1912) described the sole outcrop in the region of possible extension of the Douglas Fault eastward of its most easterly accepted position, there has been no resolution of the question of fault extension.

In the summer and early autumn of 1984 several hundred kilometers of seismic reflection lines were conducted throughout Douglas and Bayfield Counties by three different and competing seismic crews. Until these data are released to the public, or a deep test well is drilled in the area of dispute, the additional geologic information necessary for the definitive solution to this question will remain buried by the 30 to 180 m of Pleistocene sediment cover that masks the Midcontinent Rift System in this region.

CONCLUSIONS

It is suggested that the trend of the Douglas Fault continues through central Ashland County and then northeastward into the central Lake Superior area, where it links up with the Isle Royale Fault. This suggestion is supported by the vertical dip and heavy-mineral interpretation of outcrops located along Fish Creek in Bayfield County, the orientation and displacement of the Isle Royale Fault, the nature of offset faulting along the north flank of the St. Croix Horst, and the structural fabric of the pre-Midcontinent Rift terrane. Geophysical support for the extension includes the position and shape of the Bayfield County gravity minima, the orientation of steep gravity gradients located offshore Lake Superior, and interpretations of regional seismic refraction profiles. The effect of extending the trend of the Douglas Fault east and northeastward from Bayfield County, Wisconsin, is to increase the width of the Bayfield Basin north and east of the area of Chequamegon Bay, and to project the St. Croix Horst into the central sector of the Lake Superior Basin.

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